Dear editor,

We carefully considered the comments by the 3 reviewers on our manuscript “Impact of capillary rise and recirculation on crop yields” submitted on 13 Apr 2017 as hess-2017-223.

In accompanying documents we react in detailed point-by-point replies on the reviewers remarks. We could meet almost all demands; in cases where we could not we provided clear arguments. In addition to that we re-simulated all cases with the recently released public Swap version 4.0.1 and we supplied an example in supplementary material that enables readers to verify the core of this paper.

With this letter we upload:

- Abstract
- The revised manuscript (with and without annotations)
- Supplementary material
- Reply to reviewer #1
- Reply to reviewer #2
- Reply to reviewer #3

We think the paper has improved considerably and we appreciate the constructive suggestions by the reviewers.

Yours sincerely,

Joop Kroes and co-authors

Response to Referee #1 (reviewer1_hess-2017-223-RC1.pdf)

Reviewer's General comment 1: "The authors are ignoring the work of the early Dutch physical scientist, Symen Barend Hooghoudt"
Our reply to General comment 1:
As the reviewer suggested we read [1], [2] and [3]. We agree with the reviewer that Hooghoudt did quantative work on capillary rise and crop yields, especially in [1]. Indeed Hooghoudt mentions the relation between capillary layers and yields in at least 2 publications mentioned by the reviewer. But his relations are always related to groundwater tables. Recirculation as we discuss is not mentioned. However the quantitative work done by Hooghoudt on capillary rise and crop yields was long before computer models, it should be recognised and we will refer to his early work when we talk about the importance of capillary rise and refer to his earliest publication [1] in line 90.

*References*:
[1] Hooghoudt, S.B., 1937. Contributions to the Knowledge of Some Physical Soil Properties. No. 43 (13) B, p. 461-676. Determination of the Conductivity of Soils of the Second Kind (In Dutch: Verslagen van Landbouwkundige Onderzoekingen, no. 43(13) B, Dep. van Economische Zaken, Directie van den Landbouw. Algemeene Landsdrukkerij), The Hague.
[2] Hooghoudt, S. B. (1952). Tile drainage and subirrigation. *Soil Science*, *74*(1), 35–48.
[3] Raats, P. A. C., & Ploeg, R. R. van der. (2005). Hooghoudt, Syman Barend. In D. Hillel (Ed.), *Encyclopedia of Soils in the Environment. Vol. 2* (pp. 188–195). Elsevier, Amsterdam.

Reviewer's General comment 2 : "I do not understand Figure 2b."
Our reply to General comment 2:
Figure 2b illustrates the hydrological condition "Free Drainage with recirculation across bottom of Rootzone". As stated below the figure this condition b is a common free drainage situation which includes upward flow due to recirculating percolation water. Recirculation also happens in free drainage situations. We quantified recirculation separately from capillary rise using model experiments illustrated in figure 2a and 2b. see also the special paragraph in lines 250-264
To make the role of recirculation even more explicit we changed line 101 from "The driving force for induced capillary rise is the difference in soil water potential," into "The driving force for induced capillary rise "and recirculation" is the difference in soil water potential,"

Specific comment From reviewer: l. 42 and l. 623:
Our reply: SSA was changed into SSSA

Specific comment From reviewer: l. 52-54:
Our reply: The use of names of USDA soil taxonomy can be avoided here. Aquepts were explained because this is relevant. The sentence with names of Histosols and Inceptisols was deleted because it has very little added value.

Specific comment From reviewer: l. 57, 69, 72, and 125:
Our reply: We verified the references and give both scientific and common name for those crops where the reference also uses Scientific names. This was the case in l.69 (quinoa) and l.72 (coybean) where we added the scientific name according to the reference.
This comment also made us look at the reference Geerts et al (2006) which was missing in the References and therefore added to the References.

Specific comment From reviewer: l. 96:
Our reply: i) the “ss” was a typing error and is changed into “as”
ii) Zipper et al.(2015) quantified “groundwater yield subsidy” as harvested biomass in $Mg.ha^{-1}$ Dry Matter. The unit was added to the text.

Specific comment From reviewer: l. 101:
Our reply: clarified by defining the difference ( =” at different soil depths”)

Specific comment From reviewer: l. 106:
Our reply: “Richards equation” was applied throughout the text

Specific comment From reviewer: l. 109:
Our reply: we defined SWAP at the suggested location. And added the latest reference to the model: Kroes et al. (2017).

Specific comment From reviewer: l. 109 and 138:
Our reply: WOFOST is defined at the first place where it is mentioned, similar to SWAP.

Specific comment From reviewer: l. 153:
Our reply” “van Genuchten” (no capital letter, but “v” in “van”) was applied

Specific comment From reviewer: l. 179:
Our reply: CO2 as $CO_2$

Specific comment From reviewer: l. 190:
Our reply: “is grown” changed to “are grown” and the sentence was improved.

Specific comment From reviewer: l. 195-196:

Our reply: Table 1 is extended with an explanation of the acronyms used for the names of the case studies.

Specific comment From reviewer: l. 214:
Our reply: by referring to Table 1 this should become clear.

Specific comment From reviewer: l. 246:
Our reply: this is too much detail, and also explained in the extended material. So we deleted part of the sentence between brackets and referred to the extended material(s).

Specific comment From reviewer: l. 259:
Our reply: ’artificial restriction’ is not mentioned before, se we deleted the phrase “that inherently include the mentioned ’artificial restriction’”

Specific comment From reviewer: l. 275:
Our reply: DM indeed stands for Dry Matter. We agree that it was confusing. But with the explanation given in Table 1 we hope that this is clear now (see also our previous reply to comments: l. 195-196). DM is used 47 times, the first wime DM is used as Dry Matter we give now an explanation.

Specific comment From reviewer: l. 296, 305, and 306:
Our reply: These acronyms are now explained in Table 1 (see also our previous reply to comments: l. 195-196).

Specific comment From reviewer: l. 336
Our reply: we moved the abbreviation $FD_{rc}$ to the end of the sentence where it directly is linked to Table 4. We feel that the tables 1 and 4 together with the update text make the text readable enough and an additional list of abbreviations is not required.

Specific comment From reviewer: l. 345:
Our reply: capital letters were deleted

Specific comment From reviewer: l. 349-350:
Our reply: in the text we use “the Netherlands”, only in References we allowed “The”

Specific comment From reviewer: l. 372:
Our reply: see our reply to Specific comment From reviewer: l. 336

Specific comment From reviewer: l. 383:
Our reply: Sentence was extended to clarify the differences : “differences between downward flux across the bottom of the rootzone ($q_{percolation}$ in Figure 2) of 3 hydrological conditions”

Specific comment From reviewer: l. 393, 394:
Our reply: clearly was deleted

Specific comment From reviewer: l. 421-422:
Our reply: We started with the statement “High upward flow values are found in loamy soils as is expected”. Low values for loamy soils were found because of high water stress which reduce upward flow and can be more important than soil type. The sentence was slightly rephrased to make this more clear.

Specific comment From reviewer: Line 430:
Our reply: We looked in more detail at figures 46 and 47 in Tolman (1937, p.157) and concluded that this type of macro-scale hysteresis is automatically accounted for by the dynamic numerical scheme of SWAP and does not require any special modelling option for hysteresis of the θ-h relationship.
Reference:
Tolman, C. F. (1937). *Ground Water*. Retrieved from https://ia801500.us.archive.org/16/items/in.ernet.dli.2015.1788/2015.1788.Ground-Water.pdf

Specific comment From reviewer: l. 452:
Our reply: “then” changed to “than”

Specific comment From reviewer: l. 460:
Our reply: we changed “difference” into “impact of upward flow on crop yields” because it is more clear and that is the core of our message.

Specific comment From reviewer: l. 494,
Our reply: all References have year in parenthesis

Specific comment From reviewer: about definitions in Tables 1, 5 and 6
Our reply: Table 1 was already updated; Tables 5 and 6 have now explanation of $FD_{nc}$, $FD_{rc}$ and Ave

Specific comment From reviewer about Figures 4, 5, 6, and 7::
Our reply: Number on the y-axis are rotated by $90^0$ , so they face the reader now.

**Response to Referee #2 (reviewer2_hess-2017-223-RC2.pdf)**

*Reviewer's first major concern*: "such a demonstration would necessitate comparing the accuracy of yields predicted with the bucket approach versus the proposed approach, which was not properly done in this study and would imply quite substantial additions to the manuscript."

*Our reply to the first major concern:*
The idea of the reviewer is strongly appealing and we would have done so if the measurements at the experiments were sufficient. However, the measured data sets are insufficient to calibrate and validate the soil and crop parameters in such detail that they allow proper statistical evaluation of the bucket approach and the approach with full simulation of capillary rise and recirculation. The calibration of both model approaches has too much freedom with the available datasets, which upsets a reliable validation. Therefore we used the measured data sets to illustrate that with common soil and crop input values SWAP-WOFOST yields realistic and plausible results for the crops considered in this study. Further, crop growth and soil water flow are simulated by SWAP-WOFOST with state of the art concepts. Therefore we may expect that the model itself can be used to show the effect on crop yield of different boundary conditions with respect to zero flux, recirculation and capillary rise.

*Reviewer's second major concern*: "description of the methods is rather incomplete, as central elements of the study are not presented" and in detail: "How is the numerical method blocking recirculation implemented? What is the domain vertical discretization? How is yield affected by water limitation in SWAP (provide at least a couple of sentences)? How were the 72 sets of Mualem – van Genuchten parameters obtained (e.g. artificial neural network, pedotransfer function, etc.)?"

*Our reply to the second major concern:*
The numerical method to block recirculation is explained in line 252-256: "A synthetic modelling option has been implemented to stop upward flow from reaching the root zone, without inhibiting percolation. This option is implemented in the numerical solution of the Richards equation and minimizes vertical conductivity just below the root zone in situations that the model simulates upward vertical flow." However, this explanation is not very detailed and we add an extra phrase about the used numerical technique and referenced to details in Supplementary Material (S4) that is part of this paper. We implemented this option in SWAP version 4 which is available online since June 2017 (www.swap.alterra.nl). Our explanation in the Supplementary Material (S4) will also serve as support to the user manual (Kroes et al., 2017). This should increase transparency and will allow future users to simulate similar conditions.
Furthermore we repeated all simulations with Swap version 4.0.1 which is available on internet. The field case study for potatoes (V-Potato) has been made public with input for the Conditions A and B so everyone is able to repeat this case and get identical results as given in Table 3. The results presented in April 2017 were simulated using Swap version 3.75, a version that was not released to public/internet. Repeating all simulations with the newer version Swap4.0.1 implied slight changes to most of our output but have no impact on the core of our results and most important : left our conclusions unchanged. We made new graphs, tables and all numbers according to the latest simulations with Swap4.0.1. As stated before these are minor changes that have no impact on the conclusions but contribute to transparency.

The domain of the vertical discretization is briefly summarized in line 234-250. We applied 72 different soil schematizations which is explained in line 226-237. Each soil schematization consists of one or more soil horizons, each with different soil physical/hydraulic properties. This is described in detail by Wösten et al. (2013a) and available on internet http://www.wur.nl/nl/show/Bodemfysische-Eenhedenkaart-BOFEK2012.htm. We added a sentence to clarify this.

We will insert sentences to clarify how yield is affected by water limitation. In line 200 we will insert: "Oxygen and drought stress reduce transpiration which subsequently reduce crop assimilation. Oxygen stress is described with the process-based method of Bartholomeus et al. (2008) and parameterised as described by Hack et al. (2016)" The reference list is extended with: Bartholomeus, R. P., Witte, J. P. M., van Bodegom, P. M., van Dam, J. C., and 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

*Reviewer's third major concern*: "the quality of the yield model is not as good as suggested by the mean error indicator, which is the indicator mostly referred to throughout the results and discussion." And "the mean error is not such a good model quality indicator. In Table 2, 4 out of 5 Nash-Sutcliffe indices for yield are below zero, which suggests that the yield model is not accurate"
A negative NS index means that a the observed mean is a better predictor than the model outcome.

*Our reply to the third major concern:*
The reviewer has a point. The simulation results could be improved. The negative Nash-Sutcliffe (NS) index demonstrates that the observed mean is a better predictor than the model outcome. However, one has to bear in mind that perfect calibration is not the objective of this study. As mentioned in line 198, we used calibration values from earlier studies (Kroes et al. 2015 and Hack et al., 2016). No detailed assimilation measurements were executed on the fields and the meteorological data was not measured on site, but taken from meteorological stations sometimes more than 30km away. Furthermore, no detailed information concerning fertilizer applications and soil carbon is available, therefore we considered it constant in time. In lines 311-314 we mention that the calibration can be improved. We removed the large negative NS value of -32.5 for Yield in B-Potato because it is based on an insufficient number of (n=2) observations and extended the discussion section where the field experiments are debated.

In this research we want to demonstrate that for crop growth modelling a proper soil modelling component that includes recirculation is important. We know from experience that WOFOST with a simple soil model underestimates water availability in the rooting zone and consequently overestimates drought stress (A regional implementation of WOFOST for calculating yield gaps of autumn-sown wheat across the European Union. Van Boogaard, H., Wolf, J., Supit, I., Niemeyer, S., Ittersum, M., 2013. Field Crops Research, vol143, March 2013, p. 130-142). The results in this study clearly demonstrates that the (simulated) yield reduction resulting from over-estimated drought stress is reduced when capillary rise and recirculation are taken into account. We will add a reference to the above mentioned paper to the reference list and extend the discussion with a separate paragraph about bucket approaches versus full simulation of capillary rise and recirculation.

Specific comment From reviewer

Title: The title should mention that the paper presents simulated results.
*Our reply:* “Impact of capillary rise and recirculation on simulated crop yields” is fine

Line 31 (L31): It is unclear what the unit “a” represents
*Our reply:* the unit “a” (abbreviation of Lat. *annus*) is changed into the unit “year” or the unit “season”

Line 137: The chosen time step is one day
*Our reply:* For crop growth WOFOST applies a time step of one day with integration of light interception during the day. However, SWAP calculates soil water flow at very small time steps ranging between a few seconds and a few hours depending on the variation in boundary conditions. The exchange of information between the 2 sub models SWAP and WOFOST occurs at the end of day and therefore does not allow impact analyses during the day. Such detailed analyses would require a different crop growth model. We added a sentence at the beginning of the method description to clarify timing.

Line 183: Feddes et al. (1978) stress function and Jarvis (1989) compensation function are known to be entangled
*Our reply:* For drought stress we applied Feddes et al. (1978) combined with Jarvis (1989) compensation function using a compensation factor (ALPHACRIT) of 0.7 (see manual Kroes et al., 2017). We mention the compensation factor and refer to Jarvis (1989) and Jarvis (2011) in the Results and Discussion sections of the text. Jarvis (1989) is added to the references.

Line 252 and many other places: The term “upward flow” is ambiguous as capillary rise and upward recirculation are both upward flow
*Our reply:* you are very right that “upward flow” may have 2 meanings. It may refer both to recirculation and capillary rise. Previous reviewers indicated this and made us introduce Figure 2. We will screen the text on “upward flow” We will only speak of “upward flow” when it can refer to both “recirculation” and “capillary rise”; if not, we will replace it by the specific term.

Line 409-434: Please use references to support your claims.
*Our reply:* we inserted three references: Ahuja et al, 2014, Guderle and Hildebrand (2015) and (Boogaard et al., 2013).

Typos: Line 96: “ss”?
*Our reply:* “ss” in Line 96 will be changed into “as”

References:
*Our reply:* Thank you for the suggestions. These references are relevant and we included three of the five mentioned references.

**Response to Referee #3 (reviewer3_hess-2017-223-RC3.pdf)**
Interactive comment by Referee P.Kowalik, 9 august 2017

Reviewer's first major concern is with the title: "I do not agree with the term "recirculation" here, much better would be "water retention"

*Our reply to the first major concern:*
This seems logical but this change will have a large impact om the paper and make it too static. Indeed water is retained first and then recirculated. We feel that we would then have to insert "water retention" as additional process. It would complicate the article and have no impact on the conclusions.
We had a lot of discussions about the title and feel that the current title is the best and most clear one.

Reviewer's second major concern: "suggest to add some remarks about CROP model which is still in use in many countries"

*Our reply to the second major concern:*
We will make a reference to the historical development of the SWAP model and mention the CROPR model (Feddes et al., 1978) as one of the models to describe the above ground dry matter production. In later years SWATR was succeeded by SWAP and CROPR by WOFOST.

Reviewer's third major concern is about the synthetic modelling option : "it is not logical and realistic. The fantasy of authors is too great here"

*Our reply to the third major concern:*
We agree that the incorporated synthetic modelling option is unrealistic. But that is exactly the point we want to make! This synthetic option is used to stop all upward flow, which in turn reduces simulated yields. This is practically impossible to carry out in field experiments and we therefore used this synthetic modelling experiment. We are convinced that we implemented this well and we made it available online as we indicated to the 2nd reviewer in SWAP4.0. We feel that by doing so our fantasy is not too great and can at least be shared with many others. In this way we were able to mimic the boundary conditions of bucket type of models.

*Title:*

**Impact of capillary rise and recirculation on simulated crop yields**

*Joop Kroes[1], Iwan Supit[1,2] Jos Van Dam[3], Paul Van Walsum[1], Martin Mulder[1]*

[1] *Wageningen University & Research - Environmental Research (Alterra)*

[2] *Wageningen University & Research – Chair Water Systems and Global Change*

[3] *Wageningen University & Research – Chair Soil Physics and Land Management*

*Abstract*

This paper describes impact analyses of various soil water flow regimes on grass, maize and potato yields in the Dutch delta, with a focus on upward soil water flows capillary rise and recirculation towards the root zone. Flow regimes are characterised by soil composition and groundwater depth and derived from a national soil database. The intermittent occurrence of upward flow and its influence on crop growth are simulated with the combined SWAP-WOFOST model using various boundary conditions. Case studies and model experiments are used to illustrate impact of upward flow on yield and crop growth. This impact is clearly present in situations with relatively shallow groundwater levels (85% of the Netherlands), where capillary rise is a well-known source of upward flow; but also in free-draining situations the impact of upward flow is considerable. In the latter case recirculated percolation water is the flow source. To make this impact explicit we implemented a synthetic modelling option that stops upward flow from reaching the root zone, without inhibiting percolation. Such a hypothetically moisture-stressed situation compared to a natural one in the presence of shallow groundwater shows mean yield reductions for grassland, maize and potatoes of respectively 26, 3 and 14 % or respectively about 3.7, 0.3 and 1.5 ton dry matter per ha. About half of the withheld water behind these yield effects comes from recirculated percolation water as occurs in free drainage conditions and the other half comes from increased upward capillary rise. Soil water and crop growth modelling should consider both capillary rise from groundwater and recirculation of percolation water as this improves the accuracy of yield simulations. This also improves the accuracy of the simulated groundwater recharge: neglecting these processes causes overestimates of 17% for grassland and 46% for potatoes, or 63 and 34 mm year$^{-1}$, respectively.

## 1. Introduction

Crop growth strongly depends on soil moisture conditions. Climate variables determine these conditions through rain that penetrates directly into the root zone or comes available via lateral flow. The moisture distribution in the soil strongly depends on soil physical properties that determine vertical flow. Upward soil water flow becomes an especially vital supply term of a crop when the soil water potential gradient induced by the root-extraction manages to bridge the distance to the capillary fringe, inducing increased capillary rise. In this paper we follow the definition of capillary rise, given by SSSA (2008), as the "phenomenon that occurs when small pores which reduce the water potential are in contact with free water". This implies that capillary rise as a source for upward flow to crop roots requires the presence of a groundwater table. In conditions without a groundwater table there may also be a contribution of upward flow to crop roots through the process of recirculation. Recirculation is a known process discussed already by Feodoroff (Rijtema and Wassink, 1969) but has never been quantified. We quantified recirculation separately from capillary rise using model experiments.

The contribution of (intermittent) upward flow to the total water budget can be significant. For example Kowalik (2006) mentions that during the grass growing season, in soils with the groundwater close to the soil surface (Aquepts) the capillary rise induced by root extraction varies between 60 and 150 mm per year. Babajimopoulos et al. (2007) found that under the specific field conditions about 3.6 mm/day of the water in the root zone originated from the shallow water table, which amounts to about 18% of the water transpired by a maize crop. Fan et al. (2013) analysed the groundwater depth globally and concluded that shallow groundwater influences 22 to 32% of global land area, and that 7 to 17% of this area has a water table within or close to plant rooting depths, suggesting a widespread influence of groundwater on crops. This is especially the case in delta areas where high population densities occur and agriculture is the predominant land use.

Wu et al. (2015) showed that capillary rise plays a main role in supplying the vegetation throughout the season with water, hence a strong dependence of vegetation upon groundwater. Han et al. (2015) applied HYDRUS-1D with a simplified crop growth model and concluded for cotton in a north-western part of China that capillary rise from groundwater contributes almost to 23% of crop transpiration when the average groundwater depth is 1.84 m. According to Geerts et al. (2008) the contribution from capillary rise to the quinoa [Chenopodium quinoa Willd.] production in the Irpani region (Peru), ranges from 8 to 25% of seasonal crop evapotranspiration (ETc) of quinoa, depending mostly on groundwater table depth and amount of rainfall during the rainy season. The contribution from a groundwater table located approximately 1.5 to 2 m deep may represent up to 30% of the soybean [Glycine max (L.) Merr.] water requirements in sandy pampas (Videla Mensegue et al., 2015).

In 85% of the area in the Netherlands the average groundwater table is less than 2 meter below the soil surface in (De Vries, 2007), where root extraction can induce capillary rise from groundwater. Wesseling and Feddes (2006) report that in summers with a high evapotranspiration demand, crops partially depend on water supply from soil profile storage and induced capillary rise. Van der Gaast et al. (2009), applying the method of Wesseling (1991), found for the Netherlands a maximum capillary flow of 2 mm/d to the root zone in loamy soils where the groundwater level is at 2.5 meter below the soil surface.
Although the contribution of capillary rise to the total water budget can be significant, it is an often neglected part of the crop water demand in situations of shallow groundwater levels (Awan et al., 2014). The capillary properties of a soil strongly depend on soil type. Rijtema (1971) estimated that loamy soils have an almost 2 times higher capillary rise than sandy soils.

Integrated approaches are needed to relate water availability to crop yield prognosis (Van der Ploeg and Teuling, 2013; Norman, 2013). The importance of capillary rise as supplier of water to crops has been shown by many researchers (e.g. Hooghoudt, 1937; Huo et al., 2012; Talebnejad, and Sepaskhah, 2015; Han et al., 2015); however we found only a few studies that use an integrated modelling approach (Xu et al., 2013; Zipper et al. 2015) to quantify capillary rise for different hydrological conditions (including free drainage) using physically based approaches. In this study we explicitly consider the effect of crop type, soil type, weather year and drainage condition on capillary rise. Zipper et al. (2015) introduced the concept of groundwater yield subsidy as the increase in harvested yield ($kg/ha^{-1}$) in the presence of shallow groundwater compared to free drainage conditions. Following their line we introduce the concept of soil moisture yield subsidy as additional yield increase in free drainage conditions due to recirculation of percolated soil moisture.

The driving force for induced capillary rise and recirculation is the difference in soil water potential, referred to as heads, at different soil depths. There are several models available that solve these head differences numerically. Ahuja et al. (2014) evaluated 11 models commonly applied for agricultural water management. Six of these models use simple ‘bucket’ approaches for water storage and have in some cases been extended with more or less empirical options for capillary rise. Five models have the ability to numerically solve Richards equation for water movement in the soil. Examples are HYDRUS (Šimůnek et al., 2008) and SWAP (Feddes et al., 1988, Van Dam et al., 2008).
We applied the integrated model SWAP-WOFOST (acronyms for Soil Water Atmosphere Plant - WOrld FOod Studies) to solve head differences and crop yield simulations. Kroes and Supit (2011) applied the same integrated model to quantify the impact of increased groundwater salinity on drought and oxygen of grassland yields in the Netherlands. They

recommended further analyses using different crops and different boundary conditions. We now apply this model with different boundary conditions using 45 years of observed weather and three different crops. For the lower boundary we use different hydrologic conditions that influence the vertical flow. For the soil system itself we use a wide range of soil physical conditions. The importance of the soil system was already stated by several authors like Supit (2000). We build on their suggestions and apply the tools for different crops and boundary conditions. Before we applied the model to different boundary conditions we validated it at field scale.

This paper quantifies the effects of (intermittent) upward flow on crop growth under different conditions of soil hydrology, soil type and weather. The effects are separately quantified in terms of flow source, namely capillary rise and recirculated percolation water. Therefore we introduced a synthetic model option and performed a numerical experiment. We studied forage maize, grassland and potatoes and we hypothesize that neglecting upward flow will result in neglecting a considerable amount of soil moisture that is available for crop growth. We quantify this amount and show the importance of including upward flow for crop growth modelling. Our main research questions are: i) Can upward flow with capillary rise and recirculated percolation water as source be quantified separately?, ii) What is the contribution of capillary rise and recirculated water to crop yield and groundwater recharge?

## *2. Materials and methods*

### *2.1 Modelling approach*

We applied the coupled SWAP and WOFOST modeling system, using a one day time step. SWAP (Van Dam et al., 2008; Kroes et al., 2017) is a one-dimensional physically based transport model for water, heat and solute in the saturated and unsaturated zone, and includes modules for simulating irrigation practices. The first version of SWAP, called SWATRE, was developed by Feddes et al. (1978). This version also included a module for crop production, CROPR that applied principles of C.T. de Wit (1965) and is still applied in several countries. SWAP simulates the unsaturated and saturated water flow in the upper part of the soil system, using a numerical solution of the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial \left[ K(h) \left( \frac{\partial h}{\partial z} + 1 \right) \right]}{\partial z} - S_a(h) - S_d(h) - S_m(h) \qquad (1)$$

where: $\theta$ is volumetric water content (cm$^3$ cm$^{-3}$), $t$ is time (d), $K(h)$ is hydraulic conductivity (cm d$^{-1}$), $h$ is soil water pressure head (cm) and $z$ is the vertical coordinate (cm), taken positively upward, $S_a(h)$ is soil water extraction rate by plant roots (d$^{-1}$), $S_d(h)$ is the extraction rate by drain discharge in the saturated zone (d$^{-1}$) and $S_m(h)$ is the exchange rate with macro pores (d$^{-1}$).

The numerical solution of this equation uses variable time steps that depend on boundary conditions and an iteration scheme. For example, high fluxes require time steps that are much smaller than 1 day (see Kroes et al, 2017 for a detailed explanation).

Root water extraction and lateral exchange with surface water are accounted for. In this study we do not use the option to exchange water flow with macro pores. The soil hydraulics are described by the Mualem–van Genuchten relations and the potential evapotranspiration is calculated with the Penman–Monteith equation (Allen et al., 1998). At the bottom boundary hydraulic heads, supplied by a separate regional hydrological model can be used to simulate interaction between bottom boundary fluxes and groundwater levels. Drainage and infiltration through the lateral boundary account for the flow to surface water. The surface water system is simulated using a simplified, weir controlled, water balance. Note that the surface water system in its turn interacts with the groundwater system. In previous years, SWAP has been successfully used to study soil-water-atmosphere-plant relationships in many locations with various boundary conditions (e.g. Feddes et al., 1988; Bastiaanssen et al., 2007). See Van Dam et al. (2008) for an overview. A recent list is available at http://www.swap.alterra.nl. Eitzinger et al. (2004), Bonfante et al. (2010), Oster et al. (2012), and Rallo et al. (2012) amongst others tested the model performance.

WOFOST is a crop growth simulation model, its principles are explained by Van Keulen and Wolf (1986). Van Diepen et al. (1989) presented the first WOFOST version. WOFOST is applied in many studies (e.g. Rötter, 1993; Van Ittersum et al., 2003; de Wit and Van Diepen, 2008; Supit et al., 2012; De Wit et al., 2012). Crop assimilation is calculated as function of solar radiation and temperature, using a 3 point Gaussian integration method accounting for leaf angle distribution and extinction of direct and diffuse light. The assimilation is reduced when water or nutrient stress occurs. Subsequently, the maintenance respiration is subtracted and the remaining assimilates are partitioned over the plant organs (i.e. leaves, stems, roots and storage organs). For maize and potatoes the partitioning is development stage dependent. For perennial grass however, a constant partitioning factor is assumed. By integrating the difference between growth and senescence rates over time, dry weights of various plant organs are established. In SWAP-WOFOST, crop assimilation depends on the ambient $CO_2$ concentration as well (see: Kroes and Supit, 2011; Supit et al., 2012). To account for unknown residual stress caused by diseases, pests and/or weeds an additional assimilation reduction factor is introduced. The rooting density decreases exponentially with depth. To withdraw water from deeper soil layers for crop uptake a form of compensatory root uptake is used in case the upper part of the soil is very dry (Jarvis, 2011). The increasing atmospheric $CO_2$ concentrations during relatively long historical simulation periods (>20 years) is accounted for.

*2.2 Case studies for validation*

SWAP-WOFOST is validated using results of 7 case studies at 6 locations in the Netherlands (Figure 1) where grassland, maize and potatoes are grown and observations were available from hydrology, soil and crop. The main characteristics of the 7 cases are summarized in Table 1. The soil texture ranges from sand to clay. The observations included parameters, such as groundwater levels, yields and in some cases soil moisture contents, soil pressure head and evapotranspiration. The weather data were collected from nearby weather stations or from onsite measurements. Observations for case studies 1 and 2 (DM-Grass and DM-Maize in Table 1) were available for a period of 22 years (1992-2013) from one field where grassland and maize was grown for respectively 7 and 15 years.

We used the model calibrations carried out by Kroes et al. (2015) and Hack et al. (2016) and limited our calibration efforts to parameter values for drought and management (Table 1), focussing on validation of results. Planting and harvest dates were given. Oxygen and drought stress reduce transpiration which subsequently reduce crop assimilation. Oxygen stress is described with the process-based method of Bartholomeus et al. (2008) and parameterised as described by Hack et al. (2016). Drought stress was parameterised using the dry part of the reduction function proposed by Feddes et al. (1978). Drought stress is absent when the soil pressure head *h* exceeds the critical value of *h3*. Drought stress increases linearly between *h3* and at *h4* (wilting point). The critical pressure head *h3* differs between lower and higher potential transpiration (respectively *h3l* and *h3h*) rates. In conditions with drought or oxygen stress, the reduction in stressed parts is partly compensated by extra root water uptake in those parts of the root zone with more favorable soil moisture conditions (Jarvis, 1989).

For all cases a so-called management factor was used to close the gap between observed and actual yield. The input crop parameters for maize only differed with respect to the management factor which ranges from 0.85-0.95. The management factors are relatively high because the case study locations have good management. It is very likely that we miss some processes even though our modelling approach is mechanistic, because it is still relatively simple. Some processes like pests and diseases are not included and may play a role in the field; the calibration was done on experimental farms where the impact from diseases and pests is minimal.

For potatoes the input crop parameters were kept the same for all 3 cases (Table 1). Maximum rooting depth for grassland, maize and potatoes were respectively 40, 100 and 50 cm.

Soil water conditions were different for all locations and boundary conditions varied, depending on local situation and available data (Table 1). In most cases a Cauchy bottom boundary condition was applied using a hydraulic head based on piezometer observations from the Dutch Geological Survey (https://www.dinoloket.nl/). Observed groundwater levels were used as lower boundary condition for Borgerswold (crop: potato). In 2 cases a lateral boundary condition was applied with drainage to a surface water system (Table 1). The simulation results were analysed using an R-package (Bigiarini, 2013) and the statistics are presented in Table 2.

*2.3 Soil crop experiment to analyse the role of recirculation and capillary rise*

To analyse the impact of soil type on upward soil water flow we modelled soil-crop experiments using 72 soils. Each soil schematization consists of one or more soil horizons, each with different soil physical properties. The method is described in detail by Wösten et al. (2013a) and the data are available at http://www.wur.nl/nl/show/Bodemfysische-Eenhedenkaart-BOFEK2012.htm. The 72 soils were aggregated from 315 soil units of the 1:50000 Dutch Soil Map using soil hydraulic clustering methods and considering the following properties: maximum groundwater depth, saturation deficit between a certain depth and the soil surface, transmissivity for horizontal water flow, resistance for vertical water flow and availability of water in the root zone (Wösten et al., 2013b). The resulting soil hydraulic properties were subsequently used as SWAP-WOFOST input. The bottom of the soil profile is set to 5.5 meter below the soil surface. At this depth, the simulated root zone soil water fluxes are not affected anymore by the actual depth of the soil profile bottom. The root zone lower boundary is dynamic, it depends on root growth and consequently varies in time.

For each soil we applied 3 hydrological conditions (Figure 2), ranging from relatively dry (a) to relatively wet (c) The latter is the natural situation in most of the Netherlands. This hydrological condition has a fluctuating groundwater level derived from a national study (Van Bakel et al., 2008). This national study used simulation units which are unique in land use, crop type and drainage conditions resulting in daily groundwater fluctuations Lateral infiltration and drainage are accounted for ($q_{infiltration}$ *and* $q_{drainage}$ in Figure 2 c). We selected three large simulation units for grassland, maize and potato with long term average groundwater levels between 40 and 120 cm below the soil surface , covering respectively 1806, 794 and 58102 ha using data from Van Bakel et al. (2008). See the supplementary material (S2) for more detail and the supplementary material of Kroes and Supit (2011) for an additional explanation of the study from Van Bakel et al (2008).

The other two conditions (a) and (b) are unsaturated and have no groundwater due to a free-draining bottom boundary ($q_{leaching}$, see Figure 2, conditions a and b). Condition (a) has been included in this study to explicitly demonstrate the role of recirculation as source of upward flow. A synthetic modelling option has been implemented to stop upward flow from reaching the root zone, without inhibiting percolation. This option is implemented in the numerical solution of the Richards equation and minimizes vertical conductivity just below the root zone in situations that the model simulates upward vertical flow. We did this using an implicit scheme also for the conductivity in such situations. Code adjustment was necessary to carry out the model experiment (no recirculation) and to demonstrate (quantitatively) the added value of simulating more detailed water fluxes in the soil profile in comparison to simple bucket approaches. When crop models are used for yield forecasting these detailed processes play an important role; neglecting them generally may cause large errors. We want to improve our understanding of processes in the soil-crop continuum and thereby minimizing errors. This synthetic option will be distributed with the latest model release.

The upward flux across the bottom of the root zone can either stem from capillary rise or from percolation water that is recirculated ($q_{recirc}$ and $q_{caprise}$, see Figure 2 conditions b and c). The capillary rise (Figure 2 c) has two sources: i) groundwater and ii) recirculated percolation water. In all hydrological conditions percolation across the root zone and leaching across the lower boundary of the model profile occurs ($q_{percolation}$ and $q_{leaching}$ in Figure 2). All fluxes are calculated using small variable time steps (< 1 day); however results are accumulated to daily net fluxes, which implies that small variations within a day cannot be seen from the results. Recirculation depends on crop water demand, soil hydraulic properties and presence of soil moisture.

The crop parameters were kept the same as for the case studies, with a few exceptions: i) for grassland an average management factor of 0.9 was used, ii) timing of grass-mowing was done when a dry matter threshold of 4200 kg.ha$^{-1}$ DM (Dry Matter) was exceeded, iii) for maize and potatoes the harvesting dates were respectively set to 25-Oct and 15-Oct.

The 3 crops and 3 lower boundary conditions resulted in 9 combinations. Each combination was simulated with 72 soils for a period of 45 years (1971-2015) with meteorological data from the station De Bilt (KNMI, 2016). In a subsequent analysis we grouped the results of these 72 soils to 5 main soil groups clay, loam, peat, peat-moor and sand (Figure 3) to be able to analyse the impact at grouped soil types.

The implementation of the synthetic modelling option is explained in supplementary material (section S4) with references to open source model SWAP version 4.0.1 which was used to carry out all the simulations.

## 3 Results

*3.1 Case studies for validation*

The first 2 case studies are from one location (De Marke) where a grassland-maize rotation was practised. The results show that the hydrological conditions (Figure 4 and Table 2) were simulated accurately for those years for which observed data were available (1991-1995). From 1995-1997 the groundwater levels drop as a result of low precipitation (about 700 mm/year). The fall of the year 1998 shows rising groundwater levels that correspond well with very wet conditions at that moment. The simulated grassland yields are overestimated by 133 kg.ha$^{-1}$ DM and the simulated maize yields are underestimated by 257 kg.ha$^{-1}$ DM which differences are well within acceptable ranges (Figure 5 and Table 2).

For the other 2 maize case studies (C-Maize and D-Maize) groundwater levels and soil moisture are well simulated (Table 2). The simulated maize yields (Table 2) are less acceptable for case C-Maize as is indicated by a zero or negative Nash-Sutcliffe efficiency (NS) which suggests that the observed mean is a better predictor than the model. One should consider that the NS efficiency is sensitive to sample size and outliers. In 1976, a very dry year, the soil hydrology dynamics and the resulting yield were well captured. The yield of case study D-Maize has a small bias of 333 kg.ha$^{-1}$ DM between observed and simulated.

The simulated hydrological conditions for the 3 fields of the potato-cases R-Potato and V-Potato show a good fit with the observed (Table 2). The simulated yields (Table 2) show the largest deviation from the observed for case B-Potato. The more recent experiments of potato cases studies R-Potato and V-Potato show differences between simulated and observed yields of respectively 1374 and -288 kg.ha$^{-1}$ DM (Table 2). These case studies unfortunately cover only one year. The case R-Potato performs less due to the complex situation in the subsoil with drainage conditions that require more observations to improve the simulations.

However one has to bear in mind that perfect calibration is not the objective of this study. We used calibration values from earlier studies (Kroes et al., 2015 and Hack et al., 2016). No detailed assimilation measurements were executed on the fields and the meteorological data was not measured on site, but taken from meteorological stations sometimes more than 30 km away. Furthermore, no detailed information concerning fertilizer applications and soil carbon is available, therefore we considered it constant in time.

Even though some yields are not accurate enough to satisfy statistical criteria for good model performance, we think that the dynamics of soil hydrology and crop yield are acceptably captured. With more field information and calibration a better result could be achieved but we think that current tuning of SWAP-WOFOST for the 3 crops allows an application at a larger scale with various hydrological boundary conditions.

Before the analysis at a larger scale we simulated the impact of upward flow for the case studies. We carried out additional simulations without upward flow towards the root zone, using the specially programmed synthetic model option. Results of these 3 cases are given in Table 3 for the situation with and without upward flow. This table shows that suppressing upward flow lowers yields by 6, 3 and 20% respectively for grassland, maize and potato . The groundwater recharge was reduced with respectively 3, 4 and 94% (Table 3). Detailed results can be found in the supplementary material (S1). In supplementary material S4 input data for case 3 (V-Potato) can be found. In a next step we carried out a larger scale experiment to quantify this impact for different soil crop and climate conditions.

*3.2 Soil crop experiment to analyse the role of capillary rise*

The 3 crops from the case studies were simulated with 72 soils from the national database using 3 different bottom boundary conditions and 45 years with weather from 1970-2015.

Results of simulated upward flow of 45 years weather, 72 soils and 3 lower boundary conditions are summarized with mean values in Table 4. The highest values for upward flow to the root zone during crop growth were found for average groundwater conditions (Ave) with long-term mean values for grassland, maize and potatoes of respectively 194, 74 and 112 mm/year. Differences among hydrological conditions at the bottom of the root zone are caused by differences in weather, growing season, dynamic position of the root zone and demand of root water uptake. Even in free drainage situations the upward flow to the root zone caused by soil water recirculation can be considerable, ranging from 17 – 78 mm long-term average ($FD_{rc}$ in Table 4). In free-draining soils the variation of upward flow to the root zone ranges from about 10 mm in wet and cold to 120 mm in dry and warm years with a high evaporative demand (Figures 6, upper part). In general upward flow is highest in loamy soils where soil physical conditions are optimal. Especially in the presence of a groundwater level differences in upward flow between soils are relatively small compared to differences among years and within one grouped soil type (Figure 7, lower part).

The upward flow is inversely related to the rooting depth: the larger the rooting depth, the smaller the upward flow. Grassland, potatoes and maize have rooting depths of respectively 40, 50 and 100 cm and an upward flow of respectively 194, 112 and 74 mm per growth season (Table 4). Note that the high value for perennial grassland is also caused by a much longer growing season. The percolation is highest for grassland for the same reasons (Table 4). These high values are largely due to the precipitation excess during winter in the Netherlands.

Upward seepage across the bottom boundary does not occur in the free-drainage conditions (Figure 2 a and b). Leaching is highest (Table 4) in the synthetic free-drainage condition without capillary rise (Figure 2 a). Note that the values in Table 4 for seepage and leaching are given for a calendar year whereas the other mean values are given for a growing season. Yearly values are used for the bottom boundary because these values give an indication for the yearly deeper groundwater recharge which may also be influenced by variations of vertical fluxes close to the rootable zone during the remainder of the year. The leaching flux at 5.5 m depth (Table 4, $q_{leaching}$) increases when upward flow is suppressed (lower transpiration, more groundwater recharge), with respectively 44, 2 and 16 mm.year$^{-1}$ for grassland, maize and potatoes. In Dutch conditions with shallow groundwater (Figure 2 c) very often at greater depth leaching does not occur because excess water due to precipitation and/or upward seepage is discharged via drainage systems. The average condition we used has no leaching but seepage of 227, 155 and 291 mm.year$^{-1}$ for grassland, maize and potatoes (Table 4, $q_{seepage}$).

As can be expected, the synthetic condition without upward flow and without groundwater (Figure 2 a), has the lowest simulated mean yields for all crops (Table 4). The highest mean yields are simulated when average groundwater situations including capillary rise are considered (Table 4, Ave). The relative mean yield increase is lowest for maize and highest for grassland (Table 5) which is probably caused by the difference in rooting depth.

The simulation results with 3 different lower boundary conditions (Figure 2 conditions a, b and c) are also compared by subtraction. The subtraction enables a quantification of the contribution of the 2 different sources of upward flow: groundwater and recirculating percolation water.

The elimination of recirculating percolation water to the root zone in free drainage conditions (synthetic condition a compared to b, Figure 2) reduces grassland, maize and potato yields with respectively 14, 0 and 7 % (Table 5). The higher yields are caused by upward flow using recirculating percolation water as source.

A comparison between situations with free drainage (condition b, Figure 2) with average groundwater levels (condition c, Figure 2) shows a similar yield reduction: respectively 14, 2 and 8 %. The higher yields are caused by capillary rise with groundwater and recirculation as source.

When one compares situations with free-drainage conditions without upward flow (synthetic condition a, Figure 2) with average groundwater levels (condition c) yield-reductions of grassland, maize and potatoes are respectively 26, 3 and 14 % (Table 5) or respectively about 3.7, 0.3 and 1.5 ton.ha$^{-1}$ dry matter (Table 4). These yield differences quantify the contribution of the sum of the two different sources of upward flow: groundwater and recirculating percolation water.

The impact of upward flow on groundwater recharge is highest for potatoes and lowest for maize. For grassland, maize and potatoes differences between downward flux across the bottom of the root zone ($q_{percolation}$ in Figure 2) of 3 hydrological conditions were calculated of respectively 17, -11 and 46 % ($q_{percolation}$ in Table 5) or 63, -5 and 34 mm ($q_{percolation}$ in Table 4). Low recharge values for maize are caused by deeper rooting systems which reduce these differences because groundwater levels are closer to the bottom of the root zone. For potatoes this difference in yield can reach values of more than 4 ton.ha$^{-1}$ dry matter in stress conditions (Table 6). The results are presented in more detail in the supplementary material (S3).

*4. Discussion*

The case studies and soil-crop experiments in this paper demonstrate the combined interaction of recirculation and capillary rise on crop yields. This impact is clearly present in situations where a groundwater level is present (85% of NL) but also in free-draining situations the impact of upward flow is considerable. According to our simulation results, grassland, maize and potato yields increase with respectively 14, 0 and 7% in free drainage conditions when upward flow is included (Table 5). This increase is mainly caused by internal recirculation, i.e. a part of the downward flux past the root zone is redirected upward to the root zone as a result of gradient driven flow. When upward flow also has groundwater as a source simulated yields increases by another 14, 2 and 8% respectively. This increase is supported by a stronger capillary rise due to proximity to the groundwater. Comparing the simple simulations (no upward flow, no groundwater influence) to those with an average groundwater level and capillary rise shows yield increases of 26, 3 and 14%. About half of these yield increases are caused by internal recirculation as occurs in free drainage conditions and the other half is caused by an increased upward capillary flow from the groundwater.

Crop models that apply tipping bucket approach consider the soil system as a reservoir with only percolation and no upward flow (an overview with a model comparison is provided by Ahuja et al, 2014). Such models do not account for soil moisture redistribution within and below the root zone. Similar to Guderle and Hildebrand (2015) our simulation results show that a detailed vertical flow improves predictions of root water uptake. Simple tipping bucket models generally overestimate drought stress and groundwater recharge and subsequently underestimate crop yield. The irrigation demand may be overestimated as well. The high percolation may also result in overestimation of groundwater recharge (leaching). Groundwater depth is important, because it determines the distance that the capillary flux has to bridge to reach the root zone and should be accounted for in crop modelling.

In the ideal situation one should compare the bucket approach to the approach with full simulation of capillary rise and recirculation using independent data sets. However the measured data sets are insufficient to calibrate and validate the soil and crop parameters in such detail that they allow proper statistical evaluation of the two approaches. The calibration of both model approaches has too much freedom with the available datasets, which upsets a reliable validation. Therefore we used the measured data sets to illustrate that with common soil and crop input values SWAP-WOFOST yields realistic and plausible results for the crops considered in this study. Further, crop growth and soil water flow are simulated by SWAP-WOFOST with state of the art concepts. Therefore we may expect that the model itself can be used to show the effect on crop yield of different boundary conditions with respect to zero flux, recirculation and capillary rise.

Furthermore we know from experience that WOFOST with a bucket approach underestimates water availability in the rooting zone and consequently overestimates drought stress (Boogaard et al., 2013).

Our analysis shows that soil properties and soil profile layering are important because differences in soil hydraulic properties influence vertical water flow. High upward flow values are found in loamy soils as is expected (Table 6, max row), but if water stress is high and upward flow is low the influence of soil type decreases and low upward flow values were found for loamy soils (Table 6, min row). Comparing the minimum yield values it shows that there is a large difference between these soil types in free-drainage conditions with and without upward flow. This means that the storage capacity of loamy soils is larger than the one of sandy soils as can be expected. The yield variation between soil types in water stress conditions is large and illustrates the need for a proper soil schematization especially in stress full hydrological conditions. An adequate soil schematization is relevant for all models but especially for those that use a bucket approach. As the influence of recirculation increases, the yield variation becomes less and the influence of soil type decreases. In situations without water stress the soil type is less important. In conditions where groundwater and capillary rise occurs (Ave) yield variation is hardly influenced by soil type.

Modelling concepts should consider dynamic interactions between soil water and crop growth. Crop models in general should consider recirculation of soil water and, especially in low lying regions like deltas, groundwater dynamics should be considered as well.

Precipitation, soil texture and water table depth jointly affected the amount of groundwater recharge and time-lag between water input and groundwater recharge (Ma et al., 2015). We quantified some of these issues, but several items remain, such as the impact of rooting depth on crop yield and transpiration. Also soil and water management practises like ploughing and irrigation, are not considered. Furthermore the rooting pattern needs a more detailed analysis; we applied an exponential decrease of root density and compensation of root uptake according to Jarvis (2011) but the macroscopic root water uptake concept is still simple and requires a more detailed analyses (Dos Santos et al. 2017). Another item we neglected is the preferential flow of water by the occurrence of non-capillary sized macropores (Bouma, 1961, Feddes, 1988), which is relevant in especially clay soils. Hysteresis of the water retention function is also not considered. An additional analysis of these issues is recommended, especially the impact of different rooting patterns on capillary rise should be addressed.

The impact of soil type on yield increases when environmental conditions become dryer; situations without groundwater and without recirculation have less yield and higher yield variation than situations where groundwater influences capillary rise (For detailed information on results see the supplementary material S1 and S3).

## *5. Conclusions*

We quantified the impact of upward flow on crop yields of grassland, maize and potatoes in layered soils. We compared situations with average groundwater levels with free-drainage conditions with and without upward flow. The largest impact of upward flow on crop yields was found when one compares situations with average groundwater levels with free drainage conditions without upward flow. From these differences one may conclude that neglecting upward flow has a large impact on simulated yields and water balance calculations especially in regions where shallow groundwater occurs. The comparison shows long term average yield-reductions of grassland, maize and potatoes of respectively 26, 3 and 14 % (Table 5) or respectively 3.7, 0.3 and 1.5 ton Dry Matter per ha (Table 4). Reduction of the percolation flux can be considerable; for grassland and potatoes the reduction is 17 and 46% (Table 5) or 63 and 34 mm (Table 4).

About half of the yield increases is caused by internal recirculation as occurs in free-drainage conditions and the other half is caused by an increased upward capillary flow from groundwater. Improved modelling should consider upward flow of soil water which will result in improved estimates of crop yield and percolation.

We think that the quantification of upward flow on yield is a novelty, especially with respect to the interaction between recirculation, capillary rise and crop growth. Studies about the relation between soil hydrology and crop growth should quantify this upward flow because neglecting this flow and its impact implies neglecting yield changes which may have a large economic value in the Dutch Delta and in other deltas in general. Another aspect which cannot be found in the referenced studies is the lack of a quantification of the impact of capillary rise and recirculation on crop yields. Correct quantification of the water fluxes contributes to the understanding of crop production and will help the institutions in charge of yield forecasting.

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# Tables

*Table 1. Main characteristics of case studies used to verify setup of model combination SWAP-WOFOST*

| Case study[1] | Crop | Location | Period | Soil type | Observations[2] | Reference | Drought stress[3] | MF[4] | RZ[5] | BBC[6] | Lateral Boundary |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DM-Grass | Grass | De Marke | 1995-1996, 2005-2008, 2013 | dry sandy soil | Gwl, Yield, Theta20cm | Hack et al. (1996); Verloop et al., 2014 | h3h = -200.0 cm<br>h3l = -800.0 cm<br>h4 = -8000.0 cm | 0.8 | 40 | Cauchy | No Drainage |
| DM-Maize | Silage maize | De Marke | 1992-1994, 1997-2003, 2009-2012 | dry sandy soil | Gwl, Yield, Theta20cm | Hack et al. (1996); Verloop et al., 2014 | h3h = -400.0 cm<br>h3l = -500.0 cm<br>h4 = -10000.0 cm | 0.85 | 40 | Cauchy | No Drainage |
| C-Maize | Silage maize | Cranendonck | 1974-1982 | Cumulic Anthrosol | Gwl, Yield | Schröder (1985) | see DM-Maize | 0.9 | 40 | Cauchy | No Drainage |
| D-Maize | Silage maize | Dijkgraaf | 2007 | Umbric Gleysol | Gwl, Yield, ET,Theta20cm | Elbers et al. (2010) | see DM-Maize | 0.95 | 100 | Cauchy | No Drainage |
| B-Potato | Potato | Borgerswold | 1992, 1994 | Sandy loam | Gwl, Yield | Dijkstra et al., 1995 | h3h = -300.0 cm<br>h3l = -500.0 cm<br>h4 = -10000.0 cm | 0.8 | 100 | Observed groundwater | No Drainage |
| R-Potato | Potato | Rusthoeve | 2013 | lichte kleibodem | Gwl, Yield, Qdrain | Van Den Brande (2013) | see B-Potato | 0.8 | 100 | Cauchy | Drain tubes at -90 cm |
| V-Potato | Potato | Vredepeel | 2002 | Sandy loam | Gwl, Yield | De Vos et al., 2006 | see B-Potato | 0.8 | 50 | Closed | Drain ditch at -100 cm |

*[1] The name of each Case study is a combination of an acronym for the Location and the crop type, using the acronyms DM=De Marke, C=Cranendonck, D=Dijkgraaf, B=Borgerswold, R=Rusthoeve and V=Vredepeel*

*[2] Gwl = Groundwater level, Yield = Actual Yield as Dry Matter of Harvested product, Theta20cm= Soil moisture content at a depth of 20cm below surface, Qdrain = drainage from field to surface water via tube drains, ET = Evapotranspiration measured via Eddy Correlation method.*

*[3] h3h = h below which water uptake reduction starts at high Tpot; h3l = h below which water uptake red. starts at low Tpot; h4 = No water extraction at lower pressure heads; Drought stress was parameterised using the dry part of the reduction function proposed by Feddes et al. (1978), Drought stress is absent when the soil pressure head h exceeds the critical value of h3. Drought stress increases linearly between h3 and at h4 (wilting point). The critical pressure head h3 differs between lower and higher potential transpiration (Tpot) (respectively h3l and h3h) rates.*

*[4] MF = Management Factor to account for imperfect management*

*[5] RZ = Maximum depth of root zone (cm)*

*[6] BBC = Bottom Boundary Condition. The Cauchy bottom boundary condition uses a hydraulic head based on piezometer observations from an open data portal (see text)*

*Table 2. Results of Case studies: simulated and observed values*

| Case study | Name[1] | unit | Simulated mean | Observed mean | ME[2] | RMSE[3] | NS[4] | d[5] | n[6] |
|---|---|---|---|---|---|---|---|---|---|
| DM-Grass | Yield | $kg.ha^{-1}.yr^{-1}$ DM | 11183 | 11049 | 133 | 1347 | 0.6 | 0.9 | 7 |
| | Gwl | m-soil | -1.31 | -1.30 | -0.01 | 0.45 | 0.3 | 0.9 | 77 |
| | Theta | $m^3.m^{-3}$ | 0.28 | 0.27 | 0.01 | 0.05 | 0.5 | 0.9 | 43 |
| DM-Maize | Yield | $kg.ha^{-1}.yr^{-1}$ DM | 11593 | 11850 | -257 | 2864 | -3.3 | 0.4 | 14 |
| C-Maize | Yield | $kg.ha^{-1}.yr^{-1}$ DM | 14097 | 13788 | 310 | 2595 | -1.2 | 0.7 | 9 |
| | Gwl | m-soil | -1.41 | -1.36 | -0.05 | 0.25 | 0.4 | 0.9 | 61 |
| D-Maize | Yield | $kg.ha^{-1}.yr^{-1}$ DM | 15973 | 16306 | -333 | | | | 1 |
| | LAI | $m^2.m^{-2}$ | 2.08 | 2.47 | -0.34 | 0.62 | 0.7 | 0.9 | 10 |
| | ETact | $mm.yr^{-1}$ | 1.33 | 1.93 | -0.61 | 0.89 | 0.5 | 0.9 | 232 |
| | Gwl | m-soil | -1.03 | -1.07 | 0.03 | 0.06 | 0.9 | 1.0 | 112 |
| | Theta | $m^3.m^{-3}$ | 0.29 | 0.27 | 0.01 | 0.03 | 0.5 | 0.8 | 219 |
| B-Potato | Yield | $kg.ha^{-1}.yr^{-1}$ DM | 10543 | 9246 | 1297 | | | | 2 |
| | Gwl | m-soil | -1.10 | -1.10 | 0.00 | 0.03 | 1.0 | 1.0 | 123 |
| R-Potato | Yield | $kg.ha^{-1}.yr^{-1}$ DM | 9984 | 8610 | 1374 | | | | 1 |
| | Gwl | m-soil | -1.07 | -1.10 | 0.03 | 0.19 | 0.6 | 0.9 | 887 |
| | qDrain | mm | 1.06 | 0.62 | 0.44 | 1.41 | 0.4 | 0.8 | 1084 |
| V-Potato | Yield | $kg.ha^{-1}.yr^{-1}$ DM | 11071 | 11359 | -288 | | | | 1 |
| | Gwl | m-soil | -1.03 | -1.07 | 0.04 | 0.12 | 0.8 | 0.9 | 353 |

*[1] Gwl = Ground Water Level; Theta = Volumic Soil Moisture Content at a depth of 20 cm below the soil surface; LAI=Leaf Area Index; ETact = actual EvapoTranspiration; qDrain = Drainage flux*

*[2] ME: Mean Error between simulated (sim) and observed (obs), in the same units of sim and obs, with treatment of missing values. A smaller value indicates better model performance*

*[3] RMSE: Root Mean Square Error between sim and obs, in the same units of sim and obs, with treatment of missing values. RMSE gives the standard deviation of the model prediction error. A smaller value indicates better model performance.*

*[4] NS: Nash-Sutcliffe efficiencies range from -Inf to 1. Essentially, the closer to 1, the more accurate the model is. NS = 1, corresponds to a perfect match of modelled to the observed data. NS = 0, indicates that the model predictions are as accurate as the mean of the observed data. -Inf < NS < 0, indicates that the observed mean is better predictor than the model.*

*[5] d: The Index of Agreement (d) developed by as a standardized measure of the degree of model prediction error and varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all. The index of agreement can detect additive and proportional differences in the observed and simulated means and variances; however, it is overly sensitive to extreme values due to the squared differences.;*

*[6] n: the number of values used with the 4 statistical criteria to compare simulated and observed results.*

*Table 3. Results of case studies: values and differences of yield, capillary rise and percolation fluxes, resulting from simulations with and without capillary rise*

| Case study[1] | Model Result | Condition A[2] | Condition B[3] | *Differences* A-B | Unit | *Differences* (%) 100*(A-B)/A |
|---|---|---|---|---|---|---|
| DM-Grass | $Y_{act}$ | 12928 | 12213 | 715 | kg.ha$^{-1}$. season$^{-1}$ DM | 6 |
| | $q_{caprise}$ | 30 | 0 | 30 | mm.season$^{-1}$ | 100 |
| | $q_{percolation}$ | 313 | 305 | 9 | mm.season$^{-1}$ | 3 |
| DM-Maize | $Y_{act}$ | 12803 | 12788 | 15 | kg.ha$^{-1}$. season$^{-1}$ DM | 0 |
| | $q_{caprise}$ | 7 | 0 | 7 | mm.season$^{-1}$ | 100 |
| | $q_{percolation}$ | 91 | 88 | 3 | mm.season$^{-1}$ | 4 |
| V-Potato | $Y_{act}$ | 11071 | 8877 | 2194 | kg.ha$^{-1}$. season$^{-1}$ DM | 20 |
| | $q_{caprise}$ | 101 | 0 | 101 | mm.season$^{-1}$ | 100 |
| | $q_{percolation}$ | 16 | 1 | 15 | mm.season$^{-1}$ | 94 |

*[1] Cases studies DM-Grass and DM=Maize were simulated for limited periods of respectively 2005-2008 and 1991-1994 to have a continuous sequence of years, Case study V-Potato was simulated for one year*
*[2] Condition A has actual bottom boundary conditions (according to table 1);*
*[3] Condition B has actual bottom boundary conditions (table 1) but without capillary rise to root zone;*

*Table 4. Results of soil crop experiments: mean values of 6 model results from 3 different hydrological conditions: $FD_{nc}$ (Free Drainage with No reCirculation), $FD_{rc}$ (Free Drainage with Recirculation) and Ave (Average Drainage conditions)*

| Crop | Model Result | $FD_{nc}$ | $FD_{rc}$ | Ave | Unit |
|---|---|---|---|---|---|
| Grassland | $Y_{act}$ | 10494 | 12147 | 14177 | kg.ha$^{-1}$.season$^{-1}$ DM |
| | $q_{caprise}$ | | | 194 | mm.season$^{-1}$ |
| | $q_{recirc}$ | 0 | 78 | | mm.season$^{-1}$ |
| | $q_{percolation}$ | 317 | 338 | 380 | mm.season$^{-1}$ |
| | $q_{seepage}$ | 0 | 0 | 227 | mm.yr$^{-1}$ |
| | $q_{leaching}$ | 301 | 257 | 0 | mm.yr$^{-1}$ |
| Maize | $Y_{act}$ | 12318 | 12378 | 12643 | kg.ha$^{-1}$.season$^{-1}$ DM |
| | $q_{caprise}$ | | | 74 | mm.season$^{-1}$ |
| | $q_{recirc}$ | 0 | 17 | | mm.season$^{-1}$ |
| | $q_{percolation}$ | 52 | 57 | 47 | mm.season$^{-1}$ |
| | $q_{seepage}$ | 0 | 0 | 155 | mm.yr$^{-1}$ |
| | $q_{leaching}$ | 396 | 394 | 0 | mm.yr$^{-1}$ |
| Potato | $Y_{act}$ | 8864 | 9521 | 10365 | kg.ha$^{-1}$.season$^{-1}$ DM |
| | $q_{caprise}$ | | | 112 | mm.season$^{-1}$ |
| | $q_{recirc}$ | 0 | 42 | | mm.season$^{-1}$ |
| | $q_{percolation}$ | 39 | 50 | 73 | mm.season$^{-1}$ |
| | $q_{seepage}$ | 0 | 0 | 291 | mm.yr$^{-1}$ |
| | $q_{leaching}$ | 432 | 416 | 0 | mm.yr$^{-1}$ |

*Table 5. Results of soil crop experiments: differences (%) between results from 3 different hydrological conditions: $FD_{nc}$ (Free Drainage with No reCirculation), $FD_{rc}$ (Free Drainage with Recirculation) and Ave (Average Drainage conditions)*

| crop | model Result | differences (%) | | |
|---|---|---|---|---|
| | | **100*($FD_{rc}$ - $FD_{nc}$) / $FD_{rc}$** | **100*(Ave- $FD_{rc}$) / Ave** | **100*(Ave- $FD_{nc}$) / Ave** |
| Grassland | $Y_{act}$ | 14 | 14 | 26 |
| | $q_{percolation}$ | 6 | 11 | 17 |
| Maize | $Y_{act}$ | 0 | 2 | 3 |
| | $q_{percolation}$ | 9 | -22 | -11 |
| Potato | $Y_{act}$ | 7 | 8 | 14 |
| | $q_{percolation}$ | 22 | 31 | 46 |

*Table 6. Results for potatoes of soil crop experiments for each clustered soil type: capillary rise, recirculation and yield from 3 different hydrological conditions: $FD_{nc}$ (Free Drainage with No reCirculation), $FD_{rc}$ (Free Drainage with Recirculation) and Ave (Average Drainage conditions) . Results for upward flow of $FD_{nc}$ are zero and therefore not given.*

| hydrological condition | | Statistic | Values per clustered soil type Clay | Loam | Peat | Moor | Sand | Unit |
|---|---|---|---|---|---|---|---|---|
| $FD_{rc}$ | $q_{recirc}$ | min | 5 | 1 | 4 | 8 | 1 | mm/crop season |
| | | lower quartile | 34 | 33 | 20 | 27 | 24 | mm/crop season |
| | | median | 47 | 54 | 34 | 33 | 37 | mm/crop season |
| | | upper quartile | 61 | 78 | 50 | 39 | 51 | mm/crop season |
| | | max | 98 | 122 | 91 | 58 | 88 | mm/crop season |
| Ave | $q_{caprise}$ | min | 14 | 14 | 15 | 34 | 15 | mm/crop season |
| | | lower quartile | 65 | 80 | 72 | 100 | 84 | mm/crop season |
| | | median | 94 | 113 | 104 | 129 | 113 | mm/crop season |
| | | upper quartile | 134 | 151 | 141 | 168 | 152 | mm/crop season |
| | | max | 227 | 236 | 231 | 243 | 249 | mm/crop season |
| $FD_{nc}$ | $Y_{act}$ | min | 3.1 | 5.4 | 2.8 | 2.8 | 1.2 | 1000 kg/ha DM |
| | | lower quartile | 7.4 | 8.7 | 7.5 | 6.9 | 6.9 | 1000 kg/ha DM |
| | | median | 9.6 | 10.3 | 9.8 | 9.3 | 9.2 | 1000 kg/ha DM |
| | | upper quartile | 10.7 | 10.9 | 10.7 | 10.7 | 10.7 | 1000 kg/ha DM |
| | | max | 12.2 | 12.2 | 12.2 | 12.2 | 12.2 | 1000 kg/ha DM |
| $FD_{rc}$ | $Y_{act}$ | min | 5.0 | 7.5 | 4.8 | 3.4 | 3.3 | 1000 kg/ha DM |
| | | lower quartile | 8.5 | 9.6 | 8.4 | 7.6 | 7.8 | 1000 kg/ha DM |
| | | median | 10.2 | 10.6 | 10.1 | 9.8 | 9.9 | 1000 kg/ha DM |
| | | upper quartile | 10.9 | 11.1 | 10.9 | 10.8 | 10.8 | 1000 kg/ha DM |
| | | max | 12.4 | 12.4 | 12.4 | 12.4 | 12.4 | 1000 kg/ha DM |
| Ave | $Y_{act}$ | min | 7.4 | 8.0 | 7.8 | 7.8 | 7.7 | 1000 kg/ha DM |
| | | lower quartile | 9.6 | 9.8 | 9.8 | 9.8 | 9.7 | 1000 kg/ha DM |
| | | median | 10.5 | 10.7 | 10.7 | 10.7 | 10.7 | 1000 kg/ha DM |
| | | upper quartile | 11.1 | 11.2 | 11.1 | 11.2 | 11.1 | 1000 kg/ha DM |
| | | max | 12.6 | 12.6 | 12.6 | 12.6 | 12.6 | 1000 kg/ha DM |

# Figures


Legend

| Location no. | Location Name |
|---|---|
| 1 | DeMarke21 |
| 2 | Cranendonck16 |
| 3 | Dijkgraaf |
| 4 | Borgerswold03 |
| 5 | RusthoeveB7 |
| 6 | Vredepeel26 |

*Figure 1. Location of case studies for grassland, maize and potatoes; location De Marke has a rotation of grassland and maize on the same field.*

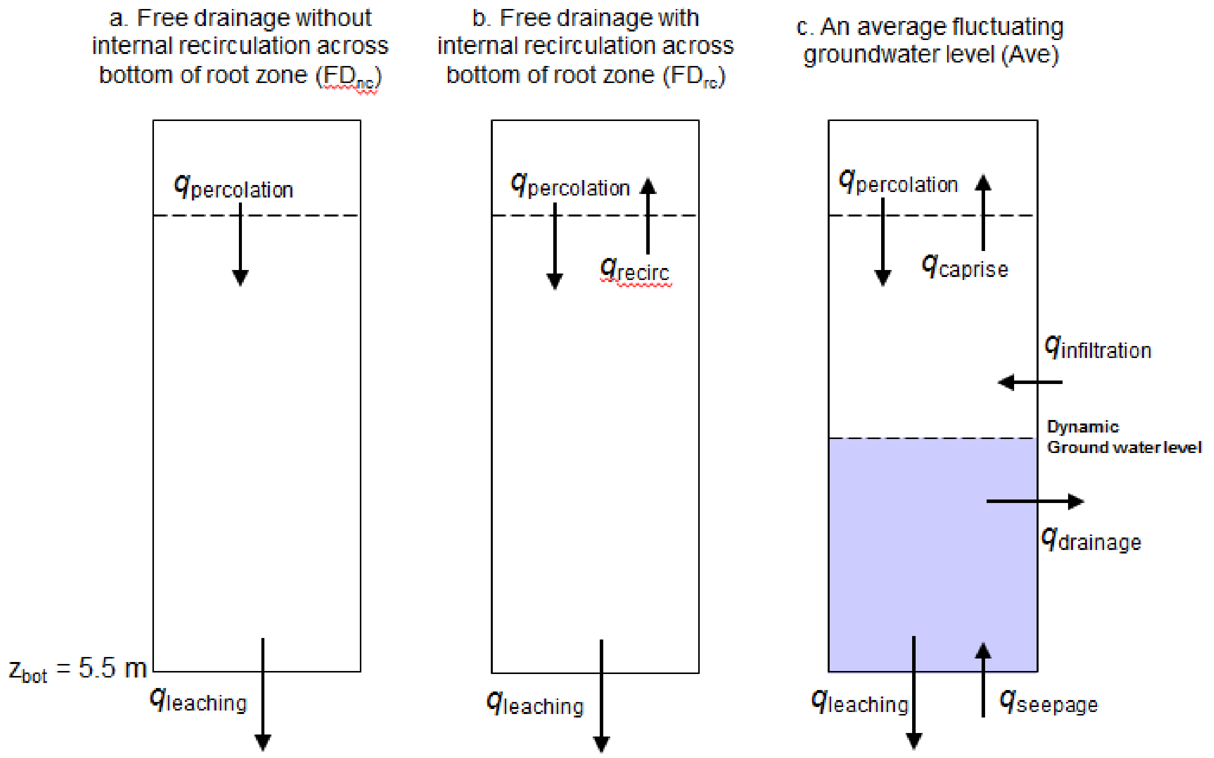


*Figure 2. Schematization of 3 hydrological conditions: a. Free Drainage without recirculation across bottom of root zone ($FD_{nc}$), b. Free Drainage with recirculation across bottom of root zone ($FD_{rc}$) and c. Average fluctuating groundwater level (Ave).*
*Conditions a and b have free-draining bottom boundary conditions without groundwater. Condition a is artificially created to explicitly demonstrate the role of recirculating percolation resulting in upward flow to the root zone. Condition b is a common free drainage situation which includes upward flow due to recirculating percolation water. Condition c is the natural situation in most of the Netherlands. This hydrological condition has a fluctuating groundwater level derived from a national study (Van Bakel et al., 2008).*

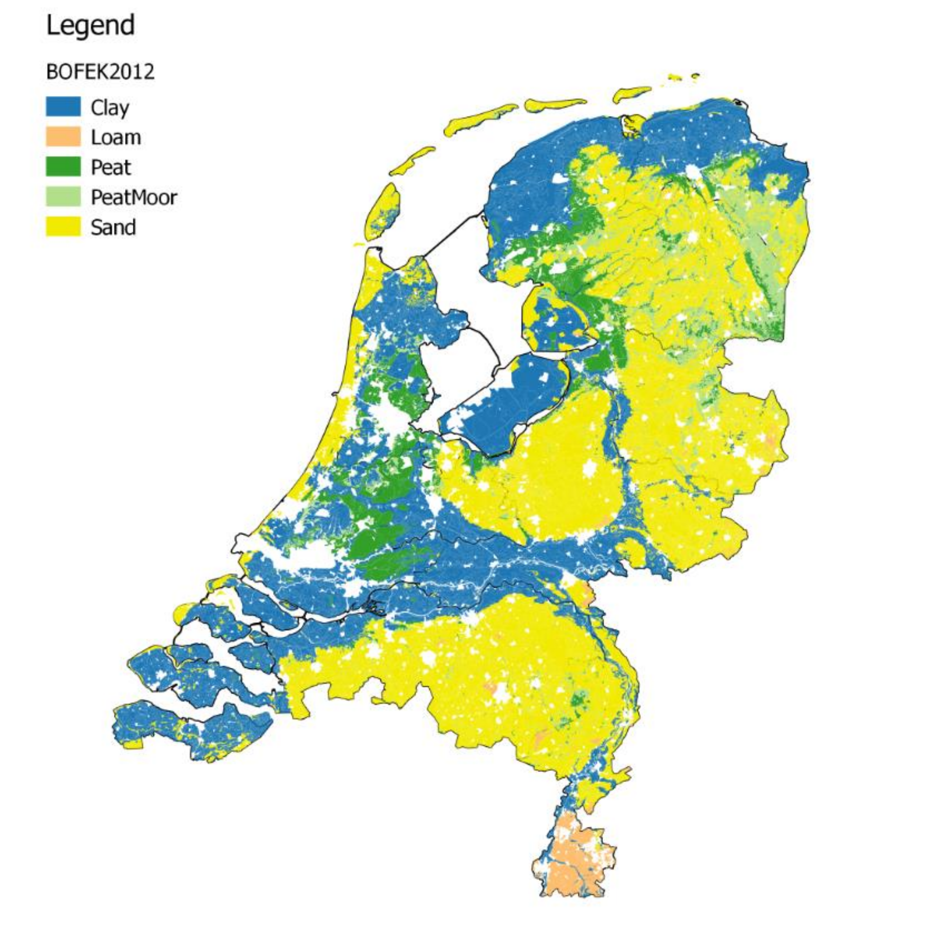


*Figure 3. Five grouped soil types, based on 72 soils of the Soil Physical Map of the Netherlands (Wösten et al., 2013)*

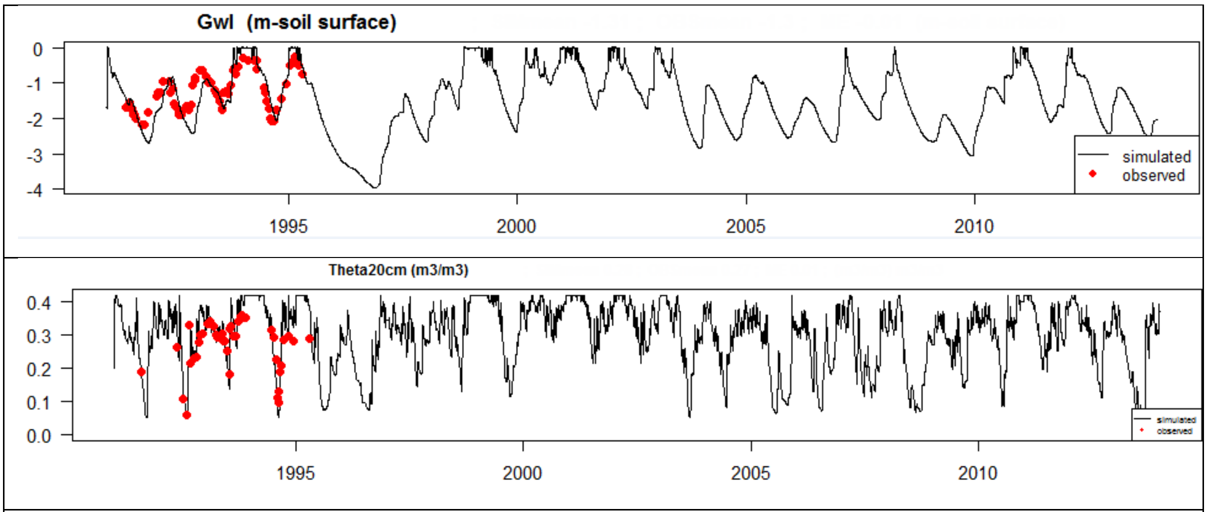


*Figure 4. Results of case studies for grassland at location 1 (De Marke):*
- *top figure = groundwater level (Gwl in m-soil surface):*
- *bottom figure = soil moisture content (Theta20cm in $m^3.m^{-3}$) at 20 cm below the soil surface*

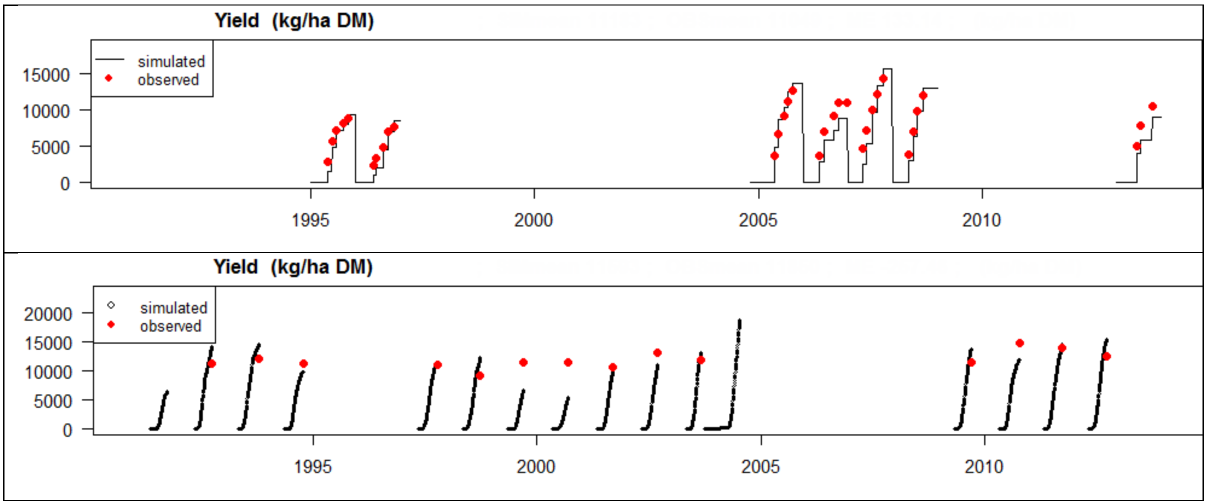


*Figure 5. Results of case studies at location 1 (De Marke) : Observed Yields ($kg.ha^{-1}$DM) as red dots and Simulated above ground biomass as black lines or as black dots*
- *top figure = yields ($kg.ha^{-1}$ DM) of grassland*
- *bottom figure = yields ($kg.ha^{-1}$ DM) of maize*

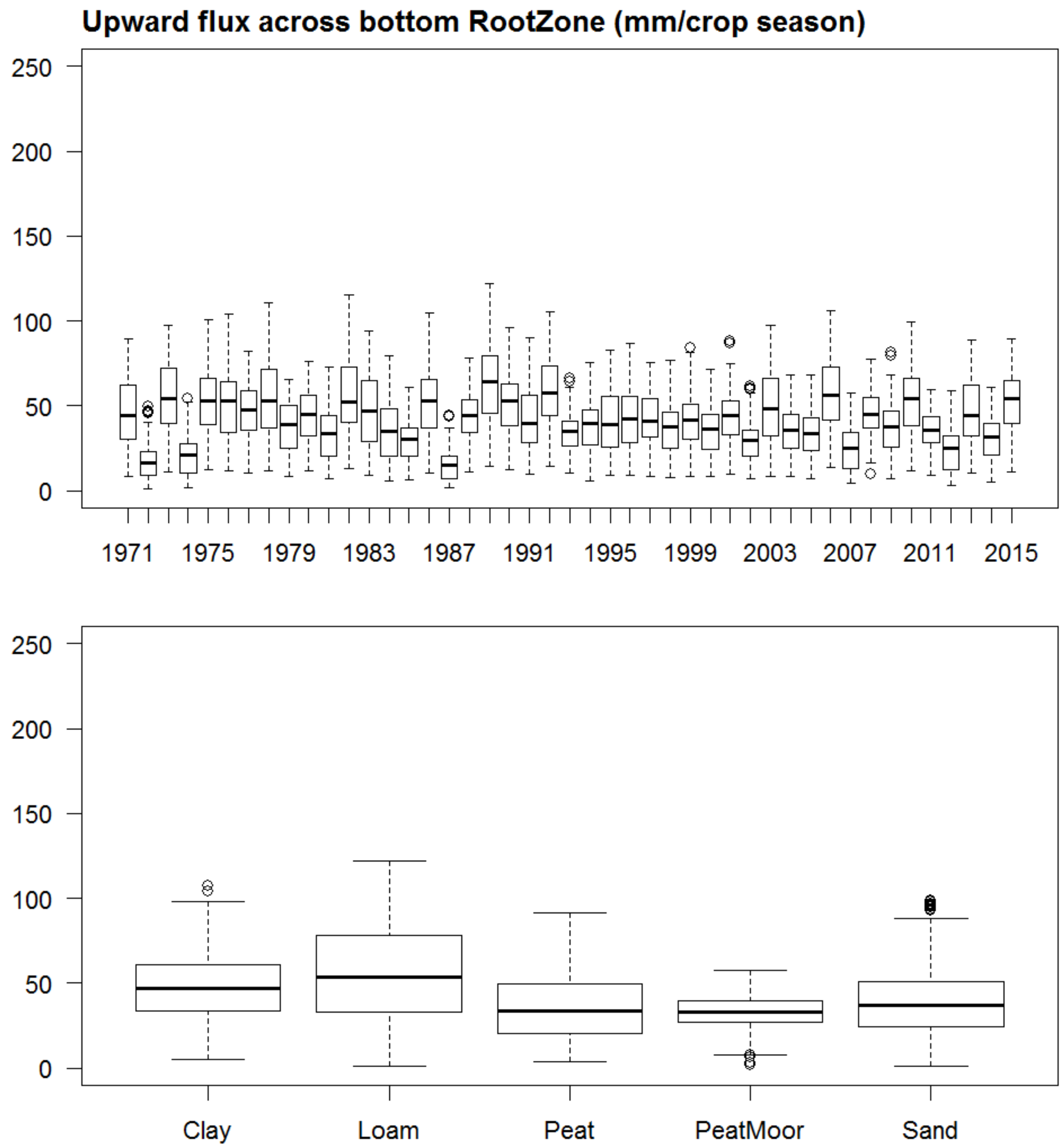


*Figure 6. Results of soil-crop experiment for potato: Upward flux across the bottom of the root zone ($q_{recirc}$ in mm.crop season $^{-1}$) for hydrological conditions with free drainage ($FD_{rc}$);*
*Upper figures: results for all 72 soils for the period 1971-2015;*
*Lower figures: results as boxplots for clustered soil types.*

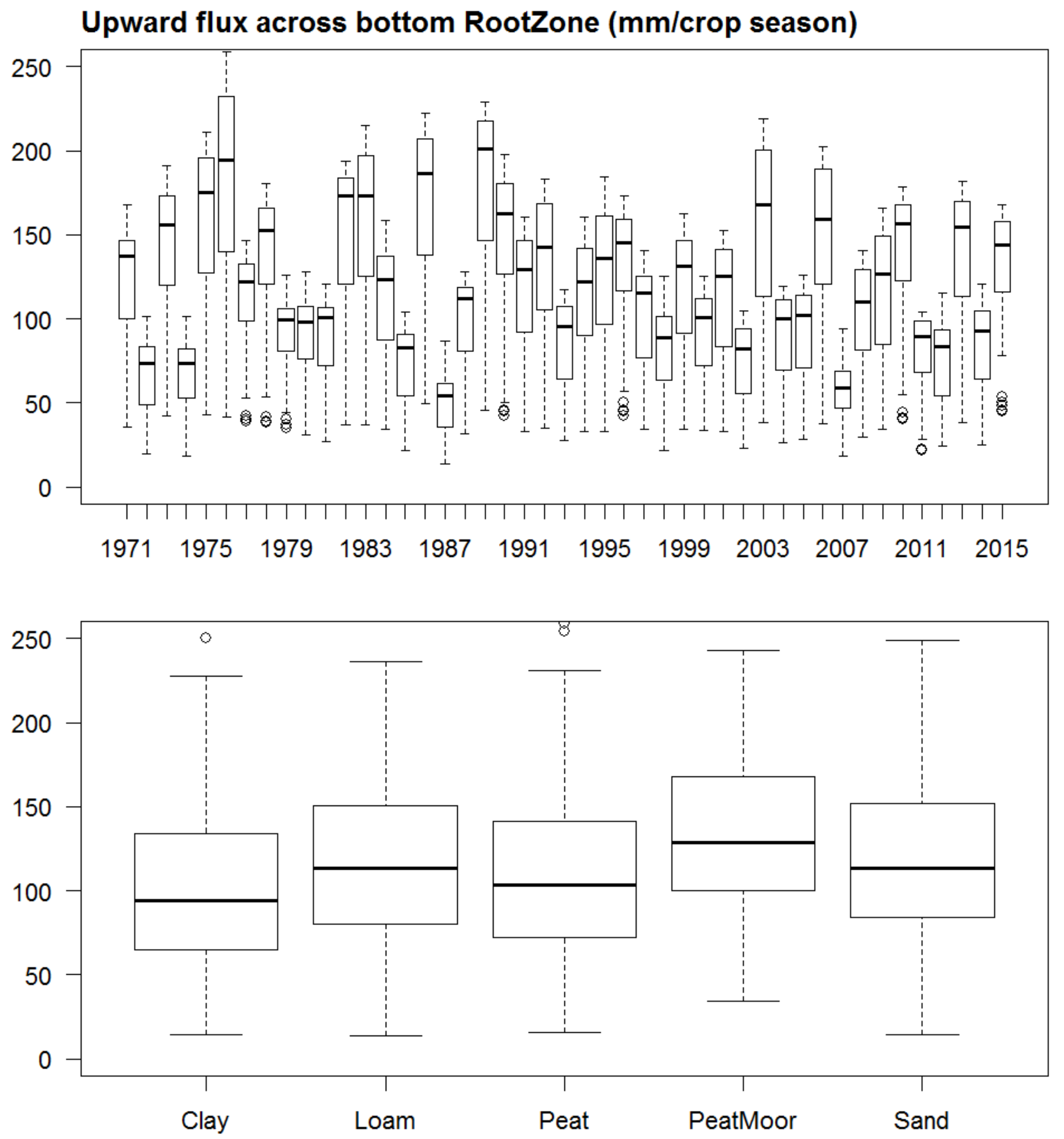


*Figure 7. Results of soil-crop experiment for potato: Upward flux across the bottom of the root zone ($q_{caprise}$ in mm.crop season$^{-1}$) for hydrological conditions with average groundwater level (Ave);*
*Upper figures: results for all 72 soils for the period 1971-2015;*
*Lower figures: results as boxplots for clustered soil types.*