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Effect of increasing conceptual model detail on simulated crop yield-drainage base relations

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ABSTRACT

The relation between the drainage base (the maximum depth to which water is drained) and crop yield is important for designing drainage systems or deriving practical drainage standards. For integrated regional water management in temperate climates, a shallower drainage base is seen as a suitable measure to cope with prolonged periods of drought. This study aims to evaluate the effect of increasing level of conceptual model detail, that was the result of drainage science developments in the last decades, on the relation between crop yield and drainage base on field scale. We simulated potential and water-limited fodder maize yields for a fictional field with a sandy soil between 1925 and 2024 under Dutch meteorological conditions, using standard parametrisations for different subroutines available in the SWAP model for the simulation of potential evapotranspiration, crop growth and oxygen and drought stress. Each of these subroutines differ in level of conceptual detail and incorporated process-based knowledge. Results show that the relation between relative yield and the drainage base changes with varying level of detail, also when other crop types, sandy soils, bottom boundary condition configurations, and drainage resistances were used. The definition of a minimum relative yield for regional water management becomes more important as simulation results indicate an increasing influence of oxygen and drought stress on crop growth between different progressive climatic periods. Such a minimum relative yield would allow for relaxation of the currently used uniform Dutch guidelines for drainage design necessary for the transition in Dutch regional water management.

1. Introduction

The design of field drainage in the form of ditches, canals and pipe drainage plays a crucial role in land reclamation, consolidation and spatial planning projects (Ritzema and Braun, 2006; Smedema et al., 2004). Drainage is essential for agriculture as it prevents waterlogging in temperate and humid climates and salinisation in (semi-)arid regions (Schultz et al., 2007). Globally, the development of drainage systems increased crop production (Bos and Boers, 2006) and contributed to rural development (Schultz et al., 2007). Land use changed drastically in the 20th century (Hurtt et al., 2006) and most drainage systems were revised or constructed during the second half of the 20th century (Ogino and Ota, 2007; Shaoli et al., 2007; Skagg and Van Schilfgaarde, 1999; Stańczuk-Gałwiaczek et al., 2018).

Initially, these drainage systems were designed based on local experiences and the design was more of an art than a science (Bos and Boers, 2006). Drainage science started to develop from the 1940s which led to the introduction of analytical equations (e.g. Hooghoudt, 1940; Kirkham, 1958; Youngs, 1966) which allowed for design equations relating drain depth and spacing to a critical precipitation amount associated with a certain return period (e.g. Castle et al., 1984; Skagg and Nassehzadeh-Tabriz, 1986). The introduction of personal computers led to the development of numerical computational models that could incorporate more processes, for example DRAINMOD (Skaggs et al., 2012) and SWAP (Kroes et al., 2017). These models can be used to update simpler design tools (e.g. Ghane et al., 2021).

The scientific development of drainage theory was both driven by and contributory to the diversification of the goals of drainage (Seijger, 2026; Skagg and Van Schilfgaarde, 1999). Early aims were focused on the hydraulic performance of drainage systems and criteria were defined

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as a minimum depth of the groundwater table (Hooghoudt, 1940) or the time of drawdown after a precipitation event (Dumm, 1954; van Schilfgaarde, 1963). With the development of numerical models, these criteria evolved to criteria based on maximising crop yield (Feddes, 1988; Skagg and Nassehzadeh-Tabriz, 1986). Regional environmental issues such as deteriorating surface water quality through leaching nutrients (Skagg and Van Schilfgaarde, 1999) and decreasing groundwater tables due to over-drainage (Schultz et al., 2007) changed the aims of drainage from agronomic cost-efficiency on a field scale to its embedment in multi-objective goals of the regional water system (Ogino and Ota, 2007; Schultz et al., 2007; Shaoli et al., 2007). The inclusion of water quality in drainage design criteria (Ayars et al., 1997) and the development of controlled and climate adaptive drainage combined with subirrigation systems are driven by this new perspective (De Wit et al., 2022; Stuyt, 2013). Currently, changing precipitation and evapotranspiration patterns due to global climate change (Caretta et al., 2022) require adaptation of most drainage systems which were mostly designed and built for the climate of the 20th century and might be working differently as originally intended (Ayars and Evans, 2015; Kundzewicz and Licznar, 2021; Schultz et al., 2007).

These global shifts in the development of drainage theory and drainage objectives are particularly evident in the Netherlands which has a long tradition of drainage. Initially, drainage science in the Netherlands focused on designing field drainage to realise optimal agronomical field conditions. The Marshall-funds after the second World War stimulated a large-scale investigation of, among others, the relation between groundwater level and agricultural yield (Visser, 1958; Fig. 1). Gradually, methods included increasingly more hydrological and agronomical processes in soil, water, plants and atmosphere, moving from analytical equations for steady flow (Ernst, 1962; Hooghoudt, 1940) and non-steady flow (Wesseling, 1969) to numerical dynamic models accommodating advanced transport processes in the atmosphere-plant-soil continuum (Fig. 2).

The progression of drainage science and the inclusion of increasingly more transport processes is especially apparent in the development of the Soil-Water-Atmosphere-Plant (SWAP) model (Heinen et al., 2024; Fig. 2). Initially started by Feddes et al. (1974), the early version of SWAP allowed for relating water management and drainage design to crop yield using mostly empirical relations (Feddes et al., 1978). Between 1978 and 1997, generic crop growth, solute transport and heat flow were added to the model (Van Dam et al., 1997). Processes included between 1997 and 2008 are, among others, surface water management

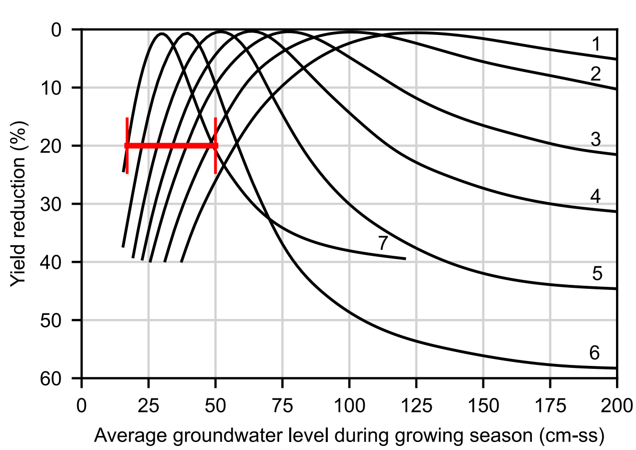


Fig. 1. Yield reduction against average groundwater level in cm below soil surface (cm-ss) during the growing season for seven soil profile groups. Soil profiles were grouped based on expected depth of drainage base for optimal agricultural use. The curves are based on expert knowledge and field studies. The red line indicates the range in acceptable groundwater levels for a yield reduction of 20% for soil profile group 7. Figure adjusted from Visser (1958).

and dynamic crop modelling using the WOFOST model (Boogaard et al., 2014; Van Dam et al., 2008). Since 2008, modelling of soil hydraulic properties and the reduction of root water uptake by oxygen and drought stress can be modelled in a more process-based manner (Bartholomeus et al., 2008; De Jong Van Lier et al., 2013; Heinen et al., 2024).

Dutch drainage design standards used in practice followed scientific developments until approximately the 1980s. Scientific insights were made tangible with tables for design depths and widths in handbooks (Groot and Stol, 1971; Grotentraast et al., 1988). Since then, these have not been updated to incorporate recent scientific developments and changing meteorological conditions. Indirectly, tables describing the relation between groundwater levels and agricultural yield were used to evaluate a change in groundwater regime due to changes in the drainage system (Koerselman et al., 1987; Molenaar et al., 1978). More recently, the development of the tool WaterVision Agriculture (Hack-ten Broeke et al., 2019) which followed the recent scientific developments (Fig. 2) by integrating more process-based model concepts, allowed for similar evaluations under changing climatic conditions (Hack-ten Broeke et al., 2016). However, it can also only be used indirectly for drainage design as drainage design parameters are not an input. As a result, the drainage standards from the 1980s are still in use, despite being based on outdated meteorological conditions and scientific insights.

Historically, Dutch water management policy has prioritised adapting to wet extremes (Bartholomeus et al., 2023). Combined with the large scale land consolidation between 1950 and 2000 (Fig. 2), this focus resulted in the development of an intensive drainage network (Ritzema and Van Loon-Steensma, 2018; Van De Ven, 1993; Van Den Bergh, 2004). On the sandy uplands (Fig. 3), this contributed to decreasing groundwater tables and consequently the desiccation of groundwater dependent nature in the sandy uplands (Boogerd et al., 1997; De Wit et al., 2022; Hoogland et al., 2010; Witte et al., 2019). It also made the water system more vulnerable to droughts (Brakkee et al., 2022; Van Den Eertwegh et al., 2021), while overly wet conditions in the growing season remain a threat for crop production (Van Oort et al., 2023). Climate change, which increases the precipitation in the wet period and the potential precipitation deficit in the growing season (Van Dorland et al., 2024), and increasing freshwater demand due to socio-economic growth will increase the pressure on freshwater availability (Van Der Brugge and De Winter, 2024). This necessitates adaptation to dry extremes (Bartholomeus et al., 2023), similar to developments in other European countries (e.g. Kröcher et al., 2023; Stańczuk-Gałwiaczek et al., 2018).

The restoration of the natural (ground)water system and using its buffering capacity is seen as a suitable way to retain water from winter to summer to deal with climate change and an increasing freshwater demand (Baptist et al., 2016; Hendriks et al., 2023; Tiebosch et al., 2022; Voskamp et al., 2022). For the sandy uplands, this entails the restoration of infiltration and seepage areas by raising groundwater levels. This requires adaptation of the drainage base, which is the maximum depth of soil that is drained by the drainage system (Fig. 4). Making the drainage base more shallow increases the base flow in streams during dry periods and hence improves aquatic ecological conditions (Hendriks et al., 2014). Depending on the local geohydrological conditions, this measure slightly increases actual transpiration and decreases required irrigation volume during the growing season, benefitting agriculture in this region during droughts when possibilities for irrigation are limited (Van Den Eertwegh et al., 2021). However, it also reduces the length of the growing season and thus crop yields because of a postponed start of the growing season due to limited trafficability of the field. There is also a higher risk of crop damage during the growing season due to limited trafficability and oxygen stress. This could limit the agricultural use of some areas (Bartholomeus et al., 2023). To quantify trade-offs between benefits for the regional water system and local field scale agricultural conditions and to investigate what type of land use would be possible in an adjusted water system, additional research on the field scale effects of

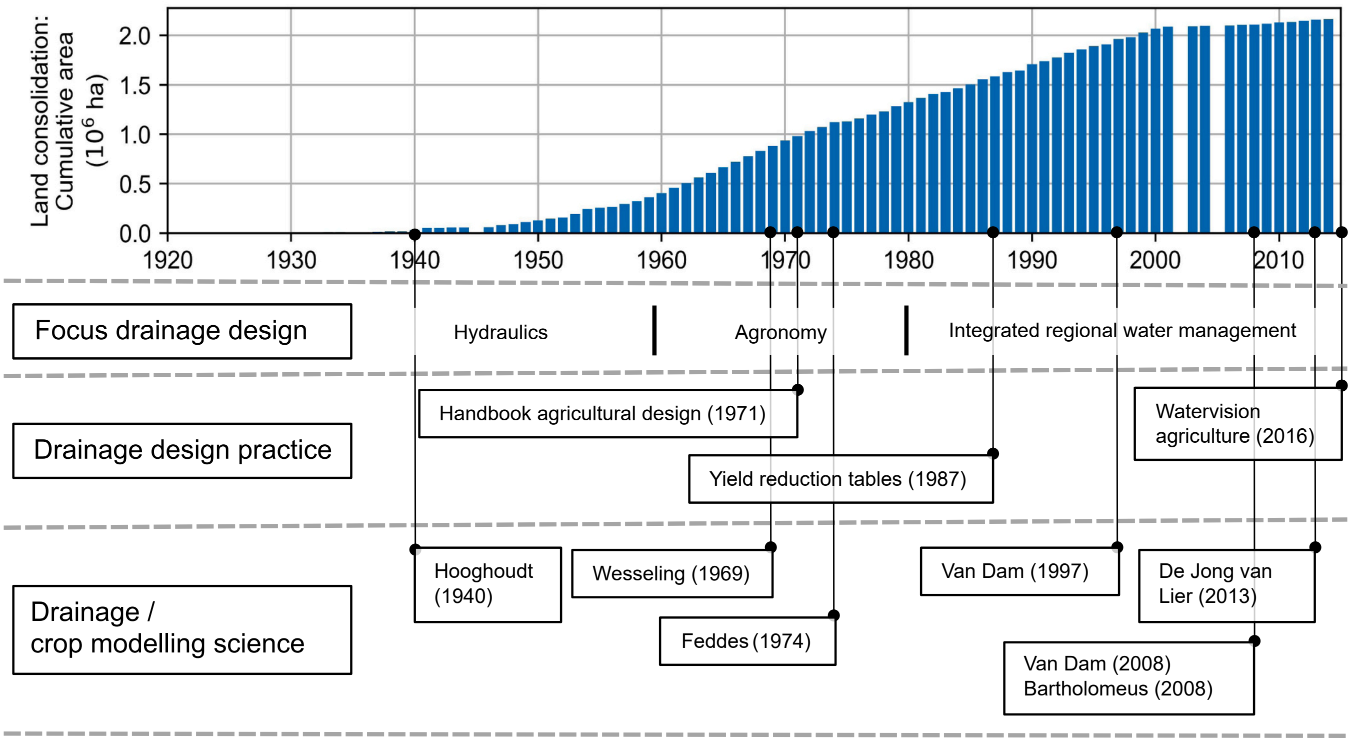


Fig. 2. Cumulative area of land consolidated between 1925 and 2015 (Rijksdienst voor het Cultureel Erfgoed, 2015) with a conceptual depiction of major developments in drainage design focus, practice and science in the Netherlands.

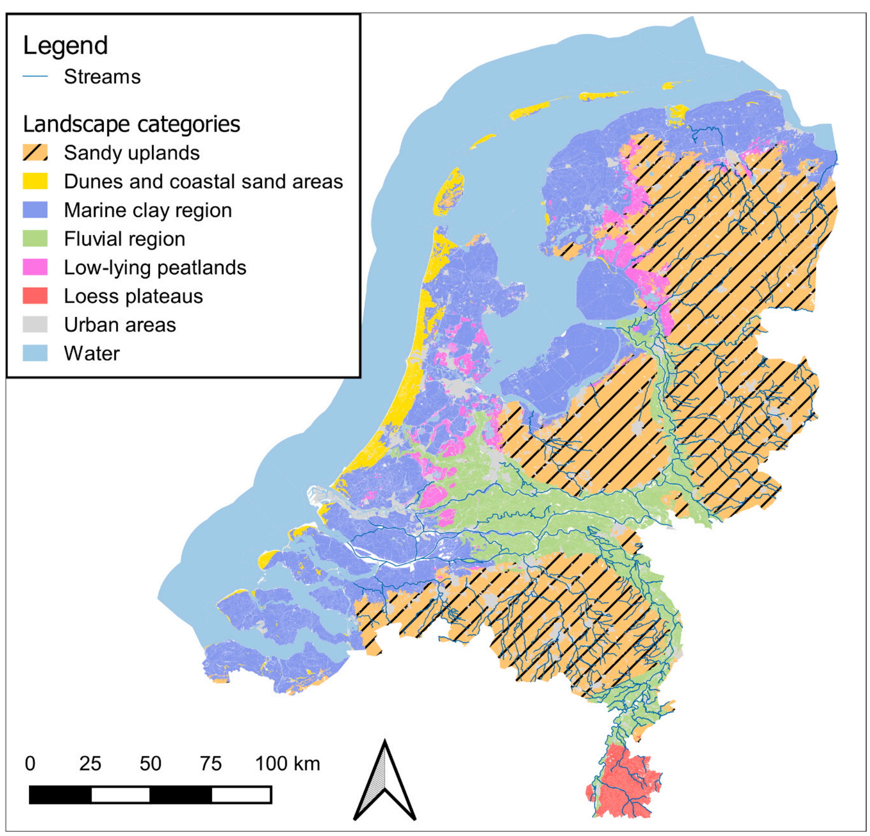


Fig. 3. Map of the different landscape types (Van Delft et al., 2025; Van Delft and Maas, 2023) and surface water bodies (Informatiehuis Water, 2021) of the Netherlands with the sandy uplands indicated in dashed orange.

changing the drainage base is required.

Choosing the appropriate level of conceptual model detail remains a

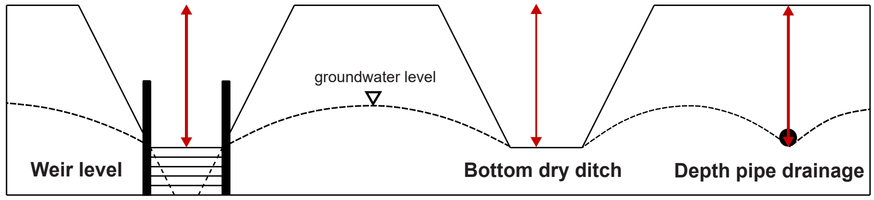


Fig. 4. Visualisation of the concept 'drainage base'.

point of discussion among geoscientists and is generally done based on the goal of the model and the availability of data (Baartman et al., 2020). Simple models can be more communicable, and their calibrated lumped parameters can include effects of multiple processes. However, this limits their applicability to the conditions they are calibrated for and renders them less suitable for modelling under climate change (Bartholomeus et al., 2011; Hrachowitz and Clark, 2017; Melsen and Guse, 2021). Detailed models with explicit process descriptions are more generally applicable but are harder to explain and to calibrate. Models are widely used within science and policy and often choices on level of model detail are implicitly made (Melsen, 2022). Moreover, for a model with many parameters like SWAP-WOFOST, the use of standard parametrisations based on literature is common (De Melo and De Jong Van Lier, 2021). For example, all the studies between 2008 and 2024 using SWAP-WOFOST, listed by Heinen et al. (2024), used standard parameters, while 59% calibrated a subset of parameters, often related to soil hydraulics. Therefore, differences in model outcomes due to different standardly parametrised levels of conceptual model detail requires further investigation.

This research aims to evaluate the increase of the level of conceptual model detail, the result of the scientific developments in the last 50 years, on the relation between yield and the drainage base and, derived from the latter, the feasible range of the drainage base associated with a certain minimum relative yield (e.g. the red line in Fig. 1). This is done in the geographical context of the sandy uplands of the Netherlands and the changing Dutch climate over the last 100 years, using the available subroutines as incorporated in the SWAP-model and their standard parametrisation used in practice. Implications for modelling and drainage practice will be discussed.

2. Methodology

The developments in drainage science in the Netherlands of the last 50 years (Fig. 2) were consolidated in the SWAP model as different subroutines that differ in number of processes included and the related level of simulation detail. This study uses these subroutines to systematically trace the effect of the level of detail of included processes on the relation between agricultural yield and the drainage base. Commonly used parametrisations of the different subroutines were used as provided by, among others, the SWAP manual (Kroes et al., 2017) and Watervision Agriculture (Hack-ten Broeke et al., 2019, 2016).

The approach consisted of two steps (Fig. 5). The first step demonstrates the relation between yield and the drainage base for five base models, which differ in the level of detail, for fodder maize simulated from 1923 to 2024. The base models have common parameters (Section 2.2) but simulate potential evapotranspiration, crop growth and oxygen and drought stress in an increasingly more detailed manner (Table 1; Section 2.3). Base models 1–4 correspond with levels of detail commonly used in the Netherlands for simulating the unsaturated zone in regional groundwater models (Van Walsum et al., 2023) and base models 4 and 5 correspond to levels of detail used in WaterVision Agriculture (Hack-ten Broeke et al., 2019). Additionally, the different levels of detail for drought stress are also available in other hydrological models such as HYDRUS-1D (Šimůnek et al., 2025). For each of these base models, the drainage base was varied (Section 2.1).

To evaluate the effect of changing meteorological conditions over the last century, results were aggregated for the 30-year periods 1925–1954, 1960–1989 and 1995–2024. The effect of changing atmospheric CO_2 concentration on crop growth was not considered, because no reliable parameters were available for concentrations lower than 360 ppm (De

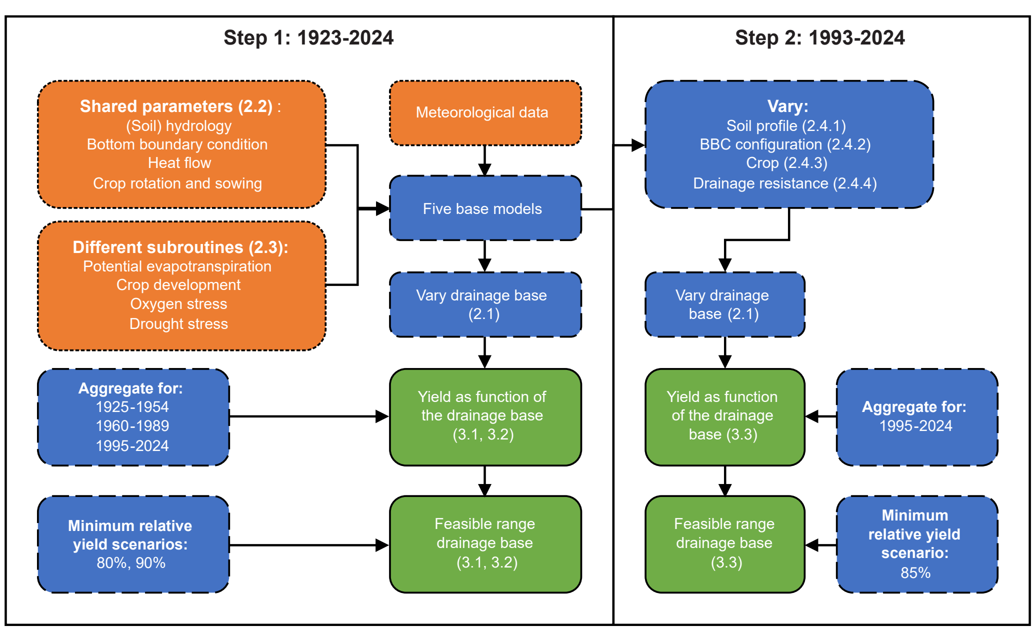
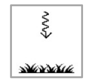
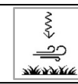
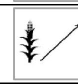
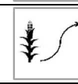
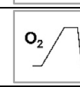
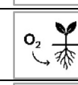
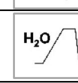
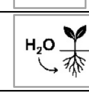


Fig. 5. Modelling approach with input (orange, dotted border), methodological steps (blue, dashed border) and results (green, solid border). Corresponding section numbers are given between brackets.

Table 1
Overview of the five levels of increasing model complexity levels and their used SWAP subroutines. The model subroutine of De Jong Van Lier et al., 2013 simulates root water uptake differently than the other subroutines, as it implicitly compensates the reduction of root water uptake due to drought or oxygen stress in one part of the root system by increased uptake in another part of the root system.

Model subroutine	Level of detail	Method	Icon	Base model 1	2	3	4	5
Potential evapo-transpiration	Low	Crop factor and reference evapotranspiration (Makkink, 1957)		X				
	High	Penman-Monteith (1965)			X	X	X	X
Crop development	Low	Static (Kroes et al., 2017)		X	X			
	High	Dynamic using WOFOST (Boogaard et al., 2014)				X	X	X
Oxygen stress	Low	Feddes (1978)		X	X	X		
	High	Bartholomeus et al. (2008)					X	X
Drought stress	Low	Feddes (1978)		X	X	X	X	
	High	De Jong van Lier et al. (2013)						X

Wit et al., 2019).

Using the resulting relationships between yield and the drainage base, feasible ranges of the drainage base required to achieve a minimum relative yield of 80% and 90% were determined. These percentages serve as an example of criteria that could be the outcome of a societal process balancing economical, ecological and socio-cultural stakes (Jacobs et al., 2016) and strike a balance between maximum and economically infeasible yields.

The second step applies the methodology of the first step to different soil profiles, bottom boundary condition configurations, crops and drainage resistances (Section 2.4; Fig. 5) to check if differences between the base models found in step one are consistent across contexts. A shorter period was simulated (1995–2024) and feasible ranges of the drainage base were determined for a minimum relative yield of 85%.

In and output data together with Python scripts documenting the methodology are available at https://doi.org/10.4121/78749828-6401-4065-828b-87c05663c566. This repository also contains the SWAP model input files for the different base models. Specific details and assumptions are described in the following sections.

2.1. Yield and the drainage base

The value of interest in this study is the agricultural yield as affected by different choices for regional surface water management, accounted for by the drainage base. This study focuses primarily on potential yield, defined as the non-limited yield under optimal growing conditions and is determined by the radiation and temperature during the growing season, and water-limited yield, defined as the potential yield reduced by oxygen stress due to waterlogging and drought stress due to insufficient water availability (Ravensbergen et al., 2024; Van Ittersum et al., 2013). Actual yield, which can be measured and, in addition to the factors mentioned before, is determined by nutrient availability, weeds, pests and diseases and farm management (Ravensbergen et al., 2024; Van Ittersum et al., 2013), was not simulated in this study. Irrigation was also not considered as this can offset effects of varying the drainage base and depends on regional water management. For fodder maize and grass, yield was defined as the total above ground biomass, which includes the dry weight of dead and alive leaves, stems, and storage organs. For other crops, only the total dry weight of the storage organs was considered.

The drainage base is defined as the maximum depth below soil surface (ss) to which water can be drained and represents either the water level regulated by weirs or the bottom of field ditches or pipe drainage (Fig. 4). The drainage base can function as a design criterium and is therefore considered constant in this study, varying between 30 and 200 cm-ss. Intervals of 10 cm were considered sufficiently detailed to demonstrate the method to identify feasible ranges and optima on the one hand while reducing simulation runtime on the other hand.

Besides its effect on the water-limited yield, the drainage base also affects the potential yield by its influence on the carrying capacity of the field and thus the start of the growing season (Feddes, 1988). Therefore, the relative yield in this study is defined per base model for each year separately as the water-limited yield divided by the highest potential yield across all values of the drainage base. Differences between annual potential yields between base models 3–5 were negligible, allowing for the intercomparison of their relative yields. Base models 1 and 2 using the static crop growth subroutine do not explicitly simulate biomass production. Therefore, the ratio between the actual and potential transpiration was used to calculate the water limited yield for these models, following the approach of De Wit (1958).

2.2. Base models: common parameters

The common parameters constitute field conditions at a fictional representative field in the sandy uplands of the Netherlands. In total, the 100-year period between 1923 and 2024 was simulated at a daily time scale. The memory in the system of this scale was found to be approximately one year, such that 1923 and 1924 were used as the model warmup period. To evaluate the effect of changing meteorological conditions, results were aggregated for the 30-year periods 1925–1954, 1960–1989 and 1995–2024, using a 5-year interval in between.

2.2.1. Meteorology

Daily meteorological data of weather station De Bilt (52.1° N, 5.18° E, 1.9 m above mean sea level) of the Royal Netherlands Meteorological Institute, located in the centre of the Netherlands, was used as model input. From its measurements, the minimum, average and maximum temperature, average relative humidity, average wind speed, precipitation, sun hours and global radiation were used in the simulation. Similar to the approach of Bartholomeus et al. (2015), missing data in April 1945 were replaced with the data from April 1944 and vapor pressure was calculated from relative humidity using the approach of Allen et al. (1998).

Between 1923 and 2024, wind measurements were performed at different heights (Supplementary Material A.1) and were therefore converted to wind speeds at a height of 2 m above ground assuming a logarithmic wind profile (Allen et al., 1998). The adjusted measurements still showed significantly different averages and variances of the periods in which different measurement heights were used. Average wind speeds changed the most between the periods 1953–1961 and 1961–1993 when the height of the measurement device was 38.3 m and 10 m, respectively. The use of a logarithmic profile for the relation between the wind at 38.3 and 2 m is less accurate as the relation is sensitive to the degree of atmospheric instability and the surface roughness of the area surrounding the meteorological station (Wierenga and Rijkoort, 1983). Further bias correction of the wind measurements was out-of-scope for this study. Therefore, the potential evapotranspiration during 1953–1961 is underestimated as, using the Penman-Monteith equation (Allen et al., 1998) and average temperature, humidity and global radiation between 1953 and 1993, the average wind speed between 1953 and 1961 results in a 4.9% decrease of potential evapotranspiration compared to the average wind speed between 1961 and 1993.

Global radiation was derived from sun hours per day, using the method of Allen et al. (1998), like the approach of Bartholomeus et al. (2015). For consistency, these derived radiation values were used for the entire simulation period instead of the observed radiation. The coefficient of determination of the derived values compared to the measured global radiation (from 1958 onwards) was 96.4% and the relative error of the total received radiation during the growing season, averaged over 30 years was at maximum 1%.

2.2.2. Soil profile

The BOFEK clustering of soil profiles of the Dutch soil map (Heinen et al., 2022) was used to determine the most relevant soil profile of the Dutch sandy uplands. Cluster 3015 (weakly loamy sandy soils III) represents 22.5% of the sandy soils in the Netherlands. Its hydraulic properties, derived from the Staring series (the national soil water retention and conductivity library; Heinen et al., 2020), and textural properties are given in Table 2. Soil hysteresis was not considered, and soil properties were assumed constant. The depth of the simulated profile was taken as 3 m, assuming the soil between 1.2 and 3 m has the same properties as the deepest layer of the soil profile. A maximum rooting depth of 40 cm-ss was used, following the parametrisation of Watervision Agriculture (Hack-ten Broeke et al., 2019, 2016), as roots were assumed to be unable to penetrate soil layers with a bulk density of more than 1.6 g cm^{-3}.

Table 2
Textural and hydraulic parametrisation with fitted Mualem-Van Genuchten (MVG) parameters for each soil horizon of soil profile cluster 3015 (Heinen et al., 2021, 2020; Wageningen Environmental Research, 2024). Top and bottom of each horizon are given in cm below soil surface (cm-ss).

Horizon Property	1	2	3	4
FAO horizon description (FAO, 2006)	Ap	Bhe	BCe	Cg
Top (cm-ss)	0	25	40	60
Bottom (cm-ss)	25	40	60	120
Organic matter (mass-%)	5.7	2.2	1	0.3
Clay content (mass-%)	3	3	3	3
Silt content (mass-%)	10	8	8	6
Sand content (mass-%)	87	89	89	91
Bulk density (g cm^{-3})	1.365	1.576	1.633	1.672
Residual water content (cm^3 cm^{-3})	0.02	0.02	0.02	0.01
Saturated water content (cm^3 cm^{-3})	0.434	0.387	0.387	0.366
MVG α (cm^{-1})	0.022	0.016	0.016	0.016
MVG n (-)	1.349	1.524	1.524	2.163
MVG l (-)	7.202	2.440	2.440	2.868
Fitted saturated hydraulic conductivity (cm d^{-1})	83.24	22.76	22.76	22.32

The bottom boundary condition for water flow was chosen as a Cauchy boundary condition to simulate infiltration and seepage to the regional water system. A hydraulic resistance of 1000 d was used following the average of the calibrated models of De Wit et al. (2024) and Van Der Gaast et al., 2006 of fields in different parts of the Pleistocene sandy soil areas. A sinusoid with a period of a year and a maximum on the 1st of March was used to describe the external hydraulic head. The weighted average of the average highest and lowest groundwater level in the sandy soil areas was used to determine the annual average head (120 cm-ss) and amplitude (50 cm) of the sinusoid.

Heat flow within the soil profile was simulated using the air temperature as top boundary condition and a zero-flux bottom boundary condition.

2.2.3. Hydrological processes

Other hydrological processes that were simulated besides precipitation and groundwater recharge mentioned in previous paragraphs are transpiration, soil evaporation, interception, runoff, and drainage. Actual soil evaporation is simulated using Darcy's law and the reduction function according to Boesten and Stroosnijder (1986) for the top boundary compartment. Interception was simulated using the method of Von Hoyningen-Huene (1983) and Braden (1985) with a commonly used maximum interception amount of 0.25 mm d^{-1} leaf area index^{-1} (Kroes et al., 2017). Runoff occurred when ponding exceeded 2 mm. Drainage was calculated by $q = \frac{h_{soil} - h_{base}}{\gamma_{dr}}$, with q the flow towards the drain (m d^{-1}), h_{soil} the groundwater level in the soil (m), h_{base} the drainage base (m, see Section 2.1) and γ_{dr} the drainage resistance (d). Infiltration from the ditch to the soil was not allowed to mimic the effect of the drying up of field ditches.

2.2.4. Crop

Fodder maize is the most grown arable crop in the Dutch sandy uplands (Statistics Netherlands, 2025). A crop rotation of fodder maize (16th of April to 31st of October) and a fictional winter cover crop (15th of November - 15th of April) was simulated for every year. The two levels of model detail in the parametrisation of fodder maize are treated under Section 2.2.4. Both levels of crop model consider a potential delay in sowing and germination of the crop due to overly cold and wet field conditions. The fictional cover crop resembles (un)intentional plant growth during the winter season and is simulated as a vegetation with a minimum canopy resistance of 94 s/m and a constant leaf area index (0.7 m^2/m^2), crop height (12 cm), root depth (10 cm), and crop transpiration factor (0.7).

2.3. Base models: different levels of detail

2.3.1. Potential evapotranspiration method

Two methods to calculate potential evapotranspiration are commonly used in the Netherlands. The first combines the reference evapotranspiration according to Makkink (1957) with a crop factor. The Makkink reference evapotranspiration is provided standardly by the Royal Netherlands Meteorological Institute and is interpreted as the evapotranspiration of a well-watered grass field. It is calculated from the average daily temperature and total shortwave radiation (Hiemstra and Sluiter, 2011):

$$ET_{\mathrm{ref}} = C * \frac{\Delta}{\Delta + \gamma} * \frac{R_{\mathrm{sw}}^{\downarrow}}{\lambda * \rho_{\mathrm{w}}} \quad \text{Eq. 1}$$

With ET_{ref} the reference evapotranspiration (m d^{-1}), C a constant, commonly taken as 0.65 (De Bruin, 1987), Δ the slope of the saturation water vapor pressure (kPa °C^{-1}), γ the psychometric constant (kPa °C^{-1}), $R_{\mathrm{sw}}^{\downarrow}$ the incoming shortwave radiation (J m^{-2} d^{-1}), λ the heat of vaporisation (J kg^{-1}) and ρ_{w} the bulk density of water (1000 kg m^{-3}). The potential evapotranspiration ($ET_{\mathrm{pot,mak}}$) of a crop can be obtained by multiplying the reference evaporation by a crop factor f, which depends on the development stage of a crop (Feddes, 1987):

$$ET_{\mathrm{pot,mak}} = f * ET_{\mathrm{ref}} \quad \text{Eq. 2}$$

The division of the potential evapotranspiration between evaporation and transpiration for partly covered soils was done using the crop and soil factors obtained from the standard input files of SWAP 4.0.1.

Secondly, potential evapotranspiration can be calculated according to the method of Penman-Monteith (1965). This equation includes the influence of turbulent transport of heat and water besides the incoming radiation as driver for evapotranspiration (Monteith, 1965):

$$ET_{\mathrm{pot,pm}} = \frac{86400}{\lambda * \rho_{\mathrm{w}}} * \frac{\Delta(R_{\mathrm{n}} - G) + \frac{\rho_{\mathrm{a}} c_{\mathrm{p}}}{r_{\mathrm{a}}}\left(e_{\mathrm{s}}(T_{\mathrm{a}}) - e_{\mathrm{a}}\right)}{\Delta + \gamma\left(1 + \frac{r_{\mathrm{s}}}{r_{\mathrm{a}}}\right)} \quad \text{Eq. 3}$$

With $ET_{\mathrm{pot,pm}}$ the potential evapotranspiration (m d^{-1}), R_{n} the net radiation (J m^{-2} d^{-1}), G the energy flux to deeper soil layers (J m^{-2} d^{-1}), ρ_{a} the density of air (kg m^{-3}), c_{p} the specific heat capacity of air (J kg^{-1} °C^{-1}), r_{a} the aerodynamic resistance (s m^{-1}), e_{s} the saturated vapor pressure (Pa), T_{a} the air temperature (°C), e_{a} the air vapor pressure (Pa), r_{s} the canopy resistance (s m^{-1}) and the factor 86400 (s d^{-1}) for unit conversion. This equation uses more physics-based relations compared to the Makkink reference evapotranspiration, although the parameters r_{s} and r_{a} are often derived from empirical relations (De Bruin, 1987). The division of the total evapotranspiration between evaporation and transpiration was done using the soil and canopy resistances and the soil cover fraction. Parameters were derived from Watervision Agriculture (Hack-ten Broeke et al., 2019, 2016).

2.3.2. Crop development

The simple crop growth module within SWAP does not calculate yield but simulates the transpiration and interception of water of a crop in a basic manner. The required leaf area index and root depth as function of development stage were parametrised for fodder maize following the standard parameters included in SWAP version 4.0.1 (Kroes et al., 2017).

The dynamic crop development model WOFOST is also available as SWAP subroutine. It simulates the crop development stage, the potential and actual intercepted light and subsequent CO_2 assimilation, plant respiration and the partitioning of assimilates across plant organs under influence of crop traits, temperature and radiation (De Wit et al., 2019). The parametrisation of the WOFOST model was done using the WOFOST crop database (De Wit, 2025) using parameters for the fodder maize variety "Fodder_maize_nl". Additional parameters concerning root development and transpiration were taken from the parametrisation of Watervision Agriculture (Hack-ten Broeke et al., 2019, 2016). All these parameters describe a genotype that is not representative of the historically used genotypes within the simulation period. However, this research did not intend to represent historical conditions but aimed principally to evaluate the effects of changing meteorological conditions. Hence the same genotype was used for the entire simulation period.

2.3.3. Oxygen stress

The root water uptake of a crop can be reduced due to both oxygen and drought stress. Oxygen stress, defined as a state of reduced metabolism of plant roots due to insufficient soil aeration, can be simulated within SWAP using the Feddes function (Feddes et al., 1978) or the more process-based approach of Bartholomeus et al. (2008). The piecewise linear function of Feddes describes the reduction in root water uptake in a soil compartment as function of the pressure head, using two thresholds pressure heads h_1 and h_2. Root water uptake is reduced proportionally if the pressure head is between h_1 and h_2 and reduces to zero when the pressure head is larger than h_1. These threshold values depend on the crop type and were taken from the standard parametrisation of Wesseling (1991).

The subroutine of Bartholomeus et al. (2008) calculates the reduction in root water uptake using a minimum gas filled porosity which is based on root and microbial respiration, the diffusivity, and the oxygen concentration gradient in the soil (macro scale, vertical transport) and to the root (micro scale, horizontal transport). In case the actual gas filled porosity is lower than this minimum, root respiration is adjusted accordingly, and root water uptake is reduced proportionally. This subroutine was parametrised using the values of the standard input files included in SWAP 4.2.0 (Kroes et al., 2017).

2.3.4. Drought stress

A plant experiences drought stress when the atmospheric evaporative water demand exceeds the maximum extraction rate of the roots (Vanderborght et al., 2024). Similar to oxygen stress, this can be modelled by multiple SWAP subroutines: 1) with the empirical Feddes function (Feddes et al., 1978) and 2) with the more process-based method of De Jong Van Lier et al., 2013 which simulates water flow from the rhizosphere to the leaves. In the subroutine using Feddes' function, root water uptake is calculated for each discretisation layer separately and integrated over depth afterwards. Feddes' piecewise linear function describes the reduction of root water uptake in a discretisation layer as a function of the prevailing pressure head in that layer. Between two threshold pressure heads (h_3 and h_4) the reduction of root water uptake is proportional. For pressure heads lower than h_4 root water uptake reduces to zero. The threshold h_3 can vary between two values depending on the atmospheric transpiration demand. The threshold pressures are crop dependent and were taken from the standard parametrisation of J.G. Wesseling (1991).

De Jong Van Lier et al., 2008 developed a more process-based model, implemented as a SWAP subroutine, in which they simulate radial water flow from the rhizosphere to roots using the matric flux potential, which is defined as the integral of the unsaturated hydraulic conductivity function. The plant transpiration is subsequently calculated by integrating the difference between the matric flux potential at wilting point and at the conditions in the rhizosphere over depth, weighed by a parameter dependent on the root radius and root length density. Root water uptake is thus calculated for the entire root zone, extracting water from those locations which require the least energy. Compared to the approach using Feddes' function, this leads to compensation of reduction of root water uptake due to oxygen or drought stress in a certain discretisation layer by increased root water uptake in another layer. Drought stress occurs when pressure heads in the complete root system decrease such that the total soil water flow to the roots becomes less than the potential transpiration. De Jong van Lier et al. (2013) later extended the concept by also including radial and axial resistances within the plant system. This subroutine was parametrised using the reference values given by De Melo et al. (2025b) and using the same values for the root radius and specific root length as used for the calculation of oxygen stress with the subroutine of Bartholomeus et al. (2008).

2.4. Effect choice of soil profile, crop, bottom boundary condition, and drainage resistance

To assess the extent to which the results of step 1 depend on the chosen parametrisation, the base models were also run for other relevant soil profile clusters in the sandy uplands of the Netherlands, different configurations of the Cauchy bottom boundary condition, crops, and drainage resistances. Only the period of 1995–2024 was analysed with a modelling warmup period of 2 years starting in 1993.

To get representative soil profiles and bottom boundary condition configurations for the Dutch sandy uplands, the different ecological landscape types were used as defined by Kemmers et al. (2011) and Van Delft and Maas (2023) based on the local geomorphology, soil type and surface water dynamics. These areas are characterised by plateaus, intersected by brook valleys (Ritzema and Van Loon-Steensma, 2018). Most of the sandy soils consist of cover sand, deposited by wind at the end of the Pleistocene. The soils of the southern sandy uplands consist mainly of this cover sand, while the northern and eastern sandy uplands also have glacial deposits (Van De Ven, 1993). Within the sandy uplands, six ecological landscape types occur in areas currently used for agriculture: cover sand areas, drifting sand areas, tectonic terraces with coarser sandy soils of alluvial origin, glacial ridges and plateaus, and old farmlands where soils have been altered by century-long agricultural practice and stream valleys (Kemmers et al., 2011).

2.4.1. Sandy soil profile cluster

The two BOFEK2020 clusters (Heinen et al., 2021) occurring the most in each of the different landscape types of the sandy uplands, excluding nature areas, were determined. These were clusters 3002 (Loamy sandy soils with clayey top layer), 3004 (Loamy sandy soils I), 3005 (Loamy plaggic sandy soils), 3012 (Weakly loamy plaggic sandy soils), 3014 (Weakly loamy sandy soils II), 3015 (Weakly loamy sandy soils III), 3019 (Weakly loamy sandy soils IV), 3021 (Loamy sandy soils III). The simulation results for soil profile clusters 3019 and 3021 were similar to those of clusters 3014 and 3004, respectively, and were omitted from the analysis for clarity. All these soil clusters represent at least 5% of the soils of the total sandy uplands except for cluster 3002 which occurs mainly in the less widespread stream valley landscape type. Clusters 3004 and 3005 are loam-rich sandy soil clusters and clusters 3012, 3014 and 3015 are loam-poor sandy soil clusters (Supplementary Material A.2). Cluster 3002 has a 30 cm clay top layer. For depths larger than 120 cm-ss, the soil was assumed to be the same as the soil of the lowest horizon. For soils which had glacial influence this might be erroneous, but using the same assumption for all the soils in this analysis allows for their intercomparison. The maximum root depth per soil profile cluster is given in Supplementary Material A.3.

2.4.2. External head bottom boundary condition

The groundwater regime of a field depends on the position in the regional groundwater system. Therefore, the average groundwater level and the amplitude of the sinusoid describing the external head of the Cauchy bottom boundary condition were derived for the different ecological landscape types. Using the national model for variation in groundwater depth (Wageningen Environmental Research, 2025), the mode of the combined average highest and lowest annual groundwater level of all cells within a landscape type was determined (Table 3). The landscape types of cover sand plains, glacial ridges and plateaus and alluvial plateaus were combined as well as old farmland and drifting sand plains as the values of the average groundwater level and the amplitude were within 10 cm of each other.

Table 3
Average groundwater level in cm below soil surface (cm-ss) and the amplitude of the external hydraulic head at the bottom boundary condition for the different landscape categories.

Landscape categories	Alias name	Average groundwater level (cm-ss)	Amplitude (cm)
Stream valley	Shallow	-75	35
Cover sand plains /Glacial ridges and plateaus /Old alluvial plains	Less shallow	-100	50
Old farmland /Drifting sand plains	Deep	-200	40

2.4.3. Crop type

Other important crops grown in the Dutch sandy uplands are grass, potato, winter wheat, sugar beet and spring barley (Statistics Netherlands, 2025). The parametrisation of the different levels of detail for the simulation of growth of these crops was determined in the same way as for fodder maize. Standard static crop growth parameters were not available for sugar beet and spring barley. The most important parameters for each crop are given in the Supplementary Material A.4.

2.4.4. Drainage resistance

The drainage resistance, which equals approximately 1.7 times the drain spacing, varies between 100 and 500 d on the Dutch sandy uplands (Van Der Gaast et al., 2006). Hence, three drainage resistances were chosen to evaluate its effect on the relation between yield and the drainage base: 100, 250 and 500 d.

3. Results

3.1. Yields of the different time periods

In general, independent of the drainage base and the modelling concept used, average annual water-limited and potential yields decreased between the periods 1925–1954 and 1960–1989 and increased between the periods 1960–1989 and 1995–2024 (Fig. 6a,b). The increase between 1960–1989 and 1995–2024 is larger than the decrease between 1925–1954 and 1960–1989. For example, for a drainage base of 100 cm-ss, water-limited and potential yields decreased between 1925–1954 and 1960–1989 with 2–7%, depending on the base model, and 2%, respectively (Supplementary Material B.1). Between 1960–1989 and 1995–2024 they increased with 12–13% and 14%, respectively. Hence, for most drainage bases and base models, relative yields decreased with 1–5% between the consecutive periods, which is reflected in the decreasing feasible ranges of the drainage base for a minimum relative yield of 90% (Fig. 6d).

The patterns in water-limited and potential yields can be explained by the change in average received radiation and temperature sum in the growing season between the periods (Supplementary material B.1). For example, for a drainage base of 100 cm-ss, the average received radiation in the growing season (sowing to harvest) decreases with 3.2% between 1925–1954 and 1960–1989 and increases with 7.1% between 1960–1989 and 1995–2024. The temperature sum during the growing season increased with 0.7% between the periods 1925–1954 and 1960–1989 and with 8.8% between the periods 1960–1989 and 1995–2024 (Supplementary material B.1). The increase in temperature also increases the length of the growing season, as the soil will be drier and warmer earlier, which increased the growing season length with 0.8% between the periods 1960–1989 and 1995–2024 for a drainage base of 100 cm-ss (Supplementary material B.1). The bias in wind speed input data could have influenced these patterns in potential and water-limited yields, as it results in a bias of lower potential evapotranspiration (Section 2.2.1) and hence lower potential yields and higher water-limited yields before 1961 compared to after. However, this bias

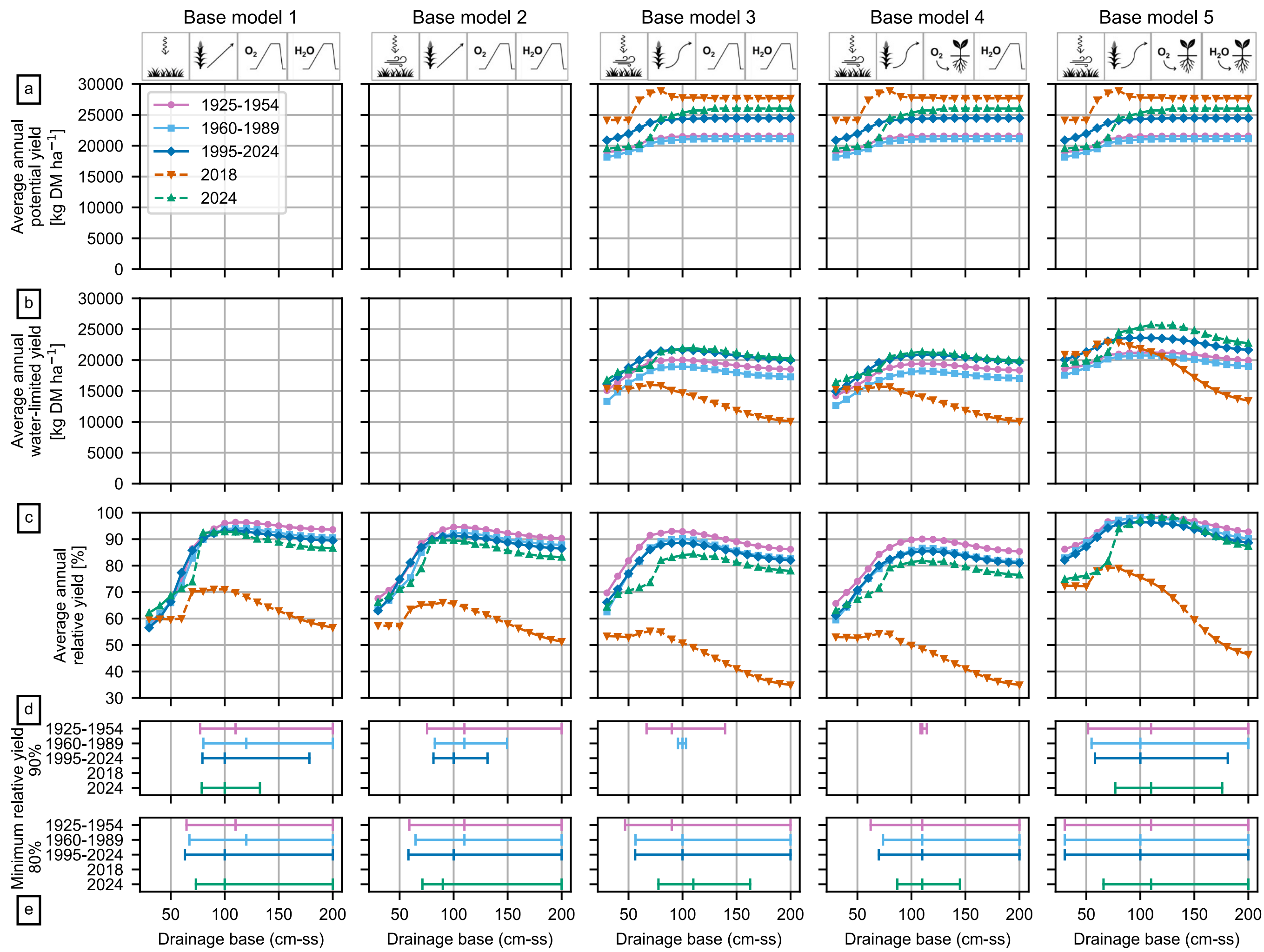


Fig. 6. Average annual potential (a), water-limited (b) and relative (c) yield as function of the drainage base in cm below soil surface (cm-ss) for increasing level of model detail, averaged over the periods 1925–1954, 1960–1989 and 1995–2024 and for an extreme dry (2018) and wet (2024) year. The bottom two rows show the feasible range of the drainage base for a minimum relative yield of 90 (d) and 80% (e) and the drainage base associated with the highest relative yield indicated in between.

cannot explain the simulated trends, as it is opposite.

3.2. Effect of increasing level of model detail

The relation between the drainage base and annual average relative yield changes with each increase in model complexity (Fig. 6c). Changing from Makkink reference evapotranspiration with crop factor (base model 1) to Penman-Monteith evapotranspiration (base model 2) results in increasing and decreasing relative yields for drainage bases shallower and deeper than 80 cm-ss, respectively. This can be explained by that the annual actual evaporation and transpiration are higher for base model 2 compared to base model 1. For example, for a drainage base of 100 cm-ss, the evaporation and transpiration between 1995 and 2024 are 20% and 8% higher for base model 2 compared to base model 1, respectively, reducing the annual drainage flux (Supplementary Material B.1 and B.2). The Penman-Monteith potential evapotranspiration was expected to be larger due to its consideration of the aerodynamic resistance which increases its potential evapotranspiration estimates in winter when radiation is low. However, these large differences are more likely to be caused by the use of standard crop and soil factors and transpiration resistances which do not represent equal average conditions. The difference in evapotranspiration is reflected in the feasible range of the drainage base for a minimum relative yield of 90% which is smaller for base model 2 compared to base model 1 (Fig. 6d). For a minimum relative yield of 80% the range in the drainage base is similar for both base models (Fig. 6e).

Using a dynamic (base model 3) instead of static crop growth simulation (base model 2) also gives higher and lower relative yields for a drainage base shallower and deeper than 80 cm-ss, respectively. The range in the drainage base for base model 3 compared to base model 2 is therefore larger and smaller at a minimum relative yield of 80% and 90%, respectively. Root extension is restricted when oxygen stress occurs, which prevents more oxygen stress later in the growing season. This explains the higher relative yields at drainage bases shallower than 80 cm-ss (Supplementary Material B.4). The lower relative yields at drainage bases deeper than 80 cm-ss can be explained by the propagation of the effects of stress in a certain period throughout the growing season. For example, plant stress during the development of a canopy reduces the leaf area index, which affects the absorbed radiation in subsequent days, reducing further growth (Supplementary Material B.3 and B.4).

Simulating oxygen stress in a more process-based manner (base model 4) reduces water-limited yields independent of the drainage base compared to base model 3. Consequently, the feasible range of the drainage base decreases as well between base model 3 and 4, independent of the time period and minimum relative yield. In general, oxygen stress simulated with the approach of Bartholomeus et al. (2008) occurs at lower pressure heads compared to the approach of Feddes et al.

(1978) for the soil type chosen (Bartholomeus et al., 2008), which can explain the lower crop yields of base model 4. Higher oxygen stress also reduces root extension, leading to a shallower root system which might lead to increased drought stress later in the growing season, further reducing yields (Supplementary Material B.4).

Changing the simulation of root water uptake and drought stress to the method of De Jong van Lier et al. (2013, base model 5) increase water-limited and relative yields independent of the drainage base, resulting in yields much higher than for the other base models. Consequently, the feasible range of the drainage base increases considerably for both minimum relative yields, almost spanning the complete simulation range for a minimum relative yield of 80%. The higher water-limited yields can be attributed to the implicit compensation mechanism for root water uptake, reducing the influence of drought and oxygen stress if these occur in only a part of the root system (De Melo and De Jong Van Lier, 2021; Supplementary Material B.3 and B.4).

These differences between the base models are similar for a single year with extreme weather conditions compared to 30-year averages. In a wet year like 2024, the steep increase in yield between a drainage base of 70 and 80 cm-ss for all base models can be attributed to an increase of the growing season length, due to the soil being warm and strong enough to allow for earlier sowing (Supplementary Material B.5). For extreme dry years such as 2018, the relative yield of base models using static crop growth is much higher than for the base models using dynamic crop growth. For drainage bases deeper than 140 cm-ss, relative yields of base models 1 and 2 are even higher than the relative yields of base model 5. This is likely due to the propagation of reduced growth throughout the growing season in the dynamic crop growth subroutine, which is not accounted for in the static crop growth subroutine. Also, the rate of CO_2 assimilation does not increase under extreme warm conditions as opposed to the transpiration rate, further increasing the difference between relative yields simulated with the static and dynamic crop growth subroutines.

3.3. Sensitivity of increasing level of model detail

3.3.1. Sandy soil profile cluster

The effect of the progressive increase in level of detail in modelling the relation between crop yield and the drainage base as described in Section 3.2 for soil profile cluster 3015 was also observed for the other simulated soil profile clusters, particularly the loam-rich soil profile clusters (3004, 3005) and the cluster with a relative deep maximum rooting depth (3012; Fig. 7a). Compared to cluster 3015, these clusters show higher relative yields for drainage bases deeper than 80 cm-ss for base model 1 and 2 and for every drainage base for base model 3–5. This is reflected in comparable and larger feasible ranges for the drainage base for a minimum relative yield of 85% for base models 1, 2 and 5 and base model 3 and 4, respectively. These higher relative yields can be attributed to deeper roots (3012) and the higher water retention and slower decreasing hydraulic conductivity with decreasing pressure head in loamy soils (3004, 3005). The latter results in a higher capillary rise during the growing season and consequently less drought stress.

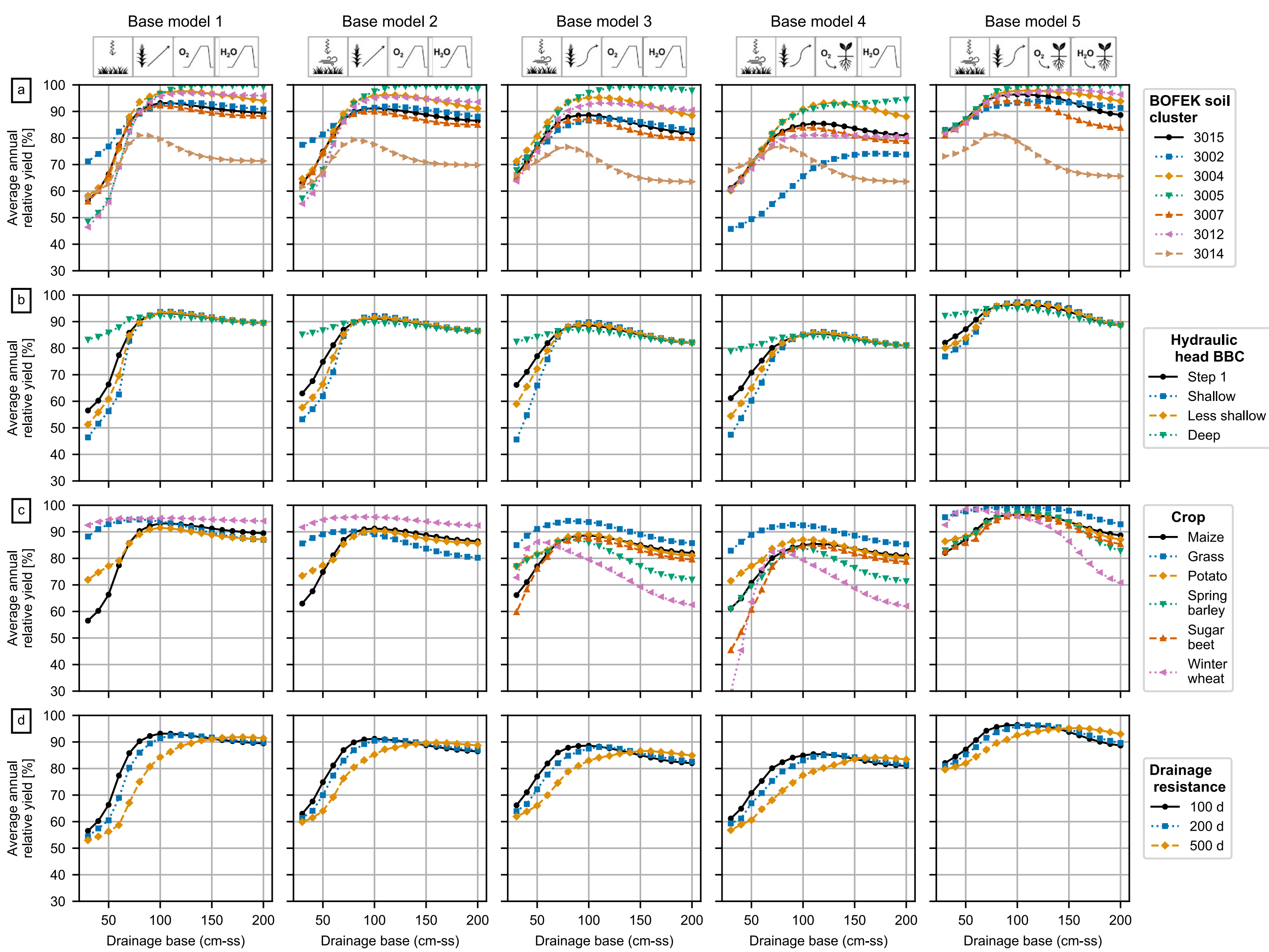


Fig. 7. Relative yield as a function of the drainage base (in cm below soil surface (cm-ss)) for (a) different soil profile clusters, (b) external hydraulic head configurations of the bottom boundary condition (BBC), (c) crops and (d) drainage resistances. The values simulated in step 1 are indicated in black.

The effect of the progressive increase in level of model detail was different for the loam-poor soil profile clusters with a shallow maximum rooting depth (3007, 3014) for drainage bases deeper than 150 cm-ss where base models 1 and 2 have higher relative yields than base model 5 (Fig. 7a). Base model 5 simulates more transpiration reduction and soil water potentials do not decrease as low as for base models 1 and 2 (Supplementary Material B.3). In addition, capillary rise is limited in clusters 3007 and 3014, compared to cluster 3015, limiting the possibility for compensatory root water uptake at the bottom of the root zone for base model 5.

Soil cluster 3002, which has a clay top layer of 30 cm, also shows different changes between the detail levels of the base models compared to soil profile cluster 3015. Switching between a static and dynamic growth module (base model 2 and 3, respectively) reduces yields over the whole range in the drainage base and the more detailed simulation of oxygen stress (base model 4) reduces relative yields additionally by 10–20% (Fig. 7a). Both effects are reflected in the narrower feasible ranges of the drainage base for a minimum relative yield of 85% for these base models (Fig. 8a). The lower conductivity at high pressure heads of the clay layer causes more oxygen stress resulting in less root and crop development, reducing yields overall. However, this study did not incorporate typical clay processes such as shrinkage and swelling and preferential water flow, limiting the applicability of the results found for this soil cluster.

3.3.2. External head bottom boundary condition

The effect of the progressive increase in level of model detail remains the same when using other configurations of the external hydraulic head of the bottom boundary condition (Fig. 7b). For drainage bases deeper than 70 cm-ss, additional inflow through the bottom only increases the drainage flux and has little influence on conditions in the root zone. Compared to configuration of step 1, the feasible range of the drainage base for a minimum yield of 85% does not change much for the shallow and less shallow configuration, except for base model 5 where it is slightly smaller (Fig. 8b).

The deep external hydraulic head configuration decreases the effect of varying the drainage base as for each base model, the difference between the maximum and minimum relative yield over all drainage bases is less than 10%. Because of the lower groundwater level there is more soil water storage available and more infiltration through the bottom of the model domain, compared to the configuration used in step 1.

3.3.3. Crop type

The differences between the base models for fodder maize also hold for potato and sugar beet (Fig. 7c). The feasible ranges for the drainage base for a minimum relative yield of 85% are also similar across all base models except base model 4 (Fig. 8c).

The differences between base models 3–5 for spring barley and winter wheat are also similar to fodder maize. Compared to fodder maize, relative yields for spring barley and winter wheat decrease faster with a deeper drainage base. The meteorological conditions during the grain filling phase are more important for these crops as their yield is defined as the biomass of only the storage organs. Higher potential transpiration and thus susceptibility for drought stress during this phase explains lower yields for deeper drainage bases (Supplementary Material B.6). Consequently, their feasible range of the drainage base for a minimum relative yield of 85% extents less deep (Fig. 8c). Winter wheat has higher relative yields compared to fodder maize for drainage bases shallower than 60 cm-ss for base model 3 and 5 and relative yields simulated with base models 1 and 2 are hardly influenced by the drainage base. This can be explained by three causes: (1) its early growing season (October 1st - July 31st) compared to fodder maize (April 16th – September 30th), (2) the high values for h_1 and h_2 of Feddes' root water uptake reduction function (Supplementary Material A.4) leading to the simulation of almost no oxygen stress for base models 1–3 and (3), for base model 5, the high transpiration of winter wheat early in the growing season, leading to a larger potential for drought stress during the grain filling phase such that, for a high drainage base, the reduction of drought stress outweighs the increase of oxygen stress in the beginning of its development.

For grass, the differences between the different base models are minor, although the pattern between base model 3–5 is similar to the pattern for fodder maize (Fig. 7c). The drainage base has little effect on the relative yield for all base models, as reflected in the feasible range of the drainage base for a minimum relative yield of 85% (Fig. 8c). This can be explained by the year-round growing season of grass and multiple harvests in a year, causing less propagation of oxygen and drought stress on further crop growth compared to other crops (Supplementary Material B.7).

3.3.4. Drainage resistance

An increasing drainage resistance does not change the differences between different base models, but it moves the feasible range of the

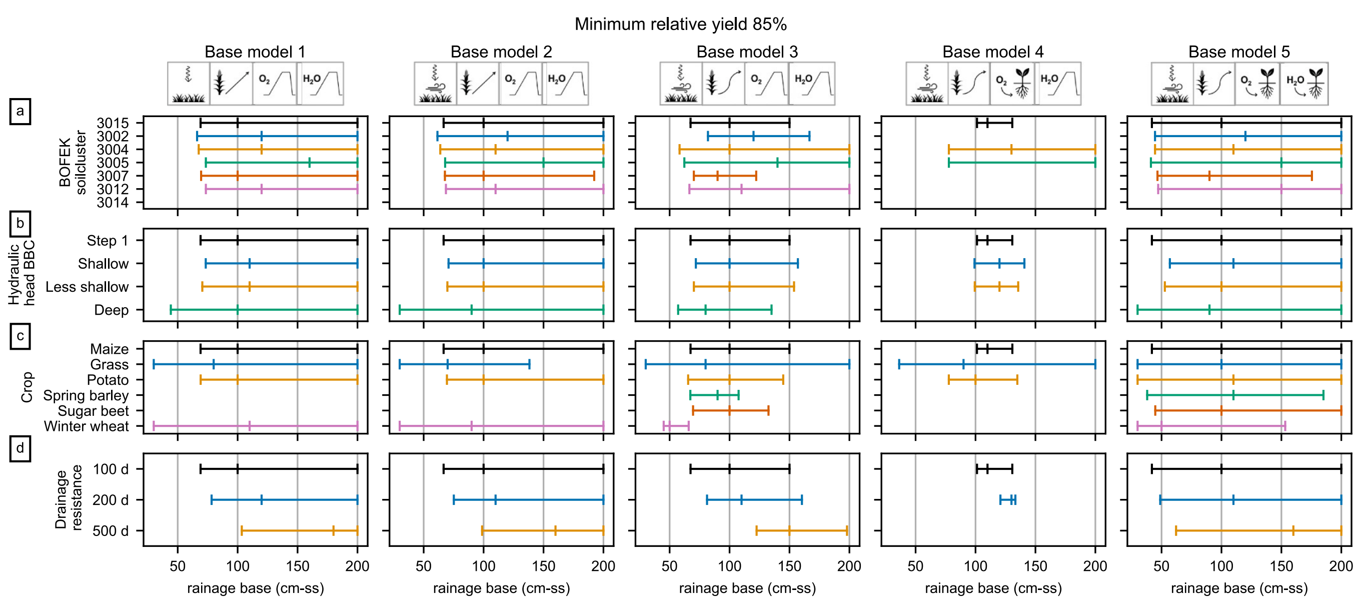


Fig. 8. Range in possible drainage bases in cm below soil surface (cm-ss) for a minimum yield of 85% for (a) the different soil profiles, (b) external hydraulic head configurations of the bottom boundary condition (BBC), (c) crops and (d) drainage resistances. The values simulated in step 1 are indicated in black.

drainage base for a minimum relative yield of 85% to deeper levels for all models (Figs. 7d and 8d).

4. Discussion

4.1. Validity simulations

4.1.1. Fodder maize yields

Potential and water-limited yield are best estimated using crop models as done in this study but can also be estimated using field experiments or maximum yields as reported by surveys among farmers (Van Ittersum et al., 2013). Field measurements of yields at well-managed fields used for testing of new fodder maize varieties serve well as a benchmark for water-limited yields, for which an annual average yield of approximately 20 t ha^{-1} between 1995 and 2015 was measured (Schils et al., 2020). Simulated water-limited yields between 1995 and 2015 for base models 3, 4 and 5 and for a common drainage base of 100 cm-ss (Grotentraast et al., 1988) were 22.2, 21.4 and 24.2 t DM ha^{-1}, respectively. Although genotype and soil hydrological and drainage conditions are different between the observed and the simulated water-limited yields, this indicates that the simulated water-limited yields are relatively high. Water-limited yields are also relatively high compared to measured actual fodder maize yields between 2008 and 2024 for the provinces within the Dutch sandy uplands (Statistics Netherlands, 2025), taking into account a typical difference between actual and water-limited yields of approximately 20% of the water-limited yields (Van Ittersum et al., 2013). Average simulated water-limited yields are 6.6 (30%), 5.8 (27%) and 8.6 (36%) t DM ha^{-1} larger than observed actual fodder maize yields for base models 3, 4 and 5, respectively (Supplementary Material C.1). This might be caused by an underestimation of the potential evapotranspiration (evaporative water demand) by using meteorological data (wind speed, relative humidity) averaged over 24 h instead of the averaged over daytime, which is more accurate (Allen et al., 1998; Kroes et al., 2017). Nevertheless, water-limited fodder maize yields for a drainage base of 100 cm-ss of base models 3, 4 and 5 follow the annual trend in actual yields decently (Pearson R of approximately 0.6; Supplementary Material C.1), given that the spatial aggregation scale of the simulations is smaller and therefore more variation is expected (Ravensbergen et al., 2023).

Similar to the simulated trend of increasing water-limited and potential yields between the different subsequent time periods, observations of actual maize yields also showed an increasing trend. In North-Brabant, one of the provinces in the Dutch sandy uplands, corn yields increased from 9.0 to 16.3 kg DM ha^{-1} (+81.1%) between 1950 and 2010 (Witte et al., 2019). More recently, Schils et al. (2020) found a non-genetic increase of actual fodder maize yields in the Netherlands of 65 kg DM ha^{-1} year^{-1} between 1990 and 2015, attributed to a larger temperature sum and earlier sowing date. The simulated change in water-limited yield between 1960–1989 and 1995–2024 in this study has the same order of magnitude, and, in addition to the factors described by Schils et al. (2020), was explained by an increase in global radiation. This pattern is described as global brightening following the global dimming between 1950 and 1980 (Wild, 2009).

The simulation results of this study indicate that the effect of oxygen and drought stress is becoming more prominent over the consecutive periods as water-limited yields increase less than the potential yields. The ratio of observed on-farm actual yields to yields of the maize variety testing fields as mentioned before also show a decreasing trend, although these observed trends cannot be attributed solely to changing meteorological conditions (Laidig et al., 2014; Schils et al., 2020).

4.1.2. Limitations in available field data

For this study, field data with sufficient level of detail to calibrate the different modelling combinations, as was done by for example Cai et al. (2018a), were not available. The simulated differences between the base models can therefore not be attributed solely to the different levels of model detail, as they also depend on the use of standard parameters. However, the patterns between different levels of model detail are consistent across different sandy soils, crops and bottom boundary conditions, making it likely that these patterns are due to differences in model conceptualisation. Also, Cai et al. (2018a) found that model concepts describing root water uptake with and without compensation performed similar but differed in their calibrated soil hydraulic parameters. This shows the importance of these parameters for root water uptake modelling (De Jong Van Lier et al., 2024) and that calibration not necessarily leads to different behaviour between different model concepts, which is related to the principle of equifinality (Beven, 1993; Hrachowitz and Clark, 2017).

Therefore, this study adds to previous calls (e.g. De S. Nóia Júnior et al., 2023; Orellana et al., 2012; Rötter et al., 2018; Silva and Giller, 2020) for well-equipped long term field experiments to calibrate models with as many parameters as SWAP-WOFOST. To test the different components of SWAP-WOFOST and their combined behaviour, further field and laboratory research measuring soil properties, soil oxygen and water, root development, transpiration and crop development and growth is necessary. This requires further collaboration between crop scientists and soil hydrologists to build datasets that capture both above and belowground processes (Garcia-Vila et al., 2025; Jarvis et al., 2022).

4.2. Effect of increasing level of model detail

The increase in level of detail over the last 50 years to simulate evapotranspiration, crop development, oxygen, and drought stress has changed the relation between the drainage base and crop yield. Simulating evapotranspiration and crop development in more detail increases and reduces relative yields for shallow and deeper drainage bases, respectively. Using a detailed approach for oxygen stress reduces relative yields independently of the drainage base, as opposed to the process-based method of drought stress and root water uptake which results in an overall increase of relative yields. This pattern is consistent across different soils, bottom boundary configurations, crops, and drainage resistances. These differences in model detail matter when applying a subroutine using standard parameters.

This study showed a drastic change in model behaviour between base models 1–4 and 5. The higher simulated water-limited yields for any drainage base of base model 5 result in a wider possible range for drainage bases for a certain minimum relative yield, except for soils which have limited capacity for capillary rise. This is caused by the compensation of oxygen or drought stress in certain part of the root system by additional water uptake elsewhere in the root system. Hence, the transpiration of the whole plant is less affected by partial waterlogging or drying of the soil. This compensation mechanism is an observed phenomenon (Dara et al., 2015; Thomas et al., 2020) and important to incorporate in crop models (e.g. Jarvis, 1989; Vanderborght et al., 2024).

The radically different root water uptake concept of base model 5 requires rethinking of the conceptualisation and parametrisation of other model components, for example the simulation of root growth, for which the modelling concept of the Jong van Lier et al. (2013) is sensitive (De Melo et al., 2025b), and the combination of this concept with the simulation of oxygen stress. The parametrisation and level of detail of these other model components might have been sufficient for simulating drought stress using Feddes' equation, but not for a more process-based approach of root water uptake. Field studies as described in Section 4.1.2 are necessary to determine region and crop specific calibrated parameter sets, as was done successfully in temperate climatical conditions by Cai et al. (2018b) and in tropical conditions by De Melo et al. (2025a). Additionally, a soil column study, similar to the work of Thomas et al. (2024), measuring soil water and oxygen under partial waterlogging would give insight in the dynamics of root development and root water uptake under oxygen stress, which could be used to combine the detailed simulation approach of both oxygen and drought stress.

The results of this study cannot be used to determine which base model and corresponding level of model detail is most valid, since no calibration was performed for each of the base models. Previous research has shown that more process-based approaches are required in the modelling of the interacting processes in the soil-water-plant-atmosphere continuum to allow for spatial or temporal extrapolations (Bartholomeus et al., 2015, 2012; De Melo and De Jong Van Lier, 2021). These studies indicated that models using a reference evapotranspiration with crop factors or Feddes' root water uptake reduction function have serious limitations in their general applicability. Therefore, model configurations using the Penman-Monteith equation (Allen et al., 1998) for potential evaporation and approaches of Bartholomeus et al. (2008) and De Jong Van Lier et al. (2013) for oxygen stress and drought stress, respectively, are likely to outperform models using the subroutines of lower conceptual model detail in this study. However, as mentioned before, parameterisation and testing of these more process-based model subroutines requires attention in further research.

4.3. Implications for drainage design

This research found that potential fodder maize yields are increasing more than water-limited yields over the consecutive time periods, indicating the progressive larger influence of oxygen and drought stress. The demand for water discharge and availability during the growing season, needed to match the increasing potential yields driven by higher temperatures and increased global radiation, is too large to accommodate for. Witte et al. (2019) contributed the decreasing groundwater levels in the province of Noord-Brabant, which impacted water related functions other than agriculture like nature and drinking water supply, to the higher transpiration of crops, changing land use and drainage conditions. From a regional perspective, this necessitates the definition of the water (discharge) demand, or corresponding water-limited yield, for which the regional and field water system should be designed. Although it is uncertain if actual yields will keep increasing in the future (Silva and Giller, 2020), it might be relevant to define an acceptable minimum water-limited or relative yield that can be supported by local and regional water management. In the Netherlands, where agriculture is highly intensive, ecological values are more difficult to accommodate for compared to economic values (Seijger and Hellegers, 2023). A minimum acceptable relative yield to design the water system for could be a means to also incorporate ecological, socio-cultural and economic values of other stakeholders than agriculture (Jacobs et al., 2016). Such a design criterion could vary spatially, depending on the stakeholders involved.

An acceptable minimum yield would provide opportunities for the necessary transformation of the Dutch regional water system, where a new balance must be established in water availability for nature, agriculture, drinking water and industry (Bartholomeus et al., 2023). For example, accepting a minimum relative yield of 85% would allow deviations from the uniform design rule for the drainage base in the Netherlands (95–110 cm-ss for arable land and 85–90 cm-ss for grassland, depending on the subsoil type (Grotentraast et al., 1988)). As shown in Fig. 8d, changes in the design drainage base should be accompanied by changes in the drainage resistance by adjusting the drainage spacing to ensure sufficient drainage capacity during wet periods.

5. Conclusion

Using standard parametrisations for different SWAP subroutines, simulations of different levels of conceptual model detail for the computation of potential evapotranspiration, crop growth and oxygen and drought stress, show considerable differences in the relation between crop yield and the drainage base. This finding highlights that decisions about the level of conceptual model detail together with the use of standard parameters, also in models other than SWAP that employ the same modelling concepts, influence derived recommendations for drainage design. In the context of the Dutch sandy uplands, which are increasingly confronted with amplifying dry periods and wet periods due to climate change, similar to other temperate climatic regions, a shallower drainage base is a promising solution to increase regional water availability. The simulated expanding gap between water-limited and potential yield for all drainage bases over the past 100 years indicates the increasing limiting role of water management and resulting oxygen and drought stress. Consequently, it is critical for regional water management design to choose between further accommodating potential yields and settling on water-limited yields that are regionally sustainable and desirable. Accepting a minimum relative agricultural yield would permit to deviate from uniform design rule for the drainage base currently used in the Netherlands. Future studies focused on specific regions could use the methodology in this study to define new design rules. Additional testing and parameter calibration is necessary, especially when applying the highest level of conceptual model detail for root water uptake and drought stress. Further field and laboratory studies that dynamically measure soil physical properties, soil oxygen and water contents, root growth, transpiration, and crop development are needed to evaluate the individual components of SWAP-WOFOST and their integrated behaviour. This would allow further model development regarding root growth simulation and an integrated approach for oxygen and drought stress.

CRediT authorship contribution statement

J.M. van den Brink: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J.C. Van Dam:** Writing – review & editing, Supervision, Methodology, Conceptualization. **H.M. Mulder:** Writing – review & editing, Software. **C.J. Ritsema:** Writing – review & editing, Conceptualization. **R.P. Bartholomeus:** Writing – review & editing, Supervision, Project administration, Methodolog, Funding acquisition, Conceptualization.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Copilot in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Research data availability

Model in- and outputs and Python scripts used to build and run models and visualise its outputs are deposited at https://doi.org/10.4121/78749828-6401-4065-828b-87c05663c566 and https://git.wur.nl/brink233/papermodeldetail#.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2026.110383.

Data availability

The link to research data and code is provided in section "Research data availability"

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