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Development of subsurface drainage systems: Discharge – retention – recharge

J.A. (Janine) de Wit[a,b,*], C.J. (Coen) Ritsema[b], J.C. (Jos) van Dam[b], G.A.P.H. (Gé) van den Eertwegh[c], R.P. (Ruud) Bartholomeus[a,b]

[a] KWR Water Research Institute, Nieuwegein, The Netherlands
[b] Soil Physics and Land Management, Wageningen University & Research, The Netherlands
[c] KnowH2O, Berg en Dal, The Netherlands

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ABSTRACT

Sufficient freshwater is needed for water dependent sectors such as agriculture, nature, drinking water, and industry. However, even in low-lying, flood prone countries like the Netherlands, climate change, weather extremes, economic growth, urbanization, land subsidence and increased food production will make it more complex to guarantee sufficient freshwater for all sectors. Furthermore, the frequency and amplitude of extremely dry and wet weather conditions is expected to increase. The current Dutch water management system is not designed to anticipate these extremes. Over the last decades, drained Dutch agricultural fields, land consolidation and urbanization resulted in declining groundwater tables. Additionally, the fresh water demand of different sectors (agriculture, industry, drinking water) increased, causing an increased pressure on the regional groundwater system. As a consequence, the annual groundwater table in sandy soil areas dropped over time with the effect that, nowadays, fresh water is becoming scarce in dry periods. In this paper we provide insight in the shifting water management strategy in the Netherlands (1950–2020), with the corresponding drainage systems, developing from conventional drainage (approx. 1950–1990), to controlled drainage (1990's onwards), climate adaptive drainage (2010 onwards) and subirrigation systems (2018 onwards). Furthermore, we provide insight in the effect of subirrigation on groundwater levels and crop yields, based on both international literature and measurements of Dutch field pilots. Although subirrigation can contribute to improved soil moisture conditions for crop growth on field scale, we show that the water volume needed for subirrigation can be large and could put a significant pressure on the available regional water sources. Therefore, efficient and responsible use of the available external water sources for subirrigation (e.g. surface water, treated waste water, or groundwater) is required. Finally, the implementation of controlled drainage with subirrigation asks for correct implementation in the regional balance: it requires an integral, catchment-wide approach.

1. Introduction

The Netherlands is a low-lying, flood prone country, located in a delta in Western Europe (50º - 54º N and 3º - 7º E) (Fig. 1-I). Sufficient freshwater is needed for the water dependent sectors as agriculture, nature, drinking water, and industry. These sectors account for 193 billion euros, ±16% of the Dutch economy (Ministerie van and Ministerie van, 2016). However, climate change, weather extremes, economic growth, urbanization, land subsidence and increased food production, among other things, will make it more complex to guarantee sufficient freshwater for all sectors.

Due to climate change, the range of weather extremes from extremely dry to extremely wet is expected to increase and to occur more frequently (Klein Tank et al., 2014; Philip et al., 2020; van Oldenborgh et al., 2009). The Dutch sandy Pleistocene uplands (Fig. 1-I) are particularly drought sensitive as these are rain fed and water supply from rivers is limited (Deltaprogramma, 2014). However, June 2016 was extremely wet in parts of the Pleistocene uplands, with flooding as a result. The years 2018, 2019 and 2020 were extremely dry in these regions (van den Eertwegh et al., 2021) (Fig. 1-II). However, the water management system is not designed to anticipate both weather extremes. The challenge is therefore to design a resilient soil-water system

* Corresponding author at: KWR Water Research Institute, Nieuwegein, The Netherlands.
E-mail address: janine.de.wit@kwrwater.nl (J.A. (Janine) de Wit).

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to be able to anticipate both (extremely) wet and dry periods.

In the Netherlands, most agricultural fields have been drained to quickly get rid of excess water (Ritzema and Stuyt, 2015). Lower groundwater tables and an increase in crop production were the results. Over the past decades, however, excessive drainage contributed to desiccation. Additionally, groundwater is used for drinking water production and industrial applications, resulting in declining groundwater tables. These activities affect nature areas by drought stress, less upward seepage water, and brooks and fens that become dry (Hoogland et al., 2010). The combination of the increasing food production, a reduction of the available amount of fresh water, and an increase in the fresh water demand, will lead to more fresh water scarcity and necessity for more efficient use of fresh water resources (Witte et al., 2019). These future challenges ask for a good understanding of historic developments and future needs in the use of drainage systems within the regional water management.

Subsurface drainage is essential to make the areas suitable for agriculture, because of the otherwise too shallow groundwater table. From ± 1000 A.D. onwards several drainage systems have been applied in the Netherlands (Haartsen et al., 2010; Hoeksema, 2007; Hooghoudt, 1952; Ritzema and Stuyt, 2015; Ritzema and van Loon-Steensma, 2018; Van Baars, 2005). After the Second World War, the Dutch population grew and more food production was needed. Agricultural fields were intensively drained to lower the groundwater table (Fig. 2). Furthermore, land consolidation (Van den Noort, 1987; Vitikainen, 2004) and urbanization impacted the water levels (Witte et al., 2019) (Fig. 2). Nowadays, drainage systems still quickly discharge fresh water out of regions. Additionally, the water demand for irrigation (agriculture), drinking water production and industry increased, resulting in increased groundwater abstractions. As a consequence of this intensified drainage, urbanization and increased groundwater abstractions, the yearly average groundwater table in the sandy Pleistocene uplands (Fig. 1-I) dropped by ± 33 cm over the last century (Knotters and Jansen, 2005). This desiccation (Fig. 2) negatively affects biodiversity (Hoogland et al., 2010; Witte et al., 2019).

Besides measures to anticipate flooding and waterlogging, measures for water retention are needed to be able to anticipate weather extremes, to lower the anthropogenic pressure on the groundwater system, and to guarantee the water availability for different sectors in dry periods. Drainage systems can contribute to this. Besides discharging water, they have the potential to retain and recharge water in the soil-water system as well. In the latter case, drainage systems are used for subirrigation. These systems are typically relevant for areas with relatively shallow (1–3 m-ss) phreatic groundwater levels, like the Dutch sandy Pleistocene uplands, because of the highest urgency regarding declining groundwater levels and increased irrigation water demand.

The objective of this article is to provide insight into the development of drainage systems including the corresponding drainage strategies and the consequences for the groundwater and surface water system (Fig. 2). This article includes the functionality of different drainage systems in agriculture, and the effect of drainage/subirrigation systems on the groundwater table and water balance components, based on both international literature and field experiments in the Dutch sandy Pleistocene uplands. We describe drainage/subirrigation systems applied in the Netherlands over the last decades, including their effect on the field water balance. Additionally we discuss the challenges for future implementation of drainage/subirrigation systems in the (regional) water system, balancing between discharge, retention and recharge.

2. Drainage systems

2.1. Strategy drainage systems in the Netherlands

From the Second World War onwards the Dutch strategy was to increase drainage capacity and quickly discharge water surplus (Fig. 2). Later on, drainage systems were adapted to also be able to conserve water during periods when drainage was not needed. The water management approach shifted in 2008 to a three-step approach with decreasing priority: (1) retain excess of water in the field, (2) store water in the (regional) drainage system, and finally (3) discharge water to the river (Deltacommissie, 2008; Ritzema and Stuyt, 2015). This approach anticipates hydrological events: a decrease in peak discharges during heavy rainfall to prevent flooding and an increase in water storage for use in dry periods (Ritzema and van Loon-Steensma, 2018). Such adaptive water management is necessary to create enough storage capacity before heavy rainfall occurs. The different water strategies resulted in an evolution of drainage systems over the last decades (Table 1), as further described in the next paragraph.

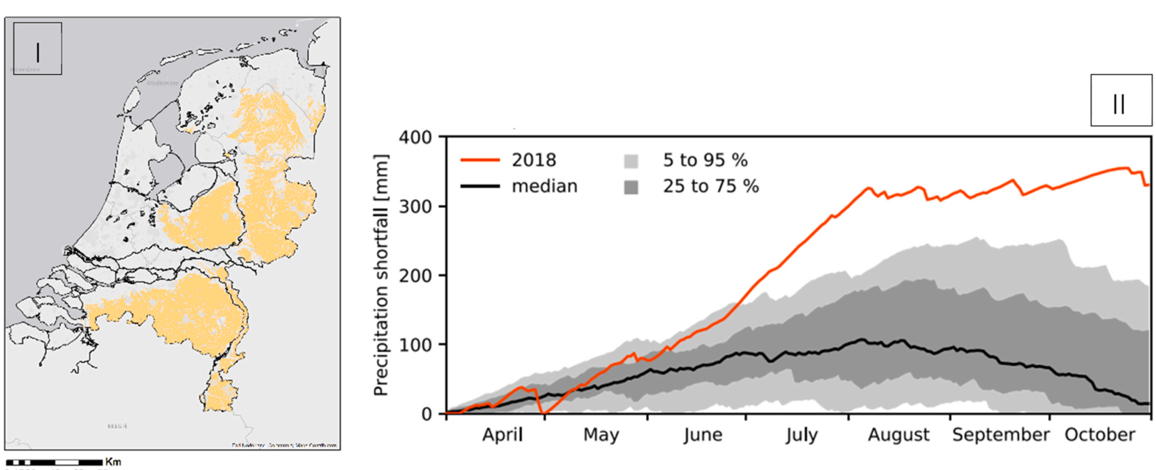

Fig. 1. I: The Netherlands with the (drought sensitive) sandy Pleistocene uplands (yellow) (± 0 – 100 m+MSL). II: The climate in the Netherlands is typically oceanic, meaning: fresh summers and cool winters. Precipitation is 850 mm per year on average, the reference evapotranspiration (according to Makkink, 1957) is ± 559 mm per year on average (Klein Tank et al., 2014).The cumulative rainfall deficit (precipitation minus reference evapotranspiration in the growing season) ranges between 100 mm for average years (black line, based on years 1981–2010, Weather Station De Bilt) and more than 300 mm for dry years such as 2018 (van den Eertwegh et al., 2021) (red line).
Figure II is adapted from Philip et al. (2020).

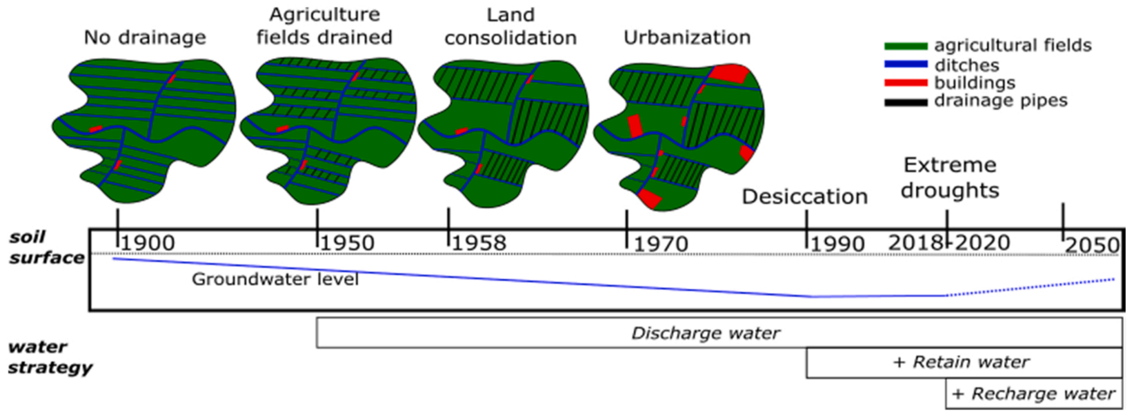

Fig. 2. Timeline with developments which impacted the landscape design and the groundwater levels in the Netherlands. Desiccation started already around 1950; the main water management strategy was to discharge water. From 1990 onwards the agricultural management anticipated on preventing drought stress through i) discharge water to avoid flooding or waterlogging, and ii) retain water when possible. From 2018 onwards the agricultural management changed more to i) discharge water to avoid flooding or waterlogging, ii) retain water in the soil during rainfall, and iii) recharge water to prevent agricultural and hydrological drought. The scheme applies to groundwater-dependent systems (i.e. <3 m-ss).

Table 1
Subsurface drainage systems in the Netherlands (1950–2020) related to the corresponding water management strategy, method to control the drainage level, authority to control the system and scale to which the strategy applies.

Drainage system	Drainage strategy	Drainage level controlled via	System controlled by	Water system scale
No drainage	–	–	–	–
Conventional drainage	Discharge water	–	–	
Controlled drainage	Discharge water Retain water	Ditch	Water Board and/or farmer	Regional water system
Composite controlled drainage	Discharge water Retain water	Control pit	Farmer	Field water system
Composite controlled drainage with subirrigation	Discharge water Retain water Recharge water	Control pit	Farmer	Field water system

2.2. Subsurface drainage systems in the Netherlands

2.2.1. No drainage

The term drainage is internationally used to describe that the groundwater table is lowered through measures as ditches and drainage pipes (Stuyt, 2013). Here, we focus on fields with subsurface pipe drainage (Stuyt, 2013). The period with no drainage is mainly the period before the Second World War. Agricultural fields were surrounded by ditches, but pipe drainage was not common, resulting in bulging groundwater tables between the ditches (Fig. 3-I). Yield losses occurred in wet years due to waterlogging.

2.2.2. Conventional drainage

Conventional drainage consists of single drainage pipes discharging on a ditch (Fig. 3-II). The drainage pipes are installed higher than the maintained ditch level; drainage stops if the groundwater level is below the height of the drainage system (Stuyt, 2013). Conventional drainage was installed on a large scale after the Second World War (Stuyt, 2013). The primary purpose of conventional drainage is to reduce high groundwater tables in winter and early spring for tillage purposes and to prevent water logging during the growing season (Ritzema et al., 2008, 2006). Lowering the groundwater table results in a flatter groundwater table. However, conventional drainage may also introduce drought stress in the summer period, as less water is available (Tan et al., 2002). Nowadays, about 34% of the Dutch agricultural land contains pipe drainage (Massop and Schuiling, 2016).

2.2.3. Controlled drainage

Controlled drainage (or: level-controlled drainage, (Stuyt, 2013)) consists of single drainage pipes connected to the ditch, comparable with conventional drainage, but with drainage pipes below the maintained ditch level (Fig. 3-III). Doing so, conventional drainage is modified to control the drainage outflow through controlling the water level in a ditch by a weir. The purpose of controlled drainage is to (i) prevent unnecessary drainage and conserve water in the regional water system during rainfall, and (ii) reduce peak outflows during discharge. The ditch level is often controlled for a region by water management authorities. This means that effects of controlled drainage can be different for upstream and downstream parcels.

2.2.4. Composite controlled drainage

Composite controlled drainage contains a drainage system where the single drains are connected by one collector pipe at the end of the field (Fig. 3-IV-1). The collector pipe is connected with the control pit and the control pit is connected with the adjacent ditch. The difference between controlled drainage and composite controlled drainage is that the drainage level by composite controlled drainage is regulated by the control pit via the farmer for one agricultural field, instead of by a water management authority for a larger region. The control pit contains a fixed weir structure. The water level in the control pit is equal to the water pressure in the drainage pipes. The system allows to retain water within agricultural parcels and to maintain specific groundwater levels, controlled by the farmer:

1. Discharge water to lower the groundwater level during wet periods. Drainage outflows can be reduced and controlled. Drainage occurs if the weir crest in the control pit < the water level in the control pit.
2. Retain and store water in the soil-water system to prevent fast decline of the groundwater level during dry periods and raise the groundwater level during periods of rainfall. Water retention occurs if the weir crest in the control pit > the water level in the control pit.

The dual-purpose of this system fluctuates several times during a crop season, with a focus on water management at field scale. The timing

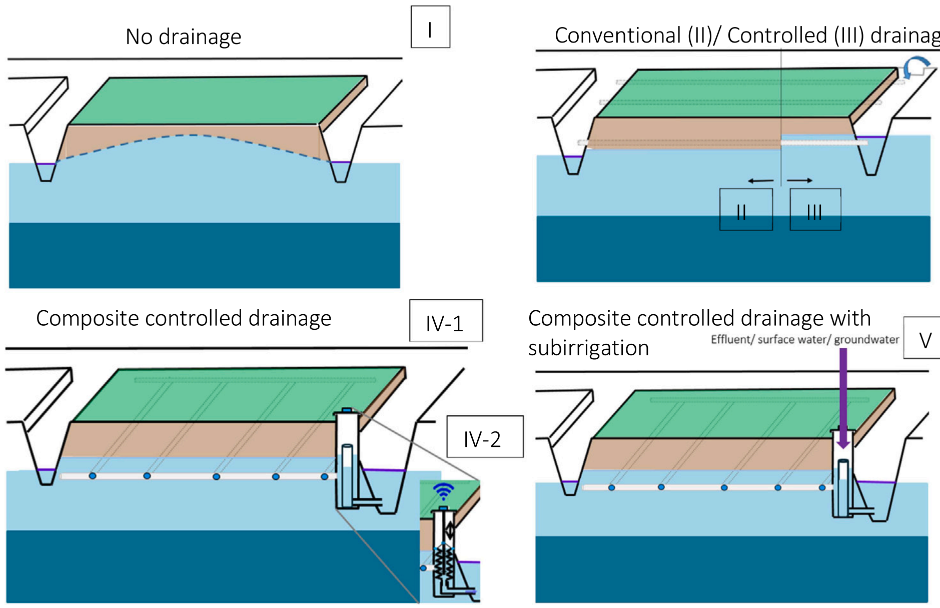

Fig. 3. Agricultural field without pipe drainage (I), with conventional drainage (II), with controlled drainage (III), with composite controlled drainage with a fixed weir (IV-1) or an online controlled weir structure (IV-2) and composite controlled drainage with subirrigation controlled by a fixed weir or online controlled weir structure (V).

of these functions depends on the geographical characteristics of the area as local rainfall patterns, regional surface water management (winter and summer water levels maintained by water authorities), water supply area or free drainage area, soil type, and regional groundwater flow. Composite controlled drainage works effectively in areas that are nearly flat (surface slope < 1%) (Ayars et al., 2006; Carstensen et al., 2020; Massey et al., 1983). In-field differences in the groundwater table are automatically levelled.

2.2.5. Climate adaptive drainage

Climate adaptive drainage (CAD) is a technological advanced example of composite controlled drainage, where the weir structure in the control pit can be automatically online controlled (van den Eertwegh et al., 2013) (Fig. 3-IV-2). An important difference between a 'basic' composite controlled drainage and CAD is the process of managing the drainage level in the control pit. For CAD the drainage level can be controlled remotely through the internet and any drainage level (between a physical maximum and minimum) can be set. For 'basic' composite controlled drainage the drainage level can only be controlled manually and only few drainage levels can normally be set. By combining the CAD-system with a CAD-management algorithm, the required drainage level can be set automatically based on weather forecasts and the current hydrological status of the field, thus actively controlling the soil moisture conditions in the root zone (Bartholomeus et al., 2015).

The CAD-management algorithm (Bartholomeus et al., 2015) combines field measurements (precipitation, groundwater table, soil moisture content, crest level, and ditch level), the actual weather forecast, and the numerical hydrological SWAP model for the unsaturated zone (Kroes et al., 2017) combined with the optimization algorithm PEST (Doherty, 2010) to estimate the optimal crest level. The algorithm takes into account preventing oxygen stress (according to Bartholomeus et al., 2008), and preventing unnecessary discharge.

2.2.6. Composite controlled drainage with subirrigation

The current (composite) controlled drainage systems can be modified to systems for controlled drainage with subirrigation (Fig. 3-V), by supplying (external) water into the control pit. This water could flow into the control pit directly or through active pumping. The water pressure in the drainage systems raises as consequence of subirrigation. If the water pressure in the drainage system is higher than the groundwater level, water infiltrates from the drainage pipes into the soil. The goal of subirrigation is to raise the groundwater level (Fig. 4) and to increase the soil moisture content in the root zone. Thus, controlled drainage with subirrigation could serve three purposes:

1. discharge water,
2. retain water,
3. recharge water.

An external source of water should be available for subirrigation. This can be surface water, water from ponds, recycled drainage water, groundwater or treated (industrial or domestic) waste water (Allred et al., 2003; Ayars et al., 2006; Bartholomeus et al., 2018a, 2017, 2018b; de Wit et al., 2021a; Drury et al., 1996; Hay et al., 2021; Narain-Ford et al., 2020, 2021; Ng et al., 2002; Smith et al., 1985; Tan et al., 2002). Composite controlled drainage with subirrigation is applied in various field experiments in the Dutch sandy Pleistocene uplands (Bartholomeus et al., 2018a, 2017, 2016, 2018b; de Wit et al., 2021b). Fig. 4 shows the measured and modeled groundwater table of two Dutch field experiments Lieshout and America (de Wit et al., 2021a). The groundwater table raises directly once water is pumped into the drainage system (grey blocks in Fig. 4). As a result, the groundwater table fluctuates ± 70 / 80 cm below soil surface at the start of the crop season (Fig. 4). The groundwater table is ± 100 cm higher with external water supply than without water supply in the mid crop season (Fig. 4). However, Fig. 4 also shows that the water supply is not enough to maintain the groundwater level in extremely dry seasons (2018 and 2019). The average water supply was ±400 mm/year in Lieshout (using treated industrial waste water) and ± 900 mm/year in America (using groundwater) in the growing season (±160–190 days) (de Wit et al., 2021a). That is a high amount compared to the average yearly precipitation surplus in the Netherlands of about 250 mm/y (Fig. 1-II). Additionally, the amount is considerably higher than the average precipitation deficit in the summer period of about 50–100 mm/y (Philip et al., 2020). So, although subirrigation could alleviate drought stress at agricultural fields, it could also provide a significant pressure on available water sources. Therefore, it is important to recognize that the

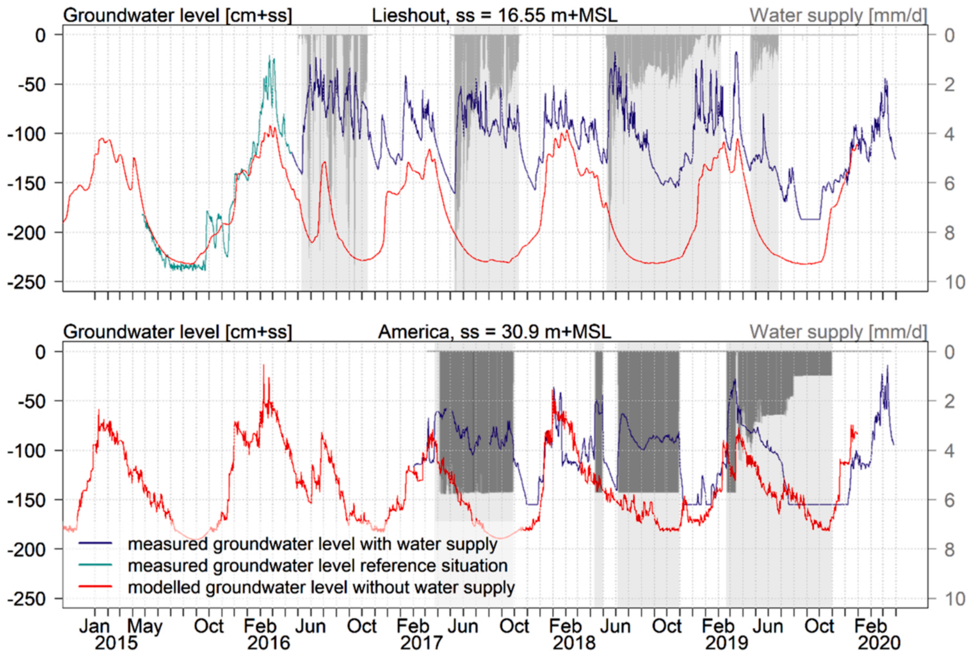

Fig. 4. Groundwater levels (cm+ soil surface, cm+ss) in two field experiments with a subirrigation-system: with water supply/subirrigation (blue, measured), reference situation (green, measured), and without water supply (red, modeled). The grey blocks represent the period of water supply (subirrigation), the dark grey blocks represent the amount of water supply.
Figure adapted from de Wit et al. (2021a).

use of a specific water supply source for subirrigation will propagate through the regional water system and will affect different components of the regional water balance. Subirrigation using surface water for example can be critical in areas without supplemental water, as ditches can become dry in drought periods. Additionally, especially when using treated wastewater or surface water as supply source, water quality issues are important (Beard et al., 2019; Dingemans et al., 2018; Narain-Ford et al., 2020, 2021). All in all, responsible use of available water resources for subirrigation is a key issue.

3. Effects of drainage systems on the water balance

Drainage systems directly affect the (ground) water system and all components of the water balance at field scale (Fig. 5).

Besides in countries like the Netherlands, drainage systems are commonly applied in the USA (Doty and Parsons, 1979; Skaggs et al., 2012), in arid regions with irrigated agriculture like Egypt and Pakistan (Abdel-Dayem and Ritzema, 1990; Ritzema, 2007), in Australia (Christen et al., 2001), and in India (Ritzema et al., 2008). Tables 2 and 3 provide an overview of field experiments on conventional drainage vs.

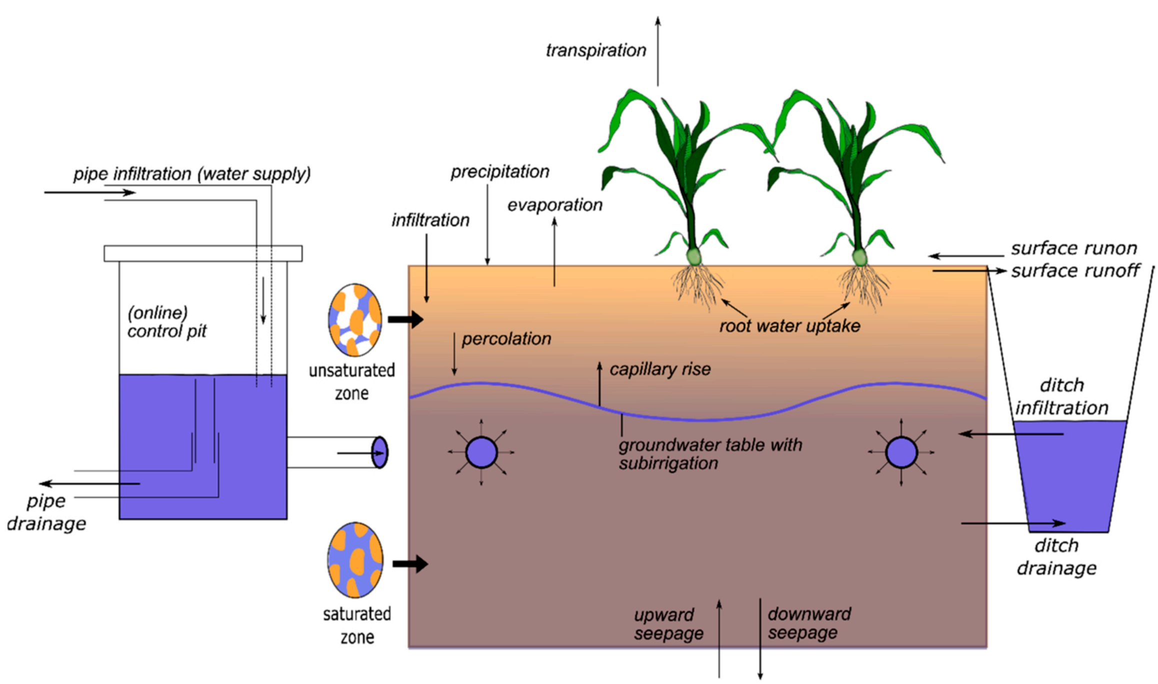

Fig. 5. The soil water column at field scale with the water balance components in the (un)saturated zone.

Table 2
Literature overview focused on i) effects of (composite) controlled drainage compared to conventional drainage for groundwater table, relative increase of crop yield, crop type, and ii) system design characteristics: drain spacing and drain depth. The values in de table are copied from the reference paper.

Reference	Country	Soil	Groundwater table (m-ss)		Crop		Drain characteristic	
			Conventional drainage	Controlled drainage	Yield (%)	Type (-)	Spacing (m)	Depth (m)
Abdel-Dayem and Ritzema (1990)	Egypt	Clay	–		+ 10 + 130	Rice Wheat	15–60	1.2–1.7
Grigg et al. (2004)	USA	Silt loam	–	–	-3	Corn	15	1.25
Wesström and Messing (2007)	Sweden	Loamy sand	0.80	0.20–0.60	+ 2–18	Grain	10	1.0
Delbecq et al. (2012)	USA	Silty (clay) loams	–	–	+ 5.8–9.8	–	–	–

Table 3
Literature overview focused on i) effects of composite controlled drainage with subirrigation ('sub') compared to systems without subirrigation ('no sub') for groundwater table, relative increase of crop yield ('yield'), crop type ('type'), and water supply amount ('amount') and water supply period ('period'), ii) system design characteristics: used water source, drain spacing and drain depth. The values in de table are copied from the reference paper.

Reference	Country	Soil	Groundwater table		Crop		Water supply		Water source	Drain characteristic	
			No sub (m-ss)	Sub (m-ss)	Yield (%)	Type (-)	Amount (mm)	Period (d)		Spacing (m)	Depth (m)
Hooghoudt (1952)	NL	Heavy clay	1.0	0.40/ 0.45	+ 84	Hay	4 mm/d	100	Surface water	2.0	0.6/ 0.8
Massey et al. (1983)[a]	Site 1 /USA	Loamy sand	–		–	–	227[a]		–	40	1.0
	Site 2 /USA	Loamy sand	–		–	–	171[a]		–	30	1.0
	Site 3 /USA	Loamy sand	–		–	–	296[a]		–	15	1.0
Doty and Parsons (1979)	USA	Sandy loam		0.6 higher	[b]	–	410 (1975), 260 (1976)	135	–	32	1.2
Smith et al. (1985)	USA	Sandy loam	1.0[c]	0.70	–	–	305.1	135	Surface water	15	1.0
Drury et al. (1996)	Canada	Clay loam	1991: 1.22, 1992: 0.92, 1993: 1.30, 1994: 1.10	1991: 0.95, 1992: 0.55, 1993: 0.60, 1994: 0.50	–	–	109 (1991, 1993, 1994) 5.7 (1992)[d]	±76	Irrigation pond	7.5	0.6
Fisher et al. (1999)	USA	Silt loam	–		7 (1995), 45 (1996)	Corn	–		–	5	0.75
Mejia et al. (2000)	Canada (1995)	Silt loam	1.30	0.91[e]	+ 13.8	–	223	–		18.3	1.0
	Canada (1996)		1.21	0.75	+ 6.6	–	248	–			
Ng et al. (2002) and Tan et al. (1999)	Canada	Sandy loam	1.31	0.82	+ 64	Corn	183.9	60	Surface water (lake)	6.1	0.60
Allred et al. (2003)	USA	Clay	–		Dry years + 34.5 + 38.1 Wet years + 14.4 + 9.7 Average + 19.6 + 17.4	Corn Soybeans Corn Soybeans Corn Soybeans	–		Re-use runoff water	2.4–4.9	0.76–0.91
Hornbuckle et al. (2005)[f]	Australia	(clay) loam	0.3 higher				143	17	–	36	1.8–2.2
Wesström et al. (2014)[f]	Sweden	Sandy loam	0.30–0.70		+ 6–10 + 20	Potatoes Wheat	2002: 60 2003: 80	–	–	16	1
Jouni et al. (2018)[g]	Iran	Silty clay	1.11	0.71	+ 27	Wheat	731	±242	–	80	2.0

[a] : The values are based on the 27-year average results predicted by the model DRAINMOD, validated on 3 field sites. Most important assumptions in the model: water level in the outlet was constant (this reduced the soil storage available for precipitation and increased drainage and surface runoff). The values are per growing season, the exact days of a growing season are not given in the paper.
[b] : Yield increases with increasing pipe drain spacings. No yield was measured at a reference situation.
[c] : It was not a reference situation, but different subirrigation systems were used for differences in groundwater table effects through subirrigation. The average results of control method C are presented.
[d] : The year 1992 is reported. However, almost no subirrigation was added due to a large amount of rainfall in the growing season. The year 1992 is not included in the calculation of water supply to a 'standard' growing season of 180 days.
[e] : The controlled drainage experiment with a drainage level of 0.50 m – ss is used ($CWT_{0.50}$)
[f] : The experimental fields were fields with free drainage (conventional drainage) and controlled drainage, both with subirrigation.
[g] : Only yield of the wheat from the experiments free drainage and controlled drainage 70 cm is shown. Another experiment, and two other crops are also reported in the article.

controlled drainage and controlled drainage vs. subirrigation respectively, providing quantitative information on the effect of the different drainage systems on water retention and water supply.

3.1. Controlled drainage vs. conventional drainage

The main difference in strategy between controlled drainage and conventional drainage is retention of water (Fig. 3, Table 2), to reduce discharge and keep the groundwater level and soil moisture availability at a sufficient level for crop growth. This process affects different water balance components:

- Pipe drainage decreases compared to conventional drainage because the ditch water level could be controlled (Bonaiti and Borin, 2010; Drury et al., 1996; Hornbuckle et al., 2005). The decrease of pipe drainage follows partly due to an increased soil water storage capacity through the controlled drainage. Riley et al. (2009) showed a decreased pipe drainage of 14% in a lysimeter experiment. Skaggs et al. (2010) reported in different controlled drainage field experiments in the USA a decrease in pipe drainage of 16–29% in clay soils, and 17–85% in sandy loam. Jeong et al. (2018) reported a decrease of 51% in silty clay soils. Wesström and Messing (2007) observed a decrease of 5–35% in sandy loam. Rozemeijer et al. (2016) published data for the Netherlands, with drainage values (November-April) in a reference period of 303 mm for conventional drainage compared to 163 mm (2009–2010) and 127 mm (2010–2011) for controlled drainage. Controlled drainage thus leads to an increase in water retention (Table 2), i.e. water that would have been discharged to the surface water when using conventional drainage remains in the groundwater system with controlled drainage (Skaggs et al., 2010).
- Actual evapotranspiration (ET_{act}) increases through improving drainage conditions and improved soil moisture conditions (Abdel-Dayem and Ritzema, 1990), and herewith less drought stress in summertime. This leads to increased crop yields (Table 2). The reviewed field studies in Skaggs et al. (2010) showed a maximum ET_{act} increase of 10% for corn with controlled drainage compared to conventional drainage. Evans and Skaggs (1985) reported an increase of 2–5% for corn yield in the USA. Doty et al. (1975) found a general rule that the silage yield of corn could increase by 0.5 t/ha for each day that the water table was maintained at less than 100 cm below soil surface in a sandy Coastal Plains soil (USA). However, Grigg et al. (2004) reported a decrease of 3% in corn yield with controlled drainage in the USA (Table 2) because of a too shallow water table for the roots early in the growing season. This shows that proper management of controlled drainage systems is required in order to increase water availability to prevent drought stress, while preventing oxygen stress too (Bartholomeus et al., 2008; Hack-ten Broeke et al., 2016).
- Surface runoff could either increase or decrease, depending on the hydrological boundary conditions, soil physical properties and rain intensities. An increase is modeled by Singh et al. (2007) and Skaggs et al. (2010) and observed in a lysimeter experiment (Riley et al., 2009) and field experiment (Drury et al., 1996; Grigg et al., 2004). Wesström et al. (2014) reported a decrease in runoff through controlled drainage compared to conventional drainage, from 254 to 319 mm to 151–187 mm per year (1 July – 30 June).
- Downward seepage (groundwater recharge) increases as result of controlled drainage (Singh et al., 2007). However, downward seepage is a difficult water balance term to measure. Skaggs et al. (2010) stated therefore that the downward seepage rate with controlled drainage will be approximately equal to the natural drainage rate that occurred before installing the controlled drainage system. This will be the case if ET_{act} with controlled drainage is equal to ET_{act} of the original situation.

Controlled drainage thus leads to an increase in water retention. This water is available for crops, recharges the groundwater or slowly discharges to the surface water through the subsoil. It should be noted, however, that significant water retention with controlled drainage could only be achieved if shallow drainage levels are maintained already in spring. Furthermore, once water has been discharged in early spring, significant water retention can only be realized as significant rainfall occurs too.

All in all, the development of difference drainage systems, affected the water balance terms over time (Table 2):

- **No drainage:** ET_{act} is limited as consequence of too wet conditions. Because of the wet conditions, surface runoff and ditch drainage are high.
- **Conventional drainage:** Compared to 'no drainage', discharge through pipe drainage increases, groundwater recharge and runoff decrease. ET_{act} increases as result of less oxygen stress and earlier opportunities for tillage. However, excessive drainage and herewith too low groundwater levels in summertime may result in drought stress and reduced ET_{act}.
- **Controlled drainage:** Compared to 'conventional drainage' pipe drainage decreases and downward seepage increases (Table 2). Surface runoff may either increase or decrease. ET_{act} mainly increased, but can decrease with poor water level control (i.e. creating too wet conditions).

3.2. Composite controlled drainage with subirrigation vs. (composite) controlled drainage

The main difference in strategy between composite controlled drainage and subirrigation is active recharge of water (Fig. 3, Table 2) to raise the groundwater level and increase soil moisture availability for crops. Water balance components are strongly affected by subirrigation:

- Pipe infiltration increases through subirrigation, which is by definition the main difference between composite controlled drainage and composite controlled drainage with subirrigation: water is actively added to the system. The infiltration amount found in international literature varies between 170 and 410 mm, but the water supply periods differ as well (Table 3). When the water supply data from Table 3 are transposed to a 'standard' growing season of 180 days, cumulative infiltration ranges between approximately 250 – 1500 mm/180days. Ranges are high, due to differences in required raise of groundwater level, length of the growing season, and water losses through lateral ditch drainage and downward seepage (Smith et al., 1985). The groundwater table is typically raised by approximately 30–40 cm (Table 3). The main water supply source used for subirrigation is surface water (Table 3).
- ET_{act} increases through subirrigation, but it is strongly related to the effects in groundwater table. Due to a shallower groundwater table, an upward flux is expected from the water table through the unsaturated zone to the root zone. However, the rate of upward flux decreases rapidly when the distance between the water table and the rootzone increases (Smith et al., 1985). For example, the upward flux could be 6 mm/d at a water table depth of 70 cm below the rootzone, but decreases to 2 mm/d at water table of 90 cm below the rootzone for a sandy loam soil (Smith et al., 1985). However, this flux strongly varies between soil types (Table 2). Increased yields have been found, ranging from + 6.6% (Mejia et al., 2000) to + 64% for corn in the USA (Ng et al., 2002). Assuming a linear relationship between relative yield and relative transpiration (de Wit, 1958), transpiration will show a similar increase.
- Downward seepage increases through subirrigation (Massey et al., 1983; Smith et al., 1985). Downward seepage values are strongly site dependent, as recharge depends on the soil hydraulic conductivity, the natural water table depth, and the water level in adjacent ditches or canals (Massey et al., 1983; Smith et al., 1985). In general, higher

ditch levels result in less lateral drainage to ditches and more downward seepage (Hooghoudt, 1952).

- The exact annual effects of subirrigation on water balance components depend on the required increase in groundwater level, soil properties, site conditions, ditch water level, crop characteristics and drain criteria (Singh et al., 2007; Skaggs et al., 2010, 2012). The maintained drainage and ditch level have been identified as most important factors for the results on the increased groundwater table and water balance components (Hooghoudt, 1952; Jouni et al., 2018; Mejia et al., 2000). Most advantages with subirrigation are reached in drier summers, rather than in wet summers (Mejia et al., 2000). Given the large amounts of water recharged through subirrigation systems, the order of magnitude of different water balance components will be mostly in the range of hundreds of mm on a yearly basis.

All in all, the development of subirrigation caused differences in water balance terms compared to only composite controlled drainage (Table 3):

- **Composite controlled drainage:** the water balance components are similar to controlled drainage.
- **Composite controlled drainage with subirrigation:** the modified composite controlled drainage aims to recharge water as well. During periods of drainage (discharge) the water balance components will be similar to composite controlled drainage. In subirrigation periods, the components pipe infiltration, downward seepage / groundwater recharge and ET_{act} increase compared to composite controlled drainage (Table 3).

The differences in water balance terms caused by development of drainage systems are summarized in Table 4.

4. Local and regional implementation of controlled drainage with subirrigation

Changes in drainage systems were mainly triggered by land use changes as consequence of social and economic changes as clearly showed in literature, resulting in declining groundwater tables (Fig. 6). Although the water management is now in a process towards a more adaptive approach (Van der Brugge et al., 2005), a resilient soil water system is needed to anticipate the expected (future) weather extremes (Fig. 2). Tables 2 and 3 show that controlled drainage systems can contribute to water retention when compared to conventional drainage systems, but also that subirrigation could be applied to actively recharge the groundwater. Doing so, crop water availability could be managed in a more adaptive manner. However, literature also shows that only part of the water used for subirrigation is used for root water uptake, and part of the applied water feeds the groundwater system (increased downward seepage). Furthermore, the total amount of water used for subirrigation can be large, which could put a significant claim on the available water sources. Therefore, subirrigation systems should be implemented in such a way that they fit within the regional management.

Local and regional scale components affect the desired effects of controlled drainage systems with subirrigation (Fig. 7). Requirements for such a system on local (field) scale are the technical design of the drainage system in relation to environmental characteristics. Local characteristics directly affect the water table and thus the growing conditions of crops. Depth and spacing of drain pipes varies throughout the reported field experiments (Tables 2 and 3). Drain spacing is often a function of drainage criteria (Ayars et al., 2006; Ritzema et al., 2008; Skaggs et al., 2012). Two reasons for a narrower drain spacing are a faster water removal in drainage mode, and a more uniform water distribution in the soil in subirrigation mode (Allred et al., 2003). The required pump capacity depends on the required water supply (frequency and capacity) and the determined drainage level. More efficient water use can be obtained through non-continuous pumping or to store and infiltrate drainage water in the winter period for the growing season (Massey et al., 1983). The intended drainage level can be constant e.g. 0, 7 m-ss, or can be varied according to the crop stage and thus root development (Jeong et al., 2018), or the groundwater table (Giardini et al., 1995). Proper management is necessary to avoid too shallow water tables in the early growing season, that negatively impacts the root proliferation or might result in oxygen stress, and thereby limit crop growth (Grigg et al., 2004). The pumping strategy could be optimized to reach the intended drainage level, while minimizing the water supply (Smith et al., 1985). Soil characteristics are not changeable, but effects of controlled drainage with subirrigation differ with soil characteristics (Doty and Parsons, 1979). Fox et al. (1956) and Yu et al. (2020) reported that a soil layer with limited permeability at a shallow depth is needed with subirrigation to avoid extreme downward seepage losses. Finally, ditch levels surrounded by the field are important as a shallow groundwater table with low ditch levels results in lateral drainage, an unfavorable effect (Giardini et al., 1995). Adjusting surface water levels in adjacent canals/streams is recommended to minimize lateral drainage of infiltrated water. The implementation of a controlled drainage system with subirrigation should thus include the soil, crop, hydrological and meteorological characteristics of a site (Ayars and Evans, 2015; Skaggs, 1981, 1987).

Applied sources of water supply are collected rain water (Drury et al., 1996), surface water (Tan et al., 1999), and collected drain water (Allred et al., 2003). Besides these relatively common water sources, use of alternative water sources, like treated wastewater, is being explored (Narain-Ford et al., 2021). First of all, the water source must be of a sufficient quality to use it for subirrigation. However, given the significant changes of water balance components due to subirrigation (see previous section) also in terms of water quantity the propagation of the water use for subirrigation throughout the whole water system should be quantified. Hardly any literature is available about the application of different water sources for subirrigation and the impact of the used water source on the regional water system. However, in many countries, there are competing claims on water sources; the water demand not only comes from the agriculture sector, but also from the industry, drinking

Table 4
The effects of drainage systems (no drainage, conventional drainage, controlled drainage, composite controlled drainage, composite controlled drainage with subirrigation) on the water balance components are described as o = no effect, - = decrease of this component, + = increase of this component. All effects of a drainage system are compared to the situation with the previous drainage system. Effects based on literature overview in Tables 2 and 3.

Drainage system	Surface runoff	Ditch infiltration	Ditch drainage	Pipe infiltration	Pipe drainage	Downward seepage[a]	ET_{act}[a]	
							wet	dry
No drainage								
Conventional drainage	–	o	–	o	+	–	+	–
Controlled drainage	+	–	o	+	–	+	- / o	+
Composite controlled drainage	o	o	o	o	o	o	o	o
Composite controlled drainage with subirrigation	o	–	o	+	o	+	o / -	+

[a] actual evapotranspiration (ET_{act}) can increase (+) or decrease (-) as result of either too wet ('wet') or too dry ('dry') conditions.

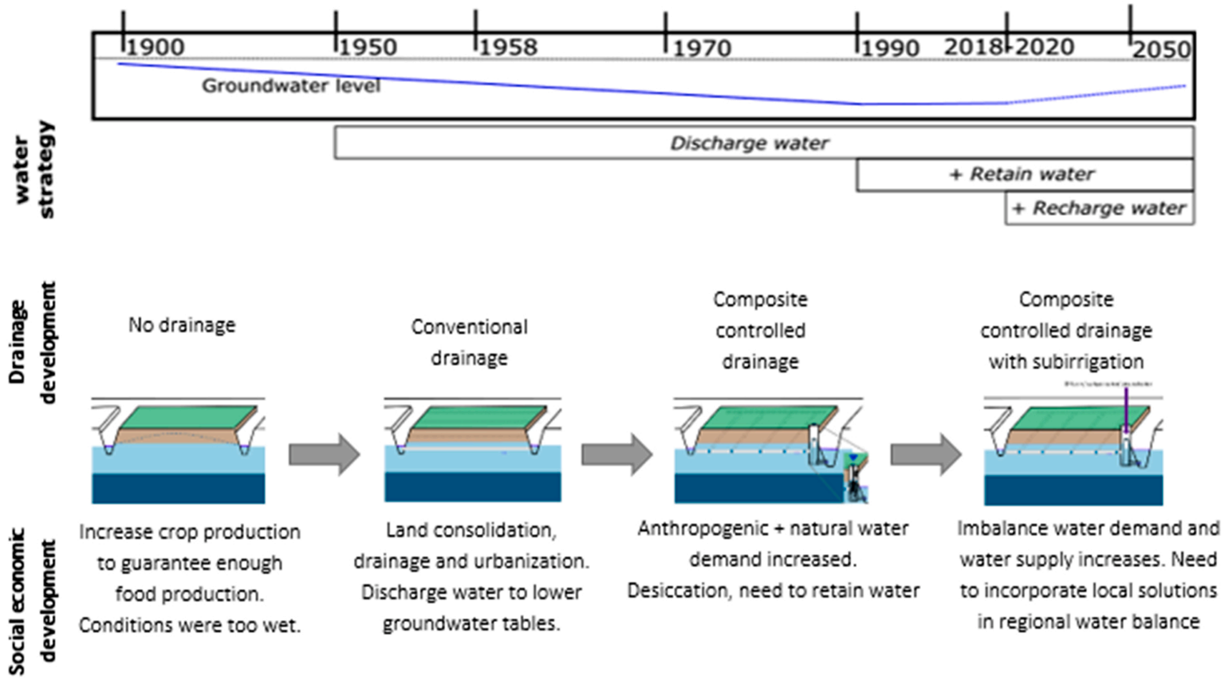

Fig. 6. Drainage development in the Netherlands occurred parallel to social and economic changes in the last decades.

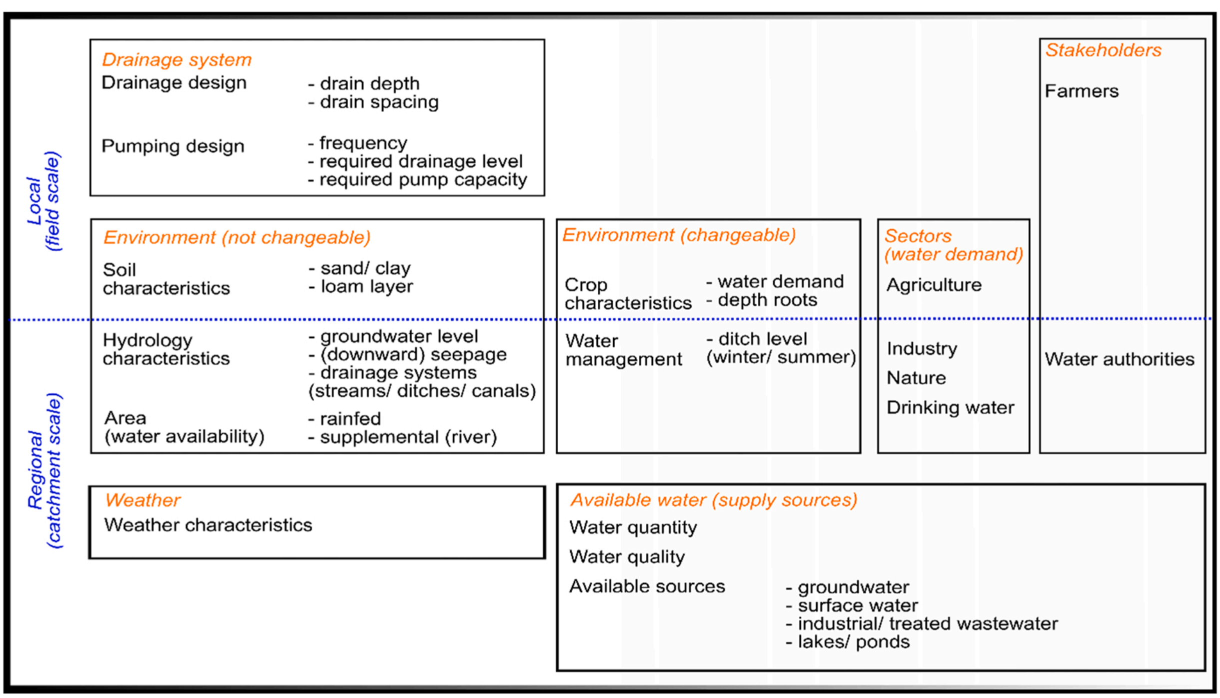

Fig. 7. Overview of local and regional scale components to take into account when implementing controlled drainage with subirrigation systems.

water, and nature (Zikos and Hagedorn, 2017). When subirrigation is applied on regional scale, the implementation requires knowledge of the entire regional water cycle, including the anthropogenic water demand of different sectors that are already putting claims on the same water sources (Fig. 8) (Pronk et al., 2021). Besides that, efficient use of water sources is required to sustain the regional groundwater table (Xue et al., 2017). In this context, controlled drainage with subirrigation is a special method as water is used for increased evapotranspiration and crop yields, while limiting (ground)water abstractions for sprinkler irrigation, but also to replenish groundwater (Table 4). Doing so, subirrigation has the potential to keep water within the regional groundwater system, that would have been discharged otherwise.

In order to incorporate subirrigation within the regional water balance, insights in the regional water availability and the propagation of water use for subirrigation throughout the whole water system needs to be quantified. Given the large ranges in water needs found in literature, it is clear that regional scale water needs for subirrigation systems should be known, before they could be incorporated in the regional water management in a responsible manner.

Controlled drainage with subirrigation has been described in

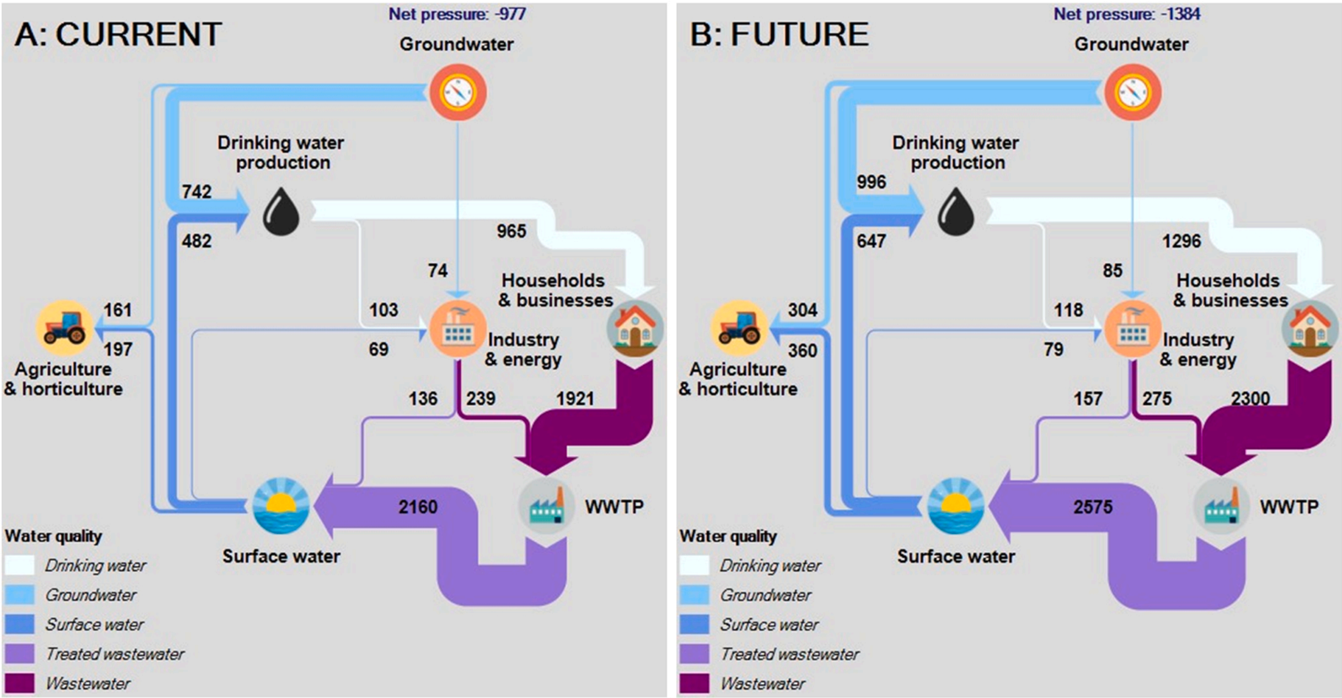

Fig. 8. Composite controlled drainage with subirrigation at field scale (part of 'Agriculture and horticulture') needs to fit in the regional water availability and demand for that water by multiple sectors. Left figure represents the anthropogenic water system of the Netherlands for the current situation, the right represents the anthropogenic water system of the Netherlands for the future (2050) situation. The flows and the net pressure on the groundwater system are given in million m^3 $year^{-1}$. Details about the flows are described in Pronk et al. (2021).
Figures adapted from Pronk et al., 2021.

literature over the past decades, focusing on effects on local scale (Table 3). It is important to apply this field scale knowledge in the current changing water strategy of water retention and water recharge on regional scale (Fig. 2). Correct implementation of controlled drainage with subirrigation in the regional water system is an integral, catchment-wide question with different challenges (Fig. 7):

- Insight is necessary in the water availability for subirrigation of each location, both in space and time.
- Efficient water supply and minimizing the water supply could be reached through optimized pumping strategy (Smith et al., 1985).
- Water resources, other than surface water, could be used for water supply, like industrial or treated wastewater. Important conditions are sufficient water quality and limited negative side effects during the propagation through the entire water system (Pronk et al., 2021).

5. Conclusion

This paper gives insight in the development of drainage systems over time in the Netherlands, occurring parallel to the structurally declining groundwater levels. Literature showed clearly that changes in drainage systems were mainly triggered by land use changes as consequence of social and economic changes (Fig. 6). However, the main Dutch water management system is still focused on discharging water (Ritzema and Stuyt, 2015; Ritzema and van Loon-Steensma, 2018). To cope with the imbalance in water demand and water supply and climate change, controlled drainage with subirrigation could be a viable measure to (i) discharge, (ii) retain and (iii) recharge water. This system has the potential to (1) improve growing conditions for crops at field scale, (2) reduce peak discharges at regional scale, and (3) discharge less water at regional scale and increase groundwater recharge.

Drainage systems affect most water balance components (Table 4). Controlled drainage increases especially ET_{act}, downward seepage and runoff, while pipe drainage decreases. The biggest advantage of controlled drainage with subirrigation is to supply water, raise the groundwater level and improve the soil moisture conditions for crop growth, while still having the option to discharge water when needed. Another advantage of controlled drainage with subirrigation compared to controlled drainage is that it could contribute to increased water retention and recharge (Table 4). However, it could significantly alter water balance components. Therefore, correct and responsible implementation of subirrigation in the regional system is needed (Fig. 7), which requires knowledge on the effects of controlled drainage with subirrigation throughout the entire water system.

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References

Abdel-Dayem, S., Ritzema, H., 1990, Verification of the drainage design criteria in Egypt, Symposium on Land Drainage for Salinity Control in Arid and Semi-Arid Regions, pp. 300–312.

Allred, B.J., Brown, L.C., Fausey, N., Cooper, R.L., Clevenger, W., Prill, G., La Barge, G., Thornton, C., Riethman, D., Chester, P., 2003. Water table management to enhance crop yields in a wetland reservoir subirrigation system. Appl. Eng. Agric. 19, 407.

Ayars, J.E., Christen, E.W., Hornbuckle, J.W., 2006. Controlled drainage for improved water management in arid regions irrigated agriculture. Agric. Water Manag. 86, 128–139.

Ayars, J.E., Evans, R.G., 2015. Subsurface drainage—what's next? Irrig. Drain. 64, 378–392.

Van Baars, S., 2005. The horizontal failure mechanism of the Wilnis peat dyke. Géotechnique 55, 319–323.

Bartholomeus, R.P., Simons, G.W.H., van den Eertwegh, G.A.P.H., 2015, Anticipating on amplifying water stress: Optimal crop production supported by climate-adaptive water management. KWR 2015.062. KWR, Nieuwegein.

Bartholomeus, R.P., Stofberg, S.F., van den Eertwegh, G.A.P.H., Cirkel, D.G., 2017, Hergebruik restwater voor zoetwatervoorziening in het landelijk gebied: Monitoring sub-irrigatie met RWZI-effluent Haaksbergen - 2016. BTO 2017.062. KWR, Nieuwegein.

Bartholomeus, R.P., van den Eertwegh, G.A.P.H., Cirkel, D.G., 2016, Hergebruik restwater voor zoetwatervoorziening in het landelijk gebied: Monitoring sub-irrigatie met RWZI-effluent Haaksbergen. BTO 2016.050. KWR, Nieuwegein.

Bartholomeus, R., van den Eertwegh, G., van Huijgevoort, M., 2018a, Subirrigatie met grondwater - Monitoring veldproef America, Waterschap Limburg. KWR 2018.029. KWR, Nieuwegein.

Bartholomeus, R.P., van Loon, A.H., van Huijgevoort, M.H.J., 2018b, Hergebruik van industrieel restwater voor de watervoorziening van de landbouw - Praktijkproef subirrigatie met gezuiverd restwater van Bavaria. KWR 2018.089. KWR, Nieuwegein.

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

Beard, J.E., Bierkens, M.F., Bartholomeus, R.P., 2019. Following the water: Characterising de facto wastewater reuse in agriculture in the Netherlands. Sustainability 11, 5936.

Bonaiti, G., Borin, M., 2010. Efficiency of controlled drainage and subirrigation in reducing nitrogen losses from agricultural fields. Agric. Water Manag. 98, 343–352.

Van der Brugge, R., Rotmans, J., Loorbach, D., 2005. The transition in Dutch water management. Reg. Environ. Change 5, 164–176.

Carstensen, M.V., Hashemi, F., Hoffmann, C.C., Zak, D., Audet, J., Kronvang, B., 2020. Efficiency of mitigation measures targeting nutrient losses from agricultural drainage systems: A review. Ambio.

Christen, E.W., Ayars, J.E., Hornbuckle, J.W., 2001. Subsurface drainage design and management in irrigated areas of Australia. Irrig. Sci. 21, 35–43.

Delbecq, B.A., Brown, J.P., Florax, R.J., Kladivko, E.J., Nistor, A.P., Lowenberg-DeBoer, J.M., 2012. The impact of drainage water management technology on corn yields. Agron. J. 104 (4), 1100–1109.

Deltacommissie, 2008, Samen werken met water: een land dat leeft, bouwt aan zijn toekomst: bevindingen van de Deltacommissie 2008, [1e dr.]. ed. Deltacommissie.

Deltaprogramma, 2014. Werk aan de delta. De beslissingen om Nederland veilig en leefbaar te houden. The Hague,.

Dingemans, M.M.L., Bartholomeus, R.P., Medema, G.J., 2018, Evaluation of the proposed EU regulation on minimum requirements for water reuse for irrigation. KWR 2018.075. KWR, Nieuwegein.

Doherty, J., 2010. PEST: Model Independent Parameter Estimation. Watermark Numer. Comput,, Brisbane, Queensland, Australia.

Doty, C., Currin, S., McLin, R., 1975, Controlled subsurface drainage for southern Coastal Plains soil.

Doty, C., Parsons, J., 1979. Water requirements and water table variations for a controlled and reversible drainage system. Trans. ASAE 22, 532–0536.

Drury, C., Tan, C., Gaynor, J., Oloya, T., Welacky, T., 1996. Influence of Controlled Drainage-subirrigation on Surface and Tile Drainage Nitrate Loss. Wiley Online Library,.

van den Eertwegh, G., de Louw, P., Witte, J.-P., van Huijgevoort, M., Bartholomeus, R., van Deijl, D., van Dam, J., Hunink, J., America, I., Pouwels, J., Hoefsloot, P., de Wit, J., 2021, Eindrapport project 'Droogte Zandgronden Nederland' (Fase 3): Droogte in zandgebieden van Zuid-, Midden- en Oost-Nederland: het verhaal - analyse van droogte 2018 en 2019 en bevindingen. KnowH2O, Berg en Dal, p. 179.

van den Eertwegh, G.A.P.H., van Bakel, P.J.T., Stuyt, L., van Iersel, A., Kuipers, L., Talsma, M., Droogers, P., 2013, KlimaatAdaptieve Drainage - Een innovatieve methode om piekafvoeren en watertekorten te verminderen - Samenvatting resultaten Fase 2 'Onderzoek en Ontwikkeling'. FutureWater, Wageningen.

Evans, R., Skaggs, R.W., 1985. Operating Controlled Drainage and Subirrigation Systems. North Carolina Agricultural Extension Service,.

Fisher, M., Fausey, N., Subler, S., Brown, L., Bierman, P., 1999. Water table management, nitrogen dynamics, and yields of corn and soybean. Soil Sci. Soc. Am. J. 63, 1786–1795.

Fox, R.L., Phelan, J.T., W.D, C., 1956. Design of subirrigaton systems. Agric. Eng. 37 (2), 103–107.

Giardini, L., Borin, M., Belcher, H., D'Itri, F., 1995. Subirrigation experiments in the Veneto Region (North-East Italy): a review of the period 1981-1989. Subirrigation Control. Drain. 207–223.

Grigg, B., Southwick, L., Fouss, J., Kornecki, T., 2004. Climate impacts on nitrate loss in drainage waters from a southern alluvial soil. Trans. ASAE 47, 445.

Haartsen, A., Beusekom, E.v., Lantschap, A.v.l.e.c.H., 2010, Ontgonnen verleden. Landschappen en deellandschappen. Directie Kennis, Ministerie van Landbouw, Natuur en Voedselkwaliteit, Ede, The Netherlands.

Hack-ten Broeke, M.J., Kroes, J.G., Bartholomeus, R.P., van Dam, J.C., de Wit, A.J., Supit, I., Walvoort, D.J., van Bakel, P.J.T., Ruijtenberg, R., 2016. Quantification of the impact of hydrology on agricultural production as a result of too dry, too wet or too saline conditions. Soil 2, 391–402.

Hay, C.H., Reinhart, B.D., Frankenberger, J.R., Helmers, M.J., Jia, X., Nelson, K.A., Youssef, M.A., 2021. Frontier: drainage water recycling in the humid regions of the US: challenges and opportunities. Trans. ASABE 64, 1095–1102.

Hoeksema, R.J., 2007. Three stages in the history of land reclamation in the Netherlands. Irrig. Drain.: J. Int. Comm. Irrig. Drain. 56, S113–S126.

Hooghoudt, S.B., 1952. Tile drainage and subirrigation. Soil Sci. 74, 35–48.

Hoogland, T., Heuvelink, G.B., Knotters, M., 2010. Mapping water-table depths over time to assess desiccation of groundwater-dependent ecosystems in the Netherlands. Wetlands 30, 137–147.

Hornbuckle, J.W., Christen, E.W., Ayars, J.E., Faulkner, R.D., 2005. Controlled water table management as a strategy for reducing salt loads from subsurface drainage under perennial agriculture in semi-arid Australia. Irrig. Drain. Syst. 19, 145–159.

Jeong, H.Y., Jun, S.C., Cheon, J.Y., Park, M., 2018. A review on clogging mechanisms and managements in aquifer storage and recovery (ASR) applications. Geosci. J. 22 (4), 667–679.

Jouni, H.J., Liaghat, A., Hassanoghli, A., Henk, R., 2018. Managing controlled drainage in irrigated farmers' fields: A case study in the Moghan plain, Iran. Agric. Water Manag. 208, 393–405.

Klein Tank, A., Beersma, J., Bessembinder, J., Hurk, Bvd, Lenderink, G., 2014. KNMI '14: climate scenarios for the Netherlands: a guide for professionals inclimate adaption. KNMI, De Bilt,.

Knotters, M., Jansen, P., 2005. Honderd jaar verdroging in kaart. Strom.: Vakbl. voor Hydrol. 11, 19–32.

Kroes, J.G., van Dam, J.C., Bartholomeus, R.P., Groenendijk, P., Heinen, M., Hendriks, R. F.A., Mulder, H.M., Supit, I., van Walsum, P.E.V., 2017. SWAP Version 4: Theory Description and User Manual. Wageningen Environmental Research,, Wageningen.

Makkink, G., 1957. Ekzameno de la formula de Penman. Neth. J. Agric. Sci. 5, 290–305.

Massey, F., Skaggs, R., Sneed, R., 1983. Energy and water requirements for subirrigation vs. sprinkler irrigation. Trans. ASAE 26, 126–0133.

Massop, H.T.L., Schuiling, C., 2016. Buisdrainagekaart 2015: update landelijke buisdrainagekaart op basis van de landbouwmeitellingen van 2012. Wageningen-UR,, Alterra.

Mejia, M., Madramootoo, C., Broughton, R., 2000. Influence of water table management on corn and soybean yields. Agric. Water Manag. 46, 73–89.

Ministerie van, V.&W., Ministerie van, E.Z., 2016. Nationaal Waterplan 2016-2021. Rijksoverheid, Den Haag.

Narain-Ford, D.M., Bartholomeus, R.P., Dekker, S.C., van Wezel, A.P., 2020. Natural Purification Through Soils: Risks and Opportunities of Sewage Effluent Reuse in Sub-surface Irrigation. Reviews of Environmental Contamination and Toxicology (Continuation of Residue Reviews). Springer International Publishing,, Cham, pp. 1–33.

Narain-Ford, D.M., Bartholomeus, R.P., Raterman, B.W., van Zaanen, I., Ter Laak, T.T., van Wezel, A.P., Dekker, S.C., 2021. Shifting the imbalance: Intentional reuse of Dutch sewage effluent in sub-surface irrigation. Sci. Total Environ. 752, 142214.

Ng, H., Tan, C., Drury, C., Gaynor, J., 2002. Controlled drainage and subirrigation influences tile nitrate loss and corn yields in a sandy loam soil in Southwestern Ontario. Agric., Ecosyst. Environ. 90, 81–88.

Van den Noort, P.C., 1987. Land consolidation in the Netherlands. Land Use Policy 4, 11–13.

van Oldenborgh, G.J., Drijfhout, S., Van Ulden, A., Haarsma, R., Sterl, A., Severijns, C., Hazeleger, W., Dijkstra, H., 2009. Western Europe is warming much faster than expected. Climate 5, 1–12.

Philip, S.Y., Kew, S.F., van der Wiel, K., Wanders, N., van Oldenborgh, G.J., 2020. Regional differentiation in climate change induced drought trends in the Netherlands. Environ. Res. Lett. 15, 094081.

Pronk, G.J., Stofberg, S.F., Van Dooren, T.C.G.W., Dingemans, M.M.L., Frijns, J., Koeman-Stein, N.E., Smeets, P.W.M.H., Bartholomeus, R.P., 2021. Increasing Water System Robustness in the Netherlands: Potential of Cross-Sectoral Water Reuse. Water Resour. Manag.

Riley, K.D., Helmers, M.J., Lawlor, P.A., Singh, R., 2009. Water balance investigation of drainage water management in non-weighing lysimeters. Appl. Eng. Agric. 25, 507–514.

Ritzema, H.P., Nijland, H.J., Croon, F.W., 2006. Subsurface drainage practices: from manual installation to large-scale implementation. Agric. Water Manag. 86, 60–71.

Ritzema, H., Satyanarayana, T., Raman, S., Boonstra, J., 2008. Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: Lessons learned in farmers' fields. Agric. Water Manag. 95, 179–189.

Ritzema, H.P., 2007. Performance assessment of subsurface drainage systems: case studies from Egypt and Pakistan. Alterra-ILRI,, Wageningen, the Netherlands.

Ritzema, H.P., Stuyt, L.C.P.M., 2015. Land drainage strategies to cope with climate change in the Netherlands. Acta Agric. Scand., Sect. B—Soil Plant Sci. 65, 80–92.

Ritzema, H.P., van Loon-Steensma, J.M., 2018. Coping with Climate Change in A densely Populated Delta: A Paradigm Shift in Flood And Water Management in The Netherlands. Irrig. Drain. 67 (2018), s1. ISSN: 1531-0353.

Rozemeijer, J., Visser, A., Borren, W., Winegram, M., Velde, Y., Klein, J., Broers, H., 2016. High-frequency monitoring of water fluxes and nutrient loads to assess the

effects of controlled drainage on water storage and nutrient transport. Hydrol. Earth Syst. Sci. 20, 347–358.
Singh, R., Helmers, M., Crumpton, W., Lemke, D., 2007. Predicting effects of drainage water management in Iowa's subsurface drained landscapes. Agric. Water Manag. 92, 162–170.
Skaggs, R., 1981. Water movement factors important to the design and operation of subirrigation systems. Trans. ASAE 24, 1553–1561.
Skaggs, R.W., Fausey, N.R., Evans, R.O., 2012. Drainage water management. J. Soil Water Conserv. 67, 167A–172A.
Skaggs, R., Youssef, M., Gilliam, J., Evans, R., 2010. Effect of controlled drainage on water and nitrogen balances in drained lands. Trans. ASABE 53, 1843–1850.
Skaggs, R.W., 1987. Principles of Drainage. Farm Drainage in the United States: History, Status, and Prospects. US Government Printing Office. US Department of Agriculture Misc. Pub,, Washington, DC, pp. 62–78.
Smith, M.C., Skaggs, R.W., Parsons, J.E., 1985. Subirrigation system control for water use efficiency. Trans. ASAE 28, 489–0496.
Stuyt, L.C.P.M., 2013. Regelbare drainage als schakel in toekomstbestendig waterbeheer: bundeling van resultaten van onderzoek, ervaringen en indrukken, opgedaan in binnen-en buitenland. Alterra-rapport 2370. Alterra Wageningen UR,, Wageningen.
Tan, C., Drury, C., Gaynor, J., Ng, H., 1999. Effect of controlled drainage and subirrigation on subsurface tile drainage nitrate loss and crop yield at the farm scale. Can. Water Resour. J. 24, 177–186.
Tan, C.S., Drury, C.F., Gaynor, J.D., Welacky, T.W., Reynolds, W.D., 2002. Effect of tillage and water table control on evapotranspiration, surface runoff, tile drainage and soil water content under maize on a clay loam soil. Agric. Water Manag. 54, 173–188.
Vitikainen, A., 2004. An overview of land consolidation in Europe. Nord. J. Surv. Real. Estate Res. 1.
Wesström, I., Joel, A., Messing, I., 2014. Controlled drainage and subirrigation–A water management option to reduce non-point source pollution from agricultural land. Agric., Ecosyst. Environ. 198, 74–82.
Wesström, I., Messing, I., 2007. Effects of controlled drainage on N and P losses and N dynamics in a loamy sand with spring crops. Agric. Water Manag. 87, 229–240.
de Wit, C.T., 1958. Transpiration and crop yields. Unknown Publisher.
Witte, J.P.M., Zaadnoordijk, W.J., Buyse, J.J., 2019. Forensic hydrology reveals why groundwater tables in the province of Noord Brabant (the Netherlands) dropped more than expected. Water 11, 478.
de Wit, J.A., Van Huijgevoort, M.H.J., Van Deijl, D., Van den Eertwegh, G.A.P.H., Bartholomeus, R.P., 2021a, Regelbare drainage met subirrigatie en slimme stuwen - Veldproeven en modelanalyses in het zandgebied van Nederland voor een robuustere waterhuishouding op lokale en regionale schaal. KWR 2021.028. KWR, Nieuwegein.
de Wit, J.A., Van Huijgevoort, M.H.J., van den Eertwegh, G.A.P.H., van Deijl, D., Bartholomeus, R.P., 2021b, Technische rapportage veldproeven met watermaatregelen Stegeren. Ontwerp en monitoring van vijf veldproeven met (automatisch gestuurde) regelbare drainage met subirrigatie en slimme stuw in Stegeren (2017–2020). KWR 2021.029. KWR, Nieuwegein.
Xue, J., Guan, H., Huo, Z., Wang, F., Huang, G., Boll, J., 2017. Water saving practices enhance regional efficiency of water consumption and water productivity in an arid agricultural area with shallow groundwater. Agric. Water Manag. 194, 78–89.
Yu, F., Frankenberger, J., Ackerson, J., Reinhart, B., 2020. Potential Suitability of Subirrigation for Field Crops in the US Midwest. Trans. ASABE 63, 1559–1570.
Zikos, D., Hagedorn, K., 2017. Competition for water resources from the European perspective. In: Ziolkowska, J.R., Peterson, J.M. (Eds.), Competition for Water Resources: Experiences and Management Approaches in the US and Europe. Elsevier, Amsterdam, pp. 19–35.