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Discussions

Groundwater-surface water relations in regulated lowland catchments; hydrological and hydrochemical effects of a major change in surface water level management

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Abstract

In lowland deltas with intensive land use such as The Netherlands, surface water levels are tightly controlled by inlet of diverted river water during dry periods and discharge via large-scale pumping stations during wet periods. The conventional water level regime in these polder catchments is either a fixed water level year-round or an unnatural regime with a lower winter level and a higher summer level in order to optimize hydrological conditions for agricultural land use. The objective of this study was to assess the hydrological and hydrochemical effects of changing the water level management from a conventional fixed water level regime to a flexible, more natural regime with low levels in summer and high levels in winter between predefined minimum and maximum levels.

Ten study catchments were hydrologically isolated and equipped with controlled inlet and outlet weirs or pumping stations. The water level management was converted into a flexible regime. We used water and solute balance modeling for catchment-scale assessments of changes in water and solute fluxes.

Our model results show relevant changes in the water exchange fluxes between the polder catchment and the regional water system and between the groundwater, surface water, and field surface storage domains within the catchment. Compared to the reference water level regime, the flexible water level regime water balance scenario showed increased surface water residence times, reduced inlet and outlet fluxes, reduced groundwater-surface water exchange, and in some catchments increased overland flow. The solute balance results show a general reduction of chloride concentrations and a general increase in N-tot concentrations. The total phosphorus (P-tot) and sulfate (SO4) concentration responses varied and depended on catchment-specific characteristics.

For our study catchments, our analyses provided a quantification of the water flux changes after converting towards flexible water level management. Regarding the water quality effects, this study identified the risks of increased overland flow in former agricultural fields with nutrient enriched top soils and of increased seepage of deep groundwater which can deliver extra nutrients to surface water. At a global scale, catchments in low-lying and subsiding deltas are increasingly being managed in a similar way as the Dutch polders. Applying our water and solute balance approach to these areas may prevent unexpected consequences of the implemented water level regimes.

Keywords

Water level management, Hydrology, Water quality, Water and solute balance modelling

1 Introduction

Water levels in the flat, low-lying polder catchments in the western and northern parts of the Netherlands are tightly regulated. Water authorities maintain either a year-round fixed water level or fixed summer and winter levels. During dry periods, these water levels are maintained by diverting river water into these catchments (e.g. Roelofs, 1991, Rozemeijer, 2012). This water inlet prevents drought damage in agriculture and wetland nature reserves. In addition, too low water levels would accelerate peat oxidation which causes land subsidence (e.g. Schothorst, 1977; Hoogland et al., 2012) and greenhouse gas emissions (e.g. Schrier-Uijl et al., 2014). During wet conditions, the water levels are maintained to prevent water damage to agriculture, roads, and buildings. Excess water is discharged towards the regional rivers and canal systems via large-scale pumping stations.

The conventional water level regime in polder catchments is either a fixed water level year-round, or a winter level that is lower than the summer level. These unnatural regimes optimize hydrological conditions for agricultural land use. During the wet winters the drainage of groundwater is enhanced by relatively low surface water levels. During the dry summer however, the infiltration of surface water to replenish groundwater and soil moisture is enhanced by high surface water levels due to the inlet of diverted river water (Hendriks et al., 2013).

Several water authorities consider changing the water level regimes to a more natural regime, where surface water levels fluctuate freely between predefined minimum and maximum water levels. Such a change in water level regime is often motivated from an ecological perspective. Restoring natural water level fluctuations stimulates dispersal and germination of plant species and increases vegetation diversity in the riparian zones (Sarneel et al., 2014). In a flexible water level regime, temporal flooding distributes seeds over the riparian gradient. The subsequent receding water levels create a variety of soil moisture conditions that meet the germination requirements of many plant species (Lenssen et al., 1998; Sarneel et al., 2014). Van Leeuwen et al. (2014) reported seed bank experiments in which the spring drawdown of water levels in a flexible regime resulted in higher species richness and diversity compared to the conventional regimes with fixed water levels.

An additional advantage of restoring water level fluctuations is the potential reduction of the amount of diverted river water inlet needed from the regional water system. As long as the minimum water level is not reached, no inlet water is needed. In addition summer storm precipitation water does not leave the polder as long as the maximum water level is not

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exceeded. The reduced need for inlet water enhances the regional water availability during droughts and may improve water quality within the polders.

Several authors reported negative consequences of diverted river water inlet for the water quality and ecology of receiving surface waters. For example, Delaune et al. (2005) and Miao et al. (2011) studied eutrophication caused by the inlet of Mississippi River water into N-limited wetland ecosystems. Roelofs (1991), Smolders et al. (2006), and Lamers et al. (2013) reported that the inlet of alkaline (HCO3 and SO4-rich) river water may also enhance the release of phosphorus from sediments in the receiving surface waters.

A final potential advantage of converting to a flexible water level regime and allowing water levels to rise during the wet winter period is the reduction of the amount of discharge that needs to be pumped out of the polder into the regional river system. This would reduce the consumption of energy and the costs for maintenance of the pumping stations and reduce the pressure on the regional water system during high discharges. Introduction of a flexible water level management is often postponed or hampered due to the fear for negative agricultural or recreational impacts, e.g. flooding of agricultural land in winter and spring and insufficient water depth for boating in summer.

Although water quality is an important issue in polder catchments in Netherlands, little is known about the combined effects of restoring natural water level fluctuations on water and solute fluxes. Small changes in nutrient concentrations in polders can result in dominance of undesired species like duckweed (Lemnaceae) or floating fern (Azolla), a severe reduction in biodiversity, and hypoxia (Janse and Van Puijenbroek, 1998; Hellman and Vermaat, 2012; Vermaat et al., 2016). The reduced impact of water inlet suggests a positive effect of flexible water level management for chemical water quality. However, other processes may induce reverse effects in these hydrological complex polder systems, such as the changing interaction between groundwater and surface water. For example, higher water levels in winter may enhance the leaching of nutrients from the enriched upper part of the soils (Rozemeijer and Broers, 2008; Van der Grift, 2016). At the same time, lower water levels in summer may enhance seepage of nutrient-rich and/or saline groundwater from the peaty subsurface (e.g. Van Beek et al., 2007; Delsman et al., 2017; Yu et al., 2017). In addition, lower surface water levels in summer may enhance peat oxidation which causes subsidence and nutrient losses. Throughout the world, an increasing amount of catchments in low-lying and subsiding deltas will be managed in a similar way as the Dutch polders. Therefore, the importance of understanding of the effect of different water level regimes increases.

A combination of water and solute mass balancing has been proven effective for disentangling the combined effect of (changes in) multiple sources and pathways of water and solutes in similar catchments. For example, Hellman and Vermaat (2012) studied the relative impact of agricultural nutrient inputs by constructing water and nutrient budgets for 13 polders in The Netherlands. Kieckbusch and Schrautzer (2007) used water and nutrient balances to study the effects of raising water levels in two catchments in Northern Germany.

The objective of this study was to assess the combined hydrological and hydrochemical effects of changing the water level management from a fixed water level regime to a flexible, more natural regime with minimum and maximum water levels. Ten study catchments were partly hydrologically isolated; the surface water connections with the surroundings were closed apart from controllable inlet and outlet weirs or pumps. The surface water level control was changed to a flexible regime with predefined minimum and maximum water levels. The catchments were intensively monitored in a dense multi-scale network of monitoring locations for surface water and groundwater levels and solute concentrations in soil moisture, groundwater, and surface water. The reference situation, the timing of the actual change in water level management, and the practical water level management varied among the study catchments. Therefore, the monitoring did not provide us with adequate data for comparing the situation before and after the implementation of flexible water level management. We therefore used water and solute balance modelling for catchment-scale assessments of changes in water and solute fluxes caused by the major change in water level management.

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2 Methods

2.1 Study area

The ten investigated polder catchments are situated in the Midwestern part of The Netherlands, between the cities of Amsterdam in the northwest and Utrecht in the southeast (see Figure 1). All polders are within the management area of water authority Amstel, Gooi en Vecht. All studied polders are below mean sea level (MSL) due to centuries of artificial drainage, land subsidence, and peat extraction. The current land surface elevations range between 5.0 m and 0.6m below MSL (Table 1). The subsurface consists of Pleistocene sands, covered with a layer of Holocene peat and clay of variable thickness (see Table1). The original thickness of this cover layer reduces from circa 8 m in the northwest (Middelpolder, Ronde Hoep) to 1 m in the southeast (Oostelijke Binnenpolder, Westbroekse Zodden) near the sandy ice-pushed ridge ‘Utrechtse Heuvelrug’. However, in the Groene Jonker and in the lakes of Botshol, Loenderveen Oost, and Muyeveld, most of this Holocene peat has been mined in the 17th and 18th century to be used as fuel.

The area has a semi-humid sea climate with an average yearly precipitation of 800mm and an average yearly estimated evaporation of 550 mm, resulting in an average estimated yearly recharge of 250 mm. The area is also fed by groundwater seepage from the Utrechtse Heuvelrug. However, whether the individual polders receive seepage or infiltrate to the regional groundwater system depends on their elevation relative to neighboring polders (e.g. Oude Essink, 2001). The Ronde Hoep, for example, lies at 2.3 m below MSL, but still loses water towards polder Groot-Mijdrecht at ca. 6 m below MSL bordering at the south.

All investigated polders are reclaimed wetland nature reserves. The Middelpolder, Ronde Hoep, and parts Muyeveld are still in extensive agricultural use (grass/reed harvest, cattle grazing). Loenderveen Oost is a fallback drinking water reservoir for the city of Amsterdam. Especially Muyeveld is rich in recreational activities (boating, fishing, camping). The Groene Jonker and the Westbroekse Zodden are partly accessible for hiking and bird watching. Most other polders are less accessible or restricted bird reserves. The studied polders differed in their percentages covered by surface water; the surface water proportion varies between 4% and 98% (Table 1). The polders with low surface water proportions, such as Ronde Hoep, Nieuwe Keverdijkse polder, and Middelpolder, have been in intensive agricultural use and still have their artificial drainage network of ditches. The catchments of Botshol, Muyeveld, and Oostelijke Binnenpolder partly consist of drained fields and partly of open surface water lakes. Open surface water dominates the catchments of Loenderveen Oost and Westbroekse zodden. The original ditch network of the Groene Jonker catchment was largely removed in a wetland restoration project. For more detailed descriptions of all studied polder catchments, we refer to Borren et al. (2012a).

The surface water levels in all catchments are human controlled through large scale pumping stations, adjustable weirs, and/or culverts. The water level management in all catchments was changed between 2008 and 2013 from a fixed year-round water level or fixed winter and summer level regime into a flexible regime in which the water levels can fluctuate freely between a minimum and a maximum level. Note that the moment of implementation of the flexible water level regime varies quite a lot among the study catchments due to the progress of legal processes (paperwork, stakeholder consultation) and on the planning of the infrastructural work. Table 1 gives for each catchment the fixed water levels of the conventional reference regime and the minimum and maximum levels of the new flexible regime. Most polders have the same or similar average water levels in the new flexible regime, except Ronde Hoep and Nieuwe Keverdijkse polder north. The new water levels in these polders are higher in the new situation.

No reference water level regime is given for the Groene Jonker, because the landscape was severely reshaped before introducing the flexible water level regime.

2.2 Monitoring

All studied polders were intensively monitored in 2011 and 2012 in a dense multi-scale network of measurement locations for surface water and groundwater levels and solute concentrations. This monitoring was mainly implemented for getting a more detailed overview of water and solute fluxes in the study catchments. We did not implement the monitoring for comparing the situation before and after the implementation of flexible water level management. This was not possible within the timeframe of the monitoring period (2011-2012), because the timing of the actual change in water level management varied among the study catchments (2008-2013).

Piezometers were installed to measure phreatic and deep groundwater heads and surface water levels. The amounts of piezometers varied from 15 in the relatively small Oostelijke Binnenpolder to 47 in Muyeveld. Part of the piezometers were distributed along the expected regional scale hydrological gradients and the other part were placed in field scale (5-50m) transects from the surface water ditches or lakes, through the riparian zones into the fields. Surface water and groundwater levels were registered at hourly time intervals using pressure sensors (van Essen instruments, Delft, the Netherlands). More details on the water level monitoring are described by Borren et al. (2012a).

Concentrations of nutrients and other macro-parameters were monitored through monthly sampling of surface water, groundwater, and soil moisture (Smolders et al., 2012). In each polder, surface water was sampled at the inlet and outlet of the catchment and at several locations distributed over the polder. Both shallow (phreatic) and deep groundwater from below the Holocene top layer were sampled from piezometers using peristaltic pumps. Soil moisture was sampled from porous ceramic suction cups that were installed close to the piezometers at depths of 25, 50, and 100 cm below the land surface. The surface water, groundwater, and soil moisture samples were analysed for pH (pH sensor), alkalinity (titration), and elements (e.g. Na, K, NH4, NO3, PO4, SO4, Cl, Ca, Mg, S, P, Fe, Mn, Si, Zn) using Auto-Analyzers (AA) and Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-OES). Details on the water quality monitoring are reported in Smolders et al. (2012).

Water quality in the regional river water that was diverted into the polders during dry periods was monitored monthly by the regional water authority Amstel, Gooi en Vecht. Amstel, Gooi en Vecht also monitored the inlet and outlet water fluxes of the catchments, either by registering the pumping hours or by monitoring water levels at weirs. Solute concentrations in precipitation water were monitored by the National Institute for Public Health and the Environment (e.g. RIVM, 2005).

2.3 Water and solute balance modelling

To assess the changes in water and solute fluxes caused by flexible water level management, water and solute balances were set up for all polder catchments. To facilitate future application by the water authority staff, the water and solute balances were built in MS Excel. The water storage in the catchment was divided in a groundwater, surface water, and field storage domain (Figure 2). All exchange fluxes between these storages and between the catchment and its surroundings were quantified at daily time steps in the water balance model. The only time-variable inputs were the measured precipitation and evaporation time series from nearby weather stations operated by the Royal Netherlands Meteorological Institute (KNMI). All other fluxes were calculated following the model formulations in Supplement A. This approach allowed for uniform scenario analyses for all catchments, assuming that the change in water level management did not have a large influence on precipitation and evaporation.

The water level management was represented in the water balance by fixed year-round or fixed summer and winter water levels for the reference conventional regime (Ref) and by minimum and maximum water levels for the flexible water level management scenarios (Flex). Exceeding these fixed or minimum and maximum levels induced water inlet or outlet to and from the polders (see Supplement A). In case of a pumping station outlet, a maximum outlet discharge was imposed.

The solute balance modelling focused on the inputs and outputs of Cl, P-tot, N-tot, and SO4 to and from the surface water domain. Average measured concentrations were assigned to all input fluxes towards the surface water (overland flow, groundwater exfiltration, seepage, precipitation, water inlet; see Figure 2). The concentrations in overland flow were not directly measured, but were assumed to be equal to the average measured soil moisture concentrations at 25 cm below the surface. For groundwater exfiltration, separate concentrations were assigned to groundwater

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flow from the topsoil (upper 30 cm) and groundwater flow from below the topsoil. The average measured soil moisture concentrations at 25 cm below surface were assigned to groundwater exfiltration from the topsoil. Groundwater exfiltration from below the topsoil was assigned the average concentrations of samples from suction cups at 50 and 100 cm below the surface and from the upper groundwater piezometers. The solute concentrations measured in samples from the deep groundwater piezometers were assigned to the seepage flux. The concentrations assigned to precipitation water came from the national monitoring network for precipitation composition (RIVM, 2005), while concentrations in the diverted river water were provided by water authority Amstel, Gooi en Vecht.

The water and solute balances were manually calibrated towards an optimal representation of the dynamics in measured surface water levels, groundwater levels, Cl concentrations, and, if available, discharge at the inlet and outlet of the polder catchments. The most sensitive parameters were the surface water and land area percentages (A_l and A_w in Supplement A), the infiltration or seepage fluxes (F_{si} or K_v, d, and h_d depending on the lower boundary definition), and/or the exfiltrating fraction of groundwater towards surface water (f_l). As an example, Figure 3 shows the model performance on simulating the surface water levels, groundwater levels, and chloride concentrations for the Middelpolder. The same information for the other polder catchments is given in Supplement B. For more details on the water and solute balance models we refer to Borren et al. (2012b).

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3 Results

The results of the water balance modelling for the reference and the flexible water level management for all catchments are summarized in Table 2, 3, and 4. Many different output results can be obtained from the water and solute balance models (Borren et al., 2012b). We focus here on the differences in water fluxes and solute concentrations between the reference and the flexible water level scenarios.

Table 2 gives the calculated average residence times and the exchange fluxes over 2003-2011 between the catchments and the regional surface water system via inlet and outlet and between the catchments and the deep groundwater system via infiltration and/or seepage. Relative to the reference scenario, flexible water level management results in longer surface water residence times in all catchments. The residence times increase with 8-204%, with the largest relative increases in the catchments with the lowest surface water area percentages (Ronde Hoep, Nieuwe Keverdijkse polder north and south). This increase in residence time is related to the decrease in inlet and outlet volumes, while the total water volume in the polders does not change much. In polders with relatively small water volumes (Ronde Hoep, Nieuwe Keverdijkse polder north and south), the decrease in inlet and outlet volumes have a relatively large impact on the residence time.

The increase in surface water residence times is directly related to the decrease in both the amount of inlet of diverted river water and the outlet to the regional water system (Table 2), while the total water volume in the polders does not change much. The inlet and outlet volumes are lower in all catchments in the flexible water level scenario. The Nieuwe Keverdijkse polder north is an exception; the water inlet increases due to the higher water levels that are maintained in the flexible water level scenario (see Table 1). As a consequence, this polder infiltrates more to the deep groundwater system. At the same time, seepage from the deep groundwater system decreases to 0 mm d^{-1} in the flexible water level regime (see Table 2). While the inlet flux in Nieuwe Keverdijkse polder north increases in the flexible water level scenario, the average

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residence time still increases like in the other polders. The residence time still increases because the total in- and outflux to and from the surface water domain are substantially reduced after introducing the flexible water level regime.

The 2003-2011 average exchange fluxes between the surface water domain and the groundwater domain (exfiltration and infiltration) and the field storage domain (overland flow and inundation) for the reference and flexible water level regimes are presented in Table 3. In most catchments, the exchange between surface water and groundwater reduces after the introduction of flexible water level management or remains approximately the same. Exception is again the Nieuwe Keverdijkse polder north, where infiltration increases due to the relatively high surface water levels of the flexile water level scenario.

Overland flow and inundation are minor components in the long term average water balances of most catchments. Due to the high groundwater and surface water levels in winter, the overland flow contribution to surface water increases substantially in some catchments with low surface water area percentages. Especially in Middelpolder and Ronde Hoep overland flow becomes and important flow route in the flexible water level scenario.

To summarize the results from the solute balance modelling, Table 4 gives the 2003-2011 average surface water concentrations of Cl, N-tot, P-tot, and SO4 for the reference and the flexible water level management scenarios. The Cl concentrations decrease in most catchments, while N-tot concentrations generally increase. For P-tot and SO4 the results vary between the polders. P-tot concentrations reduce in four catchments, but increase in three catchments. SO4 concentrations reduce in six catchments, but increase in three catchments.

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4 Discussion

This research aimed at assessing the combined hydrological and hydrochemical effects of changing the water level management from a conventional fixed water level regime to a flexible, more natural regime with minimum and maximum water levels for 10 study polder catchments. Our water balance modelling results show significant changes in the water exchange fluxes between the polder catchment and the regional water system and between the groundwater, surface water, and field storage domains within the catchment. Overall, compared to the reference water level regime, the flexible water level regime scenario showed increased surface water residence times, reduced inlet and outlet fluxes, reduced groundwater-surface water exchange, and in some catchments increased overland flow. The solute balance results shows a reduction of chloride concentrations in all catchments, a reduction in P-tot and SO4 concentrations in most catchments, and an increase in N-tot concentrations in most catchments.

4.1 Hydrological effects

The water balance modelling results help to understand the hydrological effects of the conversion towards flexible water level management. Although the water balance models drastically simplify the real situation, they performed well in simulating the surface water and groundwater levels (see Figure 3 and Supplement B). Deviations between modelled and measured water levels can have multiple causes. For example, the actual water level management is not always just based on water levels and weather variations; in some cases human decisions such as changing the water levels for maintenance or reed harvesting play a role. Some polders (e.g. Muyeveld, Loenderveen) also receive excess water from neighboring polders, which may lead to higher water levels and fluxes than expected. In addition, we modelled all polders without taking account of the spatial differences within the polder. In most polders, the seepage or infiltration rates vary due to higher or lower water levels in neighboring polders.

The results of the water balance modelling show that the introduction of flexible water level management causes major changes in the water fluxes in all studied catchments. These changes can be interpreted from the perspective of groundwater-surface water interactions (Figure 4). In a conventional water level regime (Figure 4a), surface water levels in winter are kept low, while groundwater levels are relatively high (Figure 4b). The relatively large difference between the high groundwater levels and low surface water levels induces a relatively large water flux from groundwater to surface water (Table 3). A relatively large outlet flux (Table 2) is needed to compensate for the large groundwater input and maintain the low surface levels. In summer, the high surface water levels and low groundwater levels (Figure 4c) induce a relatively large infiltration flux from the surface water to the groundwater (Table 3). To compensate for this infiltration flux and maintain the high surface water levels, a relatively large amount of inlet of diverted river water is needed (Table 2). Due to the large in and out fluxes to and from the surface water, residence times in the surface water are relatively low (Table 2). In the flexible water level regime, the groundwater and surface water level covariate; both are relatively high in winter (Figure 4e) and relatively low in summer (Figure 4f). The relatively small differences between groundwater and surface water levels result in smaller exchange fluxes between groundwater and surface water (Table 3). This also brings lower inlet fluxes in summer, lower outlet fluxes in winter and longer residence times in surface water (Table 2).

As a result of the described changes in water fluxes, the contribution of different sources of surface water changes as well. As a typical example, Figure 4 presents the surface water source proportions for the Middelpolder catchment for the reference and the flexible water level regime scenarios. The proportions are shown for a dry summer (2003), a wet summer (2007), the average of the 2003-2011 summers, a dry winter (2004), a wet winter (2006), and the average of the 2003-2011 winters. Figure 5 shows that the reduction in diverted river water inlet flux due to the conversion to flexible water level management also results in a decreasing proportion of inlet water in the catchment. The lower inlet water fractions are compensated by larger proportions of direct precipitation water. This increase in the precipitation water proportion at the expense of the inlet water proportion is a general consequence of the introduction of flexible water level management in all polders.

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Figure 5 also shows larger proportions of overland flow in the flexible water level management scenario for the Middelpolder. In wet periods, surface water levels and groundwater levels are higher in the flexible water level scenario compared to the reference scenario. In polders with high surface water percentages, the discharged groundwater and overland flow proportions are low in both scenarios. Inlet water and precipitation water are the dominant water sources in those catchments.

Deep groundwater seepage comes up as a relatively small proportion after introducing the flexible water level regime in Loenderveen Oost, Oostelijke Binnenpolder, and Westbroekse Zodden. Up to 10% of the water volume in the Oostelijke Binnenpolder consists of deep groundwater seepage in the dry summer of 2003. For Loenderveen Oost the deep groundwater seepage proportion is up to 5% and for Westbroekse Zodden up to 1%. Although the proportions are relatively low, the water quality effects of this new water source can be significant depending on the chemistry of the seepage water (see also Yu et al., 2017).

4.2 Water quality effects

The changes in fluxes and the related changes in surface water source contributions help to interpret the concentration changes due to conversion to flexible water level management predicted by the solute balance model (Table 4). These solute balance results, however, should be interpreted with care. The predicted concentrations are the combined contribution of all fluxes to and from the surface water, and biochemical processes within the surface water were not accounted for. This is not critical for the inert transport of Cl. Therefore, the Cl concentration measurements can be used in the calibration as a check on the proportions of surface water from different sources (Borren et al., 2012b; Hellman and Vermaat, 2012) (see for example Figure 3 for the Middelpolder). N-tot, P-tot, and SO4 concentrations, however, are also influenced by biochemical processes such as denitrification, adsorption, sedimentation, and plant uptake (e.g. Vermaat et al, 2016; Van der Grift et al., 2014, 2016; Yu et al., 2017). The solute balance model also assumes that the concentrations that were assigned to the fluxes towards the surface water do not depend on the change in water level regime. However, the predicted longer residence

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times in the groundwater domain may also cause a change in the concentrations of the groundwater exfiltration flux towards surface water. In addition, the lower summer water levels in a flexible water level regime may enhance peat oxidation, which could also result in higher nutrient fluxes to surface water. The difference between the predicted concentrations for the reference and the flexible water level scenarios should therefore be regarded as an indication for the direction of change rather than an exact quantification.

The solute balance model predicted a general decrease in Cl concentrations and a general increase in N-tot concentrations after the conversion to flexible water level management. The general reduction in predicted Cl concentrations is related to the reduced proportions of inlet water. Cl concentrations in the inlet water from the regional water system are relatively high, partly due to the discharge from several deep polders with a large brackish groundwater seepage flux. The Cl concentrations did not change much in the polders where the Cl concentrations in inlet water are low (Loenderveen Oost, Nieuwe Keverdijkse polder).

Although the reduced inlet also reduced the input of N-tot into the polders, the solute balance model predicted a general increase in N-concentrations. This is related to the longer residence times and the larger relative impact of evaporation on the water balance, which amplifies the effects other sources. For N-tot, atmospheric input is an important remaining input for all catchments. In some polders, higher groundwater levels in winter increased mobilization of N-tot from the enriched upper part of the soil. The Middelpolder was the only catchment for which the combination of changes did not cause an increase in N-tot concentrations. The decrease in N-tot loading from inlet water and groundwater discharge in The Middelpolder was large enough to compensate for the larger relative impact of evaporation.

For P-tot and SO4, the solute balance results varied between the polders. For most polders, the solute balance model predicted a reduction in P-tot and SO4 concentrations after the introduction of flexible water level management. Similar to the reduction of Cl, this is mainly related to the reduced proportion of inlet water with relatively high P-tot and SO4 concentrations. In some polders however, the effect of remaining P-tot or SO4 sources is amplified and counteracts the reduced inlet. The increase in P-tot concentrations in Loenderveen Oost and the Westbroekse Zodden is caused by increased groundwater inputs induced by the lower water levels in summer. The increased P-tot and SO4 concentrations in the Middelpolder and the increased SO4 concentrations in the Ronde Hoep are caused by an increased mobilization from the upper part of the soil, which is still enriched due to past agricultural activities and peat oxidation. The higher SO4 concentrations in the Nieuwe Keverdijkse polder south are caused by the longer residence times and the larger relative impact of evaporation. Like in the other polders, the SO4 loading towards the surface water is substantially reduced. However, this effect counteracted in the Nieuwe Keverdijkse polder by the large increase in residence time and associated large relative impact of evaporation.

The effects of converting to flexible water level management on solute concentrations are governed by the change in solute loading via water inlet, the change in residence times, and the change in flow route contributions. Although other studies for similar catchments did not investigate the effects of a change from fixed water levels to flexible water level management, their results partly support the findings from this study. For example, Hellman and Vermaat (2014) found increased nitrogen concentrations due to reduced outlet and increased evaporation as a result of climate change. This meets with our suggestion that the longer residence times and larger relative impact of evaporation on the water balance may cause an increase in N-tot concentrations. Based on field-scale 2-D water transport simulations for a similar polder, Van Beek et al. (2007) reported larger groundwater fluxes through the upper subsurface towards the surface water as a result of an increase in surface water levels. This supports our finding that the higher water levels in winter in a flexible water level regime may increase overland flow and solute mobilization from the enriched upper part of the soil.

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5 Conclusions

Changing the water level management in polders from fixed levels to more a natural, flexible water level regime induces relevant changes in water and solute fluxes to and from the catchment and between the groundwater, surface water, and field surface domains within the catchment. When supported by measurements of groundwater levels, surface water levels and fluxes, and solute concentrations, water and solute balance modelling is a feasible approach to study the combined catchment scale effects of changing water and solute fluxes after a major change in water level management.

Parts of the modelled effects depend on catchment specific characteristics like elevation, seepage flux, surface water proportion, and solute concentrations. However, we found a general increase of surface water residence times, reduction of inlet and outlet fluxes, reduction of groundwater-surface water exchange, and in some catchments increase of overland flow. The water quality effects of introducing flexible water level management are governed by the change in solute loading via water inlet, the change in residence times, and the change in flow route contributions. For Cl, the reduced input via inlet water led to lower concentrations in all polders. However, N-tot concentrations generally increased in spite of the reduced loads via inlet water. The effects of other N-tot sources, such as atmospheric deposition and groundwater exfiltration, were amplified by the longer residence times and the larger relative contribution of evaporation on the water balance. The change in P-tot and SO¬4 concentrations varied between the catchments as the general effect of reduced loads via inlet water was counteracted in some catchments by increased inputs from groundwater. The modelled P-tot concentrations increased in polders with a low surface water area percentage and P enriched top soils due to the increased loads from overland flow towards surface water, combined with longer residence times and increased evaporation.

This study for the first time quantified the hydrological effects and identified potential water quality risks of changing a controlled surface water level regime. Whereas an increasing amount of catchments are being managed in a similar way as the Dutch polders, our approach and findings are relevant for many low-lying and often subsiding delta's around the world.

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References

Borren. W., Rozemeijer, J., Klein, J., Hendriks, D., Van Wirdum, G., 2012a (in Dutch). Flexpeil Hydrologie deelrapport A. Systeemanalyse en monitoringsopzet. Deltares-report 1202707-001, Utrecht, The Netherlands.

Borren. W., Klein, J., Rozemeijer, J., Hendriks, D., Van Wirdum, G., 2012b (in Dutch). Flexpeil Hydrologie deelrapport C. Modellering en analyse. Deltares-report 1202707-001, Utrecht, The Netherlands.

Delsman, J.R., de Louw, P.G.B., De Lange, W.J., Oude Essink, G.H.P., 2017. Fast calculation of groundwater exfiltration salinity in a lowland catchment using a lumped celerity/velocity approach. Environ. Modell. Softw. 96, 323-334.

Hellmann, F. , Vermaat, J.E., 2012. Impact of climate change on water management in Dutch peat polders. Ecological Modelling 240 (2012) 74– 83.

Hendriks, D.M.D., H. P. Broers, R. Van Ek, J. Hoogewoud, B. Becker, 2013 (in German). Zeitliche und räumliche Verteilung der Grundwasser-Oberflächenwasser-Interaktion in den Niederlanden. WasserWirtschaft 4, 29-36.

Hoogland,T., Van den Akker, J.J.H., Brus D.J., 2012. Modeling the subsidence of peat soils in the Dutch coastal area, Geoderma 171-172, 92–97.

Janse, J.H. and Van Puijenbroek, P.J.T.M., 1998. Effects of eutrophication in drainage ditches. Environ. Pollut. 102, 547-552.

Kieckbusch, J. J. and Schrautzer, J. (2007): Nitrogen and phosphorus dynamics of a re-wetted shallow-flooded peatland, Sci. Total Environ., 380, 3–12, 2007.

Lamers, L.P.M., Govers, L.L., Janssen, I.C.J.M., Geurts, J.J.M., Van der Welle, M.E.W., Van Katwijk, M.M., Van der Heid, T., Roelofs, J.G.M., Smolders, A.J.P., 2013. Sulfide as a soil phytotoxin-a review. Front. Plant Sc. 4, 268.

Lenssen, J.P.M., ten Dolle, G.E., Blom, C. (1998). The effect of flooding on the recruitment of reed marsh and tall forb plant species. Plant Ecology, 139, 13–23.

Oude Essink, G.H.P., 2001. Saltwater intrusion in 3D large-scale aquifers: A Dutch case. Phys. Chem.Earth (B) 26, 337-344.

Sarneel, J.M., Janssen, R.H., Rip, W.J., Bender, I.M.A., Bakker, E.S., 2014. Windows of opportunity for germination of riparian species after restoring water level fluctuations: A field experiment with controlled seed banks. J. Appl. Ecol. 51, 1006-1014.

Schothorst, C.J., 1977. Subsidence of low moor peat soils in the western Netherlands, Geoderma 17, 265-291.

Smolders, A. J. P., Lamers, L. P. M., Lucassen, E. C. H. E. T., Van der Velde, G., and Roelofs, J. G. M., 2006. Internal eutrophication: How it works and what to do about it – a review, Chem. Ecol. 22, 93–111.

Smolders, A. J. P., Loermans, J., and Lamers, L. P. M., 2012 (in Dutch). Effecten van flexibel peilbeheer op bodemprocessen en waterkwaliteit. B-Ware report 2012.51, Nijmegen, The Netherlands.

RIVM. (2005), Chemical composition of precipitation over the Netherlands, RIVM, Bilthoven, The Netherlands.

Roelofs, J. G. M.: Inlet of alkaline river water into peaty lowlands: effects on water quality and Stratiotesaloides L. Stands, Aquat. Bot., 39, 267–293, 1991.

Rozemeijer, J.C. & Broers, H.P., 2007: The groundwater contribution to surface water contamination in a region with intensive agricultural land use (Noord-Brabant, The Netherlands). Environ. Pollut. 148: 695 –706.

Rozemeijer, J.C., Siderius, C., Verheul, M., Pomarius, H., 2012: Tracing the spatial propagation of river inlet water into an agricultural polder area using anthropogenic gadolinium. Hydrol. Earth Syst. Sci., 16, 2405–2415.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-636
Manuscript under review for journal Hydrol. Earth Syst. Sci.
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Van Leeuwen, C.H.A., Sarneel, J.M., van Paassen, J., Rip, W.J., Bakker, E.S., 2014. Hydrology, shore morphology and species traits affect seed dispersal, germination and community assembly in shoreline plant communities. J. Ecol. 102, 998-1007.

Van den Eertwegh, G. A. P. H., Nieber, J. L., De Louw, P. G. B., Van Hardeveld, H. A., Bakkum, R.: Impacts of drainage activities for clay soils on hydrology and solute loads to surface water, Irrig. Drain., 55, 235–245, 2006.

Van Der Grift, B., Rozemeijer, J.C., Griffioen, J., Van Der Velde, Y., 2014. Iron oxidation kinetics and phosphate immobilization along the flow-path from groundwater into surface water. Hydrol. Earth Syst. Sci., 18, 4687–4702.

Van der Grift, B., Broers, H.P., Berendrecht, W., Rozemeijer, J., Osté, L., Griffioen, J., 2016. High-frequency monitoring reveals nutrient sources and transport processes in an agriculture-dominated lowland water system. Hydrol. Earth Syst. Sci., 20, 1851–1868.

Vermaat, J.E., Harmsen, J., Hellmann, F.A., Van der Geest, H.G., De Klein, J.J.M., Kosten, S., Smolders, A.J.P., Verhoeven, J.T.A., Mes, R.G., Ouboter, M., 2016. Annual sulfate budgets for Dutch lowland peat polders: The soil is a major sulfate source through peat and pyrite oxidation. J. Hydrol. 533, 515–522.

Yu, L., Rozemeijer, J., van Breukelen, B. M., Ouboter, M., Van der Vlugt, C., Broers, H. P., 2017. Groundwater impacts on surface water quality and nutrient loads in lowland polder catchments: monitoring the greater Amsterdam area. Hydrol. Earth Syst. Sci., 2017.

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2017-636
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Tables

Table 1: Proportion of surface water area (relative to land surface area), land surface elevations, approximate thickness of the Holocene peat and clay layer, reference conventional water regimes and new flexible water level regimes for all polder catchments. Land surface elevations and water levels in m relative to mean sea level (MSL).

Catchment	Proportion of surface water (%)	Land surface elevation (m)	Thickness of Holocene peat and clay layer (m)	Reference conventional water level regime	Flexible water level regime
Botshol	64	-2.4	4.5-8	Summer: -2.45, winter: -2.70	Min: -2.65, Max: -2.45
Groene Jonker	29	-5.0	Ca. 4	NA	Min: -5.60, Max: -5.10
Loenderveen Oost	98	-1.0	Ca. 1	Fixed: -1.15 +/- 0.05	Min: -1.30, Max: -1.00
Middelpolder	18	-2.15	Ca. 10	Summer: -2.40, winter: -2.45	Min: -2.55, Max: -2.25
Muyeveld	62	-0.6	0-5	Summer: -1.15, winter: -1.10	Min: -1.20, Max: -1.05
Nieuwe Keverdijkse polder north	8	-1.2	1.5-3	Fixed: -1.65 +/- 0.05	Min: -1.5, Max: -1.2
Nieuwe Keverdijkse polder south	8	-1.2	1.5-3	Fixed: -1.65 +/- 0.05	Min: -1.7, Max: -1.4
Oostelijke Binnenpolder	50	-0.9	0-1	Summer: -1.25, winter: -1.35	Min: -1.40, Max: -1.20
Ronde Hoep	4	-2.3	Ca. 8	Summer: -2.85, winter: -3.00	Min: -2.80, Max: -2.45
Westbroekse Zodden	90	-0.7	0-1	Summer: -1.00, winter: -1.05	Min: -1.1, Max: -0.95

Table 2: The 2003-2011 average modelled residence times in surface water and exchange fluxes between the surface water domain and the regional water system (inlet and outlet) and the deep groundwater system (seepage and infiltration) for all research catchments for the reference conventional water level regime (Ref) and the flexible water level regime (Flex). Positive fluxes are into the surface water domain, negative fluxes leave the surface water domain.

	Residence time (d)		Regional Exchange				Deep groundwater exchange			
			Inlet (mm d^{-1})		Outlet (mm d^{-1})		Seepage (mm d^{-1})		Infiltration (mm d^{-1})	
Catchment	**Ref**	**Flex**	**Ref**	**Flex**	**Ref**	**Flex**	**Ref**	**Flex**	**Ref**	**Flex**
Botshol	275	329	2.91	1.85	-0.95	0.00	0.00	0.00	-1.12	-1.08
Groene Jonker	NA	275	NA	0.00	NA	-0.08	NA	0.07	NA	-0.04
Loenderveen Oost	806	874	0.50	0.11	-0.18	0.00	0.00	0.14	-0.67	-0.61
Middelpolder	56	82	1.99	0.70	-4.33	-2.88	0.00	0.00	-0.39	-0.41
Muyeveld	435	524	1.54	0.87	-1.13	-0.44	0.00	0.00	-0.75	-0.76
Nieuwe Keverdijkse polder north	60	175	0.58	1.77	-8.21	-0.10	0.13	0.00	-0.08	-1.07
Nieuwe Keverdijkse polder south	29	78	0.00	0.00	-11.43	-3.99	0.59	0.19	0.00	-0.35
Oostelijke Binnenpolder	126	209	2.70	0.00	-1.47	-0.04	0.00	0.27	-0.58	-0.46
Ronde Hoep	25	76	2.54	1.36	-16.73	-6.45	0.00	0.00	-0.43	-0.53
Westbroekse Zodden	365	511	1.03	0.00	-1.39	0.00	0.00	0.03	-0.19	-0.31

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Table 3: The 2003-2011 average modelled exchange fluxes between the surface water domain and the groundwater domain (exfiltration and infiltration) and the field storage domain (overland flow and inundation) for all research catchments for the reference conventional water level regime (Ref) and the flexible water level regime (Flex). Positive fluxes are into the surface water domain, negative fluxes leave the surface water domain.

	Groundwater exchange				Field storage exchange			
	Exfiltration (mm d^{-1})		Infiltration (mm d^{-1})		Overland flow (mm d^{-1})		Inundation (mm d^{-1})	
Catchment	**Ref**	**Flex**	**Ref**	**Flex**	**Ref**	**Flex**	**Ref**	**Flex**
Botshol	0.03	0.01	-1.28	-1.18	0.01	0.00	0.00	0.00
Groene Jonker	NA	0.17	NA	-0.35	NA	0.00	NA	0.00
Loenderveen Oost	0.02	0.02	-0.02	-0.02	0.00	0.00	0.00	0.00
Middelpolder	3.37	1.50	-1.23	-0.75	0.16	1.41	0.00	0.00
Muyeveld	0.40	0.34	-0.41	-0.35	0.00	0.00	0.00	0.00
Nieuwe Keverdijkse polder north	7.54	0.53	-0.38	-1.60	0.00	0.06	0.00	0.00
Nieuwe Keverdijkse polder south	10.55	4.07	-0.13	-0.37	0.00	0.04	0.00	0.00
Oostelijke Binnenpolder	0.40	0.44	-1.47	-0.62	0.00	0.00	0.00	0.00
Ronde Hoep	15.91	3.58	-1.68	-1.66	0.00	3.48	0.00	-0.19
Westbroekse Zodden	0.22	0.25	-0.03	-0.32	0.00	0.00	0.00	0.00

Table 4: The 2003-2011 average modelled concentrations in surface water of Chloride (Cl), Total Phosphorus (P-tot), Total Nitrogen (N-tot), and Sulfate (SO4) for all research catchments for the reference conventional water level regime (Ref) and the flexible water level regime (Flex).

	Cl (mg L^{-1})		P-tot (mg L^{-1})		N-tot (mg L^{-1})		SO_4 (mg L^{-1})	
Catchment	**Ref**	**Flex**	**Ref**	**Flex**	**Ref**	**Flex**	**Ref**	**Flex**
Botshol	836	804	0.06	0.06	3.0	3.4	39	34
Groene Jonker	NA	43	NA	0.14	NA	12.6	NA	277
Loenderveen Oost	35	35	0.07	0.14	4.2	5.0	18	12
Middelpolder	270	200	1.05	1.29	3.8	3.7	109	126
Muyeveld	61	55	0.07	0.07	3.2	3.7	30	25
Nieuwe Keverdijkse polder north	115	112	0.13	0.06	1.3	2.1	99	68
Nieuwe Keverdijkse polder south	132	138	0.17	0.15	1.4	1.8	114	137
Oostelijke Binnenpolder	38	13	0.05	0.02	2.3	4.1	21	8
Ronde Hoep	231	186	0.33	0.30	4.0	4.3	127	149
Westbroekse Zodden	34	13	0.12	0.22	3.3	5.9	21	12

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Figures

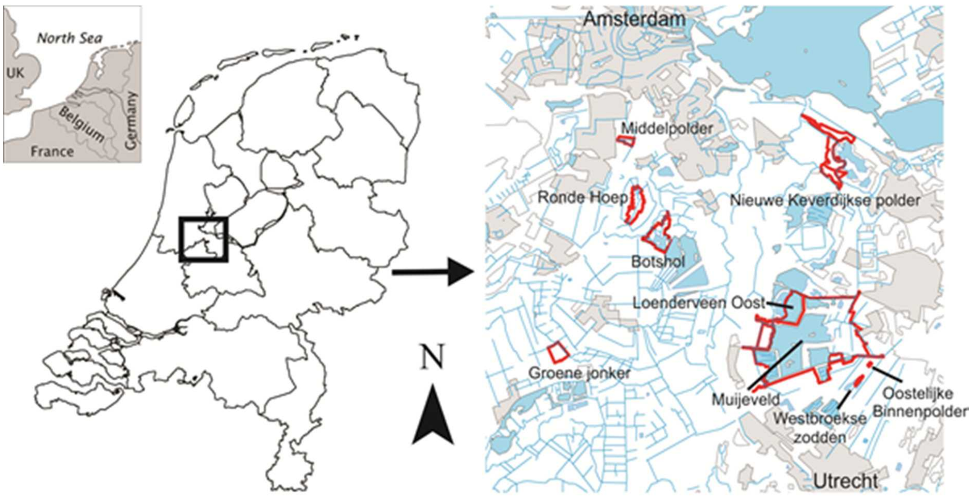

Figure 1: Study area and locations of the investigated polder catchments in The Netherlands between Amsterdam and Utrecht.

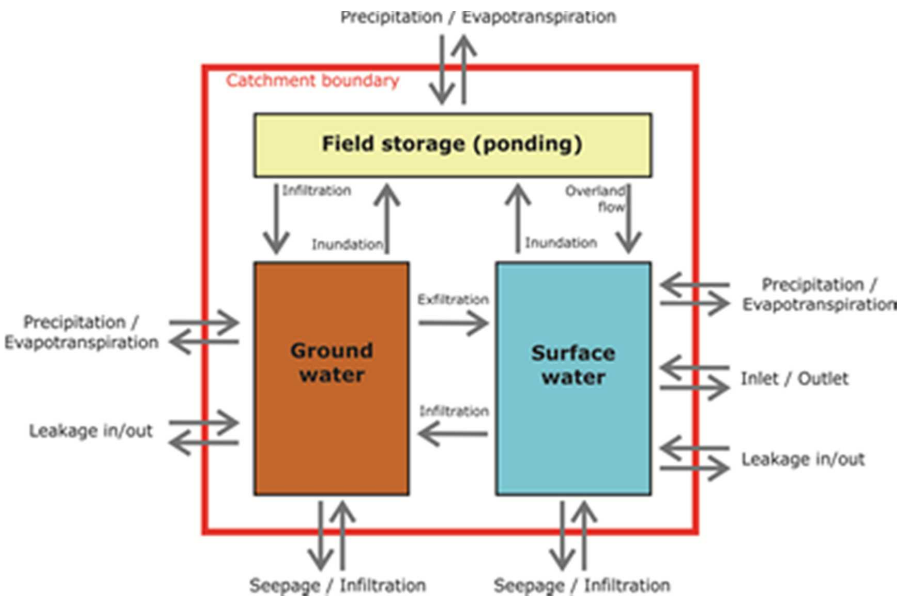

Figure 2: Visualisation of the three water and solute balance domains (field storage, groundwater, and surface water) and all water fluxes to and from these domains. See Supplement A for the water balance model formulations.

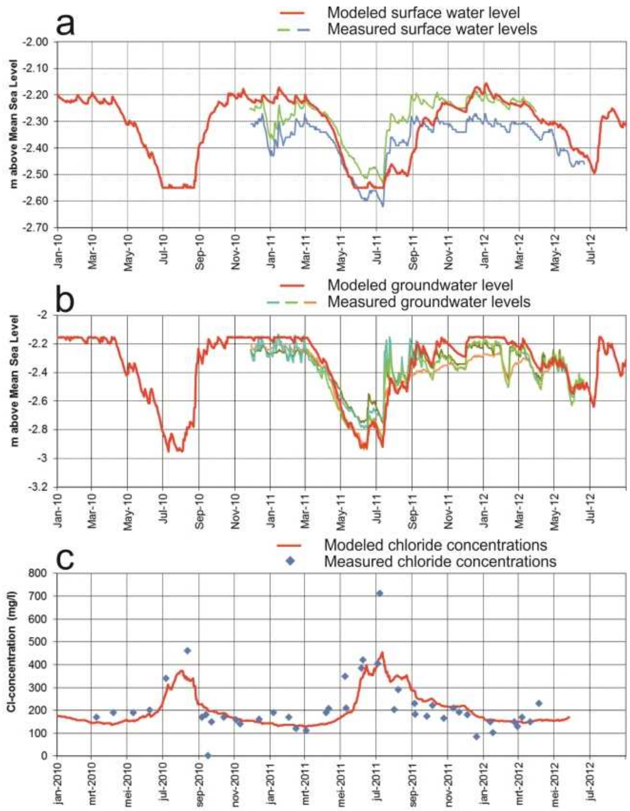

Figure 3: Model performance for the Middelpolder; modelled and measured surface water levels (a), groundwater levels (b), and chloride concentrations (c). See Supplement B for other polders.

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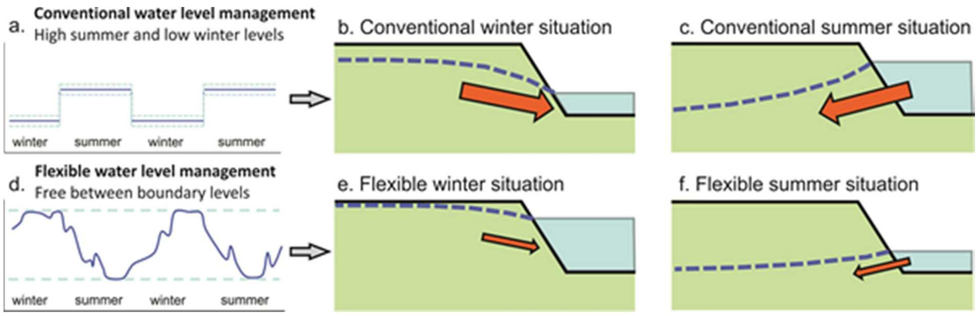

Figure 4: Groundwater-surface water interaction in conventional and flexible water level management regimes. Fig. 4a visualises a conventional water level regime. Fig 4b and 4c show the large fluxes from groundwater to surface water in winter (b) and from surface water to groundwater in summer (c). Fig. 4d visualises a flexible water level regime. Fig 4e and 4f show the relatively small fluxes from groundwater to surface water in winter (4e) and from surface water to groundwater in summer (4f).

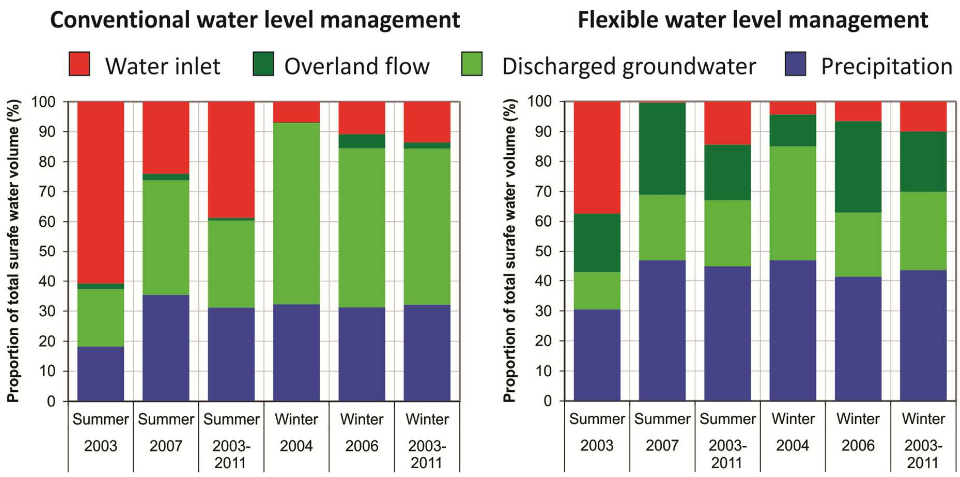

Figure 5: Proportions of water sources of surface water in the Middelpolder catchment for the conventional water level management and the flexible water level management scenarios for a dry summer (2003), a wet summer (2007), the average of the 2003-2011 summers, a dry winter (2004), a wet winter (2006), and the average of the 2003-2011 winters.