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Local and regional impact of anthropogenic drainage on fen contiguity

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Abstract

Knowledge of the hydrological mechanisms behind habitat fragmentation of fen plant communities in intensively managed regions like The Netherlands is essential to improve currently utilized fen restoration and conservation strategies. In this study, we analysed the local and regional impact of anthropogenic drainage on the groundwater supply of fens. For this purpose, we developed fine-scale groundwater flow models and collected empirical data to analyse (1) the differences in groundwater supply between an anthropogenically drained fen and a poorly drained fen in The Netherlands, and (2) the local and regional effects of the elimination of drainage ditches on the groundwater supply of fens. Our results consistently indicated the presence of recently infiltrated precipitation on top of upwelling groundwater across the anthropogenically drained fen, and a mixing gradient of recently infiltrated precipitation and upwelling groundwater across the poorly drained fen. Furthermore, our results showed that the elimination of drainage ditches from the anthropogenically drained fen increased the area and the flux of groundwater supply of both the anthropogenically drained fen and the poorly drained fen. We conclude that anthropogenic drainage not only causes a lowering of groundwater tables, but also (1) enhances the infiltration of local precipitation across fens while simultaneously preventing upwelling groundwater from entering the fen root zone, and (2) reduces the groundwater supply of adjacent fens by intercepting groundwater that is potentially directed to downstream regions. These insights support the need to reconsider the current priorities in hydrological fen restoration strategies.

1 Introduction

Although the sustainable conservation and restoration of endangered plant species in Europe has been internationally agreed upon since the early 1990s (Council of Europe, 2000), only modest progress has been made to counteract the negative effects of land reclamation and environmental degradation on fens. One of the reasons is that cur-

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5 reently utilized fen restoration strategies are often ineffective in the mitigation of habitat
fragmentation of the remaining fen plant populations (Klimkowska et al., 2007). Habitat
fragmentation is disadvantageous for species if ecological barriers prevent seed dis-
persal or the genetic exchange between populations (Ozinga et al., 2009; Hooftman
et al., 2003). For low-productive fens, these ecological barriers may consist of zones
of ceased groundwater supply, as these zones are thought to be less suitable for the
establishment and survival of most fen plant species (Sjörs and Gunnarsson, 2002).
The hydrological mechanisms behind the development of zones of ceased groundwater
supply are still poorly understood; however, this knowledge is essential to improve cur-
10 reently utilized fen restoration strategies. In this paper, we analyse how anthropogenic
drainage affects the groundwater supply of fens.

Particularly ambitious efforts to conserve and restore low-productive fens have been
undertaken in The Netherlands, because these fens usually harbour a high diversity
of plant species, many of which have a threatened status (Lamers et al., 2002). Low-
15 productive fens are typical of sites with a low nutrient availability (Bedford et al., 1999)
and a near-neutral pH (Sjörs and Gunnarsson, 2002). These site factors are usually
conditioned by the supply of both upwelling groundwater and local precipitation (Amon
et al., 2002). The excessive water supply causes shallow groundwater tables and
anaerobic conditions in the shallow subsurface (De Mars and Wassen, 1999; Boomer
and Bedford, 2008b). In addition, dissolved minerals are transported by the groundwa-
20 ter to the fen surface. Both the shallow groundwater tables and the supply of dissolved
minerals maintain the acidity of fens at a near-neutral pH level (Kemmers et al., 2003;
Almendinger and Leete, 1998), and limit nutrient availability for plant growth provided
the sulphate concentration of the groundwater is low (Boomer and Bedford, 2008a;
25 Boyer and Wheeler, 1989).

Environmental degradation of low-productive fens may consist of desiccation, acid-
ification, or eutrophication (Lamers et al., 2002). These degradation processes are
often triggered by a shift in the origin of groundwater supply as a result of water man-
agement practices. In particular, drainage (Schot et al., 2004) and groundwater ab-

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stractions (Fojt, 1994) are thought to prevent groundwater from entering the fen root zone, because they intercept groundwater that is potentially directed to the fen surface. This decreased supply of groundwater may cause a fall in groundwater tables and enhances the infiltration of local precipitation and surface water (Van Wirdum, 1991).

5 As the chemical compositions of precipitation and surface water deviate from that of groundwater, an increase of these infiltration rates are thought to cause abiotic conditions that are less suitable for the establishment and survival of fen plants (Wassen et al., 1990; Fojt and Harding, 1995).

10 Since exfiltrating groundwater mediates abiotic conditions that are suitable for fen plants (Klijn and Witte, 1998), habitat fragmentation of fen plant populations may be related to the development of zones of ceased groundwater supply, i.e., the disintegration of spatially contiguous zones of groundwater supply. Spatially contiguous zones of groundwater supply are common in natural fens, including those in Poland (Van Loon et al., 2009b), Germany (Succow and Joosten, 2001), and Siberia (Schipper et al., 15 2007). In managed fens, however, these zones have become dispersed as a result of regional changes in groundwater flow caused by anthropogenic developments (Van Loon et al., 2009a). Furthermore, it is hypothesized that the interception and subsequent discharge of groundwater by drainage ditches may further reduce the area, and thus the contiguity of zones of groundwater supply. This hypothesis is supported by 20 2-D groundwater flow and transport models (Schot et al., 2004) and hydrochemical field surveys at numerous drained fens (Grootjans et al., 1988; Wassen et al., 1990; Bootsma et al., 2002). These studies indicate that anthropogenically drained fens are not supplied with groundwater, but with locally infiltrated precipitation instead. None of the studies, however, provide a spatially explicit analysis of the impact of anthropogenic 25 drainage on the groundwater supply of fens. This knowledge is essential for the improvement of the current perception of the hydrological mechanisms behind habitat fragmentation of fens.

This paper presents an analysis of the impact that anthropogenic drainage has on the groundwater supply of fens. We not only restricted ourselves to on-site, local ef-

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fects, but also analysed how changes in water management on a local scale affect downstream regions, i.e., exert effects on a regional scale. For this purpose, we developed fine-scale groundwater flow models and collected empirical data to analyse (1) the differences in groundwater supply between an anthropogenically drained fen and a poorly drained fen, and (2) the effects of the elimination of drainage ditches on the local and regional groundwater supply of fens. We hypothesize that anthropogenic drainage (1) directs local groundwater flow to the drainage ditches and thus prevents upwelling groundwater from entering the fen root zone (Schot et al., 2004), and (2) intercepts groundwater that is potentially directed toward downstream regions and thus reduces the groundwater supply of adjacent fens.

2 Study area

The Naardermeer is a polder in the centre of The Netherlands (52° 17' N and 5° 8' W) that is comprised of fens, a number of lakes, and pastures (Fig. 1a). The Naardermeer is bordered to the east by the ice-pushed ridge Het Gooi. This ridge consists of elongated hills of sandy fluvial deposits that had been pushed up by glaciers during the Saalien glaciation. Owing to its relatively high topography (0–30 m a.s.l.), the ice-pushed ridge functions as a regional groundwater recharge area (Schot, 1989). Land cover of the ridge consists of urban areas, heaths, and forests. Groundwater abstractions for drinking water production were removed from the ridge during the 1990s in order to enhance groundwater flow to the fens in the Naardermeer.

The Naardermeer is bordered to the north, south, and west by other polders (Fig. 1a). Polders are water management districts from which excessive water is drained by means of dense ditch networks and discharged by pumping. In periods of water deficit, however, the ditch networks are used to irrigate the polders with alien surface water that is pumped in to acquire optimal conditions for agricultural crop production. Owing to their low topography (−1.7 to −1.1 m a.s.l.), these polders form the regional drainage basis of the Naardermeer, implying that infiltration conditions prevail at the downstream

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margins of the Naardermeer (Schot et al., 1988). Water losses caused by infiltration and evapotranspiration are compensated for by the supply of alien surface water to the north-western lake of the Naardermeer during the summer season (Barendregt et al., 1995).

5 The anthropogenically drained fen in the eastern part of the Naardermeer comprises a 500 m wide zone adjacent to the ice-pushed ridge Het Gooi (Fig. 1b). This fen is drained by parallel drainage ditches that are 0.4–1.0 m deep and spaced 30–60 m apart. These drainage ditches are relicts of the former agricultural use of this fen. The fen has now become an extensively managed buffer zone to protect the downstream
10 fens and Lake Naardermeer from eutrophication (Barendregt et al., 1995). The surface water levels in the drainage ditches are anthropogenically controlled at 0.4–0.7 m below ground surface by means of weir constructions and a supply of alien surface water via the ditches during periods of water deficit in summer. Ground surface elevations of the anthropogenically drained fen range from –1.0 to 0.0 m a.s.l.. As a result of this
15 relatively low topography, groundwater flow is directed from the ice-pushed ridge to the fen (Schot, 1989).

The poorly drained fen is situated along one of the lakes in the Naardermeer (Fig. 1b). This fen is drained not only by the lake, but also by few shallow drainage ditches. The impact of these draining elements on groundwater flow through the fen is
20 limited, however, as the fen is only slightly elevated above the lake level (Wassen et al., 1989). Alien surface water supplied to Lake Naardermeer does not reach the lake bordering the poorly drained fen. Owing to its low topography (–1.0 to –0.5 m a.s.l.), the poorly drained fen is supplied with both groundwater recharged at the ice-pushed ridge and brackish palaeo-groundwater (Wassen et al., 1989; Schot et al., 1988) that
25 originates from early Holocene sea water intrusions (Post et al., 2003).

Groundwater flow to, and within, the Naardermeer is through aquifers consisting of unconsolidated, fluvial deposits. The hydrological base of the study area consists of early Pleistocene clays of marine origin at –250 to –150 m a.s.l. Discontinuous resistance layers consisting of fluvial clays interfinger the aquifers laterally. The ice-pushed

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ridge consists of coarse sands that are partly intercalated with sloping clay sheets in the east. A semi-confining peat layer with a thickness up to 0.8 to 1.0 m is present in the Naardermeer. This peat layer is not present at the ice-pushed ridge.

3 Method

3.1 Groundwater modelling

Groundwater exfiltration patterns across both the anthropogenically drained fen and the poorly drained fen were established using a 3-D groundwater flow model. This groundwater flow model consisted of six model layers that were defined according to the geological stratigraphy of the catchment of the Naardermeer. The horizontal resolution of the model was 5 by 5 m. This high horizontal resolution corresponds to the resolution of the most detailed digital elevation model available (Van Heerd et al., 2000) and serves to accurately establish groundwater exfiltration patterns on a local scale. The groundwater flow model was based on the MODFLOW code (McDonald and Harbaugh, 1988) and was developed in three successive stages. Initially, we developed a regional steady-state groundwater flow model of the catchment of the Naardermeer and its surroundings (for details of the model set-up see Van Loon et al., 2009a). The model grid size was 50 by 50 m. Transmissivities were calibrated using time-averaged hydraulic heads observed in 659 observation wells between 2000 and 2005. Then, the steady-state groundwater flow model was modified into a transient groundwater flow model representative for 2006. Transient behaviour was determined by temporally varying groundwater recharge, groundwater abstractions, and surface water levels. Transient equilibrium was accomplished by resuming the model run using the modelled heads at December 2006 as starting heads for January 2006, until stable starting heads were obtained. Finally, the transient groundwater flow model was refined at the Naardermeer through telescopic mesh refinement. The boundary fluxes of the local groundwater flow model were obtained from the regional groundwater flow

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model, however, no feedback was established between these models. Changes in water storage within the studied fens as a result of this lacking feedback (Mehl et al., 2006) were prevented by (1) defining the model boundaries a few kilometres from the studied fens, and (2) accomplishing transient equilibrium for the refined model. Except for ground surface elevations, surface water levels, and drain conductivities, the resolution of the input data was the same for both the local and the regional groundwater flow models.

3.2 Corroboration with empirical data

The methods that are available to observe hydraulic heads were not sufficiently accurate to establish hydraulic head gradients on the small spatial scale of this study. Therefore, we corroborated the modelled groundwater exfiltration patterns using chemical and physical properties of water in order to identify patterns in source waters. The source waters considered in this study were (1) locally infiltrated precipitation, (2) upwelling groundwater, and (3) alien surface water. These source waters were identified using the indicators chloride (Cl), electrical conductivity (EC), and tritium (^3H). Observed gradients in the Cl, EC, and ^3H concentrations were visualised by means of isolines that were established by Kriging interpolation using a linear variogram model.

Chloride was used as an indicator of alien surface water in the anthropogenically drained fen, because (1) the Cl concentration of alien surface water is usually relatively high compared to that in the other source waters (Table 1), and (2) Cl behaves conservatively during flow, i.e., Cl is not involved in any chemical or biological process that may alter its concentration in the groundwater during flow. Based on the ion concentrations of the source waters (Table 1), we used Cl concentrations exceeding 20 mg/l as indicators of alien surface water.

Chloride was used as an indicator of upwelling brackish palaeo-groundwater for the poorly drained fen: concentrations exceeding 300 mg/l were used as indicators of brackish palaeo-groundwater, concentrations below 20 mg/l as indicators of the absence of brackish palaeo-groundwater, and concentrations between 20 mg/l and

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300 mg/l as indicators of mixtures of brackish palaeo-groundwater and source waters that contained low amounts of Cl (Table 1).

The indicator we used to establish patterns of locally infiltrated precipitation was EC, because (1) the EC of precipitation clearly deviates from the EC of the fens' other source waters (Table 1), and (2) compared to individual ion concentrations, the EC is less sensitive to the hydrochemical evolution of infiltrated precipitation that may acquire a groundwater signature during flow. We used ECs below 200 $\mu\text{S}/\text{cm}$ as indicators of recently infiltrated precipitation. Electrical conductivities exceeding 200 $\mu\text{S}/\text{cm}$ are not ambiguous for any of the source waters as high ECs may relate to the presence of (1) chemically evolved, locally infiltrated precipitation, (2) upwelling groundwater, or (3) infiltrated alien surface water.

In order to identify patterns of recently infiltrated precipitation and upwelling groundwater, ^3H was used as an indicator of groundwater-residence time. We defined ^3H signatures of groundwater using time series of ^3H in precipitation in The Netherlands (compiled from Meinardi, 1994; Knetsch, 2002, 2007) and by considering first-order decay of ^3H (see Fig. 2). Note that ^3H signatures established by this approach may underestimate groundwater residence times in the presence of alien surface water as a high ^3H load in alien surface water (Table 1) can mask the presence of pre-modern groundwater, which is poor in ^3H .

Chloride, EC, and ^3H concentrations of groundwater and surface water were determined across both the anthropogenically drained fen and the poorly drained fen. Samples were collected from observation wells at depths ranging from 0.25 to 2.0 m below the ground surface. The observation wells were installed in clusters of 2 or 4 and positioned along transects parallel to the expected direction of groundwater flow. The distance between observation clusters was at most 10 m. A total of 42 observation wells was installed for this study, 20 at the anthropogenically drained fen and 22 at the poorly drained fen. The observation wells consisted of polyethylene tubes with a screen length of 5 cm and a diameter of 1.6 cm. This small diameter was used to minimise the amount of extracted groundwater needed to obtain a representative

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groundwater sample, i.e., to minimise the interference of the hydrochemical patterns across the fens that can be caused by sampling.

Samples were analysed for CI in November 2005, April 2006, May 2006, August 2006, and November 2006. They were filtered using 0.45 μm filters, stored in polyethylene bottles at 4°C, and analysed within three days after sampling using ion chromatography in conformity with the instructions of the Laboratory of Geosciences (Utrecht University, The Netherlands). Electrical conductivities were measured using a field electrode every 4–6 weeks from November 2005 to April 2007 directly after sampling. In November 2006, 12 samples from both the anthropogenically drained fen and the poorly drained fen (total=24) were analysed for ^3H . The samples were conserved in glass bottles according to the instructions of the Centre of Isotope Research (University of Groningen, The Netherlands). The samples were then artificially enriched by distillation and electrolysis to obtain the lowest detection limit of 0.2 tritium units (1 TU=1 ^3H atom per 10^{18} H atoms).

3.3 Numerical experiment

The local and regional effects of anthropogenic drainage on the groundwater supply of fens were analysed with a numerical experiment consisting of the elimination of drainage ditches from the anthropogenically drained fen. Local effects of anthropogenic drainage were defined as changes in groundwater level, exfiltration pattern, and water balance of the anthropogenically drained fen. Regional effects of anthropogenic drainage were defined as changes in groundwater level, exfiltration pattern, and water balance of the poorly drained fen.

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4 Results

4.1 Anthropogenically drained fen

The groundwater flow model indicated permanent groundwater exfiltration into the drainage ditches, and discontinuous groundwater exfiltration outside the drainage ditches at the anthropogenically drained fen (Fig. 3). This discontinuous groundwater exfiltration could be related to the seasonal variation in precipitation and evapotranspiration rates. For the periods of precipitation surplus (i.e., precipitation exceeded evapotranspiration), a net infiltration of local precipitation was found outside the drainage ditches, which reduced the relative area of groundwater supply outside the drainage ditches to less than 5% (Table 2). Despite a slight precipitation surplus, the modelled area of groundwater supply for May 2006 was relatively large compared to those for the other months of precipitation surplus. This was caused by groundwater exfiltration at narrow zones parallel to the drainage ditches due to the temporary attenuation of local head gradients by the anthropogenically raised surface water levels on 1 May, 2006. For the periods of precipitation deficit (i.e., evapotranspiration exceeded precipitation), a net groundwater exfiltration was also found outside the drainage ditches, causing the entire fen to be supplied with groundwater. The modelled discontinuous groundwater exfiltration outside the drainage ditches was confirmed by the ECs observed across the anthropogenically drained fen (Fig. 4). The low ECs ($<200 \mu\text{S}/\text{cm}$) at the centre of the fen indicate the presence of a permanent rainwater lens of at least 1 m in depth. This rainwater lens expands in a vertical direction when there is a net infiltration of local precipitation during periods of precipitation surplus, and shrinks when locally infiltrated precipitation evaporates during periods of precipitation deficit. The shrinking of the rainwater lens is accompanied by a lowering of the groundwater table and by a shift from groundwater infiltration to exfiltration. This shift is indicated by the increased ECs at the centre of the fen from May 2006 to July 2006. Because of the permanently low Cl concentration in the groundwater ($\text{Cl} < 20 \text{ mg}/\text{l}$, see Fig. 5), these increased ECs result from upwelling groundwater, and not from the dispersal of infiltrated surface water from

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the ditches.

The observed ^3H concentrations provide further evidence of the presence of recently infiltrated precipitation ($^3\text{H} > 11 \text{ TU}$) on top of older groundwater ($3 \text{ TU} < ^3\text{H} < 11 \text{ TU}$) in the anthropogenically drained fen (Fig. 6). The observed ^3H pattern strongly resembles that of the EC, and confirms the presence of a rainwater lens of at least 1 m in depth. The relatively low ^3H concentrations (indicating infiltration before 1999 AD) in the soil under the drainage ditches confirm the modelled exfiltration into the drainage ditches; however, no pre-modern groundwater (infiltrated before 1962 AD) signified by ^3H concentrations below 3 TU was found in the anthropogenically drained fen. As the Cl concentration near the drainage ditches permanently exceeded 20 mg/l (Fig. 5), the presence of pre-modern groundwater might have been masked by ^3H enrichment of the groundwater by the infiltrated alien surface water (Table 1).

4.2 Poorly drained fen

The groundwater flow model indicated permanent groundwater exfiltration at the topographic depressions near the centre of the poorly drained fen, and discontinuous groundwater exfiltration at the topographic mounds near the margins (Fig. 3). Like in the anthropogenically drained fen, this discontinuous groundwater exfiltration could be related to the seasonal variation in precipitation and evapotranspiration rates. For periods of precipitation surplus, a net infiltration of local precipitation was found at the topographic mounds, which reduced the relative area of groundwater supply to between 40–65% (Table 2). For periods of precipitation deficit, however, a net groundwater exfiltration was also found at the topographic mounds, causing the entire fen to be supplied with groundwater (Table 2).

Observed ^3H concentrations across the poorly drained fen (Fig. 6) confirm the infiltration of ^3H -rich precipitation at the topographic mounds, and the exfiltration of ^3H -poor, pre-modern groundwater at the topographic depressions. The increasing ^3H age with increasing depth and from the topographic mounds to the topographic depressions, corresponds to a mixing gradient of brackish palaeo-groundwater and locally

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infiltrated precipitation. Evidence for this mixing gradient is provided by the permanently high Cl concentrations ($\text{Cl} > 20 \text{ mg/l}$) that increase along the same direction as the ^3H age does (Fig. 5). The absence of indicators of locally infiltrated precipitation (Cl concentrations $< 20 \text{ mg/l}$ and ECs $< 200 \mu\text{S/cm}$, see Figs. 5 and 4, respectively) indicates that precipitation mixes with upwelling palaeo-groundwater immediately after infiltration into the fen soil. The observed ECs (Fig. 4) further suggest that brackish palaeo-groundwater disperses through the fen during periods of precipitation deficit to compensate for groundwater losses by plant transpiration, and that brackish palaeo-groundwater in the shallow subsurface is diluted by locally infiltrated precipitation during periods of precipitation surplus.

4.3 Effects of the elimination of drainage ditches

The numerical experiment indicated that the elimination of drainage ditches from the anthropogenically drained fen caused the reallocation of on-site groundwater exfiltration zones from the drainage ditches to the topographic depressions as seen in the poorly drained fen (Fig. 3). Due to the rather irregular surface morphology, however, the relative area of groundwater supply outside the drainage ditches remained small compared to that of the poorly drained fen (Table 2). Nevertheless, the model results indicated the establishment of hydrological conditions similar to those of the poorly drained fen, as exfiltration fluxes outside the drainage ditches increased by several orders of magnitude (Table 2), and surface runoff, instead of drain discharge and deep infiltration, became the dominant discharge mechanism (Fig. 7). The latter implies that a larger amount of local precipitation discharges from the fen before entering the fen root zone, and that exfiltrated groundwater may disperse across the fen and re-infiltrate at downstream regions.

Although the elimination of drainage ditches from the anthropogenically drained fen only increased the on-site groundwater level with at most a few tens of centimetres (Fig. 7), the consequences for regional groundwater flow were rather large. Part of the groundwater that is currently directed to the anthropogenically drained fen was

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redirected to the poorly drained fen, causing an increase in the exfiltration flux at the latter fen (Fig. 7). As a result, the relative area of groundwater supply of the poorly drained fen increased (Table 2), as did the groundwater level and discharge flux by surface runoff (Fig. 7). These hydrological changes indicate that the elimination of drainage ditches at the anthropogenically drained fen also enhanced the groundwater supply of the poorly drained fen.

5 Conclusion and discussion

5.1 Local impacts on fen deterioration

The groundwater flow model and the empirical data of chemical and physical properties of groundwater consistently indicated the presence of locally infiltrated precipitation on top of upwelling groundwater across the anthropogenically drained fen, and a mixing gradient of locally infiltrated precipitation and upwelling groundwater across the poorly drained fen. In addition, the numerical experiment showed that the elimination of drainage ditches from the anthropogenically drained fen caused the establishment of hydrological conditions similar to those of the poorly drained fen. These results confirm the hypothesis postulated by, for example, Schot et al. (2004) that anthropogenic drainage does not only cause a lowering of the groundwater table, but also enhances the infiltration of local precipitation across fens. Simultaneously, it prevents upwelling groundwater from entering the fen root zone, as a result of the immediate discharge of exfiltrated groundwater as surface water. These local hydrological consequences of anthropogenic drainage may have far-reaching consequences for the suitability of fen habitat sites, because (1) base ions become leached from fens, instead of supplied to fens, when locally infiltrated precipitation percolates through the fen soil (Almendinger and Leete, 1998), and (2) oxic conditions, instead of anoxic or sub-oxic conditions, become established across the shallow subsurface when the groundwater supply of electron donors has ceased (Boomer and Bedford, 2008a) and aeration of the fen soil

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is enhanced (De Mars and Wassen, 1999). As the cumulative effects of these shifts in supply rates are thought to contribute to the acidification (Van Diggelen et al., 1996) and eutrophication (Fojt and Harding, 1995; De Mars et al., 1996) of fens, the hydrological consequences of anthropogenic drainage may underlie the loss of fen plant species observed at drained fens in The Netherlands (Grootjans et al., 2005; Van der Hoek and Sykora, 2006) and Sweden (Malson et al., 2008). Moreover, we think that a continuous loss of fen plant species will occur across intensively managed regions like Western Europe during the next decades or centuries as anthropogenically drained fens further deteriorate because of the depletion of the soil chemical buffering capacity caused by the permanent leaching of minerals.

5.2 Regional impacts on fen deterioration

In addition to the above mentioned local hydrological effects of anthropogenic drainage, the results of our study indicate that drainage ditches intercept groundwater that is potentially directed toward downstream regions. This regional hydrological impact of anthropogenic drainage may further reduce the availability of suitable fen habitat sites, as infiltration rates of precipitation will increase at these downstream regions to compensate for the reduced groundwater supply (Van Wirdum, 1991). Although the regional consequences of anthropogenic drainage for the suitability of fen habitat sites may not be as severe as the local consequences, the increased infiltration of precipitation into fens may accelerate plant succession towards species poorer fens or bogs compared to plant succession under more natural conditions (Van Diggelen et al., 1996), especially if large quantities of phosphorous are released from the soil (Kooijman and Paulissen, 2006). For these reasons, anthropogenic drainage may cause fen deterioration on a spatial scale that is larger than one may expect from previous studies that focused only on the local hydrological effects of anthropogenic drainage (Schot et al., 2004; Holden et al., 2004).

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5.3 Hydrological fen restoration

Knowledge of the hydrological mechanisms behind habitat fragmentation of the remaining fen plant communities in intensively managed regions like The Netherlands is essential to improve currently utilized fen restoration and conservation strategies.

5 These strategies often include measures to restore individual fen reserves e.g. by removing abstraction wells from recharge areas as suggested by, amongst others, Fojt (1994), or by lowering the ground surface of fen reserves by means of top-soil removal as suggested by Van der Hoek and Heijmans (2007). In order to mitigate habitat fragmentation of low-productive fens, however, a spatially coherent hydrological fen restoration strategy is required that is also suitable to restore zones of ceased groundwater supply outside fen reserves, as these zones are thought to be less suitable for the establishment of most fen plants (Sjörs and Gunnarsson, 2002), and thus may form barriers against fen plant dispersal. In other words, in order to overcome the dispersal limitations of fen plants in fragmented landscapes (Ozinga et al., 2009), the restoration of spatially contiguous zones of groundwater supply that are common in natural fens (Van Loon et al., 2009b; Succow and Joosten, 2001; Schipper et al., 2007) is required. Based on knowledge of the hydrology of a near-natural fen in Poland, Van Loon et al. (2009b) have speculated how to restore spatially contiguous zones of groundwater supply. The hydrological fen restoration strategy postulated by Van Loon et al. (2009b) is evaluated below using the results of the present study.

20 Van Loon et al. (2009b) speculated that the elimination of drainage ditches from fens should be given high priority in fen restoration projects in order to re-establish spatially contiguous zones of groundwater supply in fragmented fens. This statement was primarily based on the findings of Schot et al. (2004), who used 2-D groundwater flow and transport models to illustrate that drainage ditches prevent upwelling groundwater from entering fen root zones. The results presented in this paper convincingly demonstrate that the removal of drainage ditches is indeed an effective measure to rewet drained fens with exfiltrating groundwater, even though the on-site exfiltration fluxes may de-

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crease as well. This paper further showed that the elimination of drainage ditches from fens may enhance the dispersal of exfiltrated groundwater by surface runoff, which increases the availability and contiguity of potentially suitable fen habitat sites like in natural fens (Van Loon et al., 2009b; Succow and Joosten, 2001). In order to enhance the supply of exfiltrated groundwater to fragmented fens by surface runoff, however, additional measures to reduce the re-infiltration of exfiltrated groundwater may be required. This is because the infiltration conditions across managed fens are thought to prevail on a larger spatial scale than those across natural fens (Wassen et al., 1996; Van Loon et al., 2009a). Potentially suitable measures to reduce infiltration across fens include the inundation of polders and the closing of abstraction wells in fens.

Earlier ecohydrological analyses of the present study area indicated that endangered fen plant communities in the poorly drained fen recently declined in number and size due to succession towards plant communities that are more common in Western Europe (Barendregt et al., 1995; Wassen et al., 1989). This development was mainly attributed to the decreased supply of groundwater originating from the ice-pushed ridge, which enhanced the infiltration of precipitation and induced the upward movement of brackish palaeo-groundwater (Wassen et al., 1989; Schot, 1989) stored below the lake bordering the fen (Schot, 1989). Based on these findings, water management authorities closed the abstraction wells at the ice-pushed ridge in the late 1990s, with the goal of re-establishing the supply of fresh groundwater to the poorly drained fen. Although this measure has certainly increased the amount of fresh groundwater that is available for regional groundwater flow to the fen (Schot, 1989), our empirical data provide evidence that brackish palaeo-groundwater instead of fresh groundwater is still the major source of water for the fen. In other words, the fresh groundwater supply that is required to sustainably conserve the endangered fen plant communities in this area has not become re-established, even though groundwater fluxes from the ice-pushed ridge have increased over the past 10 years. One explanation for this lacking fresh groundwater supply is that the replacement of brackish palaeo-groundwater by fresh groundwater may be delayed compared to the redirection of groundwater flow. The results of our

study indicate, however, that the lack of a fresh groundwater supply may also be due to the interception of groundwater by the drainage ditches that are situated about half a kilometre upstream of the poorly drained fen. This latter explanation would imply that most of the redirected groundwater is lost by drain discharge instead of becoming available to fen plants. This renders measures that enhance groundwater flow to fens ineffective when nearby drainage ditches have not been eliminated first. As most fens in Western Europe have been reclaimed by means of the installation of drainage networks (Succow and Joosten, 2001), this is probably a commonly encountered problem that limits the effectivity of regional hydrological fen restoration measures. For this reason, we suggest that regional measures that enhance groundwater flow to fens be assigned a lower priority than local measures that support the transport of available upwelling groundwater up to the fen surface.

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Table 1. Chloride, EC, and tritium in the water sources of the Naardermeer.

	Cl (mg/l)	EC (μS/cm)	³ H (TU)
Precipitation	<10 ^a	<50 ^a	>11 TU ^b
Alien surface water	>100 ^c	590 ^c	45 ^b
Upwelling fresh groundwater	<20 ^c	240 ^c	0 ^d
Upwelling brackish groundwater	>300 ^c		0 ^d

References: ^a RIVM, 2005, ^b Knetsch, 2007, ^c Schot and Wassen, 1993, ^d Robertson and Cherry, 1989.

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Table 2. Effects of the elimination of drainage ditches on the groundwater supply of the anthropogenically drained fen and the poorly drained fen: relative area of groundwater exfiltration (%) and total exfiltration flux (m^3/d) outside the draining elements.

	Precipitation surplus (mm/d)	Relative area of groundwater exfiltration (%)								Total exfiltration flux (m^3/d)			
		Anthropogenically drained				Poorly drained							
		Current conditions	Ditches eliminated	Current conditions	Ditches eliminated	Current conditions	Ditches eliminated	Current conditions	Ditches eliminated	Current conditions	Ditches eliminated	Current conditions	Ditches eliminated
February	1.71	1.0	→	3.8	46.1	→	63.4	19	→	541	73	→	160
May	0.22	11.3 ^a	←	2.6	63.1	→	77.4	18	→	191	40	→	77
July	-3.64	100.0	↔	100.0	100.0	↔	100.0	715	→	918	104	→	115
November	2.67	0.4	→	4.4	42.6	→	59.8	23	→	684	79	→	171

^a Temporal increase of the area of groundwater exfiltration, as a result of the attenuation of local head gradients within the anthropogenically drained fen by the raised surface water levels on 1 May (see Fig. 3).

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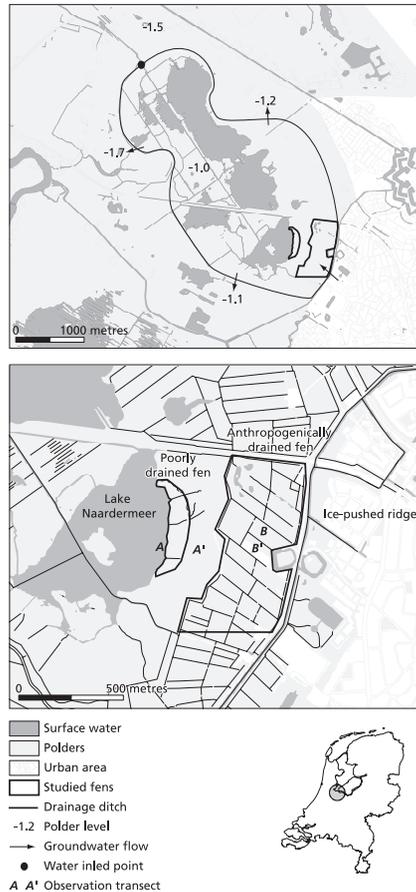


Fig. 1. Topographic maps of (a) the Naardermeer, The Netherlands, and (b) the anthropogenically drained fen and the poorly drained fen.

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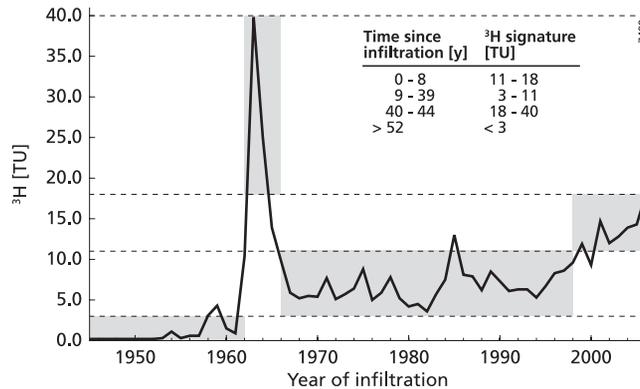


Fig. 2. Calculated ³H concentration in groundwater and ³H signatures of groundwater as a function of the year of infiltration.

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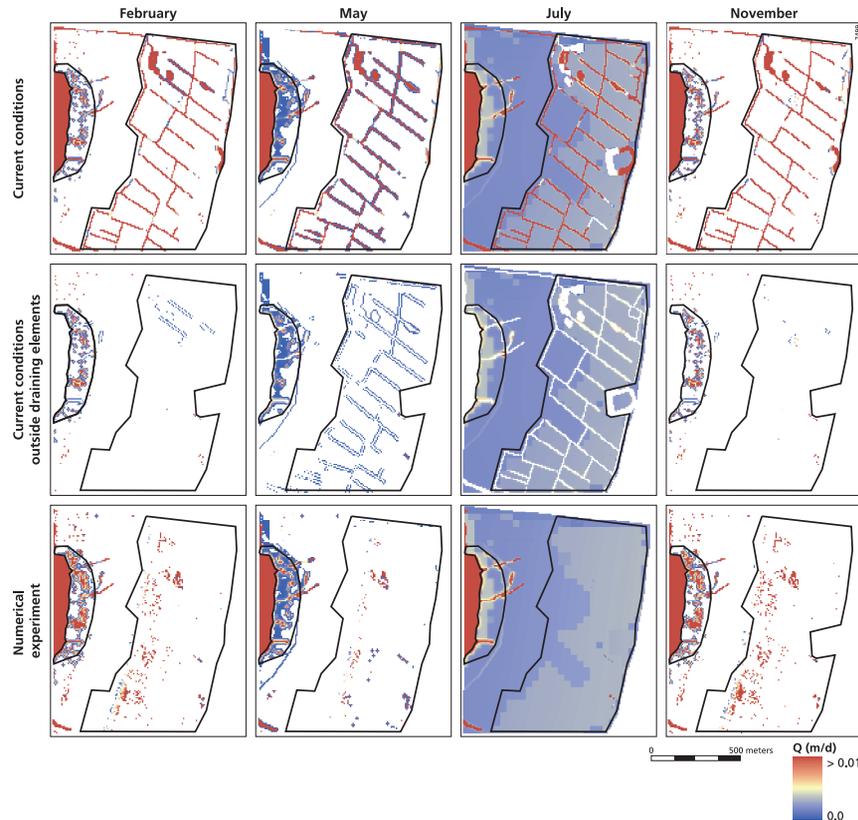


Fig. 3. Groundwater exfiltration patterns across the Naardermeer modelled for February, May, July, and November 2006. **(a)** Current conditions. **(b)** Current conditions outside the draining elements. **(c)** Numerical experiment in which the drainage ditches have been eliminated from the anthropogenically drained fen.

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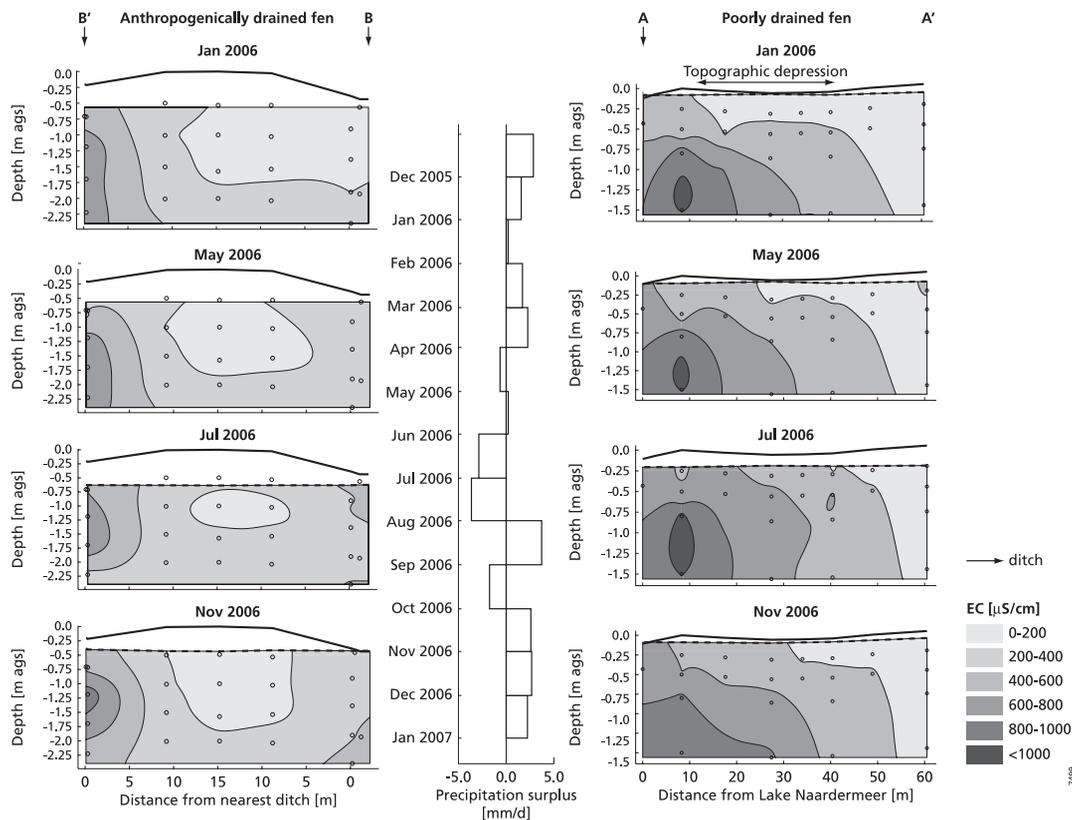


Fig. 4. ECs ($\mu\text{S}/\text{cm}$) observed across the anthropogenically drained fen and the poorly drained fen in January, May, July, and November 2006. A-A' and B-B' signify the positions of the observation transects in Fig. 1. Vertical arrows denote draining elements; horizontal arrows indicate topographic depressions.

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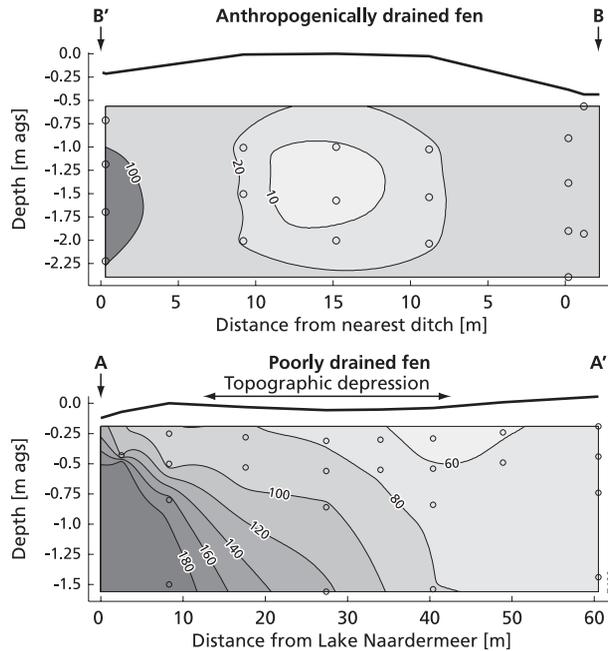


Fig. 5. Time-averaged Cl concentration (mg/l) observed across the anthropogenically drained fen and the poorly drained fen. A-A' and B-B' signify the positions of the observation transects in Fig. 1. Vertical arrows denote draining elements and horizontal arrows topographic depressions. Cl samples were collected in November 2005, March 2006, May 2006, August 2006, and November 2006.

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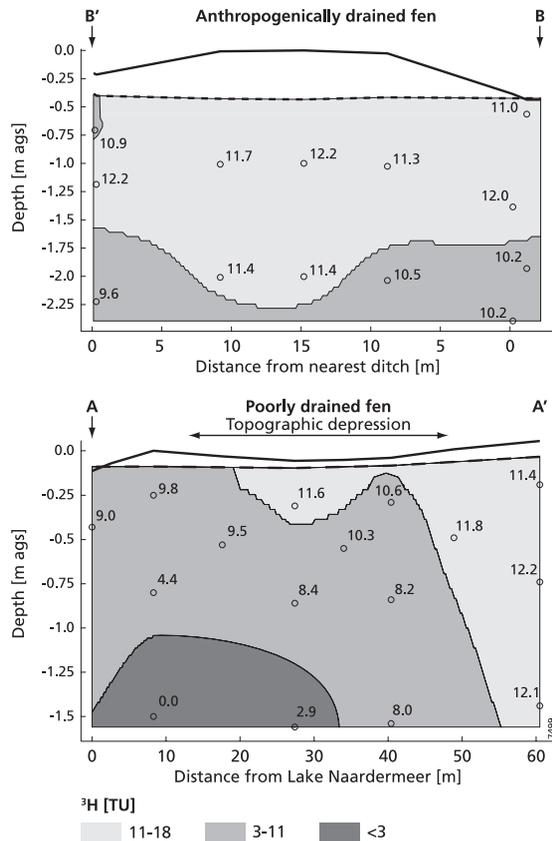


Fig. 6. Tritium concentrations (TU) observed across the anthropogenically drained fen and the poorly drained fen in November 2006. A-A' and B-B' signify the positions of the observation transects in Fig. 1. Vertical arrows denote draining elements and horizontal arrows topographic depressions.

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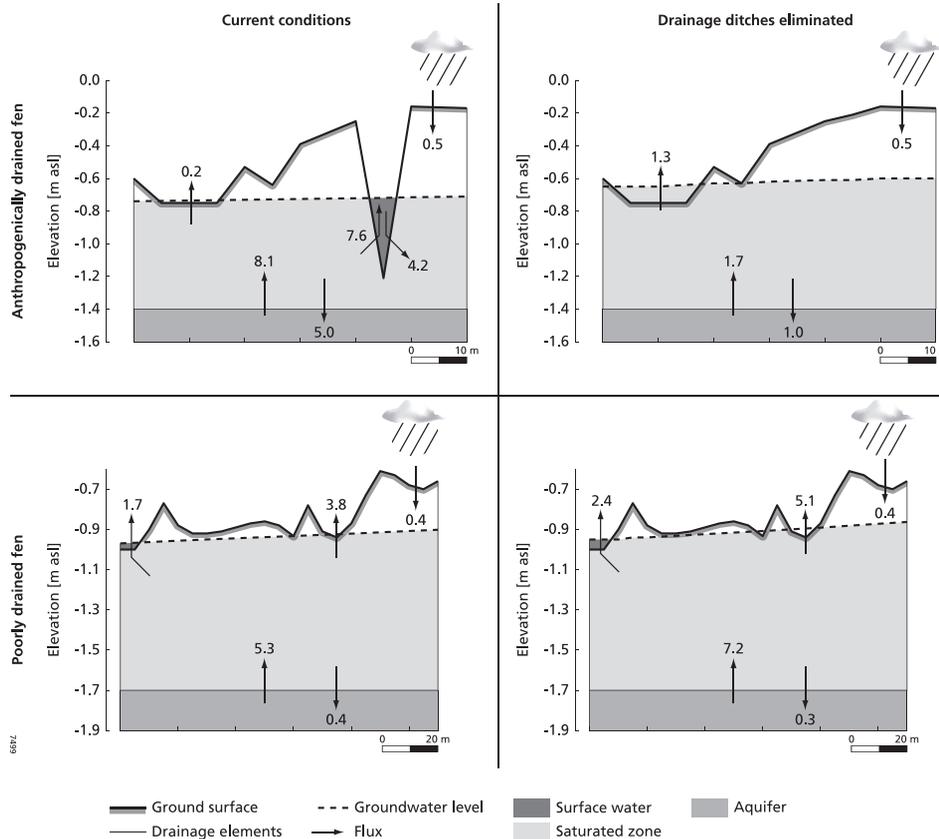


Fig. 7. Effects of elimination of drainage ditches on the water balance (mm/d) of the anthropogenically drained fen and the poorly drained fen.