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Covariance in water- and nutrient budgets of Dutch peat polders: what governs nutrient retention?

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Abstract Water and nutrient budgets were constructed for 13 low-lying peat polders in the Netherlands that varied in elevation relative to sea level (-0.2 to -2.4 m below sea level), land use (7–70% of the total polder area covered by agriculture; largely dairy farming), and surface water prevalence (6–43%). Water balances were verified with chloride budgets and accepted when both met the criterion (total inflows − total outflows)/(total inflows) <0.05. Apart from precipitation and evapotranspiration (overall means 913 vs. 600 mm), in- and outlet (171 vs. 420 mm) as well as in- and outward seepage (137 vs. 174 mm) were important items in the water budgets. Nutrient budgets, however, were dominated by terms related to agricultural land use ($\sim$60% of all inputs, 90% of N-removal and 80% of P removal) rather than water fluxes (8% and 5% of N and P inputs; 6 and 18% of outputs). After agriculture (200 kg N ha^{-1} y^{-1}), mineralisation of the peat soil and atmospheric deposition appear to be important inputs (about 94 and 21 kg N ha^{-1} y^{-1}). Major output terms were agricultural output (209 kg N ha^{-1} y^{-1}) and denitrification (95 kg N ha^{-1} y^{-1}). The average N budget was in balance (difference $\sim$1 kg N ha^{-1} y^{-1}), whereas P accumulated in most polders, particularly those under agriculture. The mean P surplus (15 kg P ha^{-1} y^{-1} in the 9 mainly agricultural polders) corresponds well with the accumulated difference observed elsewhere (700 kg P ha^{-1} in the upper 50 cm in a nature reserve versus 1400 under agriculture) after over 50 years of dairy farming. Bulk retention of N and P in these polders is taking place in the peat soil, through temporary sorption to the matrix and N is lost through denitrification. In a principal components analysis combining land use, landscape pattern, water balance and nutrient budget terms, the three-first principal components explained 63% of the variability. The first component (PC) correlated strongly with the percentage of land under agriculture ($r = 0.82$) and negatively with the percentage covered by surface water ($r = -0.74$). Most input and output terms of the nitrogen budget also correlated with this PC. The second PC covaried distinctly with the total area of a polder ($r = -0.79$) and human population density at municipality level ($r = 0.75$). Phosphorus loads in inlet and outlet water correlated with this PC. This suggests that the variability in nutrient budgets among polders is largely governed by agricultural land use.

Keywords Wetlands · Water management · Mineralisation · Land use · Fertilization · Subsidence

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Introduction

The presently low-lying peatlands of The Netherlands have been reclaimed and intensively used since the Middle Ages (Verhoeven 1992). Reclamation created a regular pattern of dikes, ditches and farmland (e.g. Bakker et al. 1994; Nol et al. 2008), of which the absolute level has been falling due to mineralisation of the peat. Comparable peatland polders have been reclaimed and drained around the world (e.g. Keddy 2000; Charlier et al. 2005; Verhoeven and Setter 2009). The process of subsidence has probably accelerated since the nineteen-fifties when mechanisation of agriculture demanded lower water tables (Schothorst 1977; Nieuwenhuis and Schokking 1997). As a consequence, water level in Dutch peatlands is managed with pumping stations in independent polder units, each with its own distribution of land and water, intensity of land use, paved area and water level (e.g. Vermaat et al. 2007). Surface water quality in these polders is probably strongly affected by the intensity of agricultural land use (Best and Jacobs 2001; Van Beek et al. 2004a, 2007), but peat mineralisation may also contribute a substantial nutrient load (Schothorst 1977; Van Beek et al. 2007), and so may the inlet of river Rhine water during periods of water shortage in summer (Lamers et al. 2002). Together, these components of water and nutrient balances and their interactions may be affected by foreseen climate change, where summer water shortage and winter precipitation are foreseen to increase (Van den Hurk et al. 2006). For example, rewetting, or the raising of the water table to counteract subsidence in a polder may enhance nutrient release and thus internal loading (Richardson 1985; Van Dijk et al. 2004), whereas the resulting expansion of reedbeds may enhance evapotranspiration thus reducing an anticipated rise in water table (Vernooij and Vermaat 2009). Nutrient dynamics in wetland soils and aquatic sediments are complex. Those of nitrogen are often dominated by microbial processes, e.g. fixation, nitrification and denitrification (Barnard et al. 2005), whereas those of phosphorus are governed by sorption and precipitation mechanisms (with Ca, Fe, Al; e.g. Richardson 1985; Qualls and Richardson 1995; Roden and Edmonds 1997; Bridgham et al. 2001, Zak et al. 2004) with oxygen availability, redox potential and pH often as forcing factors (Heathwaite 1990; Best and Jacobs 2001; Lamers et al. 2002; Van Dijk et al. 2004).

Variation in reclamation and land use history as well as hydrogeology has led to variation among polders in the size distribution and pattern of water bodies: some polders have numerous parallel narrow ditches, others have a more reticulate mosaic pattern, and again others have wider expanses of open water in broads and turbaries due to peat excavation (e.g. Bakker et al. 1994; Vermaat et al. 2007, 2008; Nol et al. 2008), or larger lakes due to subsequent erosion (Verhoeven 1992; Nieuwenhuis and Schokking 1997). The banks of these water bodies form a network of littoral transitions between land and water. These narrow, linear wetlands are considered rich in specific biodiversity elements (Blomqvist et al. 2003a, b; Herzon and Helenius 2008), and are subject to intensive management (Best et al. 1995; Blomqvist et al. 2003a; Twisk et al. 2003). These ditch banks may well perform some of the highly valued services generally attributed to wetlands (e.g. Balmford et al. 2002; Brander et al. 2006), such as nutrient and carbon sequestration (Aerts 2000; Olde-Venterink et al. 2003; Van Oene et al. 2001; Verhoeven et al. 2006), similar to buffer strips (Hefting et al. 2006). Hence, one could postulate that the density of the ditch drainage pattern may affect nutrient retention processes in these polders. These ditches then would operate in a manner similar to the wetlands and lakes that are assumed to maintain water quality in intensively exploited catchments (Verhoeven et al. 2006) provided they cover a sufficiently large proportion of the area (2–7%). Nutrient retention, in this respect could be mediated by different processes, i.e. sequestration in soils but also ditch sediments, uptake by biota including crops and fodder, and N may be lost to the atmosphere through denitrification. Single-ditch in situ studies (Meuleman et al. 2004; Toet et al. 2005) suggest that polder ditches may retain substantial quantities of nutrients from the inflowing water, but only Van Beek et al. (2004a, 2007) have up-scaled this approach to one full polder subject to regular farming land use practice. Differences among polders in ditch pattern across the landscape, however, may be reflected in differences in nutrient dynamics.

We expanded the approach of Van Beek et al. (2004a, 2007) to cover a wider range of land use patterns and of surface water area and distribution pattern. We collected data from water boards, the national statistics depository and grey literature to construct water and nutrient budgets for individual, separately managed polder units and confront these with land use and landscape pattern statistics in search for patterns of joint variability. Our specific aims were, firstly, to assess covariance among water and nutrient budgets and land use in search for the primary drivers of variability among these polders in factors governing nutrient retention, and secondly, to explore the possible relation between nutrient retention processes and landscape pattern in the allocation of water as ditches and ponds in these polders. The latter would test for a possible buffering effect of these ditches and, extrapolating from Verhoeven et al. (2006), it will address a possible edge-area effect of ditches.

Materials and methods

A polder is treated here as one single hydrologically separated unit of land and water, irrespective of its actual size. It is connected to other surface water via pumping stations. Each polder unit contains the land and its underlying topsoil (down to about 1 m; Van Beek et al. 2004a), and all surface water. It interfaces with deeper groundwater through upward and downward seepage, and with the atmosphere through precipitation, evapotranspiration and volatilization. Farming practice introduces and removes water and nutrients to this polder. Ditch sediment is considered a temporary store of matter outside the polder unit, and deeper soils and groundwater are also assumed to be external.

For each polder, water balances were compiled from internal water board and consultancy reports in the period from 1990 to 2005 (Table 1; Appendix). Chloride, total nitrogen and total phosphorus concentrations of surface and ground water (Tables 1, 2; Appendix) were obtained from the monitoring programs of water boards, and the national surface and ground water monitoring depositories (e.g. www.waterbase.nl and Griffioen et al. 2002). For precipitation, quality data were obtained from Van Drecht et al. (1996) and Fraters et al. (2004, 2007). Water balances were cross-checked for consistency with chloride mass balances and considered acceptable when the difference between summed inputs and outputs was 5% or less of the influx (Appendix). Revisions of seven balances were made after discussion with water board experts leading to adjustments in the chloride content of seepage (1 polder,Appendix), volumes of seepage water (5), the volumes of surface water pumped (3) and the chloride content of pumped surface water (2). No attempt was made to close the budgets for N and P, since these should derive from the water balance. Land use data were obtained from the municipal statistics maintained by the national statistics service (www.cbs.nl; CBS 2000a; Table 3) and digital land use maps (CBS 2000b; Kadaster 2007).

We compiled data of sufficient quality for thirteen polders (Fig. 1; Appendix), varying in size (2–141 km^2), elevation relative to sea level (-0.2 to -2.4 m below Dutch Ordnance Survey Level), land use (0–95% agriculture, generally dairy), and surface water prevalence (6–43%). Covariance was analysed first with ordinary principal components analysis, whereas the different variables reflecting aspects of retention were further subjected to forward stepwise regression. All statistical analyses were carried out with SPSS v16.

Results

Overall, the water budgets of the studied polders had only minor remaining differences between the sums of inflows and outflows (on average 27 mm, or 2% of a mean annual input of 1222 mm). The average surplus in precipitation over evapotranspiration is compensated for by pumping more water out than into these polders, whereas upward and downward seepage, on average compensate each other (Fig. 2). These averages are underlain by substantial among-polder variability. Upward seepage, for example, ranged between 0 and 423 mm, downward seepage ranged between 0 and 803 mm, depending on the position of a polder in the surrounding landscape: adjacent higher grounds lead to upward seepage, deeper neighbouring polders cause downward seepage. Precipitation ranged between 830 and 1114 mm across the polders, primarily because of spatial differences, but also because the data of different polders are available for different years (1990–2004). Observed rainfall in the polders corresponded well with the grand mean reported for these years in the

Table 1 Annual water balance terms used, the range of estimated values among the 13 polders, their derivation and data sources used

Balance term	Range (mm)	Description, sources
Inputs		
Precipitation	830–1114	Obtained from internal water board balance reports[a]. Generally interpolated with Thyssen-polygon weighing from nearby meteorological stations. Rainfall for a specific budget year and polder corresponded quite well with the means reported for the five main stations of the Royal Netherlands Meteorological Service (paired *t*-test: $p = 0.13$), but the explained variance was low (0.23) due to two outliers: the Vlietpolder (+20% compared to mean for 2000) and Staphorsterveld (−10% compared to mean for 1999). The former lies in the Rijnland area, an exceptionally wet part of The Netherlands (Heijboer and Nellestijn 2002), the latter must have had a dry year locally. Without these two the correlation is better: $r^2 = 0.68$, $p < 0.001$. The coefficient of variation in annual rainfall over the five main meteorological stations among the years studied here was 10%. Chloride concentration for Vlietpolder from Van Beek et al. (2007), otherwise adjusted according to Barendregt et al. (1995) and Van Drecht et al. (1996) depending on distance to the sea
Upward, inward seepage	0–423	From adjacent higher grounds or water bodies. Obtained from water board balances, cross-validated and/or estimated from consultancy reports. Chloride concentration of seepage from water board estimates or Van Drecht et al. (1996)
Inlet surface water	0–755	From water board data. Generally derived from extrapolated pumping hour logs and full capacity rates of pumping stations. Chloride concentrations from monitoring programs of water boards
Agricultural inputs[b]	–	Extrapolated from Van Beek et al. (2003, 2004) to specific land use characteristics of each polder. Witteveen and Bos estimated additional, unregistered water inlets by individual farmers for Ankeveen and Kortenhoef, but these were minor. Also the chloride content of agricultural in- and outputs is based on Van Beek et al. (2003, 2004)
Sewage works effluents, storm overflows and highway run-off[b]	–	From budget of the water board. Only present in the Overwaard and Nederwaard of the Ablasserwaard. Chloride concentration based on Van Mossevelde et al. (2005; 488 mg l^{-1} in storm overflows). For these two polders we include a small entry covering chloride from highway run-off
Outputs		
Evapotranspiration	514–687	Obtained from water board balances, which generally are extrapolated from a limited set of meteorological stations that measure Makkink evapotranspiration
Downward, outward seepage	0–803	Similar to upward seepage
Outlet surface water	115–730	See inlet surface water
Agricultural outputs[b]	–	Output of agricultural products from the polder parcel (hay, milk, meat), see also inputs
Difference between total inputs and outputs	0–5.2%	Annual net storage or loss not presented as a separate term, but used to assess the quality of the balance, in conjunction with the chloride balance. See text. Final differences are reported in Appendix

All are estimated in mm y^{-1} and 10^6 m^3 polder^{-1} y^{-1}. Chloride balances (10^3 kg y^{-1}) use the same budget entries and are estimated from water fluxes and concentrations of inert chloride

[a] Water board reports and other data sources are specified in detail for each polder in Appendix

[b] These three terms were negligible in the water balances, but did contribute to the chloride budgets.Agriculture contributed inputs through manure and removed chloride with hay

Netherlands (Table 1), if the two extremes are excluded. Among-year variability in rainfall for the studied years was acceptable (coefficient of variability = 10%).

The average budget for N was in balance (Fig. 2, surpluses not significantly different from zero, $p = 0.32$) whereas the P budget displayed a net surplus (~7 kg ha^{-1} y^{-1}, or 23% of inputs, Fig. 2).

Table 2 Annual nitrogen and phosphorus budget terms used, ranges observed, and their sources and derivation

Balance term	Range	Description, sources
Inputs		
Precipitation	N: 14–32 P: 0–3	Total, dry and wet atmospheric deposition of N and P is taken from Barendregt et al. (1995), Van Beek et al. (2004a), Buijsman (2004), Fraters et al. (2004, 2007) and personal communication of Maarten Ouboter. Estimated concentrations differ markedly among sites and studies
Upward, inward seepage	N: 0–8 P: 0–3	Concentrations from water board estimates or Van Drecht et al. (1996)
Inlet surface water	N: 0–14 P: 0–31	From water board or national monitoring data. Generally derived from time series of a nearby water quality monitoring station in the relevant water body. Median concentration used for the period during the year when water is pumped in, generally summer
Agricultural inputs	N: 0–384 P: 0–35	Extrapolated from Van Beek et al. (2004a, 2007) to specific land use characteristics and fertilizer practice of a polder, where possible. Involves animal manure (droppings on the field), stable slurry (mixture of dung and urine collected in the stable and sprayed over the field) and artificial fertilizer. Artificial fertilisation rates were also obtained separately from the official records in CBS (2000b)
Internal mineralisation of peat soil	N: 0–244 P: 1–10	Aerobic peat mineralises. Maintaining a ditch water level below the soil surface leads to mineralisation, which generates nutrients readily available for assimilation. Estimates of Schothorst (1977) and Van Beek et al. (2004a, 2007) were adjusted for each polder depending on ditch water level.
Slush application on banks	N: 0–14 P: 0–40	Ditch maintenance involves annual removal of aquatic vegetation and dredging of ditch sediment once every 3–10 years. This sediment is a soft watery mud, which is deposited on the bank or sprayed far into the field. Van Beek et al. (2004a) offers an experimentally verified estimate, which has been adjusted to the area of ditches in a polder
Sewage works effluents, storm overflows	N: 0–1 P: ∼0	From budget of the water board. Only present in the Overwaard and Nederwaard of the Ablasserwaard. See Table 1
Nitrogen fixation	N: 0–18	Alder carr has symbiotic Acinetobacter known to fix atmosperic nitrogen. We applied an area-specific estimate from Barendregt et al. (1995; 70 kg N ha^{-1} y^{-1}) and multiplied this with the area under alder carr
Outputs		
Evapotranspiration, volatilisation	N: 0–7	Evapotranspiration of water is no loss of N or P. We included a term for volatilisation of N during manure application based on Van Beek et al. (2007)
Downward, outward seepage	N: 0–18 P: 0–4	See upward seepage
Outlet surface water	N: 5–33 P: 0–28	See inlet surface water
Agricultural outputs	N: 56–381 P: 0–39	Van Beek et al. (2003) offer estimates for output of agricultural products from the polder parcel (hay, milk, meat), these were adjusted to the separate polders
Denitrification	N: 15–213	Denitrification from peat wetlands has been measured and reviewed by Van Beek et al. (2004b). Comparable assessments from river floodplain wetlands (Olde-Venterink et al. 2006) have been used for verification
Difference between total inputs and outputs	N: −18 to +8% P: −91 to +24%	Annual net storage or loss is not presented as a separate term. Net storage can be reflected in an increase in N or P content of the soil. See text

All are estimated in 10^3 kg N or P polder $^{-1}$ y^{-1} and reported as kg ha^{-1} y^{-1}

This mean surplus is significantly different from zero (*t*-test, $p = 0.01$). The direct inputs and outputs due to agriculture dominate both budgets of N and P (Fig. 2). Agriculture directly accounts for over 60% of the nutrient inputs into a polder, and it is responsible for 90% of the N removal, and 80% of

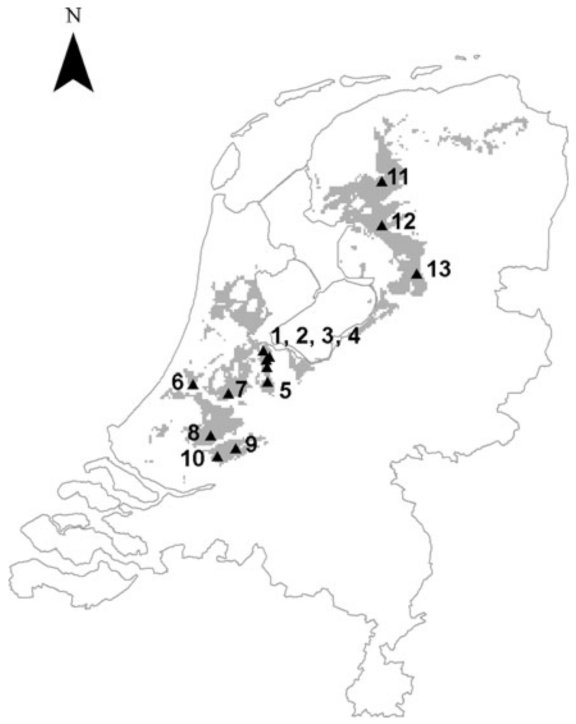


Fig. 1 Location of the thirteen polders in the low-lying peat districts of The Netherlands. Land with peat soils is hatched (adopted from Rienks et al. 2002, p. 26). Numbers correspond with those given in Appendix

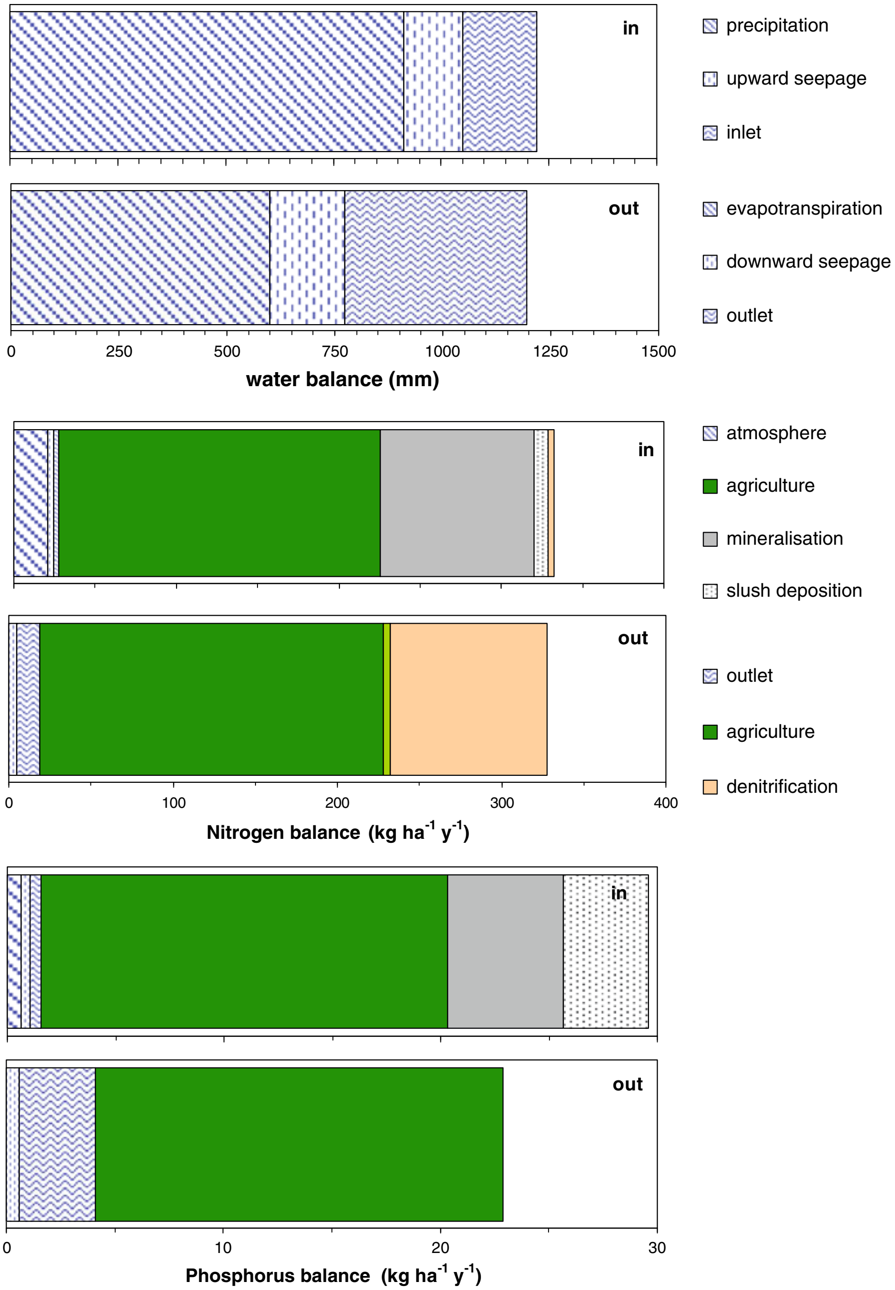
the P removal as export of hay, dairy and meat products (cf. Table 2). The two other substantial items on the input side are mineralisation of the peat soil and atmospheric nitrogen deposition. Most remarkably the items on the water balance provide only minor contributions to the nutrient fluxes, less than 30 kg N ha^{-1} y^{-1} and 2 kg P ha^{-} y^{-1}. The only major quantitative difference between the N and P budgets is the substantial role of denitrification in the former and a larger proportion of sedimentary P dredged as slush from the ditches and deposited on the banks (Fig. 2), otherwise the distribution over different budget items is comparable.

Variability among polders was assessed in a principal components analysis bringing together all quantified variables (Fig. 3; Table 4). In Fig. 3, the correlation patterns of the different variables are grouped into two panels only for accessibility, they were entered simultaneously in one single PCA. The three-first principal components together accounted for 63% of the total variability, and several clusters of closely co-varying variables are apparent (Fig. 3). The first principal component (PC1, 33% of variance) reflects a major land-use gradient with the proportion of the polder under agriculture and open water as two opposite ends (see also Fig. 4a). The fraction of open water in ditches (Fig. 3) closely covaried with agriculture, so the negative correlation between open water and agriculture is due to ponds and lakes, not ditches. Also, polder level and water level in ditches covaried with PC1, but the correlations were less than 0.55 (Table 4), and the relation of polder level and percentage agriculture was not linear: polders with little agriculture were all comparatively high (≥1 m NAP), whereas agricultural polders occurred at all elevations (Fig. 4b). Another nonlinear pattern is apparent for downward seepage (Fig. 4b): it is low for the deepest polders with little open water, but maximal in polders combining an intermediate fraction of open water and a relatively high position in the surrounding landscape. Water budget items also covaried with the first PC: more water is pumped into polders with less agriculture, and these also have higher water losses through downward seepage and evapotranspiration. The majority of the Nitrogen budget items were found to covary positively with PC1: they clustered in the right half of the plot (Fig. 3 *lower panel*, Fig. 4e, h).

The second principal component (PC2, 22% of variance) probably reflects a large scale urbanisation gradient depicted by the opposing variables population density (at municipality level) and total polder area. Polders as separately managed units appear to be larger where population density is lower. Precipitation was found to covary significantly with this PC2, possibly in part because urbanisation happens to covary with variability in long-term mean rainfall across the low peatlands in the Netherlands (Heijboer and Nellestijn 2002), but also because the highest precipitation was observed in the small Vlietpolder, with a high population density in adjacent municipalities. The third principal component (PC3, 11%) still explains a significant proportion of the total variance (Table 4). Shoreline density, N-flux from peat mineralisation and N-fertilizer use at municipality scale correlated negatively and upward seepage correlated positively with this PC.

The small input–output differences of the N-balance were found to relate to the volume of water pumped out of a polder after stepwise regressions

Fig. 2 Mean water, nitrogen en phosphorus balances of the thirteen peat polders studied. Balance terms are explained in Tables 1, 2 and 4. Minor budget entries have been left out from the legend for readability



selecting from 15 variables of land use, landscape pattern and water balance (Table 5). Overall, the differences of the P-budgets were proportionally much larger than those of the N-budgets. These P-differences related to several variables, and the proportion of land under agriculture was the most important (Table 5), confirming the patterns of the PCA. The most conspicuous P deficits were found in polders with a large proportion of land under nature protection, where hay-making is the important export term. The nitrogen differences, in contrast, were not necessarily negative in nature reserves, due to the almost constant blanket of atmospheric deposition (Fig. 4d).

Table 3 Land use, demographic and administrative data sources

Variables used	Resolution	Data source
Elevation, median polder land level relative to Dutch Ordnance (NAP, m); ditch water level; dry board (difference land level and ditch water level)	Polder	Water board reports, topographic map, digital elevation data (as compiled in Vernooij and Vermaat (2009).
Percentage of agricultural land, forested land, open water, residential built-up land, road cover	Polder	CBS (2000b)
Density of shorelines of ditches and larger open water bodies (km km^{-2}); area of these two categories; orientation of ditches (since fx NE is the same direction as SW, these are pooled to 0–180°, from N)	Polder	Top10vector, digital topographic map of The Netherlands at 1:10,000 (Kadaster 2007)
Nitrogen fertilizer use in 2002; population density in 2000	Municipality	CBS (2000a, b); www.cbs.nl

Although the polders differed substantially in ditch density and ditch orientation (19–40 km km^{-2} and 82–127°), these landscape indicators were not related distinctly to any of the nutrient budget terms. Ditch orientation did covary with the second PC, implying that larger polders had a larger proportion of the ditches oriented SE-NW.

Discussion

Agricultural nutrient inputs and outputs were found to dominate the nutrient budgets (Fig. 2), and these generally covaried straightforwardly with the areal coverage by agriculture in a polder (Fig. 3). Strictly seen, agricultural nitrogen outputs were somewhat higher than agricultural inputs, whereas agricultural phosphorus inputs and outputs were similar (although the overall balance had a surplus, Fig. 2, see below and Schothorst 1977). Polders without agriculture still received substantial inputs of N and P (Fig. 4g), i.e. from atmospheric deposition (N), mineralisation of the peat soil, and reworking of ditch sediments. Though not of prime importance, these inputs were not negligible in agricultural polders either. Next to agricultural fluxes, nitrogen was exported out of the polders mainly by denitrification and phosphorus left the polders with surface water. In this way, the studied peat polders are a net source of phosphorus to the receiving water system. Without denitrification, the N-budgets would display major surpluses (Fig. 2). Estimated denitrification rates were probably highest in the deeper polders under agriculture (Fig. 4), where ditch and groundwater tables are shallow combining extensive anoxic transition zones and an ample supply of nitrate (cf Koerselman et al. 1993; Best and Jacobs 2001; Van Beek et al. 2004b; Olde Venterink et al. 2006).

Agricultural land use also affected water balance terms (Fig. 3): polders with more open water and less agriculture had higher evapotranspiration and downward seepage, here also more water was pumped in. In these polders the maintenance of a certain high water level is often a major target for water management. Polders with more agriculture also had higher volumes of water pumped out (Fig. 4h), which is consistent with the need for drainage coupled to agricultural practice.

Most polders had annual phosphorus balances with a surplus, with the exception of three polders which contain a large nature reserve. The surpluses suggest net P-accumulation, probably the peat soil is enriched with P under agricultural practice. Beltman et al. (2009) report elevated total P, iron-bound P as well as readily available (Olsen- or acetate-lactate extracted) P in Dutch peatlands under intensive dairy farming. Drainage causes mineralisation (Schothorst 1977), which makes nutrients potentially available but oxidises iron, which would bind P (Bridgham et al. 2001; Zak et al. 2004). Probably, the soil matrix and interstitial water of these peatlands witness dynamic sorption and resorption fluxes (e.g. Fraters et al. 2007). Apparently the soil is the major site of nutrient retention in these peat polders, also since dredging of sludge redistributes the nutrients that are being stored in ditch sediments onto the land. Our aggregation at polder level precluded an analysis of spatial and temporal variability in water level across a polder or

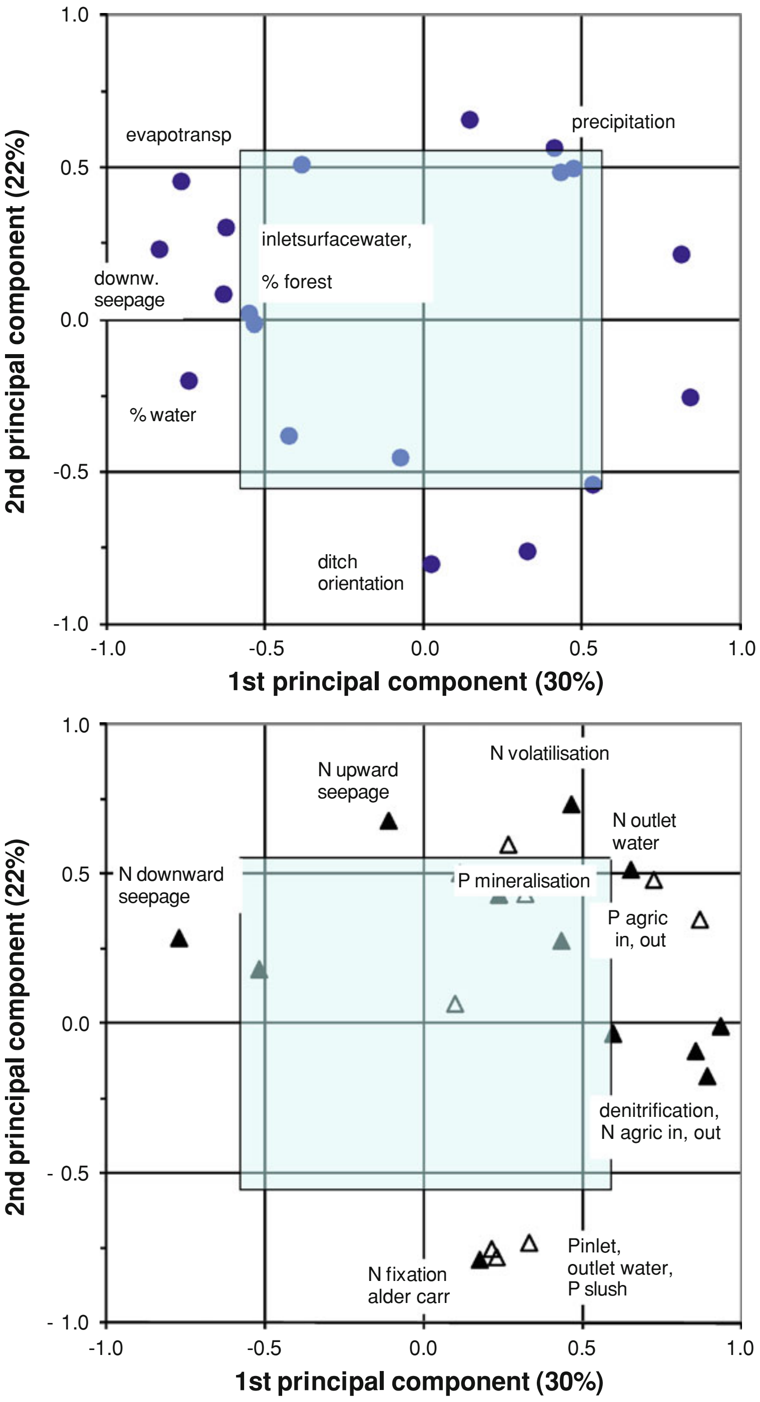


Fig. 3 Correlation coefficients of variables of land use, landscape pattern, water (*upper panel*) and nutrient balances (bottom panel, N: filled symbols, P: open symbols) with the first two principal components (see also Table 4). The shaded square indicates the area where correlations are <0.55, hence have a probability over 0.05 and are considered not significant

Table 4 Correlation of land use, water balance and nutrient balance variables[a] in thirteen peat polders with the first three components of a principal component analysis (83% explained variance)

Principal component[b] (percent of variance explained)	PC1 (30%)	PC2 (22%)	PC3 (11%)
Land use and landscape pattern variables			
Total area	0.33	***−0.76***	−0.08
Percent water	***−0.74***	−0.20	0.13
Polder level	*−0.55*	−0.02	−0.49
Percent agriculture	***0.82***	0.21	0.39
Percent forest	*−0.63*	0.08	0.32
Percent covered by roads	0.54	−0.49	−0.25
Fraction of surface water in ditches	***0.84***	−0.26	0.39
Ditch orientation	0.03	***−0.80***	−0.13
Shoreline density	−0.42	−0.38	*−0.59*
Human population density at municipality scale	0.15	*0.65*	−0.30
N-fertiliser use from municipality-scale statistics	−0.53	−0.01	*−0.62*
Water balance			
Precipitation	0.42	*0.56*	−0.11
Upward seepage	*−0.38*	0.51	*0.66*
Inlet surface water	*−0.62*	0.30	0.20
Evapotranspiration	***−0.76***	0.46	0.18
Downward seepage	***−0.83***	0.23	0.14
Nitrogen balance			
N in upward seepage	−0.11	***0.68***	−0.43
N inlet water	−0.52	0.18	0.15
N inputs from agriculture	***0.90***	−0.18	−0.04
N from peat mineralisation	0.44	0.27	*0.67*
N from ditch sediment dredging	*0.60*	0.04	0.27
N-fixation by alder symbionts	0.18	***−0.79***	−0.26
N volatilisation	0.46	***0.73***	−0.09
N downward seepage	***−0.77***	0.28	0.03
N outlet water	*0.65*	0.51	0.31
N outputs from agriculture	***0.94***	−0.01	−0.16
N denitrification in soil and sediments	***0.86***	−0.09	−0.29
Phosphorus balance			
P inlet water	0.22	***−0.75***	0.26
P inputs from agriculture	***0.87***	0.35	0.00
P from peat mineralisation	0.27	*0.60*	−0.44
P from ditch sediment dredging	0.23	***−0.78***	*0.25*
P downward seepage	0.10	0.07	*−0.55*
P outlet water	0.33	***−0.73***	0.18
P outputs from agriculture	***0.73***	0.48	0.27

A fourth principal component explained another 9%. Correlations over 0.55 are considered significant at $p = 0.05$ (italicized here) and those over 0.68 at $p = 0.01$ (italicized and bold). Variables with correlations less than 0.55 to any of these three principal components are omitted

[a] Omitted variables: water level in ditch, dry board, outlet surface water, percent built-up P-fertilizer application from municipality-scale statistics, N and P in atmospheric deposition, N in outlet water, P in inlet water, P in atmospheric deposition

[b] The first component is interpreted as a complex of factors related to the proportion of the polder that is under agriculture versus the proportion of surface water, the second to total polder area versus human population density in the municipalities that cover the polder, and the third to a less equivocal complex of water edge density, reported N-fertilizer statistics at municipality scale, P in downward seepage

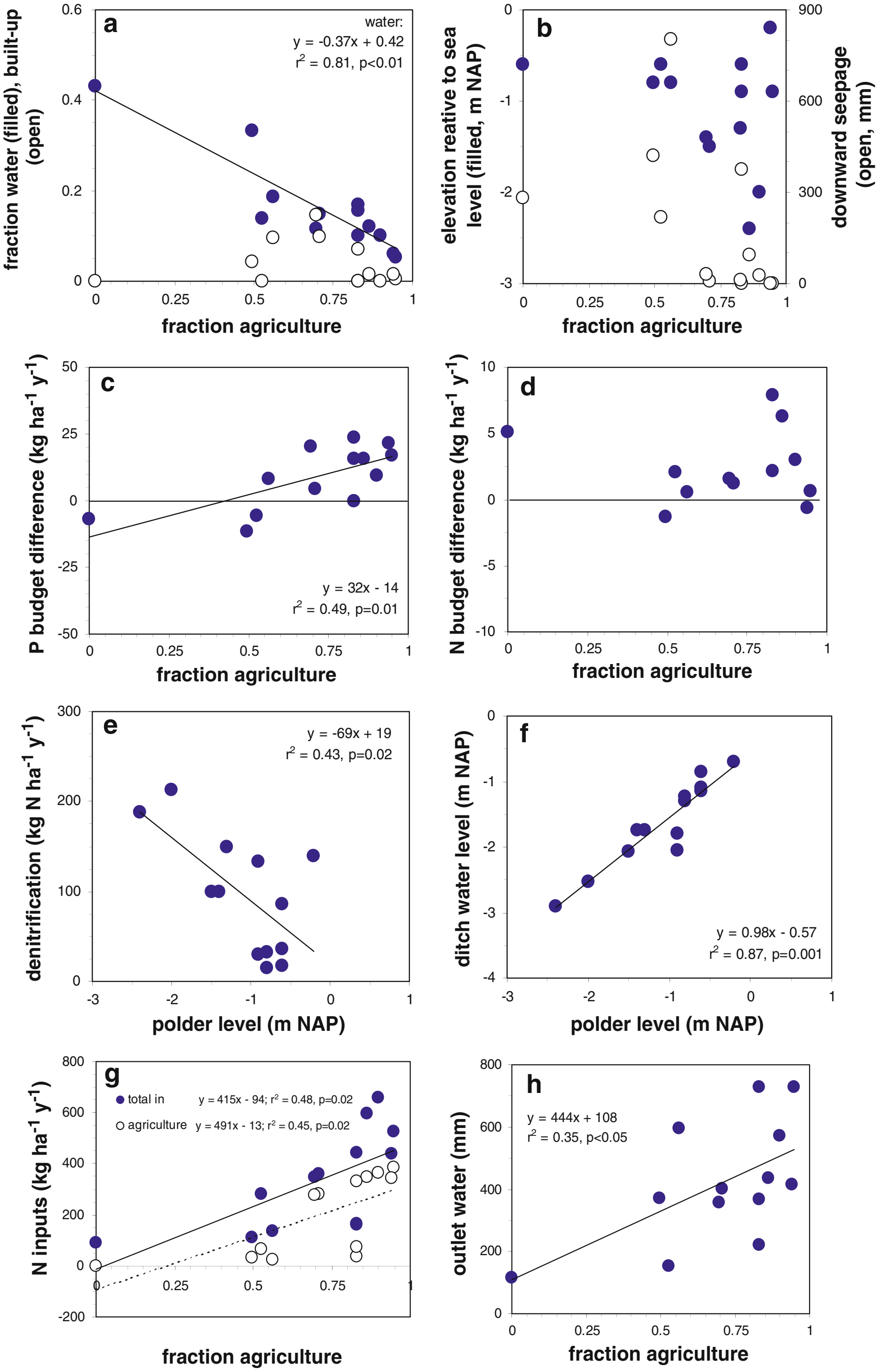


Fig. 4 Scatter plots of selected pairs of variables, based on the covariance in the PCA (cf. Fig. 3 and outcomes of the stepwise regressions of variables related to nutrient retention (from Table 5): **a** the fraction of the total polder-area covered with water (*filled symbols*) and built-up land (*open symbols*) versus the fraction of agricultural land; **b** mean polder elevation relative to sea level (*filled symbols*) and downward seepage (*open symbols*) versus the fraction of open water; **c** the difference in the annual P balance versus the fraction of land under agriculture; **d** difference in the annual N balance versus the fraction of land under agriculture) denitrification versus polder level; **e** denitrification versus polder land level; **f** ditch water level versus polder land level; **g** total and agricultural N inputs as a function of the percentage agriculture; and **h** the quantity of water let out annually as a function of percentage agriculture

field (cf Meuleman et al. 2004; Van Beek et al. 2004b; Dekker et al. 2005). Hence ditch water level closely tracked the level of the land, and did not add explanatory power to our analysis.

Intensification of agricultural practice commenced in these polders after the second World War with re-allotment and drainage schemes as well as mechanisation, increased fertilisation rates and cattle stocking

Table 5 Stepwise forward multiple regressions of a range of dependent variables reflecting retention processes with independent variables of land use, landscape pattern and the water balance

Dependent	Step	Selected independent variable	r^2	p	Slope
N budget difference	1	Outlet surface water	0.35	0.035	−0.019
P budget difference	1	Percent agriculture	0.82	0.001	137.41
	2	Fraction water in ditch	0.90	0.001	−72.66
	3	Percent built-up	0.97	0.001	170.47
	4	Polder land level	0.99	0.010	6.40
	5	Percent water	0.99	0.047	−54.48
Denitrification	1	Evapotranspiration	0.47	0.009	−0.71
N from ditch sediment dredging	1	Fraction of surface water in ditches	0.53	0.050	18.14
P from ditch sediment dredging	1	Total polder area	0.35	0.034	−0.88
N outputs from agriculture	1	Fraction of surface water in ditches	0.61	0.001	359.03
	2	Polder land level	0.78	0.002	−77.00
P outputs from agriculture	1	Percentage water	0.38	0.025	−69.29

List of independent variables entered to select from: total area, percent water, polder level, dry board, percent agriculture, percent built-up, percent covered by roads, fraction of surface water in ditches, shoreline density, human population density, fertiliser application from municipality-scale statistics, upward seepage, inlet surface water, evapotranspiration, downward seepage, outlet surface water. Presented are the explained variance (r^2) and level of significance of each added independent variable, and the slope

densities (Harms et al. 1987; Best and Jacobs 2001). If fertilisation during these past 50 years would have been responsible for a continuous surplus on the nutrient balance, then this should be reflected in the nutrient content of the top soil (cf Reddy et al. 1993). Indeed, Beltman et al. (2009) report elevated P-contents for agricultural land. Unfertilized peatland in a nature reserve and deeper soils (<60 cm) had a P content of 600–800 kg ha^{-1}, whereas the upper 50 cm soil of agricultural land contained about 1400 kg ha^{-1}. A mean surplus of 15 kg ha^{-1} y^{-1} (Fig. 4c, for 10 polders with substantial agricultural coverage) would need 47 years to accumulate such a high P content, an estimate that is remarkably close to the real time passed since the onset of agricultural intensification, given the uncertainties in our estimate and the differences in land use history among these 10 agricultural polders. Together, this adds credibility to the balances we have constructed and it suggests that farming practice and water management may have led to an approximate steady state in nutrient fluxes over the past decades.

Principal mechanisms contributing to nutrient retention in these peat polders were firstly accumulation in the peat soil [supportive soil data in Fraters et al. (2007) and Beltman et al. (2009)] and ditch sediments, and secondly denitrification, though the latter is strictly speaking not retention but a loss to the atmosphere. Retention is taken here as any process preventing loading with nutrients of the surface water. Accumulation in ditch sediments is only a temporary sink, since dredging is carried out frequently, and the retained nutrients are recycled on land. Also the N and P accumulating in the upper peat soil are probably subject to substantial turn-over, since the peat mineralises continuously as well. Still, the observed matching between our annual surplus and accumulated P content of the soil, does suggest a net retention in the soil. Our multivariate analyses do not suggest that the spatial distribution of ditches in these polders contributes distinctly to nutrient retention. Water edge, our prime indicator of landscape pattern, varied only with a factor 2 among the polders (19–40 km km^{-2}), whereas the proportion of surface water varied between 5 and 43% and covaried inversely with the proportion of land under agriculture. Retention in these aquatic sediments is probably considerable, as witnessed from the nutrient fluxes that are brought back to the land by dredging (9 kg N ha^{-1} y^{-1} or 3% of inputs and 4 kg P ha^{-1} y^{-1} or 13%).

In short, bulk retention in these peat polders appears rather governed by the peat soil and ditch sediment, than by the quantity of littoral edge present.

Whereas agricultural inputs and outputs dominate the budgets, a termination of agricultural practice would still lead to substantial nutrient fluxes: total inputs would remain at ~40% of the present (Fig. 2) if the present water management was maintained, since this involves continued mineralisation and ditch sludge dredging. A limited raising of the water table can even enhance mineralisation (Van Dijk et al. 2004).

Conclusions

1. Nutrient budgets in 13 peat polders in the lower part of the Netherlands were found to be dominated by agricultural fluxes. Water balance terms contributed only little.
2. Nitrogen budgets were found to be in balance, with denitrification the second important output next to agriculture, and peat mineralisation the second important input.
3. Phosphorus budgets suggest a net annual surplus, which is in agreement with the know history of fertilization since ~1950 and accumulated topsoil P-content observed in agricultural versus pristine peatlands. Next to agriculture, the major output is with drainage water, pumped to adjacent receiving waters. Polders with a substantial proportion under agriculture had P budget surpluses.
4. Covariance in landscape pattern, land use intensity, water and nutrient budgets was assessed in a principal components analysis. Three major components explained 63% of the variance. The first was clearly related to the proportion of a polder under agriculture, and it covaried with variability in most nitrogen budget items. The second was related to an urbanisation gradient, and P in surface water covaried with this component: higher loads in areas with less urbanisation. Thus variability in nutrient budgets among polders is largely governed by intensity of agricultural land use.
5. Retention could not be related to independent variability in landscape pattern, such as the density of littoral zones as water edge or area of surface water in a polder. Rather, the peat soil itself probably operated as the main location: P is sorbed to Fe and organic matter, and N is denitrified. Water area correlated negatively with the proportion of land under agriculture.

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Appendix

Characterisation of the 13 studied polders, and specification of the sources used to construct water balances and nutrient budgets, as well as the budgeted year

Polder name (number)	Area (ha)	Predominant land use (about 50% or more of area)	Elevation (m, relative to NAP, Dutch ordnance level)	Year(s) for which the balances have been compiled	Error water balance (% of inputs)	Error chloride balance (% of inputs)	Data sources water balances	Data sources nutrient balances	Uncertainties met when matching chloride and water balances
Nieuwe Keverdijkse Polder (1)	844	Dairy farming	−0.90	2000	−0.1	0.9	Van Ouwerkerk and Thijssen (2005) and water board monitoring data	As Nieuwe Keverdijkse Polder	Brackish upward seepage occurs from shallow former marine deposits, chloride concentration is estimated
Hilversumse Bovenmeent (2)	181	Dairy farming/ Nature conservation	−0.90	2000	2.6	−1.6	Van Ouwerkerk and Thijssen (2005) and monitoring data from waterboard Waternet	Seepage nutrient concentration estimates are based on Witteveen Bos (1999) and Ouboter (personal communication)	Chloride content of inlet and outlet water uncertain
Ankeveen (3)	731	Nature conservation/ farming	−0.80	1997–2000	5.2	1.0	As Tienhovens Oostelijke Binnenpolder	As Tienhovens Oostelijke Binnenpolder	–
Kortenhoef (4)	874	Nature conservation/ farming	−0.80	1997–2000	0.0	1.2	As Tienhovens Oostelijke Binnenpolder	As Tienhovens Oostelijke Binnenpolder	–
Tienhovens Oostelijke Binnenpolder (5)	225	Dairy farming	−0.60	1997–2000	4.4	1.6	Witteveen Bos (1999), data from Waterboard Amstel, Gooij en Vecht (now Waternet)	Witteveen Bos (1999), data from Waterboard Amstel, Gooij en Vecht	–
Vlietpolder (6)	202	Dairy farming	−2.00	2000	2.9	4.2	Van Beek et al. (2004a)	Van Beek et al. (2004a, 2007); total P-concentration of rainwater of 0.07 mg P l^{-1} from Maarten Ouboter (pers. Comm); total N-concentration of 2.2. mg l^{-1} from Best and Jacobs (2002)	–

continued

Polder name (number)	Area (ha)	Predominant land use (about 50% or more of area)	Elevation (m, relative to NAP, Dutch ordnance level)	Year(s) for which the balances have been compiled	Error water balance (% of inputs)	Error chloride balance (% of inputs)	Data sources water balances	Data sources nutrient balances	Uncertainties met when matching chloride and water balances
Groot Zegveld (7)	1913	Dairy farming	−2.40	2000	1.9	−1.5	Jansen et al. (2007), chloride data from Waterboard Stichtse Rijnlanden	Nutrient concentrations from water board monitoring data. For agricultural stocks and fluxes, estimates from Jansen et al. (2007) and Van Beek et al. (2007) were adopted	–
Krimpenerwaard (8)	13753	Dairy farming	−1.50	2000	0.8	0.6	Based on Kroes et al. (2006a, b)	Based on Kroes et al. (2006a, b)	–
Alblasserwaard-Overwaard (9)	14101	Dairy farming	−1.30	2004	3.7	−4.5	As Alblasserwaard-Nederwaard	As Alblasserwaard-Nederwaard	Inward seepage from river Rhine branches, upward or downward seepage into locally shallow sandy aquifers, water exchange with Alblasserwaard-Overwaard and chloride contribution from urban run-off are poorly known
Alblasserwaard-Nederwaard (10)	9764	Dairy farming	−1.40	2004	4.3	−5.1	Ten Bras (2008), storm overflows and highway run-off: Van Mosselvelde et al. (2005); seepage estimated from Griffioen et al. (2002) and Pomarius (personal communication)	Ten Bras (2008) and Van Beek et al. (2007)	As Alblasserwaard-Overwaard
Deelen (11)	454	Nature conservation	−0.60	1990	0.0	−4.1	Based on Grontmij (1991b), Griffioen et al. (2002) and Theo Claassen (personal communication)	Grontmij (1991b), concentrations seepage water from Rienks et al. (2002)	Seepage, inlet and outlet water not exactly monitored

continued

Polder name (number)	Area (ha)	Predominant land use (about 50% or more of area)	Elevation (m, relative to NAP, Dutch ordnance level)	Year(s) for which the balances have been compiled	Error water balance (% of inputs)	Error chloride balance (% of inputs)	Data sources water balances	Data sources nutrient balances	Uncertainties met when matching chloride and water balances
Rottige Meente (12)	1130	Nature conservation	−0.60	1990	0.8	−4.6	Based on Grontmij (1991a), Griffioen et al. (2002) and Theo Claassen (personal communication)	Grontmij (1991a), concentrations seepage water from Rienks et al. (2002)	As with Deelen
Staphorsterveld (13)	6534	Dairy farming	−0.20	1999	5.2	2.1	Internal report water board Groot Salland (2001); Griffioen et al. (2002)	Internal report water board Groot Salland (2001) and Wiegman (personal communication)	Volumes of water in upward seepage and inlet water are uncertain. The same holds for chloride content of these budget entries

A justification of the balance terms used is given in Tables 1 and 2. Polder numbers correspond with those in Fig. 1

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