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WETLAND RESTORATION

Evaluation of nutrient retention in four restored Danish riparian wetlands

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Abstract During the last 15–20 years, re-establishment of freshwater riparian wetlands and remeandering of streams and rivers have been used as a tool to mitigate nutrient load in downstream recipients in Denmark. The results obtained on monitoring four different streams and wetland restoration projects are compared with respect to hydrology, i.e. flow pattern and discharge of ground or surface water, retention of phosphorus (P), and removal of nitrogen (N). Furthermore, the monitoring strategies applied for quantifying the post-restoration nutrient retention are evaluated. The four wetland restoration projects are the Brede River restoration (including river valley groundwater flow, remeandering and inundation), Lyngbygaards River restoration (groundwater flow, irrigation with drainage water, inundation with river water and remeandering), Egeskov fen (fen re-establishment and stream remeandering) and Egebjerg Meadows (fen restoration and hydrological reconnection to Store Hansted River). Retention of phosphorus varied between 0.13 and 10 kg P ha^{-1} $year^{-1}$, while the removal of nitrogen varied between 52 and 337 kg N ha^{-1} $year^{-1}$. The monitoring strategy chosen was not optimal at all sites and would have benefitted from a knowledge on local hydrology and water balances in the area to be restored before planning for the final monitoring design. Furthermore, the outcome concerning P retention would have benefitted from a more frequent sampling strategy.

Keywords Wetland restoration · Nutrient · Biogeochemistry · Nitrogen · Phosphorus · Nutrient removal

Introduction

Denmark is in the forefront regarding implementation of measures to regulate the pressures of nutrients on the aquatic environment (Kronvang et al., 2008). The last two Danish Governmental Action Plans have included restoration of freshwater wetlands as a mitigation measure with the main aim not only to remove nitrogen (N) but also to enhance retention of phosphorus (P) and increase biodiversity (Hoffmann & Baattrup-Pedersen, 2007). In the coming years, the demands of the EU Water Framework Directive (WFD) (European Commission, 2000) will require measures to obtain at least a good ecological quality in surface water bodies which often are facing eutrophication as a major threat to ecosystem structure and function (Kronvang et al., 2005a). To meet such a demand, wetland restoration is one of the

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mitigation options that can be applied by river basin managers in Europe to reduce N and P loadings of rivers, lakes, reservoirs and estuaries (Kronvang et al., 2005b).

Unfortunately, the functioning of newly restored wetlands for N and P retention is seldom investigated and this lack of knowledge is evidently a problem when planning new restoration projects. Guidelines are needed, which can help in optimising the hydrological and biogeochemical processes in restored wetlands to achieve sustainable retention of N without negative side effects such as release of dissolved P, emission of greenhouse gases or deterioration of habitat conditions (Simek & Cooper, 2002; Hefting et al., 2003; Maljanen et al., 2003; Dahl et al., 2007; Hoffmann et al., 2009).

Nutrient retention and transformation in wetlands are strongly linked to wetland hydrology and soil geochemistry (Hoffmann et al., 2000, 2006b, 2009; Andersen, 2004; Caldwell et al., 2007). A way forward for categorising the outcome of different hydrological types of restored wetlands is, therefore, to follow the typology proposed for groundwater-surface water interaction flow types (GSI flow types) by Dahl et al. (2007) and Hoffmann et al. (2009).

Factors that may influence the outcome of monitoring results from restored wetlands are the lack of knowledge about biogeochemical processes at both shorter-(hours to days) and longer-time intervals (years) and the impact on the nutrient budgeting of the physical disturbances (soil excavations) often occurring when rewetting the area. Although restored wetlands seem to be efficient in N removal, the influence of year-to-year variations in climate has seldom been reported. Moreover, short-term studies of N removal in natural and restored wetlands are very limited although they can provide important insight into aspects that may influence the biogeochemical processes controlling N removal.

Recent studies have focused on the caveats in the P storage efficiency of restored wetlands (e.g. Scalenghe et al., 2002), and other results have documented that there can be a significant risk of net P release for shorter or longer periods following wetland restoration in specific areas (Kjærgaard et al., 2007; Zak & Gelbrecht, 2007). On the other hand, the importance of the particulate N and P depositions in temporarily inundated riparian wetlands is well documented from numerous studies (e.g. He & Walling, 1997; Kronvang et al., 2009). The P uptake in plant biomass and the leaching of dissolved P from the newly deposited and mineralised river sediments are other factors rendering it difficult to establish a P balance for restored freshwater wetlands (Hoffmann et al., 2009).

This study presents the results of studying four restored riparian wetlands in Denmark for retention of N and P. The aims of the article are (i) to quantify the rates of N and P retention in restored Danish freshwater riparian wetlands and discuss the outcomes as compared to estimations, and (ii) to evaluate and discuss the outcome of different monitoring strategies deployed to quantify the effect of wetland restoration on nutrient retention.

History of river and wetland restoration in Denmark

During the last century, numerous watercourses have been channelised or otherwise manipulated throughout Europe. As a result, only few watercourses live up to our present-day ideas of a natural watercourse, and many may be mapped as heavily modified or artificial watercourses under the EU Water Framework Directive (European Commission, 2000). In Denmark, we realised way back in the late 1970s that new legislation on watercourses was required, and since 1983, when a new Watercourse Act was adopted by the Danish Parliament, it has been legal to improve the physical conditions of Danish watercourses with the use of different restoration methods. This possibility has been widely exploited, and over the years, several thousand restoration projects have been carried out ranging from simple projects involving laying out of spawning gravel to major projects aiming at remeandering watercourses and improving the interaction between the rivers and their riparian areas (Hansen et al., 1996). Interest in restoring watercourses and wetland ecosystems to increase nutrient removal and biodiversity has also increased in other European countries (Iversen et al., 1993, 1998; Tockner et al., 1998). Thus, reinstating naturally functioning river–floodplain systems may bring catchment management benefits, particularly by increasing flood-storage capacity to reduce peak flows, enhance nutrient retention and ameliorate low flows.

In Denmark, we have gathered information on implemented stream and river restoration projects and divided these into three categories according to comprehensiveness (Hansen et al., 1996) (i) restoration undertaken locally on short stretches of the stream (category 1), (ii) restoration re-establishing the continuity and free migration in the stream (category 2), and (iii) restoration including both the stream and its adjacent riparian areas (category 3, see also below). Category 3 projects involve both the stream and the surrounding riparian areas, ensuring a higher groundwater level in the meadows and allowing the stream to flood the meadows naturally at high water levels in winter and spring. A higher water level and more frequent inundations are preferable to reduce the transport of sediments, nitrogen, phosphorus, or ochre in the stream to downstream lakes and coastal waters. Since 1983, a total of 128 large-scale category 3 projects have been undertaken in Denmark, involving remeandering of the river channel and allowing the riparian areas to become wetter and temporarily inundated. The number of projects strongly increased during the period, particularly from 2005 till the present date, when 49 projects have been carried out. This increase can be explained by the introduction of wetland restoration in the Danish Governmental Action Plans II (1998) and III (2003) intended to reduce the nutrient loadings to the aquatic environment (Kronvang et al., 2008). In general, wetland restoration projects can be divided into two distinct categories (i) restoration of riparian areas by removal and disconnection of drainage systems and ditches, thereby allowing water to flow naturally through the riparian corridor, i.e. mainly as groundwater or as a combination of surface water and groundwater, and (ii) remeandering of streams and rivers, thereby re-establishing the natural inundation of the riparian areas and floodplains at high flows, i.e. with focus on the floodplain to trap sediment and retain nutrients. In some of the projects, the whole river valley has been restored and, thus, including both of the above mentioned categories.

Since 1998, wetland restoration programmes have been an integrated part of Danish Action Plans aimed towards reducing nutrient loadings and the resulting eutrophication of marine waters (Hoffmann & Baattrup-Pedersen, 2007). National guidelines were adopted to ensure that each planned wetland restoration project was able to reduce annual N loadings by at least 200 kg N ha^{-1} of the wetland (Hoffmann & Baattrup-Pedersen, 2007). The guidelines included concentration-specific nitrate N reduction rates per inundated day for use in the project planning process. Thus, a removal rate of 1.5 kg N ha^{-1} restored wetland per inundated day was allowed if the concentration of nitrate-N in surface waters exceeded 5 mg N l^{-1} and 1.0 kg ha^{-1} day^{-1} if the concentration was below 5 mg N l^{-1} (Hoffmann & Baattrup-Pedersen, 2007). N removal during inundation was assumed to take place only at a distance of 100 m into the inundated floodplain due to exhaustion of the nitrate concentration and ceasing of water flow. The amount of N lost from the direct catchment to the restored riparian wetland was calculated utilising an empirical N loss model (Kronvang et al., 1995). A N reduction efficiency of 50% was expected in the restored wetland when tile drains and ditches were cut or blocked in the wetland area as part of the restoration project. In contrast, if water and N discharged into the riparian area with groundwater, the reduction efficiency was set to 90%. No guidelines or demands were adopted for P retention in the national wetland restoration guideline, but it is emphasised in legislation that projects should retain P, i.e. on an annual basis, net release or discharge of P to downstream water bodies was not allowed (Hoffmann & Baattrup-Pedersen, 2007).

A post-restoration monitoring programme running for one year was obligatory for all the approved restoration projects under the Second Action Plan from 1998. However, only 14 out of 38 were monitored (shallow lakes not included) because of budget constraints (Hoffmann et al., 2006a). The design of the post-monitoring programme was approved by a national scientific board and was individually planned for each project. The outcome of the monitoring programme could then be compared with the planned N reduction targets and any deviation could be discussed for later improvements in wetland restoration projects.

Materials and methods

Four different types of restored riparian wetlands in Denmark—three of them including stream restoration—were studied for their efficiency in removing, storing or releasing N and P forms. A monitoring programme was established at each of the four sites, situated in different parts of Jutland and on the island of Funen. An overview of the restoration and monitoring of each site are shown in Fig. 1. A description of the sizes of the restored wetlands, their upstream and direct catchment areas and soil types is given in Table 1. The interactions between groundwater and surface waters (GSI) follow different flow paths as schematically shown in Fig. 2 (Dahl et al., 2007). The four restored wetlands cover different wetland characteristics and have different dominant flow paths as described in Table 2. Sulphate, ammonium, nitrate, total N, soluble reactive P and total P were analysed according to Danish Standards (Danish Standards Association, 1975a, b, 1985a, b, 1990, 1991). Ferrous iron was measured by the biphyridyl method (Heaney and Davidson, 1977). Total iron was measured as ferrous iron after the addition of hydroxylamine to the sample. Not all elements were measured at each of the restored sites.

Brede River valley

Restoration of a 3.2-km straight reach of the fifth-order river Brede to a new 4.5-km meandering reach was conducted during 1994–1995. The catchment has a size of 257 km^2. The river valley is generally dominated by peat deposits, although a belt of gley soil dominates along the southern slope of the valley. Alluvial deposits are found along the original meandering river course. In the central part of the valley, peat deposits dominate the upper 1.0–1.5 m of the profile, but elsewhere in the river valley peat deposits can be up to 3.5 m thick. The hill slopes and the southern bank consist of sandy deposits. Sandy deposits are also found below the peat and gyttja layers. At all of the four investigated transects, gyttja layers are present at 0.6–1.3- and 2.0–2.5-m depth. The thicknesses of the gyttja layers generally varies from 0.1 to 0.5 m, but may reach up to 1 m. In the middle of the restored section, there is an area on the northern side with a special hard pan soil type, classified as ferric soil. From 1954 to 1994, when the river was channelised the mean ground surface subsided 0.7 m, ranging from 0.2 m in alluvial deposits to 1.0 m in the peaty and low-lying parts of the valley. Mean annual discharge in the river Brede is 3.51 $m^3 s^{-1}$ measured at a downstream hydrometric station at Brede Bridge. The average bankfull channel width and depth and bankfull discharge were, respectively, in the ranges of 12.2–13.0 m, 2.4–2.7 m and 15.3–25.3 $m^3 s^{-1}$ in the pre-restored channel as compared with, respectively, in the ranges of 13.6–15.3 m, 1.7–1.9 m and 9.8–10.9 $m^3 s^{-1}$ in the post-restored channel (Kronvang et al., 1998). The restored site occupies 63 ha of floodplain being partly rewetted because of changes in discharge conditions in the new remeandered channel.

Monitoring of hydrology and water quality started 1 year before the excavation of the new remeandered channel and ran for the subsequent 2 years at an upstream and a downstream monitoring station (Fig. 1). Daily discharge at the two monitoring stations was calculated based on established relationships to a downstream hydrometric station being in operation since 1917 (Table 3). Water samples were taken as grab samples every fortnight, and composite event sampling was undertaken with an ISCO sampler installed at each station. The ISCO sampler was triggered by a rise in water level in the river. Monitoring was conducted from January to July 1994 (pre-restored period), August to November 1994 (construction period) and December 1994 to June 1996 (post-restored period). Mass balances for water, nitrate, total N, soluble reactive P, total P and total iron were established for the upstream control catchment and the catchment to the restored river reach (7.0 km^2). The riparian wetland was divided into three sub-areas for monitoring the fate of water and nutrients following blocking ditches and increasing the groundwater table (Fig. 1). The hydraulic potentials and groundwater quality were measured in piezometer nests installed along four transects placed perpendicular to the river channel and covering the three different parts of the floodplain area (Fig. 1). The differences in hydraulic head along the four piezometer transects on each side of the restored channel were employed to calculate the flow of groundwater through the floodplain i.e. from the edge of the river valley to the river. Water samples from the piezometers were analysed for ammonium, nitrate, phosphate, sulphate, ferrous iron and total iron. The monitoring programme for the riparian areas was repeated in the period 1999–2000.

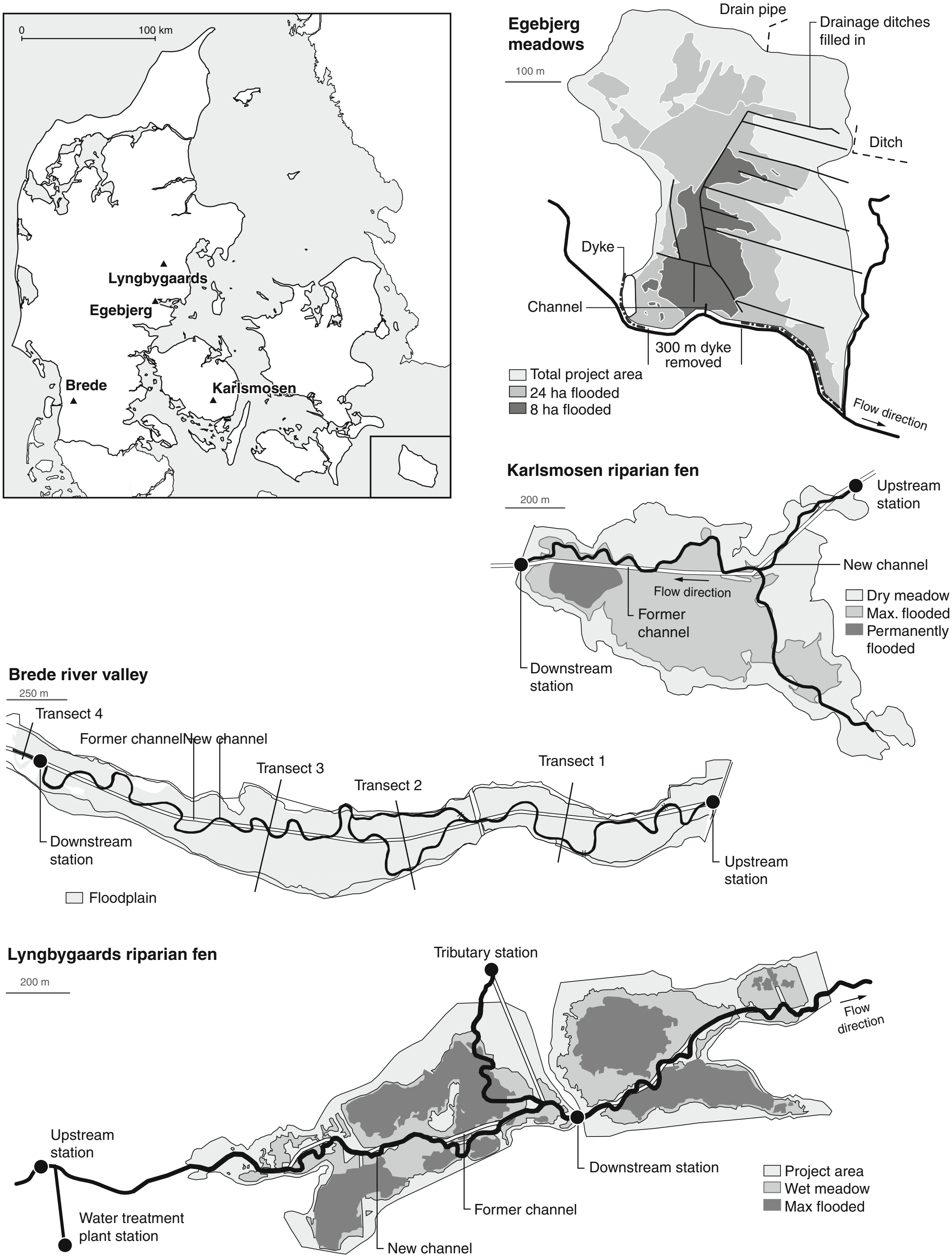

Fig. 1 Map of DK showing location of study sites together with detailed maps of the project areas. Legends show dry, wet and flooded areas except for Brede, where the whole valley is inundated during flooding events

Table 1 Area type, year of restoration, catchment size and soil type of the study sites

Site	Area type	Year	Upstream catchment area (ha)	Direct catchment area (ha)	Restored wetland area (ha)	Dominant soil type of the wetland
Brede	Riparian wetland	1994	25,700	700	63	Sand, peat and gyttja
Egebjerg	Wet meadow	1999	13,000	161	34	Peat
Karlsmosen	Riparian Fen	2002	2,001	195	65	Loamy sand
Lyngbygaards	Riparian Fen	2007	4,350	1,350	180[a]	Peat and sandy peat

Upstream catchment is the area drained by the river and located upstream the restored wetland. Direct catchment is the area drained by the restored wetland. Restored wetland area is the size of the restored area and is included in the direct catchment area

[a] 40 ha were monitored

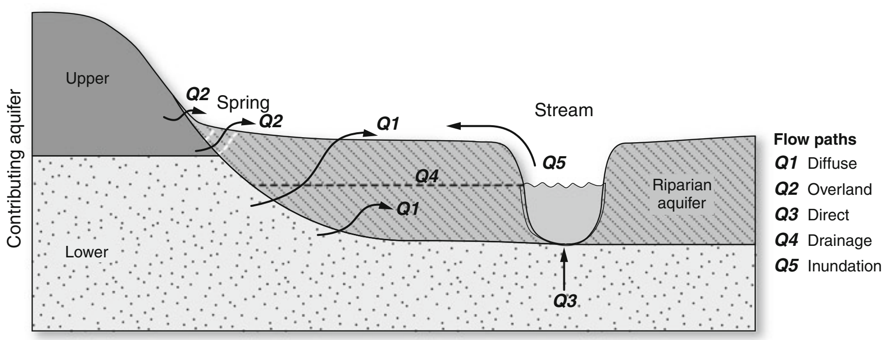

Fig. 2 Riparian buffer or floodplain with the five major hydrological flow paths: diffuse groundwater flow passing the riparian sediment (Q1), overland flow of surface runoff or groundwater entering as springs (Q2), ground water discharge directly into the stream through the stream bed (Q3), rapid flux of drainage water by subsurface tile drainage pipes or surface ditches (Q4) and inundation of floodplains by river water (Q5). Modified after Dahl et al. (2007) and Hoffmann et al. (2009)

Table 2 Type of restoration project, flow pathways affected by the restoration and information on nutrient monitoring of the study sites

Site	Type of restoration	Flow pathways affected by the restoration project	Monitoring period	Sampling frequency	Variables measured
Brede	Remeandering of the stream channel, removal of the weirs	Q2 and Q5 restored, Q4 suppressed	1 year	Fortnightly	TN, NO_3^-, TFe, SRP, PP, SO_4^{2-}, Fe^{2+}
Egebjerg	Disconnection of the drains, closing of the groundwater pumping	Q2 and Q5 restored, Q4 suppressed	8 months	From monthly up to daily	NH_4^+, Org-N, NO_3^-, TN, SRP, TP
Karlsmosen	Disconnection of the drains, remeandering of the streamchannel	Q2 and Q5 restored	2 years	Monthly	NO_3^-, TN, TP
Lyngbygaards	Disconnection of the drains, remeandering of stream channel, closing of groundwater pumping	Q1, Q2 and Q5 restored, Q4 suppressed	1 year	Fortnightly	NO_3^-, TP

Q1 diffuse flow, *Q2* overland flow, *Q3* direct flow, *Q4* drainage flow, *Q5* inundation, *TN* total N, NO_3^- nitrate, NH_4^+ ammonium, *Org-N* organic N, *SRP* soluble reactive P, *PP* particulate P, *TP* total P, Fe^{2+}, ferrous iron, *TFe* total iron, SO_4^{2-} Sulphate

Table 3 Significance of the *Q*/*Q* relationships between instantaneous discharge measurements at the stations and continuous discharge measurement at hydrometric stations

Site	Number of measurements	R^2
Brede River valley		
Upstream st.	53	0.991***
Downstream st.	47	0.974***
Karlsmosen fen		
Upstream st.	12	0.941***
Tributary st.	12	0.777*
Downstream st.	12	0.773*
Lyngbygaards fen		
Upstream st.	4	0.927*
Tributary st.	4	0.976*
Downstream st.	4	0.978*

* Significant at the 0.05 probability level

*** Significant at the 0.001 probability level

Egebjerg Meadows

Egebjerg Meadows was restored in October 1999 as the first project in the wetland restoration programme launched under The Second Action Plan on The Aquatic Environment. Egebjerg Meadows is situated along a stretch of the river Store Hansted in Jutland 6 km north-east of the city of Horsens. Before the restoration, the area was ditched and the river was embanked along the Egebjerg Meadows and, therefore, water was pumped out into the river. Land use in the area was 20 ha in crop rotation and 15 ha with grazing and haymaking. As part of the restoration, the ditches were disconnected and the pumping station was shut down (Fig. 1). Part of the embankment along the meadows, i.e. 300 m, was removed, thereby allowing the river to frequently inundate Egebjerg Meadows. The area flooded by the river varies in size from 4 ha at very low water level (i.e. 0.25 m.a.s.l.) to 8 ha at normal water level (i.e. 0.5 m.a.s.l.), and to 24 ha at high water level in the river (i.e. 1.0 m.a.s.l.). The restored site is very close to the mouth of the river, which discharges to Horsens Fiord. The catchment area to Egebjerg Meadows is 161 ha, and the area is recharged by water coming from a drain pipe and a drainage ditch. It is not known if the area is recharged by groundwater.

Inflow of water from the drain pipe was measured continuously with an electromagnetic flow meter (MAGFLO®, Danfoss, Denmark), while inflow from the drainage ditch was measured using propellers. Inflow and outflow of water to and from the river were also measured using propellers, while the direction of the water flow as well as the water level was logged continuously with a data logger (StarFlow Ultrasonic Doppler Instrument, Unidata, Western Australia). The general water level in the area was measured with two automatic water level gauges (Thalimedes, Ott, Germany), placed, respectively, close to the upland boundary and in the permanently inundated area close to the river. The measured water levels in the wetland and the flow direction logged with the data logger in the small channel at the river bank were employed to calculate the amount of water entering or leaving the wetland. These calculations were further supported by discharge measurements on days where the river was recharging the wetland. At the drain pipe and at the inflow/outflow site of the river, two ISCO samplers were set up for automatic sampling of water. Water was analysed for ammonium, nitrate, total N, soluble reactive P and total P. In the initial phase of the monitoring period, i.e. during February, March and April 2001, sampling took place daily and, subsequently, sampling took place weekly or biweekly. The monitoring period ended abruptly after 8 months as the field equipment was subjected to vandalism.

Karlsmosen Riparian Fen

Karlsmosen on Funen was restored in 2001, and the new wetland area is 65 ha. The project included cutting of 18 tile drains draining agricultural areas at the edge of the floodplain to allow water to infiltrate into the floodplain. In the project area, the channelised watercourse was remeandered, and at some central places along the channel, the stream bed level was increased to lead the water from the stream to the newly restored fen to obtain permanent surface water during the entire year (Fig. 1). The new channel dimensions were constructed to allow the stream water to flood the restored fen area at a mean winter discharge (266 l s^{-1}) or 45% of the time during the period from October to March.

Two monitoring stations were established, one upstream of the restored wetland and one downstream, to establish a water and nutrient balance for the entire restored wetland. The catchment area to the upstream monitoring station is 2001 ha, and the catchment area between the upstream and downstream monitoring stations is 195 ha including the 65 ha restored wetland. Instantaneous discharge was measured synchronously at the two stations. Water and discharge were measured at the upstream, downstream and tributary monitoring stations at 12 campaigns during the period October 2002–January 2004. Water sampling was conducted as grab sampling. Daily discharge at the three monitoring stations was calculated based on established relationships to a downstream hydrometric station being in operation since 1917 (Table 3). Water samples were analysed for total N and total P. The daily transport amounts of nitrogen and phosphorus into and out of the restored wetland area were calculated from the product of daily discharge and linear interpolated daily concentrations. A monthly mass balance was established from the calculated transports of total N and total P during the period October 2002–January 2004.

Lyngbygaards River and riparian fen-meadow

The River Lyngbygaards, situated in Jutland, is a fourth-order stream (*sensu* Strahler) which drains 131 km^2 of mainly agricultural lowlands and flows into the Aarslev Lake. In 2003, a restoration project was launched aiming at re-establishing a 'more natural' water balance, mitigating the nutrient load and improving the area's physical state and biodiversity. To fulfil these objectives, a 7.3-km channelised segment of the river was remeandered, and an area of 180 ha was transformed from arable land into riparian meadow and wetland. The restoration work started in December 2007 by disconnecting the drain pipes and by closing a pumping station in an area where drainage water was pumped out into the river. This led to an increase in the groundwater table in the riparian area. The river channel was remeandered in April 2008 and, as a result of more natural river dimensions, the riparian areas would now be exposed to inundation during periods of high flow. Within the restored area, 40 ha of riparian fen and meadow including about 2 km of stream were investigated from December 2007 to November 2008. Four sampling stations were positioned within the area to establish a water and nutrient balance for the restored wetland (Fig. 1). Two stations were placed upstream and downstream the restored area. The catchment area at the upstream station is 4,354 ha and the direct catchment area drained by the wetland is 1,350 ha. Another station was located on a tributary, being remeandered as part of the restoration project, discharging into the Lyngbygaards River. The discharge for these three stations was estimated by establishing a linear relationship with the daily discharge measured at a hydrometric station located 10.7 km downstream (Table 3). To do so, four synchronous flow measurements were realised for each of the three stations at different discharge levels to cover the whole hydroperiod. Water samples were collected weekly or fortnightly (32 sampling days) at the three stations located along the stream during the period December 2007–November 2008 and analysed for total P and nitrate. A fourth station was placed at the outlet of a water treatment plant where discharge was measured daily and water samples were generally taken on Mondays, Wednesdays and Fridays and analysed for total P and nitrate. A monthly mass balance for the riparian fen was established from the calculated transport of total P and nitrate.

Results

Brede River valley

The flow of groundwater through the restored floodplain, $Q_{wetland}$ calculated from measured hydraulic heads along the transects is shown in Table 4. $Q_{wetland}$ was found to be constant during the study period. The calculated net discharge to the river, Q_{river}, based on flow measurements at the up stream and downstream river monitoring stations, respectively, shows that besides groundwater discharge from the restored floodplain there is also a significant input of groundwater to the river from a deep lying regional aquifer, $Q_{regional}$ (Table 4). The regional aquifer is located 150 m below the river and the discharge to the river was estimated using the Darcy equation on data from Friborg & Thomsen (1995). The groundwater balance for the restored floodplain including the contribution from the regional aquifer as compared to the balance calculated from the discharge measurements from the upstream and downstream river monitoring stations show that the median deficit, dQ, is small, while the mean deficit is higher but considered less informative because the

Table 4 Monthly water balance for the restored reach of river Brede showing the net discharge, (Q_{river}) in water measured as the difference between the upstream and downstream river monitoring stations, respectively

	Median (10^5 m^3 $month^{-1}$)	Mean (10^5 m^3 $month^{-1}$)
Q_{river}	4.39	6.43
$Q_{wetland}$	1.18	1.18
$Q_{regional}$	2.64	2.64
$dQ = Q_{river} - (Q_{wetland} + Q_{regional})$	0.57 (13%)	2.61 (41%)

The discharge of ground water from the restored riparian floodplain (down to a depth of 5 m ($Q_{wetland}$) calculated using the Darcy equation and measured hydraulic heads along the transects. The discharge of groundwater from a deeper regional aquifer, $Q_{regional}$, located 150 m below the river was estimated using the Darcy equation on data from Friborg and Thomsen (1995)

monitoring period comprised five high flow months (10.5–17.9 × 10^5 m^3 per month) and 15 low flow months (i.e. below 10.5–17.9 × 10^5 m^3 per month) and only 3 months in between.

The flow of groundwater through the restored floodplain as calculated from measured hydraulic heads along the transects (Fig. 1) was 1.18 × 10^5 m^3 per month. The input (i.e. with recharging groundwater), output (i.e. discharge to the river) and retention of nitrate, ammonium, sulphate and ferrous iron within the three sub-areas of the restored floodplain are shown in Table 5 for the first year following restoration (1995) and again for the period 1999–2000. Removal of nitrate took place in two of the sub-areas during the first year following restoration (44–160 kg N ha^{-1}), while in the third sub-area there was a gain (6 kg N ha^{-1}) (Table 5). A total retention of 5,847 kg NO_3-N equalling 92 kg NO_3-N ha^{-1} was calculated for the entire restored wetland area during the first year (Table 5). The results from the two sub-areas being re-monitored in 1999–2000 also showed nitrate removal, with an average removal amounting to 141 kg N ha^{-1} $year^{-1}$ (Table 5). However, the restored wetland was again a net source of ferrous iron, sulphate and ammonium (Table 5). P was only measured a few times because all groundwater samples analysed were below the detection limit.

To allow comparison of the stream transport of nutrients and iron, the outcome of the stream monitoring regarding transport of nutrients and total iron was calculated as loss from an upstream catchment (as control) and the catchment area of the restored reach (restored) (Fig. 3). The monitoring results clearly show that autumn 1994 was disturbed by the heavy machinery digging the new meandering channel, as evidenced by the high losses of particulate P and total iron (Fig. 3).

A ratio between the restored and the control catchment (res/con) was calculated for a pre-restoration period (January–June 1994), a first post-restoration period (January–June 1995) and a second post-restoration period (January–June 1996) (Table 6). Comparison between the pre-restoration and the first post-restoration year shows a reduction in the ratio res/con for total N, nitrate and total iron, whereas an increase was found for particulate P and soluble reactive P. The second post-restoration period was very dry and had virtually no net precipitation and hence runoff during the winter and spring period (Fig. 3). A comparison of results from such a dry period with the more normal pre-restoration and first post-restoration period will give erroneous results as flow pathways and thereby nutrient fluxes between catchment and river will change in importance. Therefore, reliable retention results can only be calculated from comparison between the pre-restoration and the first post-restoration year. The percentage reduction in the res/con ratio has been employed to calculate the retention of total N, nitrate, particulate P, soluble reactive P and total iron. Thus, based on measurements at the river monitoring stations and water samples from these stations, the new restored river and restored floodplain was a sink for total N (2,640 kg N $year^{-1}$), nitrate (5,150 kg NO_3-N $year^{-1}$) and total iron (7,315 kg Fe $year^{-1}$), whereas it was a source of particulate P (154 kg P $year^{-1}$) and soluble reactive P (166 kg P $year^{-1}$). This corresponds to removal or storage rates amounting to 42.0 kg N ha^{-1} $year^{-1}$ for total N, 81.7 kg NO_3-N ha^{-1} $year^{-1}$ for nitrate and 116.1 kg TFe ha^{-1} $year^{-1}$ for total iron and net release rates of

Table 5 Input and retention of nitrate, ammonium, ferrous iron and sulphate in the upper part of the groundwater storage in the River Brede valley for the first year after restoration and five years after restoration

Transect and area (ha)	First year after restoration (1995)			%	Five years after restoration[a] (1999–2000)			%
	Input (kg $year^{-1}$)	Total retention (kg $year^{-1}$)	Retention (kg ha^{-1} $year^{-1}$)		Input (kg $year^{-1}$)	Total retention (kg $year^{-1}$)	Retention (kg ha^{-1} $year^{-1}$)	
Nitrate-N								
1 (24.9)	2,236	1,087	44	49	2,795	2,403	97	86
3 (30.0)	5,793	4,812	160	83	6,592	6,556	171	99
4 (8.4)	243	−51	−6	−21	–	–	–	
Σ (63.4)	8,272	5,847	92	71	9,387	8,959	141	95
Ammonium-N								
1 (24.9)	21	−208	−8.4	−990	40	−662	−27	−1,655
3 (30.0)	23	−138	−4.6	−600	63	−1,305	−34	−2,071
4 (8.4)	123	18	2.1	15	–	–	–	
Σ (63.4)	167	−328	−5.8	−196	103	−1,967	−31	−1,910
Ferrous iron								
1 (24.9)	97	27	1	28	14	−26	−1	−186
3 (30.0)	156	−17,386	−578	−11,145	235	−62,450	−1,620	−26,574
4 (8.4)	614	−149	−18	−24	–	–	–	
Σ (63.4)	866	−17,508	−276	−2,022	249	−62,476	−985	−25,091
Sulphate								
1 (24.9)	19,100	−14,200	−575	−74	18,200	−58,600	−2,352	−322
3 (30.0)	29,800	−32,800	−1,092	−110	37,000	−95,000	−2,473	−257
4 (8.4)	11,200	2,900	349	26	–	–	–	
Σ (63.4)	60,100	−44,100	−696	−73	55,200	−153,600	−2,423	−278

[a] Area 3 was covering an area of 38.4 ha in the 1999–2000 investigation

2.4 kg P ha^{-1} $year^{-1}$ for particulate P and 2.6 kg P ha^{-1} $year^{-1}$ for soluble reactive P.

Egebjerg Meadows

In 2001, the annual precipitation in the area was 639 mm, and the annual evaporation 554 mm, giving a net precipitation of 85 mm (Danish Meteorological Institute). The measured inflow of water to Egebjerg Meadows from the upland through the drain pipe and the drainage ditch was very stable and amounted to 325 m^3 day^{-1} or 118,569 m^3 $year^{-1}$, and this equals 87% of the precipitation surplus. Inflow and outflow of water between the river and the restored wetland were very dynamic as removal of the dike created a direct and continuous hydraulic contact between the two hydrological systems. Very rapidly, a small channel was established at the lowest point of the river bank, which made it possible to follow how inflow and outflow of water shifted with the water level in the river and in the wetland. This permitted identification of 11 flooding events of which the most prominent lasted approximately 30 days and accounted for 70% of the total river recharge of the wetland. The remaining flooding events lasted between 3 and 15 days. During the monitoring period 1.2.2001 to 8.10.2001 (250 days), the total amount of river water entering the wetland was 201,520 m^3 (806 m^3 day^{-1}), and the total amount being discharged to the river was 177,080 m^3 (708 m^3 day^{-1}) including the 325 m^3 day^{-1} of drainage water. The discrepancy between inflow and outflow is due to different water levels in the meadow at the start and at the end of the monitoring period.

The concentrations of the different N species in the inflowing water from the drain pipe and the drainage ditch were stable during the monitoring period (Table 7). Nitrate was the dominant species in both inlets with a mean concentration of 6.4 and 14.5 mg NO_3-N l^{-1} for the drainage ditch and drain pipe,

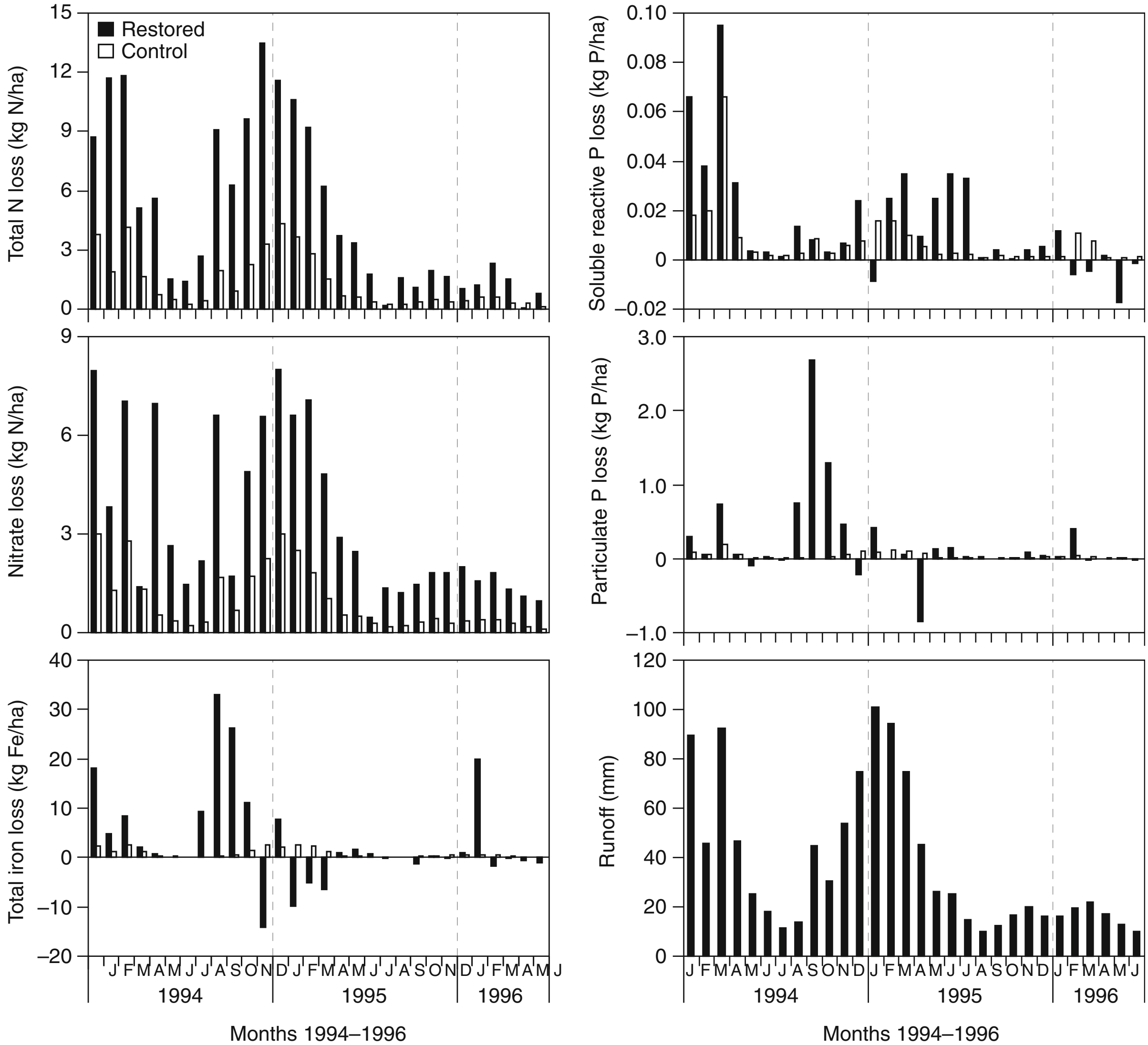

Fig. 3 Monthly loss of total nitrogen (N), nitrate, total iron, soluble reactive phosphorus (P), particulate P and runoff between the restored and the upstream control catchment in River Brede

Table 6 Ratio between the River Brede restored catchment and upstream control catchment for total nitrogen (N), particulate phosphorus (P), soluble reactive P, total iron and nitrate

Ratio (restored to control catchments)	Pre-restoration (January–June)	Post restoration 1st year (January–June)	Post restoration 2nd year (January–June)
Total N	4.2	3.9	3.1
Particulate P	0.9	3.0	0.7
Soluble reactive P	2.2	5.3	–1.5
Total iron	3.2	0.3	4.3
Nitrate N	4.9	4.0	5.8

respectively. The concentration of N in the outflow to the river Store Hansted, although generally exhibiting lower concentration than the inlets, showed some very conspicuous patterns. There were several peaks in nitrate concentrations and further inspection revealed that the peaks coincided with the start of a flooding period with river water, i.e. an increase in water level and a reversal of the flow direction at the border between the wetland and the river. Furthermore, small peaks in phosphate concentrations appeared on the same days as for nitrate (Fig. 4). Opposite to nitrate, there was a small increase in ammonium concentrations following the first days of a flooding event that resulted in a loss of ammonium from the wetland to the river. A comparison of inlet and outlet ratios between different nitrogen species showed that nitrate (84%) was the dominant ion in the inlet water, followed by organic-N (15%) and ammonium (only 1%). In the outlet to river Store Hansted, 76% was organic-N, 16% nitrate and 8% ammonium. In the river, total nitrogen concentration varied from 7.2 in February to 2.7 mg N l^{-1} in July.

The concentration of soluble reactive P in the drain pipe and in the drainage ditch was stable during the study period with means, of 0.185 and 0.057 mg P l^{-1}, respectively (Table 7). Means of total P concentration in ditch and drain water were 0.184 and 0.309, respectively, and the organic-P fraction constituted 40–69% of total P. The soluble reactive P concentration in inflowing river water was 0.039 mg P l^{-1}, but only 0.020 in water flowing out to the river (Table 7). Total P concentration in water flowing out to the river (0.27 mg P l^{-1}) was higher than in the inflow (0.21 mg P l^{-1}) and further 93% of it was

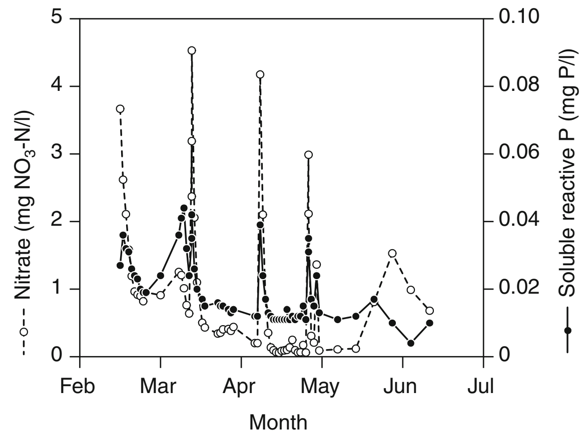

Fig. 4 Nitrate and soluble reactive phosphorus (P) concentrations in the outflow and inflow channels between the wetland and the river Store Hansted

organic P; thus, the overall pattern for the wetland revealed that phosphate in all recharging waters (i.e. drain water, ditch water and inflowing river water) was transformed to organic P.

The mass balance for N and P for Egebjerg Meadows shows a significant removal of nitrate amounting to 52 kg NO_3-N ha^{-1} $year^{-1}$, while the removal of total N is only 56 kg N ha^{-1} $year^{-1}$; 87% of the total discharge of nitrogen to the river is in the form of organic N (Table 8). Although the concentration of ammonium is higher when water is discharged to the river, there is a net retention of ammonium, 0.23 kg NH_4^+-N ha^{-1} $year^{-1}$, in the wetland due to recharge by drainage water and ditch water.

Retention of soluble reactive P in the meadow amounts to 0.45 kg P ha^{-1} $year^{-1}$, while the

Table 7 Average concentration of ammonium, organic N, total N, soluble reactive P and total P in the drainage ditch, in the drain, in the river inflow and in the river outflow at Egebjerg Meadows, for the period from 15 February to 8 October 2001

	Ammonium-N (mg l^{-1})	Nitrate-N (mg l^{-1})	Organic N (mg l^{-1})	Total N (mg l^{-1})	SRP (mg P l^{-1})	Total P (mg l^{-1})
Drainage ditch	0.09 ± 0.01 (n = 17)	6.35 ± 0.23 (n = 18)	1.21 ± 0.23 (n = 9)	8.05 ± 0.35 (n = 9)	0.057 ± 0.003 (n = 17)	0.184 ± 0.050 (n = 9)
Drain pipe	0.15 ± 0.02 (n = 48)	14.50 ± 0.33 (n = 49)	2.48 ± 0.26 (n = 16)	16.52 ± 0.85 (n = 16).	0.185 ± 0.011 (n = 48)	0.309 ± 0.021 (n = 16)
Inflow River	0.10 ± 0.02 (n = 11)	2.80 ± 0.38 (n = 11)	1.97 ± 0.22 (n = 11)	4.26 ± 0.32 (n = 11)	0.039 ± 0.029 (n = 11)	0.21 ± 0.11 (n = 11)
Outflow River	0.22 ± 0.02 (n = 68)	0.53 ± 0.07 (n = 68)	3.14 ± 0.28 (n = 21)	3.47 ± 0.26 (n = 21)	0.020 ± 0.015 (n = 68)	0.269 ± 0.167 (n = 11)

Shown with standard error and number of samples (n)

Table 8 Mass balance of ammonium, organic nitrogen (N), total N, soluble reactive phosphorus (SRP) and total P for the restored wetland Egebjerg Meadows

	Ammonium-N (kg $year^{-1}$)	Nitrate-N (kg $year^{-1}$)	Total N (kg $year^{-1}$)	SRP (kg $year^{-1}$)	Total P (kg $year^{-1}$)
Inflow drainage ditch	6.4	435.2	511.3	3.86	11.66
Inflow drain pipe	11.2	706.8	718	8.61	11.94
Inflow from river	30.2	741.3	1,442	15.88	47.26
Total inflow	47.8	1,883.3	2,671	28.35	70.86
Outflow to river	39.7	102.4	781	13.1	66.28
Total retention	8.1	1,780.9	1,890	15.3	4.58
Retention of input (%)	17	95	71	54	6
Total retention (kg ha^{-1} $year^{-1}$)	0.23	52.4	55.6	0.45	0.13

Input from the drainage ditch, the drain pipe and inflow from the river during inundation periods. Outflow from the wetland only to the river

retention of total P is only 0.13 kg ha^{-1} $year^{-1}$, revealing that a substantial amount of soluble reactive P is transformed to organic P in the wetland before being discharged to the river.

Karlsmosen Riparian Fen

Monthly input, output and net retention of total N and total P for the 65 ha restored wetland are shown in Table 9. The restored wetland removes total N during all the months monitored and total retention equalled 39.5 tonnes N during the 16 month monitoring period. For the calendar year 2003, total N retention is calculated as 21.9 tonnes N, which equals a retention rate of 337 kg N ha^{-1} $year^{-1}$. The retention efficiency of the wetland amounted to 50% for 2003 (Table 9). The restored wetland shows a net retention of total P during all months and a total retention of 776 kg P during the 16-month monitoring period. For 2003, total P retention is 529 kg P, giving a retention rate of 8 kg P ha^{-1} $year^{-1}$ or 60% of the total input.

The absolute retentions of total N and total P in the restored wetland depend heavily on the local hydrological conditions. A significant ($P < 0.05$) linear positive relationship was established between average monthly water flow into the wetland area and the retention of total N (Fig. 5). In the case of total P, a significant ($P < 0.001$) exponential relationship was established between average monthly water flow into the restored wetland and the retention of total P (Fig. 5). Upon increased input of water, the wetland area becomes more and more inundated from the river, and more and more particulate P is captured in the wetland.

Lyngbygaards River and riparian fen-meadow

Monthly input and retention of nitrate and total P for the 40 ha restored wetland are shown in Table 10. Nitrate removal by the restored wetland takes place in all the 12 months of the study. The total removal of nitrate amounted to 7,822 kg NO_3-N for the period from December 2007 to November 2008, corresponding to a nitrate removal of 195.6 kg NO_3-N ha^{-1} $year^{-1}$. An annual nitrate removal of 7.5% of NO_3-N load was calculated when comparing nitrate removal with the nitrate load in the river (Table 10).

The monthly retention of total P in the restored wetland was positive in all but two of the 12 months monitoring period. The exception being December with a release of 3 kg P and above all April with a release of total P of 192 kg P (Table 10). Thus, the yearly budget in the wetland shows a total P release of 1.58 kg P ha^{-1} $year^{-1}$. However, the large amount of total P measured in April 2008 was probably due to the digging of the meanders resulting in the entry of large quantities of soil materials in the river. Thus, when omitting the total P release in April, a total P retention in the restored wetland of 129 kg P is estimated, equalling 3.50 kg P ha^{-1} $year^{-1}$. Compared with the P load, the retention of total P ranged from −159% in April 2008 to 45% in June 2008 (Table 10). The yearly P retention was 7.7% of the total P load when omitting the loss in April, which is due to digging as mentioned above. The mass balance

Table 9 Mass balance results from monitoring of total nitrogen and total phosphorus retention in the Karlsmosen Fen during October 2002 to January 2004

Month	Total Nitrogen					Total phosphorus				
	Input (kg)	Output (kg)	Retention (kg)	Retention (kg ha^{-1})	%	Input (kg)	Output (kg)	Retention (kg)	Retention (kg ha^{-1})	%
Oct-02	1,801	878	923	14.2	51	40	22	18	0.28	45
Nov-02	1,5008	8,784	6,224	95.8	41	180	110	70	1.08	39
Dec-02	7,804	4,612	3,192	49.1	41	100	66	34	0.52	34
Jan-03	13,407	6,808	6,599	101.5	49	260	88	172	2.65	66
Feb-03	6,603	3,514	3,089	47.5	47	100	44	56	0.86	56
Mar-03	5,203	2,855	2,348	36.1	45	60	22	38	0.58	63
Apr-03	3,402	1,537	1,865	28.7	55	40	22	18	0.28	45
May-03	5,203	2,855	2,348	36.1	45	120	66	54	0.83	45
Jun-03	1,001	439	562	8.6	56	40	22	18	0.28	45
Jul-03	800	220	580	8.9	73	40	22	18	0.28	45
Aug-03	200	0	200	3.1	100	20	0	20	0.31	100
Sep-03	400	0	400	6.2	100	20	0	20	0.31	100
Oct-03	800	220	580	8.9	73	40	0	40	0.62	100
Nov-03	1,801	659	1,142	17.6	63	40	22	18	0.28	45
Dec-03	4,602	2,416	2,186	33.6	48	100	44	56	0.86	56
Jan-04	16,008	8,784	7,224	111.1	45	280	154	126	1.94	45
Total	84,043	44,581	39,465		47	1,481	703	778		53
2003	43,422	21,523	21,902	337	50	880	351	529	8.14	60

The mass balance also includes that part of the river running through the wetland. % is percentage retention of input. The two lines at the bottom show totals in kg, totals in kg for year 2003 and retention of N and P in kg ha^{-1} year^{-1}

included a model calculated nutrient input of 13 kg NO_3-N ha^{-1} year^{-1} and 0.32 kg P ha^{-1} year^{-1} from an unmonitored part of the direct catchment of the wetland (365 ha).

Discussion

Nitrogen

The N removal rates established from the post-monitoring programmes varied between the four riparian wetland restoration projects, as being 92–141 kg N ha^{-1} year^{-1} in the river Brede valley, 56 kg N ha^{-1} year^{-1} in the Egebjerg meadows, 337 kg N ha^{-1} year^{-1} in the Karlsmosen fen and 195 kg N ha^{-1} year^{-1} in the Lyngbygaard riparian fen. Natural and restored riparian wetlands are well known for their high efficiency in N removal, which is a process that can continue for decades (Zak & Grigal, 1991; Hoffmann et al., 2000; Mitsch et al., 2005). A study by Jordan et al. (2003) showed that a restored wetland receiving agricultural runoff only removed N (38%) and P (59%) in one of the 2 years monitored, with the other year showing no net retention. The nitrate removal efficiency (measured at Brede, Egebjerg Meadows and Lyngbygaard) varied between 8 and 95% in the restored wetlands while total N (measured at Egebjerg Meadows and Karlsmosen) varied between 50 and 71%. There was no correlation between N load and percentage removal of nitrate, and this finding has also been evidenced from other studies (Fennessy & Cronk, 1997; Hoffmann, 1998).

Three of the wetland restoration projects included in this article are planned and restored following the national guidelines from 1998. Therefore, the N removal potential was assessed and approved before initiating the restoration project. The fourth project, River Brede, was conducted before 1998, and no national demands for N removal existed to be included in wetland restoration projects. We can,

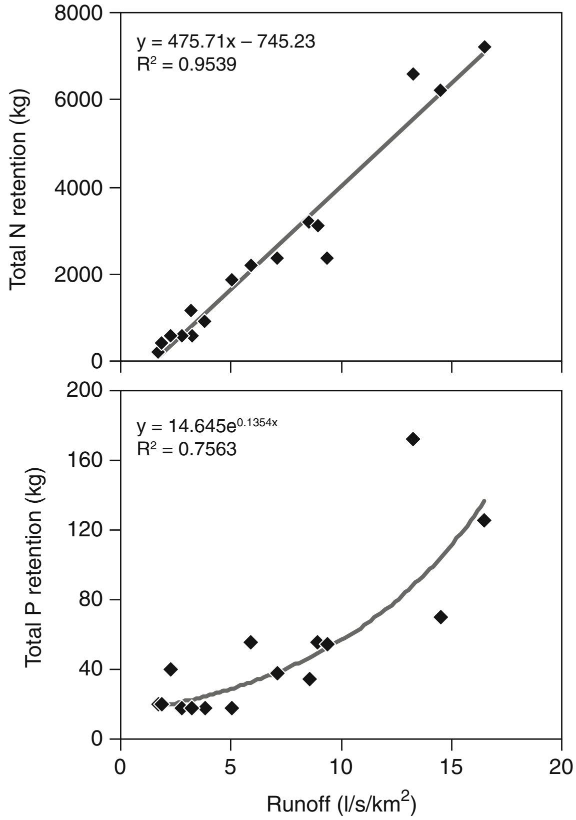

Fig. 5 Relationships between total nitrogen (N) retention and runoff; and total phosphorus (P) retention and runoff at Karlsmosen Fen

however, assess the expected N removal rates in the River Brede using the modelled number of flooding days in the hydrodynamic model MIKE11 (Kronvang et al., 1998). The expected N removal in the River Brede caused by inundations is calculated to be 980 kg N, and the N removal in groundwater was calculated to be 6,630 kg N. The results from the two monitoring strategies deployed at the restored wetland site as the groundwater mass balance measured N removal in the upper 5 m of the rewetted riparian area amounted to 92 kg N ha^{-1} year^{-1} during the first post-restoration year and 141 kg N ha^{-1} year^{-1} in the period 1999–2000, 5 years after the restoration (Table 5). The N removal was also independently measured utilising a mass balance approach by which a ratio was established between the N loss from an upstream control catchment relative to the N loss from the direct catchment to the restored river reach for a pre-restoration and two similar post-restoration

Table 10 Input and retention of nitrate-N (N) and total phosphorus (P) in the 40-ha restored riparian fen Lyngbygaards

Month	N input (kg)	N retention		P input (kg)	P retention	
		(kg)	(%)		(kg)	(%)
Dec-07	18,765	1,450	7.7	257	−3	−1.3
Jan-08	26,784	1,409	5.3	369	5	1.3
Feb-08	13,244	955	7.2	220	18	8.0
Mar-08	17,093	1,054	6.2	262	9	3.5
Apr-08	6,300	518	8.2	121	−192	−159.1
May-08	1,836	339	18.5	53	17	31.6
Jun-08	1,295	463	35.8	38	17	45.3
Jul-08	675	298	44.1	33	14	43.4
Aug-08	1,269	380	29.9	67	12	17.3
Sep-08	1,090	289	26.5	41	10	24.8
Oct-08	1,539	76	4.9	56	3	4.5
Nov-08	10,187	591	5.8	167	28	16.6
Total	100,076	7,822	7.8	1,685	−63.4	−3.8

periods (Table 6). A calculation of the N retention utilising the observed changes in the ratio showed total N retention amounting to 42 kg N ha^{-1} year^{-1} and nitrate-N removal amounting to 82 kg N ha^{-1} year^{-1} during the first post-restoration year. The second post-restoration year was the driest period observed since the mid-1970s, and hence owing to these exceptional conditions, we assume that it is impossible to measure retention processes utilising the mass balance approach due to dominance of deep groundwater inflow to the restored reach.

Our findings from the two independent estimates of N removal from the first post-restoration year utilising a groundwater mass balance and the mass balance measured upstream and downstream for the entire restored channel reach showed to be of the same magnitude. Compared to an estimated potential N removal utilising present Danish guidelines of 113 kg N ha^{-1} year^{-1}, the results of the two monitoring methods were at the same level as estimated. The River Brede valley restoration project has a relatively large direct catchment to wetland ratio of 11.1, presumably benefitting N removal due to higher incoming concentrations and loadings of inorganic N. One reason for the low N removal rate could be that most of the nitrate-N leached within the direct catchment is transported to deeper groundwater and does not appear in upper groundwater storage in the riparian areas along the river corridor. Another factor being of great importance for the post-restoration monitoring of the River Brede valley was the high regional groundwater discharge to the restored section of the river channel in the area giving rise to a high dilution of N when establishing the mass balances based on the upstream and downstream monitoring approach. Adopting two monitoring strategies at sites like the River Brede valley experiencing a high groundwater discharge into the wetland has proved to be of great value when assessing the N retention capacity of the restored area.

The Karlsmosen riparian fen has a direct catchment to wetland ratio of 3.0. The removal of N in the restored fen area was monitored during a post-restoration period of 16 months utilising the upstream/downstream mass balance approach for the entire area. Without monitoring the nutrient input from the direct catchment such a monitoring approach will only reveal a minimum estimate for the retention capacity of the restored wetland. The mass balance results show that the restored fen area has a very high N removal rate of 337 kg N ha^{-1} $year^{-1}$, which is higher than the expected N removal calculated by Funen county during the project planning, 235 kg N ha^{-1} $year^{-1}$, which were based on guidelines from Danish Nature and Forest Agency (Hoffmann & Battrup-Pedersen, 2007). One reason for the high N removal capacity of the restored wetland is that water from the river channel is directed into the restored fen area during most part of the year, so that there is almost a continuous supply of nitrogen. The dimensions of the restored river channel along the riparian fen were reduced by 75% to facilitate water to enter the fen area from the channel.

The restored Egebjerg Meadows wetland had a low direct catchment to wetland ratio of 4.8. The N removal rate in the restored wetland amounted to 56 kg N ha^{-1} $year^{-1}$ and was the lowest of the four restoration projects. The expected N removal capacity of the wetland was calculated to be approximately 200 kg N ha^{-1} $year^{-1}$, which was based on a rough estimate by technicians from Vejle County (personal communication Niels Mølgård), and this estimate did not obey the criteria set for projects within the wetland restoration programme (Hoffmann & Baattrup-Pedersen, 2007). The difference between expected and realised N removal can be explained by the restoration measures applied. The existing dike along the river channel was only partly removed, and so nitrate quickly became exhausted in the wetland after the inundation occurring through the narrow gate formed in the dike. Complete removal of the dike along the river channel would have given free access for exchange of water and N between the river and wetland area resulting in a higher N removal in the restored wetland. In situ measurements of the denitrification capacity in the topsoil utilising the ^{15}N technique yielded a denitrification rate amounting to 72 kg N ha^{-1} $year^{-1}$ which is supporting these findings (Jacobsen, 2002).

The calculated N removal rate for the restored Lyngbygaards fen area amounted to 196 kg N ha^{-1} $year^{-1}$, which is very close to the expected N removal rate of 231 kg ha^{-1} $year^{-1}$ calculated when planning the project (Hoffmann et al., 2006a).

Phosphorus

The P retention rates established from the post-monitoring programmes varied between the four wetland restoration projects. During the first post-restoration year, the restored riparian wetland became a net source of particulate P (2.4 kg P ha^{-1} $year^{-1}$) and soluble reactive P (2.6 kg P ha^{-1} $year^{-1}$) in the River Brede valley project area and also a net source of total P in the Lyngbygaards valley project (1.58 kg P ha^{-1} $year^{-1}$). In contrast, the restored fen area at Karlsmosen was a net sink for total P (10 kg P ha^{-1} $year^{-1}$) and in the Egebjerg fen area also a net sink for both total P (0.13 kg P ha^{-1} $year^{-1}$) and soluble reactive P (0.45 kg P ha^{-1} $year^{-1}$). Natural and restored riparian wetlands are well known for their high efficiency in P retention, mostly due to their biological uptake of soluble reactive P and sedimentation of particulate P in the wetland area (Peterjohn & Correl, 1984; Hoffmann et al., 2009). Several wetland restoration projects have demonstrated that restored riparian wetlands have a great potential for P retention (Kronvang et al., 2009). However, a risk of transforming a restored riparian wetland to a potential P source due to desorption of dissolved phosphate from the pool of soil P has been found in some studies (Shenker et al., 2005; Zak & Gelbrecht, 2007; Hoffmann et al., 2009). We found that many of the restored riparian wetlands underwent a net erosive phase during the first post-restoration year (River Brede and River

Lyngbygaards). The erosion is due to bank- and bed-erosion processes in the newly excavated and unprotected river channel and is clearly visible when monitoring particulate P mass balances as in the case of the River Brede valley project (Fig. 3) (Kronvang et al., 1998). In general, an important process involved when restoring riparian wetlands is the sedimentation of particulate P during periods of inundation (Kronvang et al., 2009). Particulate P is deposited on the floodplain when flow velocity of river water is decreasing on the floodplains (Kronvang et al., 2007). In the Karlsmosen Fen project, the importance of sedimentation of particulate P during high flow periods is also evidenced by the established relationship between the average monthly runoff and the net retention of total P (Fig. 5). The retention of total P increases exponentially with increasing flow giving rise to large amounts of river water entering the inundated fen area (Fig. 5). Another finding is the transformation of soluble reactive P into organic forms during passage of the inundated wetland area. This is documented from the Egebjerg fen site where the net total soluble reactive P retention amounted to 0.45 kg P ha^{-1} $year^{-1}$, whereas the net retention for total P only amounted to 0.13 kg P ha^{-1} $year^{-1}$ (Table 8). The difference can only be explained by an uptake of soluble reactive P into the algal biomass when passing the inundated slow flowing wetland and a resulting net export of organic bound P from the wetland.

Monitoring strategies for wetland restoration projects

The monitoring strategy chosen was not optimal at all the restored wetland sites. The water balance for the river Brede valley project showed that high discharges of groundwater was coming into the restored wetland area and that part of this is very old groundwater presumably without nitrate-N and hence diluting the incoming nitrate from the upstream catchment and the direct catchment to the restored wetland. Hefting et al. (2006) found that dilution can play an important role when studying nitrate removal in upper groundwater aquifers. The in situ measurements and modelling of the upper groundwater storage in the river valley showed denitrification to occur during passage of the newly restored riparian wetland. Such a monitoring strategy is valuable because it gives knowledge on the local biogeochemical processes but is also very costly and cannot be conducted at every restored site. The ratio method introduced in the river Brede valley project where we rely on changes between an upstream control catchment and the restored catchment seems to be a valuable method for use in areas where a mass-balance approach is difficult due to very complex hydrology in the study area. This method needs pre-restoration monitoring to be conducted for as long a period as possible, and care should be taken not to include the period where disturbances from excavation or post-restoration erosion is still influencing the nutrient dynamics. Another important learning from the second post-restoration monitoring year in the River Brede site is the risk for having extreme weather conditions (dry or wet years) that may severely influence nutrient transport into the wetland and hence nutrient retention (Kieckbusch & Schrautzer, 2007).

The mass-balance approaches applied at Lyngbygaards river valley and Karlsmosen fen were based on monthly to fortnightly monitoring sampling programmes and, especially, for particulate P the final outcome will include a high uncertainty (Kronvang & Bruhn, 1996). The mass-balance results from Karlsmosen fen are only giving a minimum estimate on the nutrient retention capacity of the restored wetland as no measurements were conducted on the input of nutrients from the direct tile-drained catchment. The sedimentation of particulate P in the Karlsmosen fen—and in the other project areas as well—should preferably have been measured in situ using a kind of sediment trap (Kronvang et al., 2009). In the case of Lyngbygaards river valley project, we have tried to measure and estimate all inputs into the wetland area. The mass-balance results are therefore showing the ‘true’ nutrient retention capacity of the restored wetland. The latter monitoring strategy is recommendable to be used in post-restoration monitoring as all sources to N and P in the restored wetland area is either measured or modelled. Such a post-restoration monitoring mass-balance approach should preferably utilise a more frequent sampling programme for covering especially particulate P beccause of the highly dynamic nature of particulate P as found in post-restoration monitoring of both river Brede valley and Lyngbygaards river valley projects.

The mass-balance approach in the Egebjerg fen project utilised automatic sampling equipment taking daily water samples of inflowing and outflowing waters from the restored wetland. Such a monitoring strategy gives valuable insight into the biogeochemical processes in the restored wetland area, which might not have been observed from a fortnightly or monthly sampling programme.

Independent of the sampling frequency, post-restoration monitoring of wetland projects should go on for more than 1 year as especially the dynamics of P in the restored area (P erosion/sedimentation; P sorption/desorption processes and biological P uptake) will change during time (Jordan et al., 2003; Hoffmann et al., 2009). Thus, Kieckbusch & Schrautzer (2007) showed that the annual nutrient retention could range from 32 to 96% for nitrate-N, −62 to 53% for total N, −257 to 11% for soluble reactive P and −787 to −121% during a 5 year study of a re-wetted shallow-flooded peatland in Northern Germany (Westpolder).

Conclusions

The effect of nutrient retention or nutrient removal by restoration of four Danish freshwater riparian wetlands has been analysed based on different monitoring schemes and designs utilising both mass-balances, ratio estimates and in situ measurements of denitrification with the ^{15}N method and groundwater monitoring. We have documented that all four restored wetlands were able to remove nitrogen but with clear differences in their efficiency from site to site as the N removal ranged from 50 to nearly 340 kg N ha^{-1} $year^{-1}$. Their capacities for buffering P were more inconsistent as we documented a net P release of both particulate P (2.4 kg P ha^{-1} $year^{-1}$) and soluble reactive P (2.6 kg P ha^{-1} $year^{-1}$) in the first year after restoring the river Brede valley and also a net total P release amounting to 1.58 kg P ha^{-1} $year^{-1}$ in the river Lyngbygaards valley. The other two restored riparian wetlands showed to be a net sink for total P amounting to 10 kg P ha^{-1} $year^{-1}$ in Karlsmosen fen and 0.13 kg P ha^{-1} $year^{-1}$ in the Egebjerg fen. A transformation of soluble reactive P to organic P and a net export of organic P from the wetland seemed to occur at the Egebjerg fen. The very wide range obtained for N and P retentions in the four riparian wetlands studied shows that pre- and post-restoration monitoring of wetland restoration projects are needed should reliable retention rates be obtained. Moreover, the need for longer-term post-restoration monitoring is suggested as P erosion and release processes can be a new P source for a shorter or longer period and may therefore mask the longer-term outcome of wetland restoration for P retention.

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