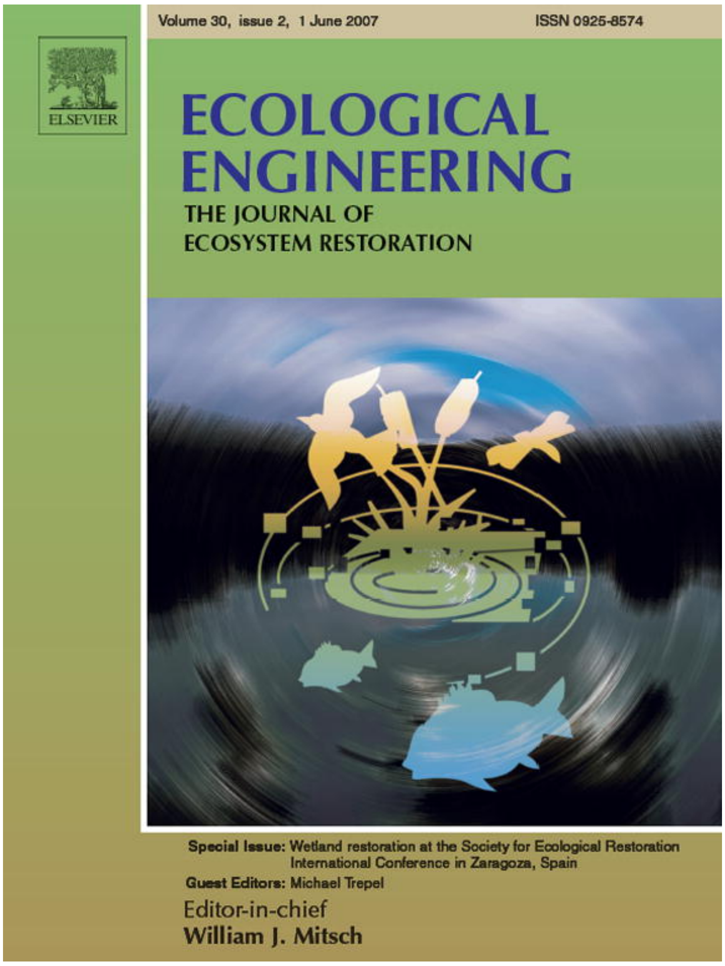
Volume 30, issue 2, 1 June 2007
ISSN 0925-8574
ELSEVIER
ECOLOGICAL ENGINEERING
THE JOURNAL OF ECOSYSTEM RESTORATION
Special Issue: Wetland restoration at the Society for Ecological Restoration International Conference in Zaragoza, Spain
Guest Editors: Michael Trepel
Editor-in-chief
William J. Mitsch

ECOLOGICAL ENGINEERING 30 (2007) 157–166

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ecoleng

Re-establishing freshwater wetlands in Denmark☆

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ARTICLE INFO

Article history:
Received 30 November 2005
Received in revised form 26 September 2006
Accepted 29 September 2006

Keywords:
Restoration
Wetland
Nitrogen removal
Monitoring programme

ABSTRACT

A national programme for the restoration of freshwater wetlands in Denmark was initiated in 1998. The purpose was to reduce nitrogen load to down-stream recipients and to enhance nature values in restored areas. In August 2005, 3060 ha of land was restored and 3769 ha of land approved for restoration. A monitoring programme for surveying the effects of the restoration of the wetlands has been set up. The programme includes basic data on land use and surveys of environmental effects and natural values.

Basic data on land use in restored wetlands has shown that areas were dominated by agriculture (42%) and meadow-land (39%) prior to the re-establishment. Areas possessing plant communities with a high conservation value had a very restricted extension prior to project implementations and only accounted for 1.2% of the total area.

Wetlands approved for restoration and wetlands already restored have been grouped in different types according to their hydrological regime. Shallow lakes cover 2985 ha, while a variety of different wetland projects ranging from areas irrigated with drainage water to restored river valleys including remeandered rivers cover 3844 ha. The mean nitrogen removal for all projects was estimated to 259 kg N ha^{-1} year^{-1}, while results from the monitoring programme have shown that wetlands remove between 39 and 372 kg N ha^{-1} year^{-1}.

1. Introduction

The area of wetlands, water holes, and lakes in Europe has declined markedly within the last decades, and in many European countries the wetland loss exceeds 50% of the original area (Jones and Hughes, 1993). Today the wetland area in Denmark constitutes 569 km^2 freshwater wetlands and 257 km^2 salt marches (Stjernholm and Kjeldgaard, 2005). In comparison, old maps show that the area of low-lying soils constituted 7460 km^2 around year 1900 (personal communication Svend Elsnab Olesen, Danish Institute of Agricultural Sciences). For lakes bigger than 1 ha, the total area at present is 586 km^2 (Nielsen et al., 2000; i.e. based on area information data from 1995). There is no precise information regarding the lake area in the past, but the area being drained by pumping stations (i.e. brackish waters, fjords, lakes, etc.) has been assessed at 1400 km^2 (Madsen and Holst, 1986), although the figure is expected to be higher because private drainage associations was not included in the assessment.

The marked decline in the wetland area in Denmark is due to agricultural drainage, preponderantly implemented with a view to increase the area of arable land, but also to urban development, afforestation, and water reclamation. It has been estimated that roughly 50% of the agricultural area not situated on low-lying soils is drained (Hansen et al., 2004; Arealdatakontoret, 1985). To assure effective runoff from the drained agricultural areas, the Danish streams and rivers have been heavily modified in the past. Based on topographical maps, 1:10000 (KMS, Kort10-Hydrografi, 2002–2005), the total length of Danish streams is 66,857 km. About 35,000 km of the

☆ Contribution to special issue wetland restoration/SER.

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doi:10.1016/j.ecoleng.2006.09.022

Danish streams are considered natural in origin, but only 15% have retained their natural channel and 98% have been physically changed to the extent that they have lost their natural physical properties (Brookes, 1987, 1988).

Concomitant with more intensive agriculture, fertilisation rates have increased and agriculture has become a major source of nutrients to European aquatic ecosystems (Kronvang et al., 2001). In many countries, agriculture is the single biggest non-point-source polluter today and elevated levels of sediments, nutrients and pesticides are entering streams, lakes, groundwaters and coastal waters. Enhanced levels of nutrients in aquatic ecosystems have led to increased primary production, and the consequences derived from this eutrophication are algal blooms, increased water turbidity, oxygen depletion, and fish kills (Kronvang et al., 2001). Several initiatives have been taken to reduce nutrient losses from point and non-point-sources, and within the European Union the member states have adopted the EU Water Framework Directive, which demands that a good ecological quality should be reached in water bodies by the end of 2015 (European Commission, 2000). But also on the national scale, action plans have been adopted to reduce nutrient input to aquatic ecosystems, e.g. restoration of drained and reclaimed wetlands.

Generally wetland soils offer favourable conditions for denitrification due to high carbon and low oxygen levels. One of the measures taken in Denmark to reduce nitrogen load to aquatic systems is to re-establish wetlands by bringing streams back to their old meandering courses, restore waterholes and lakes as well as the wetlands connected to them (i.e. river valleys and riparian wetlands such as wet meadows and fens). The Danish Action Plan on the Aquatic Environment II (DAPAE-II) from 1998 has set a national target of increasing the wetland area with 16,000 ha and the long-term objective is to restore 60,000–100,000 ha wetlands within the next two decades. The target of the DAPAE-II was to reduce the annual nitrogen load to the sea with 5600 tonnes. This figure equals a nitrogen removal rate of 350 kg N ha^{-1} $year^{-1}$. The wetland restoration programme was meant to take place during the years 1998–2003, but the programme has been prolonged so that funding of projects continues until the end of 2006, and construction works may continue for several years after 2006. Total costs are set at DKK 500 million (€ 67 million) with DKK 400 million (€ 53 million) allocated to compensation and construction works, and DKK 100 million (€ 13 million) to preliminary investigations, administration, and monitoring. A description of the legislation and the criteria, which forms the basis for the wetland restoration programme under DAPAE-II, is depicted in Box 1.

A monitoring programme was drawn up to follow the re-establishment of wetlands under DAPAE-II. Three main objectives were distinguished in this monitoring programme: First to describe and quantify the land-use in the areas prior to re-establishment, second to monitor and calculate the nitrogen removal, and third to describe alterations in biological communities in response to the re-establishment (Hoffmann et al., 2000a). In this paper, we compare nitrogen removal estimated prior to wetland re-establishment to nitrogen removal monitored in surveyed wetlands. We also give a short status of the project progress and information about former land-use in the re-established wetlands from a sample inquiry.

Box 1: Legislation as basis for the Danish Aquatic Environment Plan II from 1998.
To implement re-establishment of 16,000 ha of freshwater wetlands, a governmental circular, several governmental notices and guidelines were prepared. In the circular (no. 132, 15 July 1998) the regional authorities (i.e. Danish counties) were asked to point out areas, i.e. peat soils, low-lying soils, with the potential of being restored as wetlands. These areas should also be included in the regional planning as an addendum. The accompanying guidelines (no. 133, 15 July 1998) to the circular defined the background for the circular; the criteria for pointing out areas, and the methods to be used for identifying areas suitable for wetland restoration. The criteria used for pointing out areas were that: (1) project areas should be situated in catchments discharging to vulnerable lakes, fiords, and coastal waters, where an improvement in the environmental condition can be expected as a consequence of a reduction in the nitrogen load; (2) project areas should be situated in catchments or subcatchments where streams and rivers receive high nitrogen loads (i.e. agricultural catchment areas) or in areas where groundwater is influenced by agricultural activity; (3) project areas should enable natural hydrological and topographical conditions to maintain a fluctuating water table around the soil surface; (4) natural values should be enhanced; (5) project areas should retain phosphorous, i.e. on an annual basis there must be no net liberation or discharge of phosphorous to down-stream recipients. Additionally, according to a governmental notice (no. 966, 16 December 1998) the following criteria should also be met: (1) project areas should remove 200–500 kg N ha^{-1} $year^{-1}$; (2) re-establishment of natural hydrologic processes should be predominant in the areas (e.g. technical equipment like drains, pumps, etc., should not manipulate the water table); (3) the natural flora and fauna should benefit from the re-establishment; and (4) the net discharge or leaching of phosphorous or ochre (ferric iron) should not increase in the areas. Furthermore, the maximum compensation to landowners for ceding land for wetland re-establishment together with initial expenses was stipulated at DKK 25,000 (€ 3333) per hectare. Although re-establishment of wetlands in practice was meant to take place on a voluntary basis, the Danish counties obtained the authority to expropriate land for wetland restoration (governmental notice no. 967, 16 December 1998).

2. Methods

A paradigm has been set up which describes the objectives for surveillance of the restored wetlands (DMU, 2001). The parameters included in the monitoring programme are: topography and land use, soil characteristics, hydrology and nutrients, vegetation, and birds. It is compulsory to use questionnaire and it is compulsory to use standardized formats for reporting of data. Data on land use were gathered by use of the

Danish Area Information System (Nielsen et al., 2000) and information about cultivation and farming practice was gathered from questionnaire. To ensure data quality, guidelines for monitoring and surveying the re-established wetlands have been published in a technical instruction (Hoffmann et al., 2000a). Methods for analysis of nutrients follow Danish Standards Association and all analyses have to be performed by authorized laboratories.

Stream discharge measurements and inflow and outflow from wetlands are performed with propellers or eventually continuously by use of automatic equipment such as e.g. doppler flow meters, electromagnetic flow meters, or staff gauges coupled to data loggers (and subsequently computing stage–discharge relationships or discharge–discharge relationship to other continuous recording stream gauge stations).

Hydrological and nutrient parameters are measured or sampled once a month for 1 year as standard.

To be able to establish the influence of the re-establishment of the wetlands on the vegetation, a more detailed monitoring programme was initiated in some of the areas (see also Box 2). The monitoring was stratified to cover all existing plant communities. As the response of the vegetation to re-establishment takes place gradually over a period of years the post-monitoring will not be performed until 2009.

Originally the criteria for selecting wetlands to be included in the monitoring programme were to cover different types of wetlands (i.e. shallow lakes, irrigated and inundated fens and meadows, river valleys with groundwater flow, etc.) and further to cover the whole country as there are both geological and meteorological differences across the country. However, it has turned out that irrigated wetlands are much more frequent in the monitoring programme than inundated wetlands because it is more time-consuming, more expensive, and methodological more difficult to monitor water flow and nutrient retention in inundated wetlands.

Box 2: Nature elements in the monitoring programme.
To establish the influence of the re-establishment on the vegetation in the areas, a pre-monitoring of the existing vegetation was performed just prior to re-establishment. Three sample plots being 49 m^2 were positioned within the main vegetation types i.e. grassland, heath, different wetland types (covering gradients in moisture and nutrient availability) and different forest types (different deciduous and coniferous forest types). As the response of the vegetation to re-establishment takes place gradually over a period of years the post-monitoring will not be performed until 2009.
Bird densities and community structure were also monitored in most areas. Bird registrations were performed three times prior to and post the re-establishment of the areas. Two of the visits were performed in the morning and one visit was performed in the evening. The presence and density of breeding birds were evaluated from these visits and categorised as being either possible or sure.

2.1. *Estimation of nitrogen removal*

The first step in a wetland restoration project begins with the local authority (i.e. the county) which applies for money at the Danish Nature and Forest Agency to a feasibility study. This pilot study also includes a detailed site investigation with a topographical levelling and an assessment of environmental factors as well as consequences for wildlife (se also Box 1). If the feasibility study makes probable that environmental conditions will improve and flora and fauna will benefit from the re-establishment of the wetland the project is funded provided that the established criteria are met.

One of the criteria that needs to be fulfilled before project approval is that the estimated nitrogen removal range between 200 and 500 kg N ha^{-1} $year^{-1}$ (Box 1). This estimation is performed by the regional authorities according to published guidelines (Danish Nature and Forest Agency, 2003; Hoffmann et al., 2000a, 2003). These guidelines are available in a short version at http://www.skovognatur.dk/Service/Tilskud/Vaadomraader/Vaadomraader.htm and summarised below.

Estimation of nitrogen removal in shallow lakes is performed according to (Jensen et al., 1997) using a simple empirical equation:

$$N_{retention}(\%) = 42.1 + 17.8 \times \log 10(tw)$$

where $N_{retention}$ is the nitrogen removal in percent and tw is the residence time for water in years. The equation cannot be used for lakes with a residence time shorter than 1 week.

Nitrogen removal in various wetland types is estimated according to Hoffmann et al. (2000a, 2003) and Danish Nature and Forest Agency (2003). To improve the scientific basis for the estimates in different types of wetlands, some research projects were initiated concomitant with the initiation of DAPAE-II (Hoffmann et al., 2000a). The obtained results from these projects have led to some adjustments in the guidelines. First, wetlands flooded with stream water with nitrogen levels below 5 mg N l^{-1} in the flooding period should be set to remove 1 kg N ha^{-1} day^{-1} (i.e. flooded day), whereas wetlands flooded with water having nitrogen levels in the flooding period above 5 mg N l^{-1} should be set to remove 1.5 kg N ha^{-1} day^{-1}. These values imply that there is a continuous supply of nitrogen to the areas, i.e. that water is flowing and thereby maintaining a continuous exchange of water between the watercourse and the floodplain. Second, obtained results indicate that nitrogen removal ceases when the distance from the stream exceeds 100 m as the water is almost still (Andersen et al., 2003). Accordingly the nitrogen removal rates should be set to zero at distances exceeding 100 m. Nitrogen removal by irrigation with drainage water is set to 50% of the load provided that the hydraulic load and the nitrogen load are both adjusted to the wetland area. In most cases the drainage area lies within the topographical catchment area of the wetland, and therefore the precipitation surplus can be calculated with data from Danish Meteorological Institute and the resultant hydraulic load and nutrient load (see below) can be estimated and compared to wetland soil properties and wetland area. Drainage water may be distributed over the wetland area by use of small distributions channels or by making use of naturally occurring hollows and dips in the wetland. In some of the bigger floodplains the amount of drainage water is small compared to wetland area and all drainage water is infiltrated into the soil in a limited area of the wetland (i.e. close to the outlet point next to the hill slope). In soils with an unsaturated zone and with a high infiltration capacity water will be either partly or fully infiltrated in the soil and therefore the nitrogen removal rate can be set to 50–75 or 75–90%, respectively (Danish Forest and Nature Agency, 2003). Infiltration capacity is evaluated during the feasibility study from the topographical survey and the soil survey together with hydrological information from the area.

Studies of Danish wetlands recharged with groundwater have, irrespective of the nitrogen load, shown a high nitrogen removal efficiency (Hoffmann, 1998; Hoffmann et al., 2000b), and therefore the guideline advises a general reduction value of 90% for these minerogenic wetlands (Danish Forest and Nature Agency, 2003).

The nitrogen load to the wetlands can either be estimated or measured. To estimate the influx of nitrogen to the future wetlands a revised/modified version of an empirical model is used (Kronvang et al., 1995; Hoffmann et al., 2003):

$$N_{tab} = 1.088 \times \exp(-2.487 + 0.671 \times \ln(A) - 0.0032 \times S + 0.0243 \times D)$$

N_{tab} is the mean yearly nitrogen loss per hectare from the upland/catchment to the nearby stream/river, A the yearly runoff (mm), S the Percentage of sandy soils and D is the percentage of arable land. Thus estimation of the total nitrogen input to the restored wetland from the upland is:

$$N_{tab} - \text{total} = N_{tab} \times \text{area of upland}$$

The estimated nitrogen removal rates for the re-established lakes and wetlands are given in Table 1. For shallow lakes the mean area weighted nitrogen removal rate is at present 251 kg N ha^{-1} $year^{-1}$. The mean estimated nitrogen removal for the different wetland types varies between 229 and 293 kg N ha^{-1} $year^{-1}$. Mean estimated nitrogen removal rate for all projects is 259 kg N ha^{-1} $year^{-1}$.

2.2. Project progress

At present, August 2005, 46 projects with a total area of 3060 ha have been re-established under DAPAE-II, 31 projects with an area of 3769 ha have been approved for implementation, 12 preliminary projects, representing 1721 ha, are expected to be re-established, while 41 restoration projects have been abandoned (Fig. 1). In winter 2005/2006, the largest wetland project within this programme was re-established in Northern Jutland, Lake Vilsted, with an area of 952 ha (452 ha of shallow lake surrounded by 500 ha wet meadows).

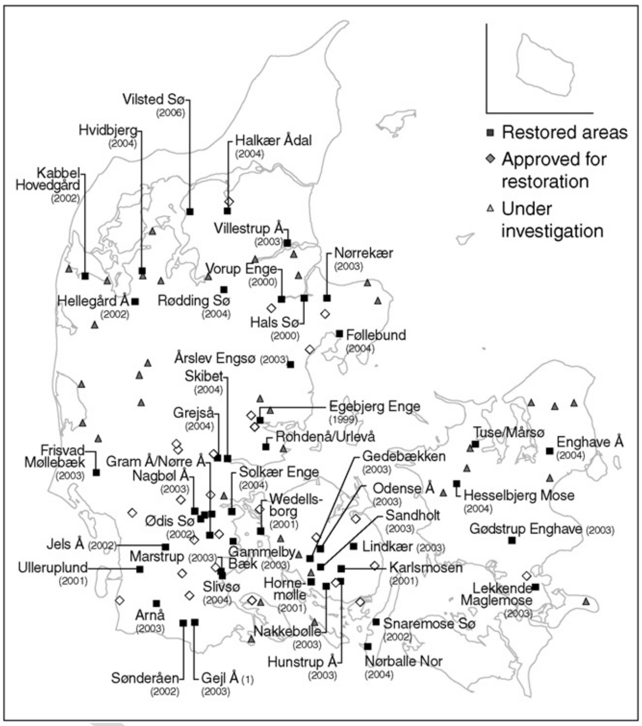

Fig. 1 – Map of Denmark showing wetland projects already carried out (squares and name of locality), approved to be carried out (diamonds) or still under investigation (triangles).

3. Results and discussion

3.1. Former land-use in the re-established wetlands

Results from the sample inquiry covering seven projects and a total area of 1365 ha show that prior to the re-establishment, 42% of the project areas were dominated by agriculture (Table 2). Approximately 65% of the agricultural areas were

Table 1 – Total area and total estimated nitrogen removal for all types of wetland restoration projects which have been approved for restoration or which have already been carried out

Project type	Area (ha)	Nitrogen removal (kg N ha^{-1} $year^{-1}$)	Total nitrogen removal (kg N $year^{-1}$)
Shallow lakes	2985	251	750,098
Irrigation	464	293	135,998
Inundation	598	290	173,429
Irrigation + inundation	748	257	192,274
River valley projects	1905	254	485,029
Fen + wet meadow + others	129	229	29,560
All areas	6829	259	1,766,387

Table 2 – Results from sample inquiry showing former land-use in seven restored wetlands

	Types/land use	Hectare	% of total
Agriculture	Crop rotation	370.1	27.1
	Environment friendly (ESAP)	7.0	0.5
	Grassland (grass production)	163.5	12.0
	Set aside	26.1	1.9
Agriculture total		566.6	41.5
Nature*	Eutrophic (meadows)	528.9	38.7
	Oligotrophic (valuable, bog, fen)	17.0	1.2
	Small lakes	9.8	0.7
	Forest (willow, alder)	41.2	3.0
	Other	16.4	1.2
Nature total		613.3	44.8
No information	No information available	185.2	13.7
Total	All areas	1365.1	100

The project areas comprise two lakes with surrounding wet meadows, five river valley projects with inundation and/or irrigation (*note:* this table and Table 3 do not correspond); ESAP: sensitive agricultural areas converted to environmentally sound agricultural practice.

* Defined as areas, which are not under agricultural practices.

in crop rotation (or 27% of the total area), 29% were cultivated grassland for either animal grazing or hay cutting (i.e. 12% of the total area), 5% were abandoned and 1% were cultivated in an environment-friendly way defined by other legislation (no. 187, 20 March 2003). Areas with meadows, bogs, fens, small lakes, and different forest types constituted approximately 45% of the total area. The majority was meadow-land with a predominance of the following plant communities: *Elytrigia repens/cirsium arvense* community, a *Lolium perenne/trifolium repens* community, a *Ranunculus repens/poa pratensis* community and a *Deschampsia caespitosa* community. These plant communities are typical in grassed areas that are renewed at intervals of 5–7 years (Nygaard et al., 1999). A *Filipendula ulmaria* community was also present, but with a low coverage. This community is typical in abandoned fields no longer used for grazing or hay cutting. Areas possessing plant communities with a high conservation value had a very restricted extension prior to project implementations accounting for only 1.2% of the total area. These areas were species-rich and possessed communities typical of nutrient poor soil e.g. *Eriphorum angustifolium*-communities. Similarly, the different forest-types also accounted for a very limited part of the total area (3%) with willow being the most important species.

Overall the natural values in the areas, as inferred from land-use and existing plant communities, were low prior to re-establishment.

3.2. *Measured nitrogen removal and nitrogen load*

Data on measured nitrogen removal rates are available from 10 of the re-established wetlands (Egebjerg Enge, Hellegård å, Kabbel, Gedebækken, Horne Møllå, Karlsmosen, Lindkær, Snaremose, Frisvad Møllebæk and Ulleruplund), but results of the monitoring failed at Hellegård Å due to unusual climatic conditions. There is good agreement between the estimated and measured nitrogen removal rate (Table 3) at Lindkær, and in three areas (Horne Mølleå, Karlsmosen, and Snaremose) the measured nitrogen removal rates are a little higher than the estimated nitrogen removal rates. While nitrogen removal efficiency is 71% and 50% for Horne Mølleå and Karlsmosen, respectively, only 28% of the load is removed at Snaremose. In the feasibility study nitrogen removal at Ulleruplund was set to 100% while measured efficiency is 67% (133 kg N ha^{-1} $year^{-1}$). However, for three of the sites: Egebjerg Enge, Kabbel, and Geddebækken, there are large discrepancies between the measured and estimated nitrogen removal rates (Table 3).

One of the reasons for the discrepancy between estimated and measured nitrogen removal might be due to differences in estimated and measured nitrogen load. In Table 4 the estimated and measured nitrogen loads are shown for the surveyed wetland sites. For several wetlands the estimated nitrogen load is higher than the measured nitrogen load, and especially for three of the re-established wetlands, Egebjerg Enge, Kappel, and Frisvad Møllebæk, the differences are so big that the measured nitrogen load is much smaller than the estimated nitrogen removal, and thus explains why the estimated nitrogen removal and measured nitrogen removal differ in the above mentioned wetlands. Also for Gedebækken and Horne Mølleå, the estimated nitrogen load is higher than the measured nitrogen load, but while Horne Mølleå performs very well, i.e. removing 71% of the nitrogen load, Gedebækken only removes 90 kg N ha^{-1} $year^{-1}$ which is 39% of the measured nitrogen load. In the feasibility study for Gedebækken the percentage nitrogen removal was set to 90%, which is the maximum recommended removal percentage for irrigated wetlands and clearly overestimated for this wetland. It is not known if there have been any changes in land-use in the catchment areas of the surveyed wetlands but results from another study have shown that if the percentage nitrogen removal remains stable nitrogen removal rates vary with the input of nitrogen and therefore even minor changes in land use in the catchment following the re-establishment will affect removal rates (Hoffmann et al., 2006).

3.3. *Effects of climate*

Climatic factors are of great significance for nitrogen removal rates as both precipitation and temperature affect denitrification rates both by influencing the nitrogen input and the microbial metabolism. Large precipitation deficits prevailed in several of the areas. How precipitation affects nitrogen removal can be illustrated by results from Karlsmosen.

The restored wetland Karlsmosen is 65 ha. Two nearby streams, Hågerup å and Hundtofte å, with a total upland of 2000 ha, inundate the wetland. Both streams were remeandered and resized to normal dimensions as a part of the re-establishment. Inundation begins at mean winter discharge, i.e. 266 l s^{-1}, which takes place 45% of the time in the period from October to March. Karlsmosen also receives drainage water from 140 ha upland. Discharge of water from Karlmosen takes place to Hågerup å. The nitrogen removal

Table 3 – Measured and estimated nitrogen removal rates in 10 surveyed wetlands

Site	Area (ha)	Wetland type	Monitoring period (kg N ha^{-1} $year^{-1}$)	Measured N-removal (kg N ha^{-1} $year^{-1}$)	Changed land-use (kg N ha^{-1} $year^{-1}$)	Measured + changed land-use (kg N ha^{-1} $year^{-1}$)	Estimated N-removal (kg N ha^{-1} $year^{-1}$)
Egebjerg enge[a]	34	Irrigation + inundation	November 2000–October 2001	53		53	200
Egebjerg enge[b]	34			72–688	–	72–688	200
Hellegård å[c]	66	River valley, irrigation	January 2002–July 2002, July 2002–June 2003	–	–	–	280
Kappel[d]	28	Irrigation	November 2002–October 2003	14	25	39	140
Geddebækken[d]	39	Irrigation + surface water	January 2004–October 2005	90	35	125	215
Horne Mølleå	15	Irrigation	October 2002–October 2003	220	35	255	200
Karlsmosen	65	Irrigation + inundation	October 2002–January 2004	337	35	372	270
Lindkær	84	Irrigation	January 2004–May 2005	191	35	226	235
Snaremose	34	Irrigation, fen	October 2002–January 2005	228	35	263	200
Frisvad Møllebæk[d]	39	River valley, groundwater	October 2003–October 2004	Up to 95		(279)!	279
Ulleruplund	13	Irrigation	January 2002–December 2002	133	37	170	210

The reduction in nitrogen leaching due to changed land-use has been included for some of the areas. Monitoring started within the first year following re-establishment of the wetlands, except for Hellegård å where monitoring started 6 months before.

[a] Mass balance.

[b] Nitrate flux and denitrification measurements in Egebjeg enge.

[c] Monitoring based on detailed stage–discharge measurements upstream and downstream the wetland area both before and after re-establishment failed due to unusual climatic conditions.

[d] Uncertain due to very dry conditions and ! will probably reach estimated nitrogen removal rate in years with normal climatic conditions.

Table 4 – Area of re-established wetland, area of catchment area and estimated and measured nitrogen loads in 10 surveyed wetlands

Site	Area (ha)	Catchment area wetland (ha)	Estimated N-load ($kg\,N\,ha^{-1}$ wetland)	Estimated N-load from stream ($kg\,N\,ha^{-1}$ wetland)	Changed land-use ($kg\,N\,ha^{-1}$ wetland)	Measured N-load ($kg\,N\,ha^{-1}$ wetland)
Egebjerg enge	34	161	104	168	–	76
Hellegård å	66	625	314	–	20	188[*]
						83[*]
Kappel	28	86	138	–	70	39
Geddebækken[d]	39	284	272	272	24	230
Horne Mølleå	15	240	380	–	28	310
Karlsmosen	65	2140[a] (140)[b]	[aa]	677	35	668
Lindkær[d]	84	916	224	224	35	297
Snaremose	34	515	401	–	25	812
Frisvad Møllebæk	39	224	205	60,000[c]	23	95
Ulleruplund	13	60	173	–	37	198

The reduction in nitrogen leaching due to changed land-use has been included.

[*] Hellegård January 2002 to June 2002 (before restoration) and July 2002 to July 2003 (after restoration) respectively.

[a] Total catchment area.

[b] Area of drainage catchment area.

[aa] N-load from drainge area neither estimated nor measured.

[c] Total nitrogen in stream discharge along the wetland project.

[d] Stream flows through the wetland.

rate was estimated to be 270 kg N ha^{-1} year^{-1} including a contribution of 35 kg N ha^{-1} year^{-1} due to changed land-use (i.e. termination of farming).

The wetland acts as a reservoir during flooding events due to a large dip in the centre. This means that occasionally there is an incongruity between inflow and outflow from the wetland, especially when the dip is being filled with water (i.e. start of flooding event) and subsequently when the dip is being emptied (i.e. end of flooding event). To calculate water and nutrient balances a discharge–discharge (QQ) relationship has been established between the water gauge station at the wetland site and a water gauge station situated downstream the area in the main river (river Odense at Nørrebroby), where the water level is measured continuously. For the mass balance calculations daily values of nutrient concentrations were made by linear interpolation between measuring dates.

In the winter 2002/2003 precipitation was very low. From December 2002 to March 2003 precipitation amounted to 88 mm compared to the mean 187 mm for this period (Danish Meteorological Institute, 30 average from 1961 to 1990). Accordingly, the runoff was atypically low with very little or sometimes no water in the drains and very low discharges in the two streams that normally inundate the wetland. In periods with high discharge the nitrogen load is also high and Karlmosen removes 200–240 kg N day^{-1}, or 3–3.7 kg N ha^{-1} day^{-1} (Table 5). It is striking that the percentage nitrogen removal shows little variation, being close to 50% except when then load is very small, while the nitrogen load varies from 0.1 to 8.0 kg N ha^{-1} upland month^{-1}. In 2003 the total nitrogen removal was 21,902 kg N (337 kg N ha^{-1} year^{-1}) or 50% of the load (Table 5). A yearly balance based on the whole measuring period from October 2002 to January 2004 shows an annual removal of 29,599 kg N (455 kg N ha^{-1} year^{-1}) or 47% of the load (Table 5).

The variability in run-off patterns from year to year will probably also influence removal rates for Horne Mølleå, which is situated on the island of Funen. Although the measured and estimated nitrogen removal rates are almost identical being 220 and 200 kg N ha^{-1} year^{-1}, respectively (Table 3), this area will probably remove more nitrogen in years with higher drain water run-off, as the surveillance took place in the period 2002–2003 with the above mentioned precipitation deficit of 99 mm. Also the two wetlands Gedebækken and Lindkær will probably remove more nitrogen in years with bigger run off in the drains and the streams supplying these two wetlands with water. Both wetlands have suffered from scarcity of both drain water and stream water during the summer half 2004.

At Hellegård Å the surveillance was performed by detailed stream discharge measurements upstream and downstream the restored river valley, both before and after restoration of the river valley. It was known that stream discharge increased by 60 l s^{-1} along this stretch of Hellegård Å (normal discharge approximately 300 l s^{-1}), and therefore it should be possible to measure changes in nitrogen discharge before and after the restoration. Prior to the restoration in the period January 2002 to June 2002 precipitation amounted to 473 mm, which is much higher than the average 294 mm (Danish Meteorological Institute, 30 year average from 1961 to 1990) for this part of the country. After the restoration in the period January 2003 to June 2003 precipitation amounted to 347 mm (Danish Meteorological Institute), and comparison of the run off pattern in the pre- and post-monitoring periods was further impeded as precipitation in the period from December 2002 to March 2003 was low, i.e. 129 mm, as compared to the average 230 mm (Danish Meteorological Institute, 30 year average from 1961 to 1990). Although nitrogen discharge decreased from 19.8 kg N ha^{-1} year^{-1} before the restoration to 8.8 kg N ha^{-1} year^{-1} after the restoration this reduction

Table 5 – Measured influx and measured outflux of total nitrogen from Karlsmosen

Date	N-load ha upland (kg N ha^{-1} month^{-1})	N-discharge ha upland (kg N ha^{-1} month^{-1})	Total load (kg N month^{-1})	Total discharge (kg N month^{-1})	Removal (kg N month^{-1})	Rem (%)
October 2002	0.9	0.4	1, 801	878	923	51
November 2002	7.5	4.0	15, 008	8, 784	6, 224	41
December 2002	3.9	2.1	7, 804	4, 612	3, 192	41
January 2003	6.7	3.1	13, 407	6, 808	6, 599	49
February 2003	3.3	1.6	6, 603	3, 514	3, 090	47
March 2003	2.6	1.3	5, 203	2, 855	2, 348	45
April 2003	1.7	0.7	3, 402	1, 537	1, 865	55
May 2003	2.6	1.3	5, 203	2, 855	2, 348	45
June 2003	0.5	0.2	1, 001	439	561	56
July 2003	0.4	0.1	800	220	581	73
August 2003	0.1	0	200	0	200	100
September 2003	0.2	0	400	0	400	100
October 2003	0.4	0.1	800	220	581	73
November 2003	0.9	0.3	1, 801	659	1, 142	63
December 2003	2.3	1.1	4, 602	2, 416	2, 187	48
January 2004	8.0	4.0	16, 008	8, 784	7, 224	45
Total			84, 043	44, 581	39, 465	47
"Year"			63, 032	33, 436	29, 599	47
2003			43, 422	21, 523	21, 902	50

Runoff data are based on regression between measured data from Karlsmosen and daily runoff data from a downstream water gauge station, situated at Nørre Broby. For the three bottom rows the unit for "Total": kg N, and units for "Year" and "2003": kg N year^{-1}.

could only be attributed to changed run-off and not to re-establishment of the riparian wetland.

At Frisvad Møllebæk in southern Jutland, precipitation only amounted to 365 mm in the period July 2003 to December 2003, while the average is 505 mm (Danish Meteorological Institute, 30-year average from 1961 to 1990). This precipitation deficit resulted in lower groundwater discharge and although nitrogen removal was very efficient (i.e. 100%) measured nitrogen removal was much lower than estimated nitrogen removal.

3.4. *Effects of construction work*

There are also other causes to the observed differences between measured and estimated nitrogen removal rates. For the first mentioned wetland in Table 3, Egebjerg Enge, the mass balance showed a nitrogen removal rate of 53 kg N ha^{-1} $year^{-1}$, while denitrification measured with ^{15}N technique at a permanent inundated spot in the wetland showed a higher nitrogen removal (Jacobsen, 2002). A part of the dike (300 m) between the wetland and the stream was removed during restoration of the wetland allowing the stream to inundate the wetland. When the water level in the stream fluctuates frequently the exchange of water (and nitrate-nitrogen) between the wetland and the stream is big but when the water level stays the same the remaining part of dike acts as a barrier and water is trapped behind the dike. The solution would be to remove the rest of the dike or make more breaches along the dike to allow water to flow from the upstream part of the wetland to the downstream part of the wetland (and stream), providing a continuous supply of water and nitrogen, thereby enhancing both nitrogen load and nitrogen removal.

4. Conclusion

The Action Plan on the Aquatic Environment II will not reach its original target of re-establishment of 16,000 ha of wetland and a concomitant nitrogen reduction of 5600 tonnes. More realistically, approximately 8000 ha will be re-established and as the estimated nitrogen removal rate at present is 259 kg N ha^{-1} $year^{-1}$ total nitrogen reduction will be 2000 tonnes. Data on measured nitrogen removal rates are available from nine of the re-established wetlands, while monitoring failed in one wetland. The agreement between estimated and measured nitrogen removal rates differ considerably in four of the re-established wetlands, exhibiting much lower nitrogen removal rates than estimated beforehand. Three of the re-established wetlands have higher nitrogen removal than estimated. Nitrogen removal efficiency varies between 28 and 71% for irrigated and inundated wetlands.

Particularly climatic factors are likely to explain the discrepancy between estimated and measured rates of nitrogen removal as shown for one of the re-established wetlands, Karlsmosen, which also showed high capacity for nitrogen removal. But also other factors influence the nitrogen removal efficiency as documented for the site, Egebjerg Enge, where the construction works were not optimal for the exchange of water between the wetland and the stream, and thus the capacity for nitrogen removal (i.e. denitrification) was not exploited, and the natural hydraulic regime was not fully restored.

Monitoring of vegetation before restoration was initiated showed that the area possessing a high conservation value was very restricted, indicating that the criteria for reestablishment of wetlands were fulfilled.

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