Successful reduction of diffuse nitrogen emissions at catchment scale: example from the pilot River Odense, Denmark
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ABSTRACT
Land-based total nitrogen (N) loadings to Danish coastal waters have been markedly reduced since 2000. This has been achieved by general measures reducing discharges from all point sources and N leaching from farmed land supplemented with more local and targeted mitigation measures such as restoration of wetlands to increase the catchment-specific N retention. In the catchment of River Odense, restoration of wetlands has been extensive. Thus, in the major gauged catchment (485 km²) eleven wetlands (860 ha) have been restored since 2000. A comparison of data on N concentrations and loss from a gauging station in the River Odense with data from a control catchment (772 km²), in which a significantly less intensive wetland restoration programme has been undertaken, showed an excess downward trend in N, amounting to 124 t N yr⁻¹, which can be ascribed to the intensive wetland restoration programme carried out in the River Odense catchment. In total, the N load in the River Odense has been reduced by 377 t N yr⁻¹ (39%) since 2000. The observed downward trend is supported by monitoring data from two wetlands restored in 2001 and 2004 in the River Odense catchment.

Key words | mitigation, monitoring, nitrogen, trends, wetland restoration

INTRODUCTION
Excess nitrogen (N) in aquatic systems is a major concern worldwide and has through eutrophication significantly degraded coastal ecosystems (Galloway et al. 2003; Riemann et al. 2016). A necessary step in combating excess N loading is the development of River Basin Management Plans (RBMPs), incorporating different general and targeted mitigation measures for reducing both point and diffuse N pollution. Such a reduction is a part of the objective of the EU Water Framework Directive (WFD) (EC 2000). Since N loss to surface waters and groundwater is often largely driven by agricultural activities, there is an urgent need to obtain further knowledge about the effects of the various general and targeted mitigation measures so far adopted and their effects at both local and catchment scale (Schoumans et al. 2014).

In Denmark (43,000 km²), different mitigation measures have been adopted during the period 1985–2012 as part of the National Environmental Action Plans (NAEPs) and the plan for Green Growth (Windolf et al. 2012). The NAEPs have been directed at both point source discharges and diffuse sources of N. In 1998 mandatory catch crops were first established (6% of cropped areas sown in the spring), and even stricter rules for catch crops were given in NAEP III (10–14%) and Green Growth (extra 140,000 ha requirement of catch crops on a national scale). Moreover, NAEP II contained a plan for restoration of wetlands (16,000 ha on a national scale) as a new targeted mitigation measure with the aim of reducing N loadings to coastal waters (Hoffmann & Baattrup-Pedersen 2007).

More than 10,000 ha of wetlands have been restored in Denmark during the period 2000–2014 within the frameworks of NAEP II and III and WFD RBMP I. Nearly 9% of these restored wetland areas are located in the River Odense catchment upstream of the Kratholm monitoring station (covering approximately 1% of the area of Denmark). Hence, the catchment contains the largest area...
of restored wetlands in Denmark and is therefore unique in this context. The target of the restoration has been to reduce nutrient loadings to the downstream estuarine ecosystem that presently does not fulfil the required objective of good ecological status (Danish Ministry of Environment 2014).

The objective of this study is to demonstrate how monitoring data at catchment and sub-catchment scale can be used to analyse the effects of wetland restoration programmes on riverine N concentrations and loadings to estuaries.

MATERIALS AND METHODS

Study catchments

The River Odense catchment upstream of the Kratholm monitoring station drains a 485 km² area in the central and southern part of the island of Funen, Denmark (Figure 1). The area is a part of the Odense Fjord catchment and was formerly used as a pilot catchment for testing the implementation of the European WFD (Cherlet 2007; Environment Centre Odense 2007). The control

Figure 1  |  Map showing the River Odense catchment and the control catchment on the island of Funen, Denmark.
catchment, 11 sub-catchments also situated on Funen, drains a total area of 772 km². Precipitation, runoff, soil types and land use characteristics of the two catchments are relatively similar, average annual precipitation amounting to 860 mm for both catchments and river runoff to 275 mm and 305 mm, respectively, during the period 2000–2013. Both catchments are mainly underlain by clayey till and meltwater sand, and top soils are dominantly sandy clay soils (48 and 44%) and clayey sandy soils (45 and 49%).

The 65 ha restored wetland (Karlsmosen) is situated in the southern part of the River Odense catchment and was re-established in 2001. The project involved remeandering the formerly straightened and channelized watercourse, cutting 18 tile drains and establishing a permanently flooded fen along the main channel by raising the stream bed level. The Karlsmosen wetland is fully described in Hoffmann et al. (2011).

The 39 ha restored wetland (Geddebækken) is situated in the southern part of the River Odense catchment as a smaller tributary to the lake Arreskov. The wetland was re-established in 2003 when tile drains were disconnected, thus irrigating the wetland and creating smaller shallow lakes surrounded by wet meadows. The stream will occasionally inundate part of the wetland and high flows.

**Monitoring of water and nutrient concentrations**

Kratholm monitoring station is situated some 20 km upstream of the outlet of the River Odense in the Odense estuary and has been in operation since the 1980s. The water stage is measured continuously and instantaneous discharge monthly throughout the year. A dynamic stage-discharge relationship is applied to calculate mean daily discharge. During 1989–2010, water sampling was conducted nearly daily with an automatic sampler (ISCO) in the River Odense at Kratholm. In the control catchment, water sampling was conducted in the 11 sub-catchments following the standard frequency of 18–26 samples per year (Kronvang et al. 2005). All samples were analysed for concentrations of total N (TN) using standard methods (Danish Standards Association 1975).

The bias associated with taking 18–26 grab samples per year and utilising linear interpolation for daily estimates of TN was determined from a complete 3-year daily time series from Kratholm applying a Monte Carlo analysis. The average bias revealed an underestimation of 1–3% of the annual TN transport, depending on the year investigated (Kronvang & Bruhn 1996).

Data of TN emissions from sewage in the two catchments were collected as part of the Danish Monitoring Programme (NOVANA) (Wiberg-Larsen et al. 2013).

**Modelling of nitrogen retention in wetlands**

A new national N model has recently been developed for the entire area of Denmark (Højberg et al. 2013). It includes a chain of sub-models covering daily N leaching at field scale, a 3D groundwater model with a resolution of 500×500 m and several sub-models for N retention in surface waters. The model calculates N fluxes and sinks from fields to coastal areas in ca. 3,300 sub-catchments with an average size of 15 km².

**Trend analysis**

A trend analysis of the annual and monthly flow-weighted concentrations of TN and nitrate-N from the Kratholm station and the sum of 11 other streams on Funen was conducted using a linear regression method in SAS (SAS Institute Inc.).

**RESULTS AND DISCUSSION**

**Implemented management measures and wetland restoration**

Different management measures have been adopted as part of the Danish NAEPs and the Plan for Green Growth during the period 2000–2012 (Windolf et al. 2012). The Action Plans have been directed at reducing point source discharges (sewage) and diffuse sources of N. Generally, the River Odense and the control catchments exhibit a similar level of development and agricultural land use and livestock density (Table 1). A larger reduction in sewage emissions of N has been achieved in the control catchment (15.4 t yr⁻¹) than in the River Odense catchment in which the sewage discharges of N were nearly constant during 2000–2013 (Table 1).

The implementation of catch crops differed slightly in the two catchments during the period 2000–2013 (Table 1). The control catchment increased its percentage of cover of catch crops on spring cereal land by 5.8%, from a starting value of 7.7%, whilst the River Odense catchment increased by 3.5% from a starting value of 6.4%. Also buffer strips were established as a mitigation measure in the two catchments. Buffer strips, afforestation, wetland
restoration as well as urban development took agricultural land out of production (Table 1).

### Trend analysis estimates for nitrogen in the River Odense and control catchments

A trend analysis of flow-weighted TN and nitrate-N concentrations was conducted for the River Odense and control catchments for the period 2000–2013 (Figure 2 and Table 2). Significant $(P < 0.001)$ reductions for both parameters and catchments were detected. However, reductions in TN and nitrate-N were higher in the River Odense catchment (2.55 and 2.26 mg N L$^{-1}$) than in the control catchment (1.90 and 1.75 mg N L$^{-1}$; $P < 0.001$) (Table 2). These reductions are also reflected in the estimated reductions in TN load normalized to mean water discharge in the River Odense and the control catchment (377 t N yr$^{-1}$ (39%) and 403 t N yr$^{-1}$ (30%), respectively, during 2000–2013.

The observed trend in the two catchments cannot be explained by a reduction in TN emissions from sewage outlets as these were constant in the River Odense catchment and decreased only slightly (15 t N yr$^{-1}$) in the control catchments during 2000–2013 (Table 1). Thus, the observed downward trends in N concentrations and loss can be ascribed to adoption of general mitigation options such as catch crops and the general decline in the proportion of agricultural land due to afforestation, widening of buffer strips, restoration of wetlands, etc. (Tables 1 and 2).

The reduction in TN and nitrate-N concentrations and flow-normalised loadings were much more pronounced in the River Odense catchment than in the control catchment, despite a larger reduction in both point source emissions and more catch crops in the control catchment (Tables 1 and 2). The larger reduction (trend) of the TN and nitrate-N loss found in the River Odense catchment as compared to the control catchment amounted to 124 t N and 104 t N, respectively, during the period 2000–2013. This higher reduction seems to be closely linked with wetland restoration as a significant $(P < 0.0001)$ downward trend was detected in the difference in monthly flow-weighted TN concentrations observed at the gauging stations in the River Odense and in the control catchment during 2005–2013, the period where most wetland restoration projects took place (Figure 3). That restored wetlands are efficient areas for N removal have been shown in many other studies (cf. Tockner et al. 1998; Hoffmann et al. 2011).

### Measurements of nitrogen retention in restored wetlands

A trend analysis of flow-weighted annual TN concentrations was conducted at a gauging station downstream of a restored wetland in the stream Geddebaekken that is situated within the River Odense catchment. The analysis showed an abrupt downward jump in TN after recreation of the wetland in 2004 (Figure 2). Thus, the average flow-weighted TN concentrations declined from 9.94 mg N L$^{-1}$ during the period before wetland restoration (2000–2004) to 6.75 mg N L$^{-1}$ immediately upon restoration (2005–2008) to 5.24 mg N L$^{-1}$ in 2009–2013. Moreover, the
monthly flow-weighted concentrations of TN and nitrate-N demonstrated a significant change following the 2004 wetland restoration, the nitrate-N concentration reaching nearly zero in the summer months (Figure 4). The observed downward trend in TN concentrations can be used to quantify the effect of the restored wetland for N retention. When adjusting for the general trend in TN concentrations in the control catchment (equation in Table 2) the mean estimated TN retention effect of the wetland amounted to $1.7 \pm 0.7$ t N yr$^{-1}$ during the period 2005–2013 ($44 \pm 18$ kg N ha$^{-1}$).

A mass balance of TN was also conducted for a 22-month period after the 2004 restoration (Hoffmann et al. 2005), revealing an annual TN retention of 90 kg N ha$^{-1}$ restored wetland.

The net retention of TN was also measured for one year (2003) after restoration of Karlsmosen, one of the restored wetlands in the Kratholm catchment (63 ha wetland). The established mass balance showed a net retention of TN in all months, the highest retention occurring in periods with the highest runoff (Hoffmann et al. 2005). The annual TN retention amounted to 337 kg N ha$^{-1}$ of restored wetland. Such a high removal rate cannot be expected to occur every year, other studies having documented large interannual variations in N retention in restored wetlands (Kieckbusch & Schrautzer 2007).

**Modelling of nitrogen retention in restored wetlands**

The Danish N model includes an empirical wetland sub-model for N retention that is driven by local hydrology and season as a proxy of the influence of temperature on N retention (Højberg et al. 2005). The entire model setup has been validated and lies within the same uncertainty range ($\pm 20\%$) (Højberg et al. 2005) as other N models applied in Europe ($\pm 30\%$) (Kronvang et al. 2009).

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**Table 2** | Results of the linear ($Y = \alpha + \beta X$) trend detection for TN and nitrate-N in the River Odense and control catchments. The trend for the analysed period 2000–2013 is given per catchment area ($P$ = significance level; SD = standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>$N$</th>
<th>$\alpha$</th>
<th>$\beta \pm SD$</th>
<th>$R^2$</th>
<th>$P$</th>
<th>Trend (mg N L$^{-1}$)</th>
<th>Trend (kg N ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Odense</td>
<td>14</td>
<td>6.60</td>
<td>$-0.1959 \pm 0.0399$</td>
<td>0.67</td>
<td>0.0004</td>
<td>$-2.55$</td>
<td>$-7.77$</td>
</tr>
<tr>
<td>Control catchment</td>
<td>14</td>
<td>6.21</td>
<td>$-0.1460 \pm 0.0329$</td>
<td>0.62</td>
<td>0.0008</td>
<td>$-1.90$</td>
<td>$-5.22$</td>
</tr>
<tr>
<td><strong>Nitrate-N</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River Odense</td>
<td>14</td>
<td>5.74</td>
<td>$-0.1737 \pm 0.0338$</td>
<td>0.69</td>
<td>0.0002</td>
<td>$-2.26$</td>
<td>$-6.89$</td>
</tr>
<tr>
<td>Control catchment</td>
<td>14</td>
<td>5.45</td>
<td>$-0.1327 \pm 0.0301$</td>
<td>0.62</td>
<td>0.0009</td>
<td>$-1.73$</td>
<td>$-4.74$</td>
</tr>
</tbody>
</table>

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**Figure 3** | Accumulated areas of restored wetlands in the River Odense catchment and the trend in monthly relative differences between observed TN concentrations in the River Odense and the control catchments.

**Figure 4** | Monthly discharge-weighted concentrations of TN and nitrate-N in the outlet from the sub-catchment Geddebækken within the River Odense catchment.
The model was run for the River Odense catchment for the period 2000–2010 and showed enhanced N retention following wetland restoration as described in Kronvang et al. (this issue) (Table 3). The simulated TN retention amounted to 99 t N yr\(^{-1}\) in 2010 when 80% of the restored wetlands in the River Odense catchment were established (Figure 3). The model result is in agreement with that of the monitoring data, showing an excess downward trend in TN of 124 t N in the River Odense catchment compared to the control catchment, bearing in mind that only ca. 80% of the restored wetlands were established in 2010 where the N model was last run. The model results for TN retention in the 39 ha restored wetland at Geddebækken exhibit an average rate of 2.3 t N yr\(^{-1}\).

The calculated wetland retention rates for TN using the different results are shown in Table 3 and trend and model results are very similar for the entire River Odense catchment (Table 3). However, different TN retention rates were obtained from the mass balances for the restored wetland at Karlsmosen and from the trend analysis of data for the outlet of the restored wetland at Geddebækken. The high retention rate obtained from the 1-year mass balance study for Karlsmosen might be due to high TN loadings that year and the fact that the restoration included cutting of 18 tile drain systems at the edge of the wetland. The relatively low retention rates for Geddebækken using both mass balance, model and trend approaches might be explained by the fact that not all of the restored wetland area will be loaded with nitrate from the catchment.

**Table 3** | Utilisation of different methods to calculate the effect of restored wetlands for retention of total nitrogen

<table>
<thead>
<tr>
<th>Different estimation methods and types of wetlands</th>
<th>TN retention rate (kg N ha wetland(^{-1}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimate based on trend analysis for River Odense catchment (2000–2013)</td>
<td>144</td>
</tr>
<tr>
<td>Model estimate for the restored wetlands in River Odense (2000–2010)</td>
<td>139</td>
</tr>
<tr>
<td>Mass balance for the restored wetland at Karlsmosen (2003)</td>
<td>337</td>
</tr>
<tr>
<td>Model estimate for the restored wetland at Karlsmosen (2002–2010)</td>
<td>150</td>
</tr>
<tr>
<td>Estimate based on trend analysis for the restored wetland at Geddebækken (2005–2013)</td>
<td>44</td>
</tr>
<tr>
<td>Model estimate for the restored wetland at Geddebækken (2005–2010)</td>
<td>53</td>
</tr>
<tr>
<td>Mass balance for the restored wetland at Geddebækken (2004–2005)</td>
<td>90</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

A trend analysis was carried out with emphasis on N using water quality monitoring results from two paired catchments during the period 2000–2013. The results showed different reductions in nitrogen load and concentrations. Reductions were higher for the River Odense catchment with restored wetlands of 1.8 ha km\(^{-2}\) per catchment area than for the neighbouring control catchment with restored wetlands of 0.5 ha km\(^{-2}\) per catchment area. Implementation of different mitigation measures for combating diffuse pollution explains the downward trend in the control catchment and most of the trend in the River Odense catchment, as expected. However, an excess trend for TN in the River Odense catchment compared to the control catchment (124 t N yr\(^{-1}\)) was shown to be linked to a wetland restoration programme implemented in the River Odense catchment during the period 2000–2013. The results from the trend analysis were corroborated by results on TN retention in restored wetlands simulated with a national N model and further supported by mass balance and trend estimates for two smaller restored wetlands within the River Odense catchment.

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