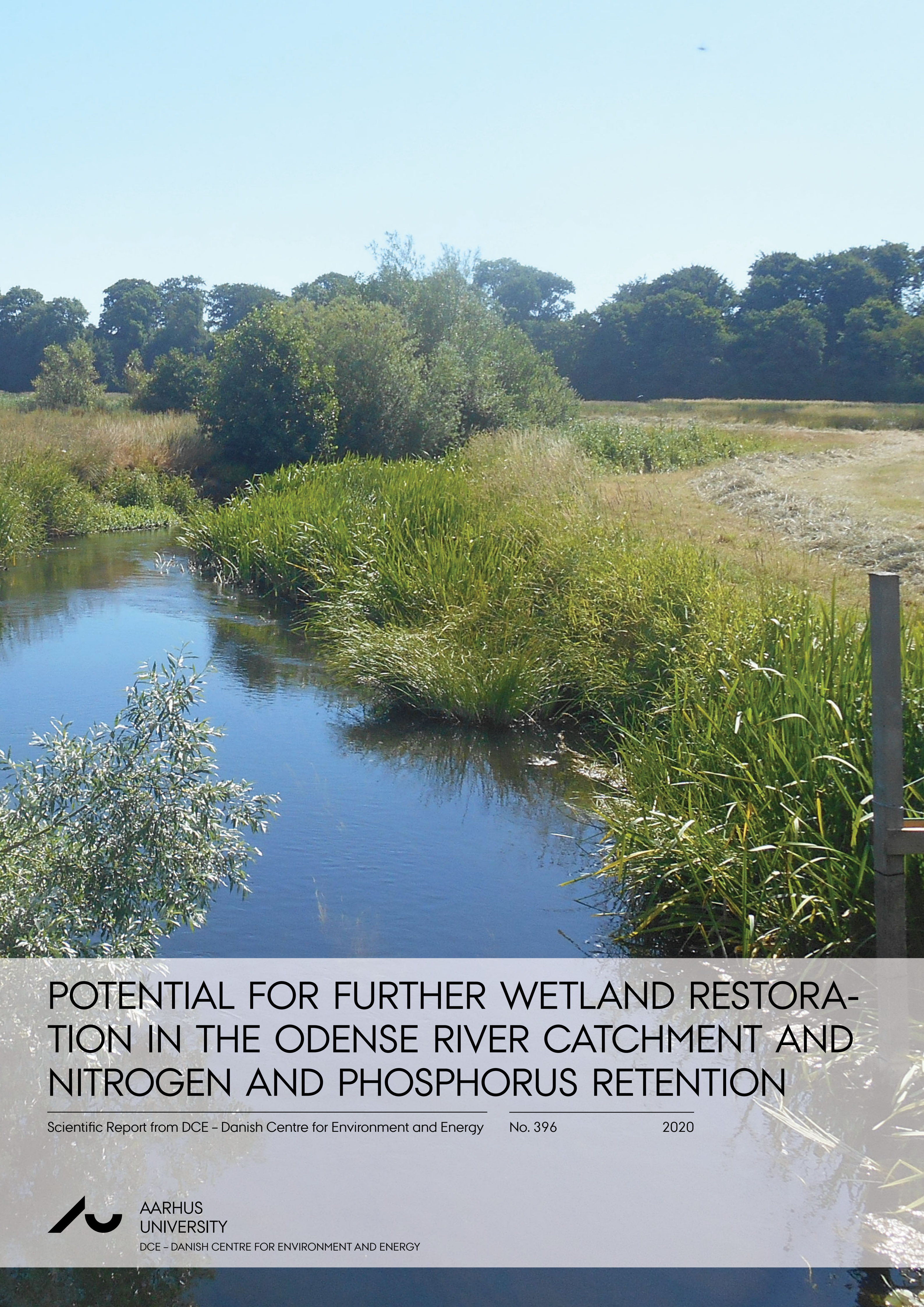

POTENTIAL FOR FURTHER WETLAND RESTORATION IN THE ODENSE RIVER CATCHMENT AND NITROGEN AND PHOSPHORUS RETENTION

Scientific Report from DCE – Danish Centre for Environment and Energy No. 396 2020

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Data sheet

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Abstract: We have used ArcGIS to map already existing wet buffer zones as well as new potential wet buffer zones along the Odense River system, Funen, Denmark. We have developed a screening tool on how to identify wet buffer zones and calculate nitrogen removal and phosphorus retention in wet buffer zones. Further it also includes a tool on how to identify and map wet buffers which may be flooded by river water at peak flow events.

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Contents

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Preface

This scientific report is part of the project "CLEARANCE- CircuLar Economy Approach to River pollution by Agricultural Nutrients with use of Carbon-storing Ecosystems". CLEARANCE is financed under the ERA-NET Cofund WaterWorks2015 Call. ERA-NET is an integral part of the 2016 Joint Activities developed by the Water Challenges for a Changing World Joint Programme Initiative (Water JPI).

We would like to thank the EU (Grant Agreement number 689271) and the Innovation Fund Denmark (Sagsnr.: 6184-00003B), the Federal Ministry of Food and Agriculture (Germany), the National Centre for Research and Development (Poland) for funding.

In this report already established as well as potential buffer zones (WBZ) located along the river Odense system were mapped using ArcGis and based on existing data concerning nitrogen removal and phosphorous retention in wet buffer zones the total potential for mitigation of nitrogen and phosphorous transport to Odense fiord was calculated.

Summary

The Odense River catchment has been subjected to intensive wetland restoration to mitigate the loss of nitrogen (N) and this restoration has led to a reduction of the N load to Odense River of 124 tons N per year. Restoration of additional areas would expectedly entail retention of more N in the catchment. In this study, potential wetland areas for restoration were found by creating an index model identifying suitable areas. The direct upland area to each wetland was calculated in ArcGIS and the N loss from each upland and the N removal from the direct upland were estimated based on soil type and drainage probability. N removal by flood inundation was founded on a flood estimate accounting for flooding 16% of the year (60 days), this estimate being calculated from measurements of the stream water level increase at monitoring stations and from predictions by the developed UPstream river length Model (UPM).

The UPM model was developed in the project with the aim of selecting areas topographically suited for flooding. The model only requires few input data and parameters as compared to models like e.g. MIKE 11, which needs cross sectional stream data for every 100 meters.

The UPM flood model fitted well both upstream and downstream in the river network. It performed best at the highest percentile ($R^2=0.85$ at p0.9995), and the amount of explained variance decreased when longer time periods were included ($R^2=0.7$ at p0.9, $R^2=0.65$ at p0.84). The UPM-based flood calculations were comparable with the flood-based stream level elevations at the 0.9995 percentile calculated using a Mike11 stream model, but large differences in flood coverage occurred at the lower percentiles. Flood estimates from MIKE11 were based on a larger amount of input data suggesting that the MIKE11 model was the more accurate. However, also the MIKE11-based flood was overestimated in several areas, limiting its accuracy.

The calculated N removal in restored wetlands amounted to 91.7 tons N using the flood estimate for 60 days and 127 tons N using the flood estimate for 127 days. There is, though, high uncertainty regarding the latter. Additionally, several restored wetlands contained shallow lakes and N retention in these cannot be calculated without including the lake residence time. As result, there were discrepancies between the measured and the calculated values.

Restoration of an additional 3,617 ha of wetlands is estimated to remove 425 tons N, not including potential removal in lakes. Currently, many streams are not flooded, but they may be so after stream re-meandering. The amount of N removed in currently flooded areas is uncertain as upland drainage area expectedly affects denitrification. At high loads, N removal through irrigation by drainage water is below the standard rate of 50% but rises above 50% at low loads. It is therefore difficult to determine the accuracy of the calculated N removal. The current phosphorus (P) sedimentation amounts to 2,750 kg P per year in restored wetlands, which may be an underestimation, however. P sedimentation in potential wetlands is estimated to 3,551 kg P per year, which may be an overestimation as the calculation does not take into account the increase in upstream wetland areas, which would reduce the P loss in the catchment.

An uncertainty arises also as to how many of the potential wetland areas can actually be restored. Wetland restoration improves the natural value of an area, but an additional N input to protected nature types within the potential wetlands might deteriorate their ecological status.

1 Introduction

In the years 1989-2002, the nitrogen (N) load to the aquatic environment from point sources such as sewage treatment plants decreased, and today land-based diffuse sources are the main factors responsible for nutrient pollution (Kronvang et al., 2005). Denmark has a high agricultural production, and the agricultural area cover 62% of the country's total area of 42938 km^2. The nutrient loss from agriculture has been found to be the main non-point pollutant of surface water (DEPA, 2009). Nitrogen is an essential nutrient for plant growth and is applied in large amounts to agricultural fields (Hatch et al., 2001). Some of the N is leached through the soil as NO_3^- and in this way enters the streams (Jensen et al., 2019). From there, it is further transported to lakes, coastal waters and estuaries (Follett, 2008). The quality of water bodies has deteriorated due to eutrophication with increasing primary production causing algal blooms, the consequences of which are decreased Secchi depth, oxygen depletion and death of fish (Kronvang, 2001).

To protect the water quality, many initiatives have been taken to reduce the nutrient load to coastal waters. One such initiative is the EU Water Framework Directive (WFD), which demands that the aquatic environment in EU member states must reach at least good ecological status (EU, 2000). The WFD acknowledges wetland nutrient removal as a tool to improve the water quality and encourages wetland restoration. In many European countries, the extent of wetlands was greatly reduced during the past century since wetland soils were considered undesirable and drained to allow expansion of agricultural land or urban areas (Hollis, 1991, Jones, 1993).

1.1 Wetland restoration

In Denmark, the Second Action Plan on the Aquatic Environment (VMPII) aimed to restore 8,000-12,500 ha of wetlands during the years 1998-2003 in order to reduce the transport of nitrogen to the sea. Thus, in 2002, 515 ha of wetlands were restored, followed by an additional 2,900 ha in 2003 (Grant and Waagepetersen, 2003). The Third Action Plan on the Aquatic Environment (VMPIII) implemented in 2004 aimed to further restore a total wetland area of 4,000 ha during the years 2004-2005 (Schmidt et al., 2004). By the year 2007, the total area of established wetlands was 5,343 ha and additional area of 3,396 ha was laid out for restoration, amounting to a total of 8,739 ha (Børgesen et al., 2009).

Since the implementation of wetland restoration as a measure to mitigate N transport to the sea with The Second Action Plan on the Aquatic Environment in 1998, over 800 ha of wetlands have been restored in the Odense River catchment alone, amounting to almost 9% of the total restored wetland area in Denmark (Windolf et al., 2016).

In restoration projects, a distinction is made between four main N removal types: irrigation with drainage water, groundwater discharge, flood inundation and shallow lakes (Naturstyrelsen, 2014).

If a wetland is to be restored on drained land, the drains must be disconnected to allow the water to infiltrate the soil. If the direct upland area to the wetland is drained, the restoration involves disconnection of the drains at the wetland boundary, thereby allowing the drainage water to flow over the wetland surface, enabling infiltration. If the wetland area around the stream is small, distribution channels can be established to allow a more even distribution of the water across the area. If drainage water is used for flooding / irrigation of the wetland, the upland / wetland ratio is important because a too high hydraulic load relative to the wetland area will result in fast flow of water directly to the stream, which will reduce the N removal efficiency and create a risk of water erosion (Hoffmann et al., 2005; Petersen et al, 2020).

Restoration implies that straightened river channels are re-meandered to allow flood inundation. This results in a reduction of the water transfer capacity, which slows down the water flow in the stream channel and reduces the stream slope (Hoffmann et al., 2005). In the upstream area of River Brede, restoration of the river channel led to 33 days of flood inundation in contrast to 0 days before the restoration (Kronvang et al., 1998). Flooding can also be encouraged by methods as simple as stopping or reducing stream maintenance as frequent harvesting of stream vegetation results in increased water transfer. By allowing uninhibited growth of vegetation, the resistance against water flow will increase, leading to enhanced sediment deposition and a higher stream bed level (Hoffmann et al., 2005).

Shallow lakes have been turned into agricultural land by drainage or water pumping, and restoration of these often requires only cease of drainage or pumping activities.

1.2 Legislation

Wetland restoration projects are conducted in catchment areas to coastal waters or lakes. There are administratively three categories of wetland restoration projects: N-removing wetlands, P-removing wetlands and peat wetlands (Miljøstyrelsen, 2018).

In an N-removing wetland, minimum N removal must be at least 90 kg N per ha per year. The hydrology should be re-established as close to the natural state as possible. The project must not result in increased P release from the project area (Miljøstyrelsen, 2018).

Projects aiming to remove P involve restoration of wetlands in upstream areas to lakes where there is a need for reduction of the P load in order to improve ecological conditions. The upland area of the stream flowing into a P wetland should cover at least 2 km^2 and the project area must remove at least 5 kg P per ha per year (Miljøstyrelsen, 2018).

Peat wetlands are located on low-lying soils with a carbon (C) content of at least 12% (from 2020 only 6% C). The restoration project should lead to a reduction of greenhouse gas emissions equivalent to 13 tons CO_2 per ha per year. The project should also contribute with an N removal of at least 30 kg N per ha per year. Wetland restoration of peat soils aims to re-establish the natural hydrology to the highest possible extent. The project should not lead to P release from the restored area (Miljøstyrelsen, 2018).

For all projects, economic efficiency is estimated in DKK per kg N per ha per year, per kg P per ha per year or per ton CO_2 equivalents per ha per year (Miljøstyrelsen, 2018).

Wetland restoration is often conducted on privately owned soil, mainly agricultural land, and thus entails loss of economically viable land for the land owner. Therefore, farmers are offered either a monetary compensation or land consolidation. Wetland restoration on agricultural land depends on whether a farmer wishes to participate or not as participation is voluntary (Naturstyrelsenb).

The funds for wetland restoration projects are limited, hence financing of projects is prioritised according to the nutrient removal with the highest economic efficiency. Regarding restoration of peat soils, the prioritising criteria include economic efficiency, total yearly CO_2 equivalent reduction, highest N removal per ha per year as well as distance to Natura 2000 habitats (Miljøstyrelsen, 2018).

1.3 Objectives:

A further restoration of riparian wetlands in Odense River catchment will expectedly reduce the transport of nitrogen (N) to Odense Fjord. The potential for further N removal is assessed by:

1. Creating an index model to identify areas for potential wetland restoration.
2. Calculating direct upland areas to each wetland using GIS-based tools.
3. Calculating the N loss from each upland.
4. Classifying the potential wetlands according to removal type (irrigation, inundation, groundwater or shallow lakes).
5. Estimating N removal from soil type and drainage information.
6. Performing similar calculations for already restored wetlands and comparing the calculated N removal with available measurement data.
7. Discussing the implications for further wetland restoration in the Odense River catchment.

2 Methods

2.1 The input data for the index model are the following:

1. Høje Målebordsblade, showing the wetland signature in the years 1842-1899. Already at that time, many wetland areas had been modified, so the wetland signature visible in Høje Målebordsblade does not accurately depict all past wetland areas (see Figure 2.1). The wetland signature has been digitalised within a 100 m wide buffer around a digitalised stream from 2016 ("Kort10-vandløb 2016").

Figure 2.1. Close-up image of one of the wetland areas (green areas with stylised grass) in Høje Målebordsblade. The wetland appears to have been partly modified by ditches and the dried out land has become farmland.

2. Agrosinks Extended Wetlands, a GIS layer showing the estimated peat distribution in 1900. It is based on maps from the beginning of the 1900s and shows low-lying soils as well as soil classification from the 1970s, ochre maps from the 1980s and low-lying soils as defined by the Geological Survey of Denmark and Greenland, GEUS (Greve et al., 2008).

3. Flood calculation. Flooding is modelled for the Odense River catchment to identify areas prone to flooding. Also the slope of the terrain (based on the Digital Elevation Model, DEM) will be used, as it shows the flat areas in the landscape, and can be used to set the wetland boundary in an area where other data have identified a potential for wetland restoration. The calculation is described in section 2.2.

4. Slope of the terrain. Slope is calculated based on the Digital Terrain Model (DTM). The method is described in section 2.3.

2.1.1 Datasets used

- GeoDanmark-vandløb 1:10,000, downloaded from https://download.kortforsyningen.dk/, a very detailed stream shapefile, updated every year.
- GeoDanmark-søer 1:10,000, downloaded from https://download.kortforsyningen.dk/, a very detailed polygon shapefile containing lakes, updated every year.
- DHM/Rain 0.4x0.4 m downloaded from https://download.kortforsyningen.dk/, a hydrologically correct digital elevation model. Cells have been altered where streams are crossed by bridges to render the stream continuous.
- Odense catchment, extracted from the Danish Catchment Database (DCE) 1:5,000, the catchment boundary of Odense River.
- Jordbundskort 2014 1:20,000, DCA (Danish Centre for Food and Agriculture), downloaded from http://miljoegis.mim.dk/cbkort?profile=jordbrugsanalyse. A polygon shapefile converted from raster, which contains the JB1-11 soil classification (Adhikari et al., 2013).
- IMK-markkort 2018, downloaded from https://kortdata.fvm.dk/download/, a polygon dataset containing agricultural fields and the current crops.
- Agrosinks Extended Wetlands (AEW) (Greve et al., 2008), a polygon shapefile containing the possible peat distribution in 1900. The layer is based on maps from the beginning of the 1900s showing low-lying soils as well as soil classifications from the 1970s, ochre maps from the 1980s and low-lying soil maps from GEUS.
- Agro Sinks Peat 2010 (Gyldenkærne and Greve, 2015), showing mineral and organic low-lying soils based on soil drillings conducted in 2009-2010.
- Høje Målebordsblade as WMS service (Web Map service from Danish Map Supply) https://kortforsyningen.dk/indhold/webservice-liste-0, scanned maps from 1842-1899 containing wetland signatures.
- Digitalised Høje Målebordsblade (HM) approx. 1:20,000, Aarhus University, a polygon dataset with digitalised wetland polygons based on Høje Målebordsblade within a 100 m buffer of Kort10-vandløb 2016.
- Restored wetlands downloaded from https://kortdata.fvm.dk/download/Tilsagn and updated by Aarhus University. A shapefile showing the restored wetlands in Denmark. Contains project name and year of restoration.
- Probable drainage (Olesen, 2009), DCA, showing the probability of drainage in both wet and dry soils based on soil type and geological properties.
- BaseMap (Levin et al., 2017), DCE. A raster dataset showing the current land use in Denmark.

2.2 Flood estimation

Flooding is calculated using the ArcGIS tool “Topo to raster” by creating an elevation raster where values from elevation points are interpolated along a stream. This elevation raster is then used to elevate the stream surface in the DEM corresponding to high stream stages. By doing so, the nearby riparian cells with values lower than the elevated stream surface are flooded. Normally, the stream surface is elevated by using measured water level values from various stations in Denmark that are available for download at https://odaforalle.au.dk. Since there are only 17 measuring stations with sufficient data in the Odense river catchment, use of measured water levels does not give a realistic interpolation across the whole catchment. To obtain a useful interpolation for the stream elevation along the entire stream stretches, and hence a valid flood estimate, more elevation points are needed. It was observed that the highest water level increases occurred downstream, leading to the assumption that the increase in water level is related to the upstream river length. The upstream river length was traced in ArcMap (see Figure 2.2.1.) and used as an explanatory variable for predicting the stream water level increase.

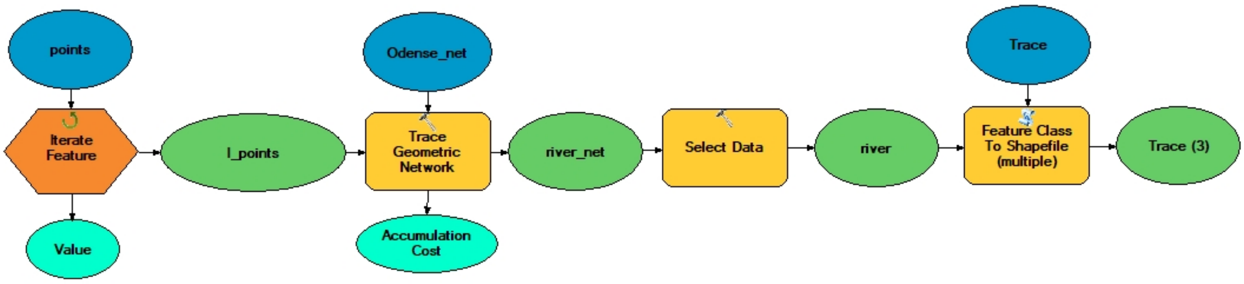


Figure 2.2.1. Model script from ArcGis calculating upstream length to random points. “Trace Geometric Network” traces the upstream river length to each point located in the stream network selected via the iterator. The upstream river sections for each point are then saved in a shapefile, allowing calculation of the upstream river length for each point.

Both the stream water level increase and the upstream river length were log10 transformed as they were not normally distributed (Wilk-Shapiro test p-values of 0.04 and 0.001, respectively). The linear model *max* (*Stream water elevation – mean (stream water elevation) ~ Upstream length* was significant with a p-value<0.01 and adjusted R^2=0.81.

To provide an even interpolation, the stream network needed to be simplified, and several small streams, especially stream clutters in forests, had to be manually removed.

The flood calculation is based on the DEM, and the elevation values must be expressed as elevation above sea level. Therefore, the stream water level increase must be calculated as a value to be added to the DEM value for each elevation point (i.e. for each 100 m). Based on the observed water level at the 13 stream stations several percentiles were calculated (0.01, 0.05, 0.1, …, 0.95, 0.99), and the 0.5 percentile was found to have the highest correlation with the DEM values at the measuring stations. In this way, the 0.5 percentile is assumed to be equal to the DEM value for each point, and the stream water level increase is calculated relative to the 0.5 percentile (see Figure 2.2.2). It should be noted that values from four out of 17 stations were excluded from the correlation calculation because the extracted DEM values did not fit with the measured water elevation over sea level:, while at For the majority of the stations the 0.9995 percentile was higher than the DEM value, but for two of the stations, the extracted DEM values were much higher than the water level at the 0.9995 percentile. This might be due to inaccurate position of the stream points in relation the DEM. For two stations it seemed that the inaccuracy could be ascribed to lack of addition of DEM values to the water elevation value of the stations as their 0.9995 percentiles were 2.25 and 2.87, while their extracted DEM values were 12.54 and 19.95. These measurements were included in the linear model because the measured variations in stream water level appeared correct, and the discrepancy was attributed to their placement above the mean sea level.

The calculated water level increases can be transformed back to metres using the power function (see Figure 2.2.3) and then added to the DEM for each elevation point.

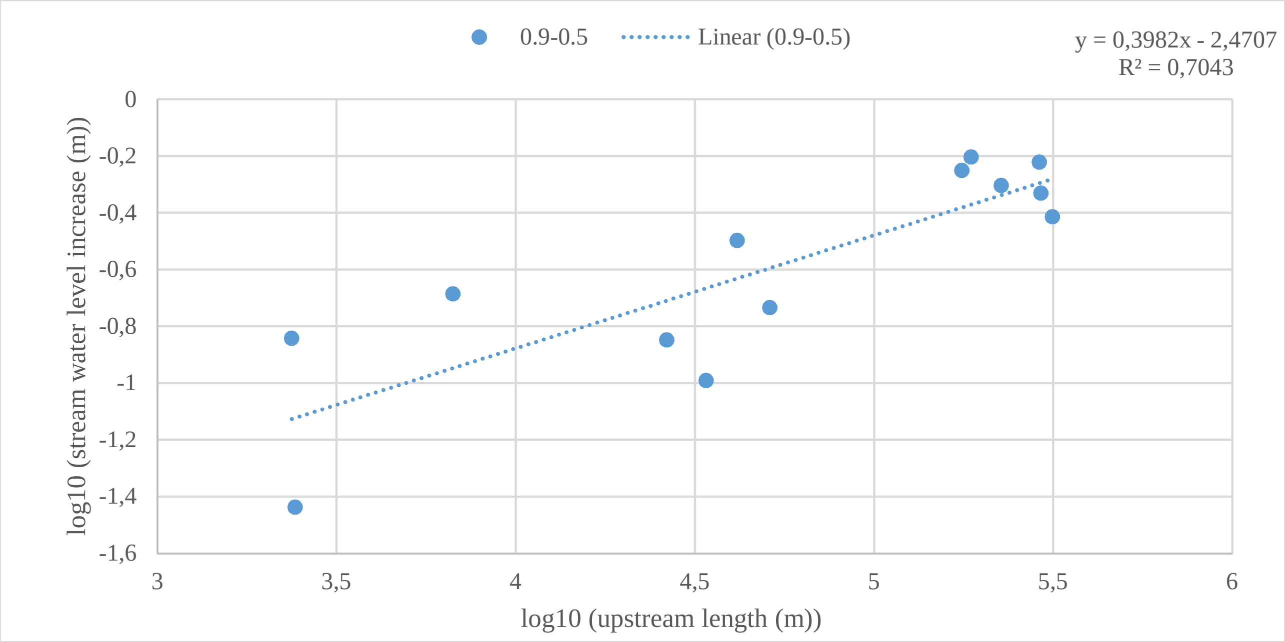


Figure 2.2.2. Linear relationship between the log10-transformed upstream length and the log10-transformed stream water level increase between the 0.5 and 0.9 percentiles. The R^2 of 0.70 shows that 70% of the variation of the dependent variable (log10-transformed stream water level increase) can be explained by the explanatory variable (log10-transformed upstream length).

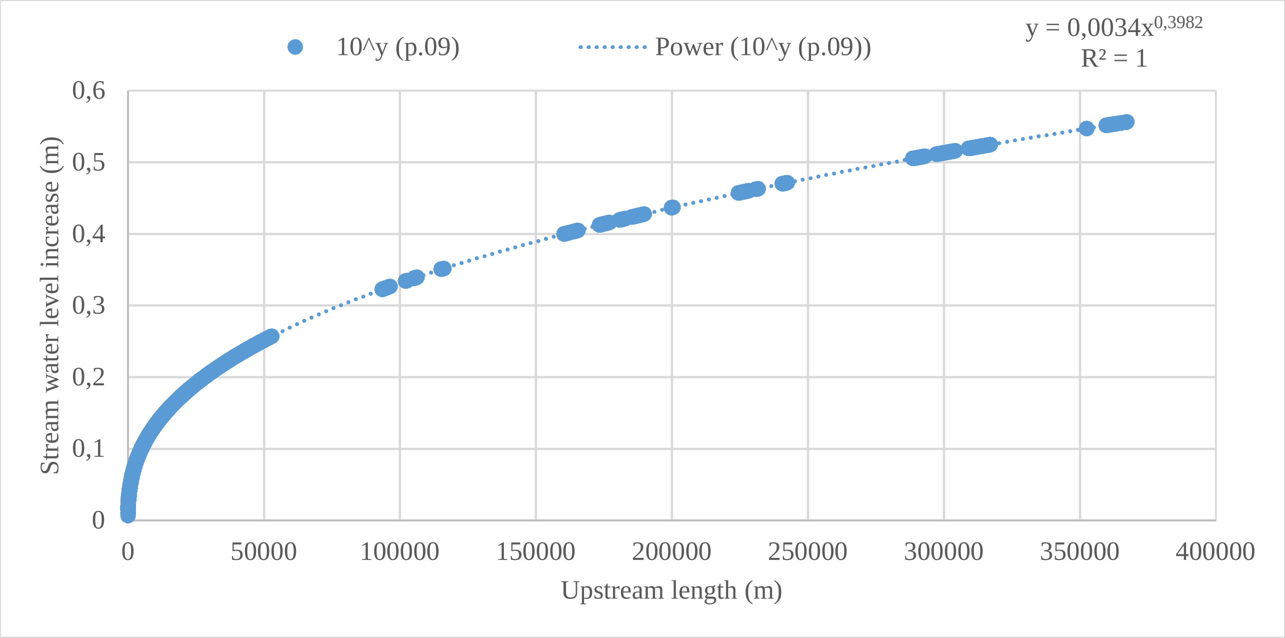


Figure 2.2.3. Estimated stream water level increase as a function of upstream length for the 0.9 percentile. The estimated values follow the shape of a power function.

Several water levels were calculated: The 0.9995 percentile to be used in the index model and the 0.9 and 0.84 percentiles for N removal calculations. The 0.9995 percentile is used in the index model as it shows flooded area at extremely high water levels, thereby setting the wetland boundary to maximum flooded area. The 0.9 percentile is used to calculate N removal through flood inundation for 36 days, and the 0.84 percentile is used to calculate N removal through flood inundation for 24 days, i.e. 60 days in total. The resulting N removal is more accurate than if the 0.84 percentile is used for all 60 days in that the water level, and hence the flooded area, is lower for the 0.84 percentile than for the 0.9 percentile.

Linear regressions for the 0.9995 and 0.84 percentile are shown in Figures 2.2.4-2.2.5 below.

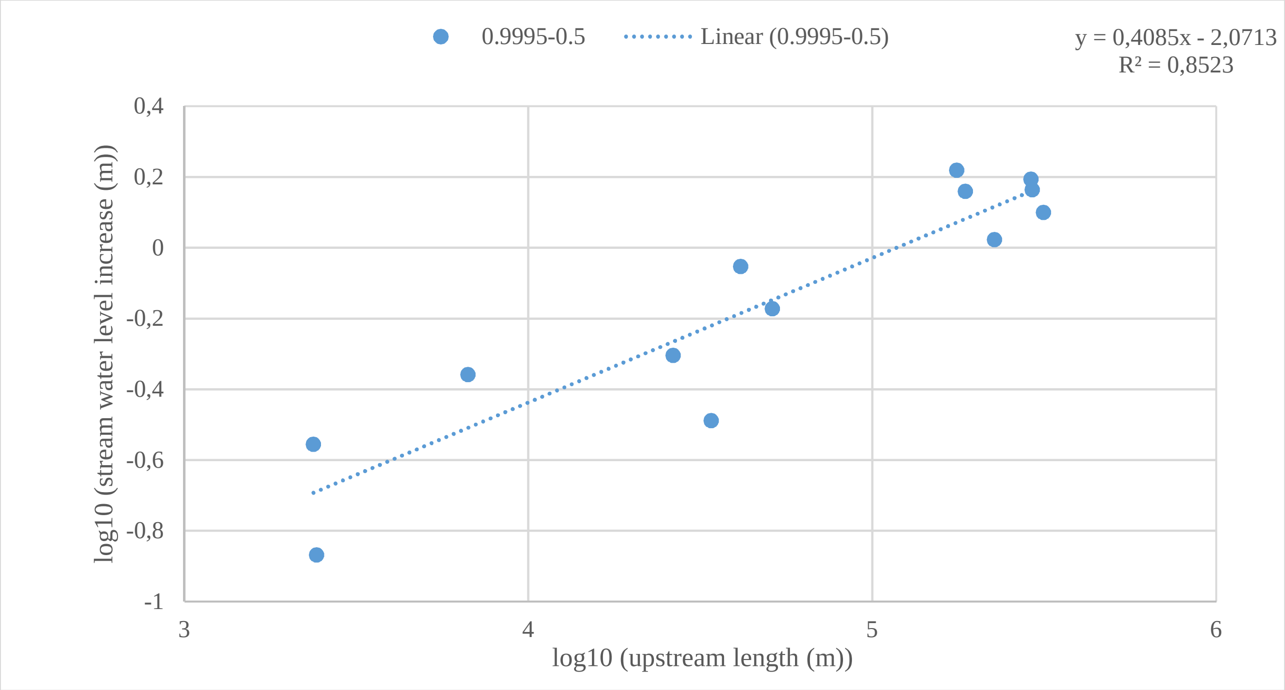


Figure 2.2.4. Linear relationship between the log10-transformed upstream length and the log10-transformed stream water level increase between the 0.5 and 0.9995 percentiles. The R^2 of 0.85 shows that 85% of the variation found in the dependent variable (log10-transformed stream water level increase) is explained by the explanatory variable (log10-transformed upstream length).

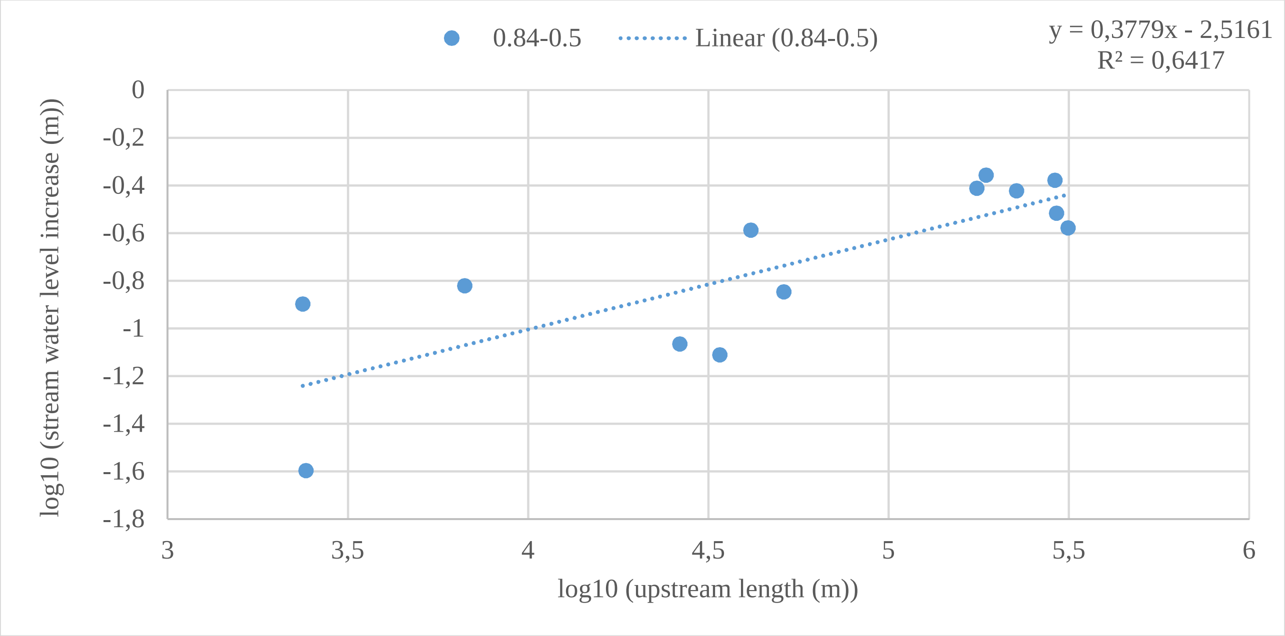


Figure 2.2.5. Linear relationship between the log10-transformed upstream length and the log10-transformed stream water level increase between the 0.5 and 0.84 percentiles. The R^2 of 0.64 shows that 64% of the variation found in the dependent variable (log10-transformed stream water level increase) is explained by the explanatory variable (log10-transformed upstream length).

Additionally, flood inundation for 35% of the year (127 days) is calculated as some of restored wetlands are known to be covered by water for more than 60 days per year (Hoffmann et al., 2006). As the flooded area decreases with the declining water level, several percentiles are used for the calculation. The

0.9, 0.8, 0.7 and 0.65 percentiles are used to calculate N removal via flood inundation for 35% of the year, and linear regressions for the 0.8, 0.7 and 0.65 percentiles are shown in Figures 7.1-7.3 in the Appendix.

Flooding can be calculated using GIS methods as shown in Figure 2.2.6:

The first step of flood calculation is an elevation raster, which contains the values by which the stream surface is to be elevated. The raster values are extracted by mask using a stream shapefile, yielding a raster layer containing the stream with interpolated elevation values. The stream raster is then converted to integer. “Euclidean Allocation” calculates the shortest distance from the stream to each surrounding cell and the distance limit is set to 1000 m. In the next step, the cells of DEM Rain (converted to integer) lying no higher than 100 cm over the stream raster are extracted, including areas that are not connected to the stream. Next, the “Cost Allocation” tool discards cells of the flood raster according to the accumulative cost. NoData is regarded as an infinite cost, hence in this step areas not connected to the stream are discarded. Finally, all the potentially flooded areas are reclassified to the same binary value (flooded / not flooded) using “Raster Calculator”.

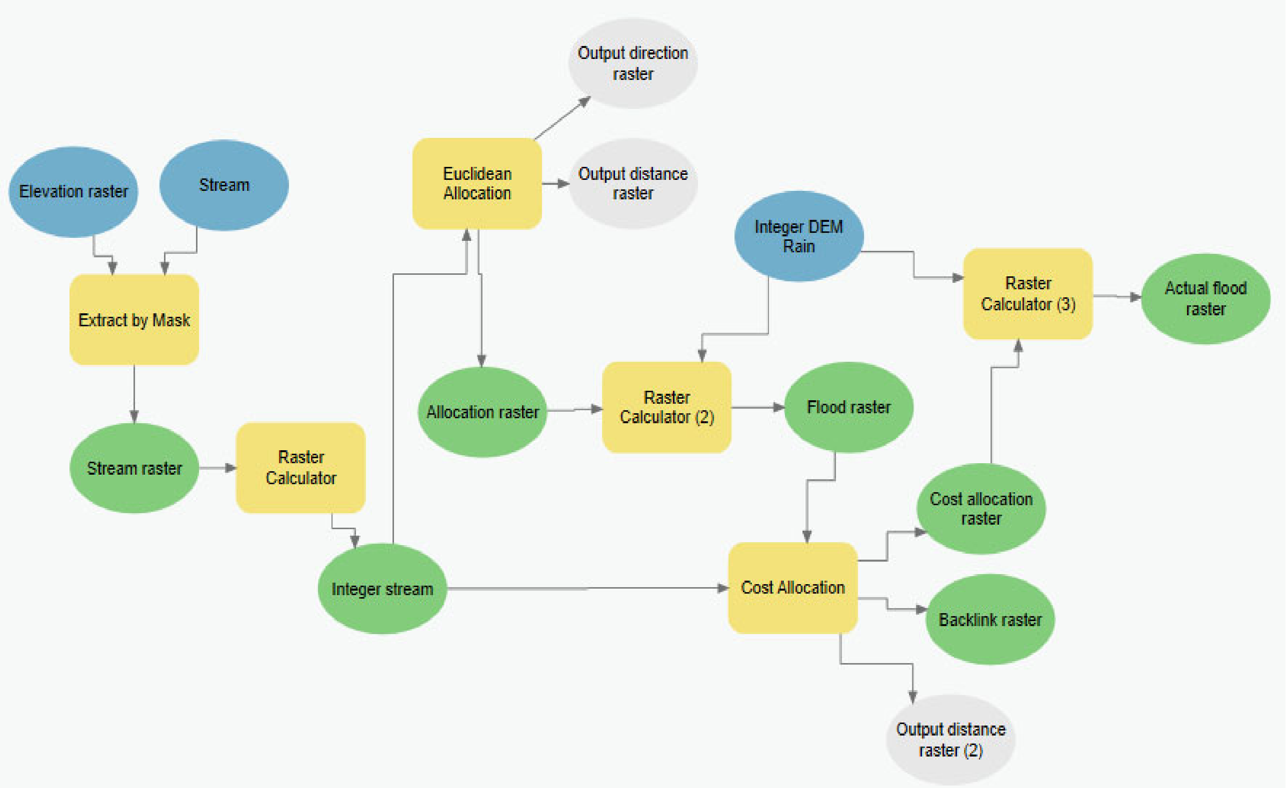


Figure 2.2.6. Flood calculation in ArcGIS. The details are described in the section below.

The flood inundation calculated using water levels estimated from the upstream river length is abbreviated to UPM (UPstream river length Model).

2.2.1 Comparison with MIKE11

The UPM calculations for the 0.9995, 0.9 and 0.84 percentiles were compared with a flood calculation based on water levels estimated with MIKE11. The water levels calculated with MIKE11 only covered Odense River, Sallinge River, Silke River, Haagerup River, Lindved River and Holmehave Bæk. The elevation points (water level) were manually placed in GIS according to the location of the measuring stations, given as distances in metres measured from a fixing point that is easily recognisable on a map. The measurements were made before 2006 and thus before restoration of many of the wetlands in the Odense River catchment. Since then, numerous streams have been restored and several distances between fixing points deviate from those reported. Therefore, uncertainty exists regarding the location of some of the elevation points in the restored wetlands.

2.3 DEM slope

The slope is calculated using the ArcGIS "Slope" tool on a DEM resampled to 1.6 m cell size.

The slope is reclassified to obtain layers of ≤ 1%, ≤ 2%, ≤ 3%, ≤ 4% and ≤ 5% slope. The layers are generalised using the "Boundary Clean" tool and the "Majority" (8 cells) filter. Next, all five slope layers are individually added to the Agrosinks Extended Wetlands (AEW) and Digitalised Høje Målebordsblade (HM) layers, and the attributes for layers, which overlap are extracted to a table. The resulting tables are merged, just as for the flood calculation. 5% slope had the highest cell count and was selected for use in the index model.

2.4 Index model

An index model is computed in Raster Calculator by summing the reclassified input raster. The input rasters are the UPM-calculated flood at the 0.9995 percentile, the calculated 5% slope, the Digitalised Høje Målebordsblade and Agrosinks Extended Wetlands, whic reclassified to the following values:

- UPM-calculated flood, 0.9995 percentile (F): 1
- 5% slope (S): 10
- Agrosinks Extended Wetlands (AEW): 100
- Digitalised Høje Målebordsblade (HM): 1000.

The sum of input raster shows where the different layers overlap (see Figure 2.4.1). For example, a value of 1111 means that all layers overlap and a value of 11 that flood and slope overlap (see Table 2.4.1).

Table 2.4.1. Overview of index model values.
F = Flood, S = Slope, AEW = Agrosinks Extended Wetlands, HM = Digitalised Høje Målebordsblade.

Value	Layers	Value	Layers
0	-	1000	HM
1	F	1001	HM + F
10	S	1010	HM + S
11	S + F	1011	HM + S + F
100	AEW	1100	HM + AEW
101	AEW + F	1101	HM + AEW + F
110	AEW + S	1110	HM + AEW + S
111	AEW + S + F	1111	HM + AEW + S + F

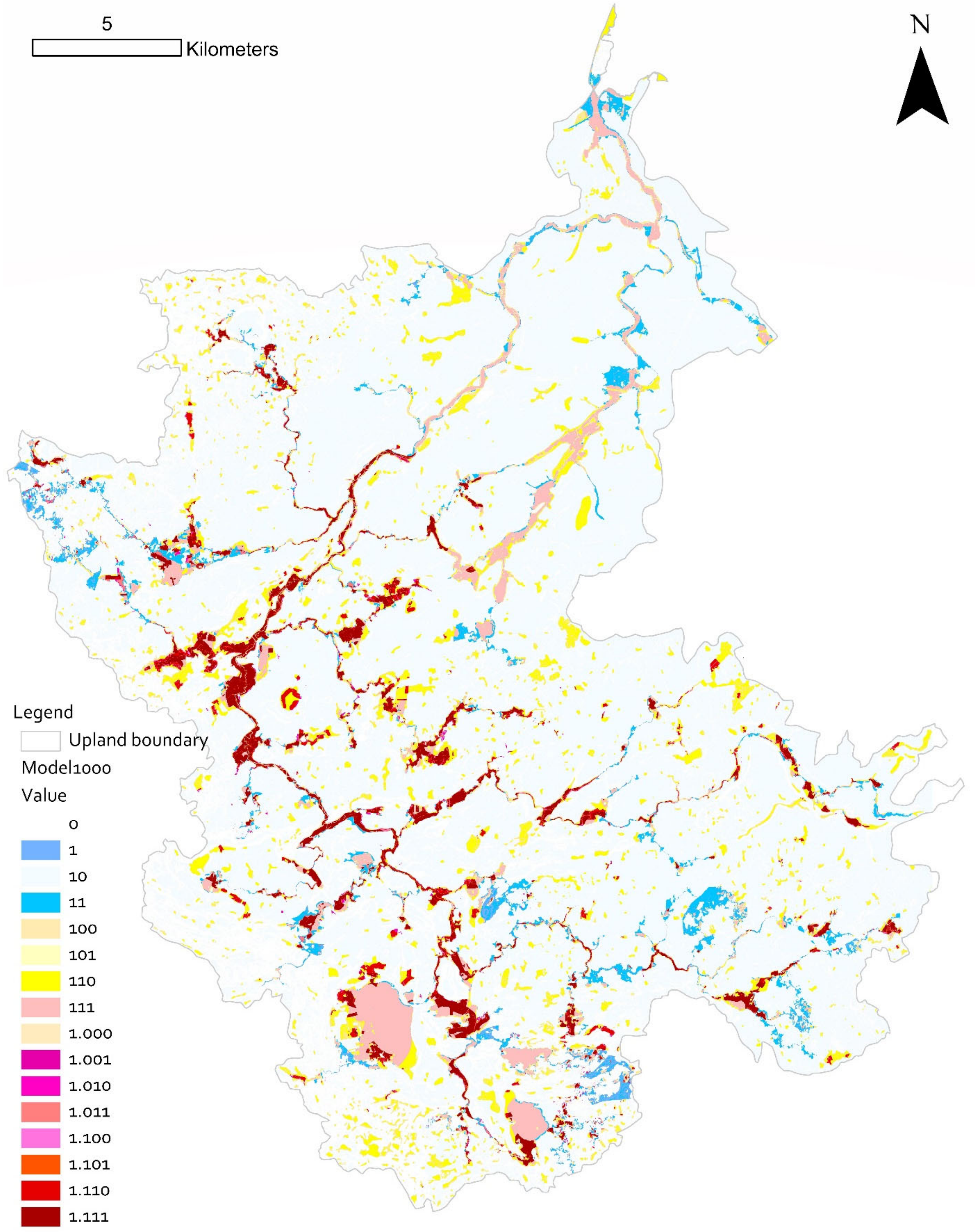


Figure 2.4.1. Index model where each layer combination is unique. 1 as first digit = presence of flood; 1 as second digit = presence of slope; 1 as third digit = presence of Agrosinks Extended Wetlands; 1 as fourth digit = presence of digitalised Høje Målebordsblade

The initial intention was that only areas where all rasters overlap would be defined as potential wetlands. However, as Høje Målebordsblade have only been digitalised within a 100 m buffer of a stream network, and the layer only covers a limited fraction of the potential wetland area. Additionally, Høje

Målebordsblade is not an accurate indicator of past wetland areas as many wetlands already had been modified with ditches at that time (Madsen, 2010). The flood calculation does not cover the whole stream network as forest ditch clutters were removed. Therefore, using the flood as a criterion for wetland restoration would exclude all the streams for which flood was not modelled. Additionally, due to the flood calculation predicting flood in areas where its occurrence otherwise seems questionable, the flooded area alone cannot be used as an indicator of wetland area.

All attributes from the index model with a value above 11 were converted to polygons to obtain continuous areas that can later be reshaped. An overview of the model values and indication of whether they were used in the raster to polygon conversion process or not is given in Table 2.4.2.

Table 2.4.2. An overview of index model values and indication of whether or not they were used to identify the potential wetlands.
F=Flood, S=Slope, AEW=Agrosinks Extended Wetlands, HM=Digitalised Høje Målebordsblade

Value	Layers	Included/excluded	Total area, ha
0	-	-	-
1	F	-	496.9
10	S	-	35169.5
11	S + F	-	1112.5
100	AEW	+	1297.5
101	AEW + F	+	310.0
110	AEW + S	+	2687.7
111	AEW + S + F	+	2061.0
1000	HM	+	60.2
1001	HM + F	+	26.9
1010	HM + S	+	71.9
1011	HM + S + F	+	82.1
1100	HM + AEW	+	151.6
1101	HM + AEW + F	+	182.3
1110	HM + AEW + S	+	429.9
1111	HM + AEW + S + F	+	1404.8

The total converted area was 9,766 ha. As only riparian wetlands were included in the analysis, wetlands not adjacent to the stream network were excluded, resulting in inclusion of 7,694 ha of riparian wetlands. To set restrictions for the number of wetlands to be analysed, wetlands with an area below 1 ha were excluded, removing 107 ha of potential wetlands. The remaining wetlands were reshaped to make the area fit better with the flat and potentially flooded areas. Also the already restored wetland area was removed from the potential wetland area and the wetlands were reshaped to exclude buildings. Large continuous potential wetland areas were split into smaller parts to better portray the variation in N removal. For example, a 600 ha large wetland area may exhibit large variations in N loads from the direct upland area and a large area may, therefore, show variations in N removal. Splitting the potential wetland into smaller sections gives the opportunity to differentiate between areas with high and low N loads and N removal. As N removal is important in wetland restoration, such splitting directly contributes to create a better overview regarding the restoration of a potential wetland area. The resulting potential wetland area was 5,007 ha.

The index model shows all the areas that likely used to be wetlands in the past. However, as many of these may not have been subjected to artificial modification, they are not a target for restoration. Wetlands are restored if (1) the wetland area itself has been drained, (2) if the direct upland area has been drained and the tiles lead the water directly into the stream and / or (3) if the stream channel has been straightened (Hoffmann et al., 2005). The layer showing drainage probability was used to estimate drained wetlands or wetlands featuring drainage in the direct upland area (or both). The final result is 3,617 ha of potential wetlands.

2.5 Calculations

2.5.1 N load

The direct upland to a wetland is defined as the area from which precipitation - and N - is flowing to the stream (Hoffmann et al., 2018b). The direct upland area is calculated in ArcGIS using the "Watershed" tool where the hydrological upland area is computed based on a flow direction raster.

The N loss from the direct upland is calculated using the following formula (Naturstyrelsen, 2014):

$$N_{loss\ per\ ha\ year} = 1.124 * \exp(-3.08 + 0.758 * \mathrm{LN(A)} - 0.003 * \mathrm{S} + 0.0249 * \mathrm{D}),$$

where
A = yearly runoff in mm
S = % sandy soil
D = % agricultural area.

The total N loss from a direct upland is calculated as follows:

$$N_{loss,total} = N_{loss\ per\ ha\ year} * direct\ upland\ area\ (ha)$$

2.5.2 N removal

Irrigation with drainage water

In wetlands irrigated by drainage water, a 50% removal rate is assumed. If the irrigated wetland area has a high infiltration capacity, the assumed removal rate is increased to 75% (Naturstyrelsen, 2014).

The probable drainage layer shows the drainage probability as a value between 0.1 and 0.9, corresponding to 10% and 90% probability. The ArcGIS tool "Zonal statistics" is used to obtain the mean drainage probability. It is assumed that an upland with a mean of at least 50% drainage probability is drained, and these direct uplands are thus classified as uplands which will irrigate the wetland with drainage water, and 50% of the N load from these upland areas will expectedly be removed (Naturstyrelsen, 2014). If infiltration occurs, N removal is estimated to 75%. To find areas with infiltration, soil permeability is roughly estimated in the upland areas found within the boundaries of the wetland. In the watershed calculation, an upland area was created for each natural bounded wetland along the river and for each wetland, soil permeability calculation was undertaken based on the Danish soil classification system (JB). JB soil types 1-3 have high to very high permeability (set to 1), JB 4 have moderate permeability (set to 0.5) and JB 5-11 have low permeability and was set to 0 (Hoffmann et al., 2018b). Organic matter varies in permeability according to its degree of decomposition, highly decomposed matter having low permeability (Hoffmann et al., 2018b). JB11 is classified as humus and is therefore assumed to be highly decomposed with low permeability (i.e. due to being in agricultural use before restoration). Drainage water flowing into wetland areas with a mean permeability above 0.5 is assumed to have enhanced N removal due to infiltration and is thus estimated to remove 75% of the calculated N load.

Flood inundation

In inundated floodplains, N removal is estimated to 1.0 kg per ha per day if the N concentrations are below 5 mg N per L and above 2-2.5 mg N per L and to 1.5 kg N per ha per day if the N concentrations are above 5 mg N per L (Naturstyrelsen 2014). The removal is dependent on a continuous supply of nitrogen, i.e. continuous water exchange and supply of N in the flooded area. N removal rates are set to zero at distances exceeding 100 m due to lack of continuous water exchange and, consequently, lack of N removal (Naturstyrelsen, 2014).

For inundated wetlands, flooding is calculated for 60 days in potential wetlands, while in restored wetlands flooding is calculated for 60-127 days as some of these are known to be flood inundated for more than 60 days per year (Hoffmann et al., 2006).

Groundwater

Typically, wetlands dominated by groundwater flow remove 90% of the N load (Naturstyrelsen, 2014). There is no available data on where groundwater flow occurs and the undrained upland areas are therefore assumed to have a diffuse flow path through the soil, presuming conservatively an N removal of 75%.

Shallow lakes

N removal in a shallow lake is estimated according to following formula:

$$N_{retention\ (\%)} = 42.1 + 17.8 \ * \ log_{10}(T_w)$$

The water residence time in years (T_w) is calculated as $T_w = \frac{V}{Q_{til}}$, where Q_{til} is the water inflow to the lake and V the water volume of the lake. The water residence time must be at least 1 week in order to calculate the N retention (Naturstyrelsen, 2014).

Due to lack of data on lake volume, N retention in lakes cannot be calculated.

Change in land use

Conversion from agricultural land use to nature results in reduced N loss from the soil. The reduction in the N load to the aquatic environment is included in the N removal effect of a restored wetland. A value of 50 kg N per ha of converted land is added to the N removal estimate in potential wetlands (Naturstyrelsen, 2014).

2.5.3 P retention

Phosphorus (P) sedimentation is calculated according to the methods in Hoffmann et al. (2018b). For each flood-inundated wetland, a stream upland area is estimated. Depending on whether the model-calculated loss of particle-bound P (PP) is <0.14, 0.14-0.36 or >0.36 kg P per ha per year in the upland area, the P deposition rate is 0.5, 1 or 1.5 kg P per flooded ha per day, respectively. The formula for model-calculated loss of PP consists of the following input data on the stream upland area to a wetland: share of sandy soil, share of agricultural soil, stream slope, base flow index (BFI), runoff and share of wetland area. The loss of PP has already been calculated for various smaller sub-catchments in the Odense River catchment, and the available data are used to estimate the P deposition rate.

P deposition is calculated within 25 m from the stream if the stream upland area is 2-10 km^2, within 75 m from the stream if stream upland area is 10-100 km^2 and within 100 m if the stream upland area is larger than 100 km^2. The PP deposition is calculated as follows:

$$\begin{aligned} &Sedimentation\ (kg\ P\ per\ year) \\ &\qquad = days\ with\ flood\ inundation\ \times\ P\ deposition\ rate \\ &\qquad \times\ flooded\ area \end{aligned}$$

The P sedimentation is calculated for 36 days (10% of the year) using the UPM-calculated flood based on the 0.9 percentile.

As no more than 10% of the PP lost from the upland area per year can be expected to be deposited during flooding, the calculated P deposition must be checked for overestimation (Hoffmann et al., 2018b). For this purpose, the following control equation from Hoffmann et al. (2018b) is used:

$$\text{PP deposition} = \text{Loss rate (PP)} \times \text{stream upland area} \times 0.1$$

If the calculated PP sedimentation exceeds the potential deposition calculated with the control equation, the latter value is used.

2.5.4 Restored wetlands

The uplands, N load and N removal are calculated with the methods described in section 2.5.1 and 2.5.2. A summary of the project area and ID is given in Table 2.4.4.1.

Table 2.4.4.1. Overview of the restored wetlands, their area and ID.

Wet ID	Project name	Area, ha
1	Maebækken	10.9
2	Sandholt Møllebæk	54.7
3	Silke River	146.9
4	Odense River near Brobyværk	104.4
5	Odense River, Phase 1	68.8
6	Odense River, Phase 2	295.7
7	Brahetrolleborg Gods	45.6
8	Geddebækken	44.1
9	Karlsmosen	62.5
10	Hammerdam	9.8
11	Posens Mose	26.1
12	Sallinge River southwest near Boltinge	2.8
13	Sallinge River northwest near Boltinge	3.1
14	Sallinge River east near Boltinge	8.5
15	Sallinge River near Findinge	36.8
16	Sallinge River near Præstebrogyden	1.8
17	Sallinge River near Dalsmøllevej	2.8
18	Sallinge River near Sallinge	23.0
19	Sallinge River near Gestelevlundevej	36.4
20	Sallinge River near Sallingelunde	16.3

An overview of the location of the restored wetlands is found in Figure 2.4.4.1.

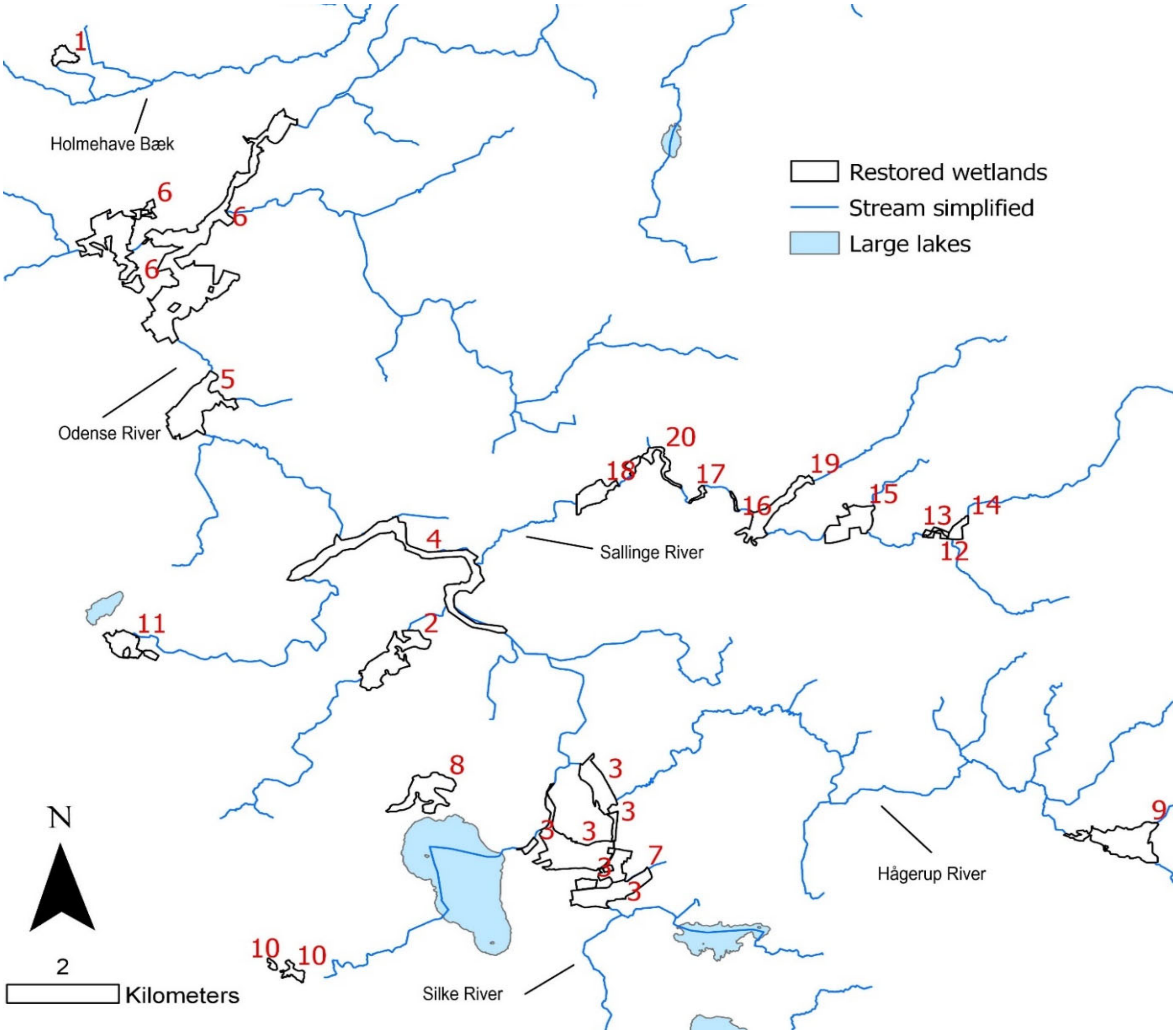


Figure 2.4.4.1. Location of the restored wetlands and their ID.

3 Results

3.1 Flood calculation

3.1.1 Upstream Length Model (UPM)

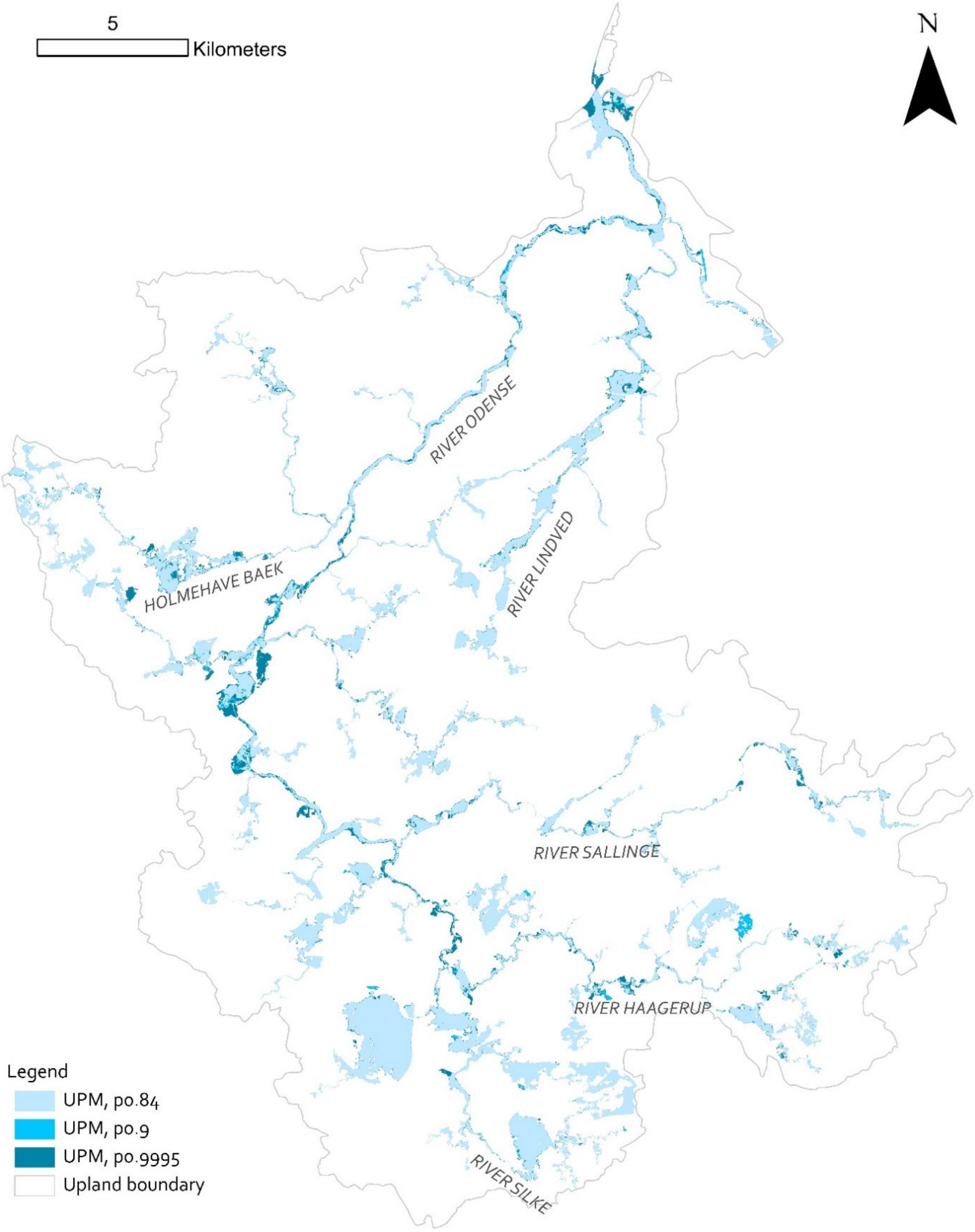


Figure 3.1.1.1. Flood calculated from stream water levels as a function of upstream length (UPM) – 0.84, 0.9 and 0.9995 percentiles are shown. The light blue areas show an overlap between multiple percentiles, the darkblue areas indicate flooding only at the highest percentiles. 0.84 percentile = flooding 16% of the year; 0.9 percentile = flooding 10% of the year; d 0.999^{h} percentile = flooding 0.0005% of the year.

In general, the modelled flood fits well with the other index layers both upstream and downstream and seems to be evenly distributed across the whole catchment. In some areas, the modelled flood has been cut off 1,000 m from the stream, which owes to the fact that the analysis was conducted within a 1000 m distance from the stream. In some areas though, the model seems to overestimate the flood as depicted below in Figures 3.1.1.2 and 3.1.1.3.

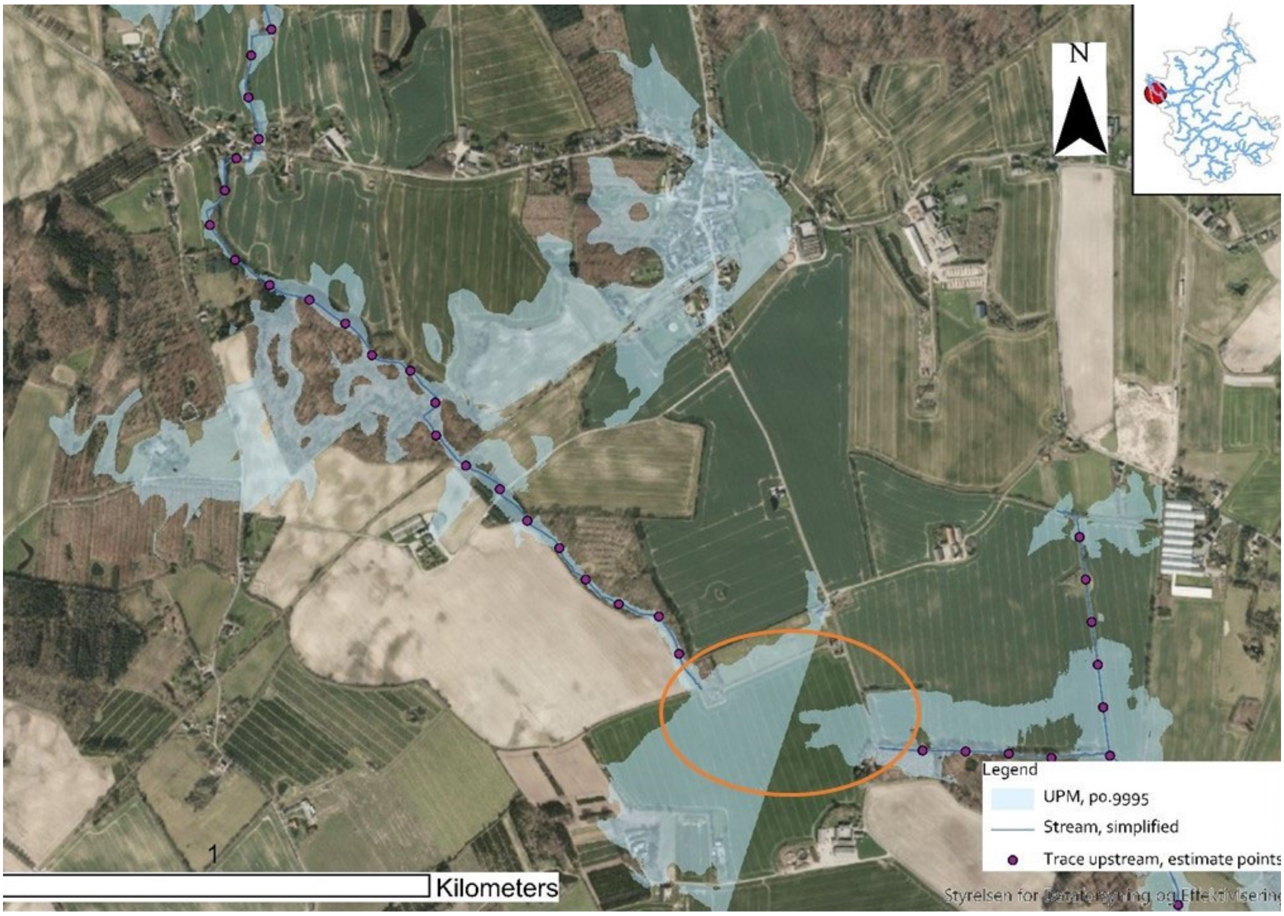


Figure 3.1.1.2. Map enlargement showing areas where flooding is overestimated. The overestimation is caused by mismatch between the stream delineation and the DEM. The stream in the centre of the map should be disconnected to the north and connected through a pipeline to the to the stream in the lower right corner (missing pipeline in the orange marking).

The overestimated flooding shown in Figure 3.1.1.2 is caused by a flaw in the stream delineation. According to the DEM the runoff is to the south-east, and hence the stream running from the centre of the figure towards the upper left corner should have been flipped and connected to the stream in the lower right corner.

The overestimated flooding shown in Figure 3.1.1.3 is also caused by false delineation of the stream. The stream in the centre of the map is wrongly drawn over a local top in the landscape forcing a raise in the estimated flood by almost a meter.

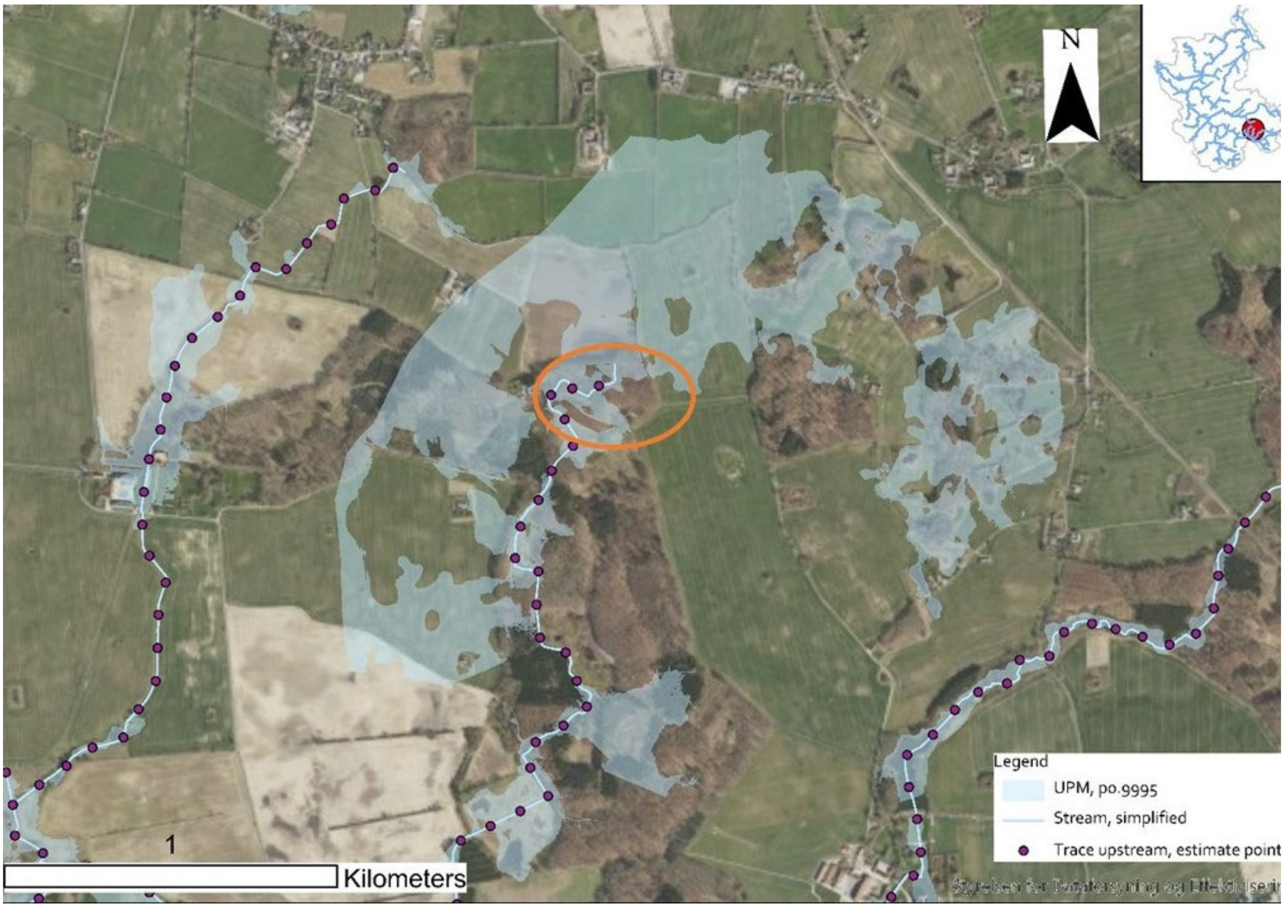


Figure 3.1.1.3. Map enlargement showing areas where flooding is overestimated. The stream in the centre is wrongly delineated over a local top in the landscape (wrong delineation in the orange marking). This results in an overestimated raise in waterlevel causing a large spillover upstream the stream cource.

As shown in Figure 3.1.1.4, the modelled flood fits very well with the wetland areas noted in Høje Målebordsblade, where the restored wetlands Silke River - VMPII / SVNI (WetID=3) and Brahetrolleborg Gods – VMPII (WetID=7) appear. Also, the calculated flood follows the wetland pattern from Høje Målebordsblade around Arreskov Lake but is limited to 1,000 m from the simplified stream due to the analysis setup. The modelled flood area also follows the pattern of the wetland signature in the Brahetrolleborg Gods restored wetland.

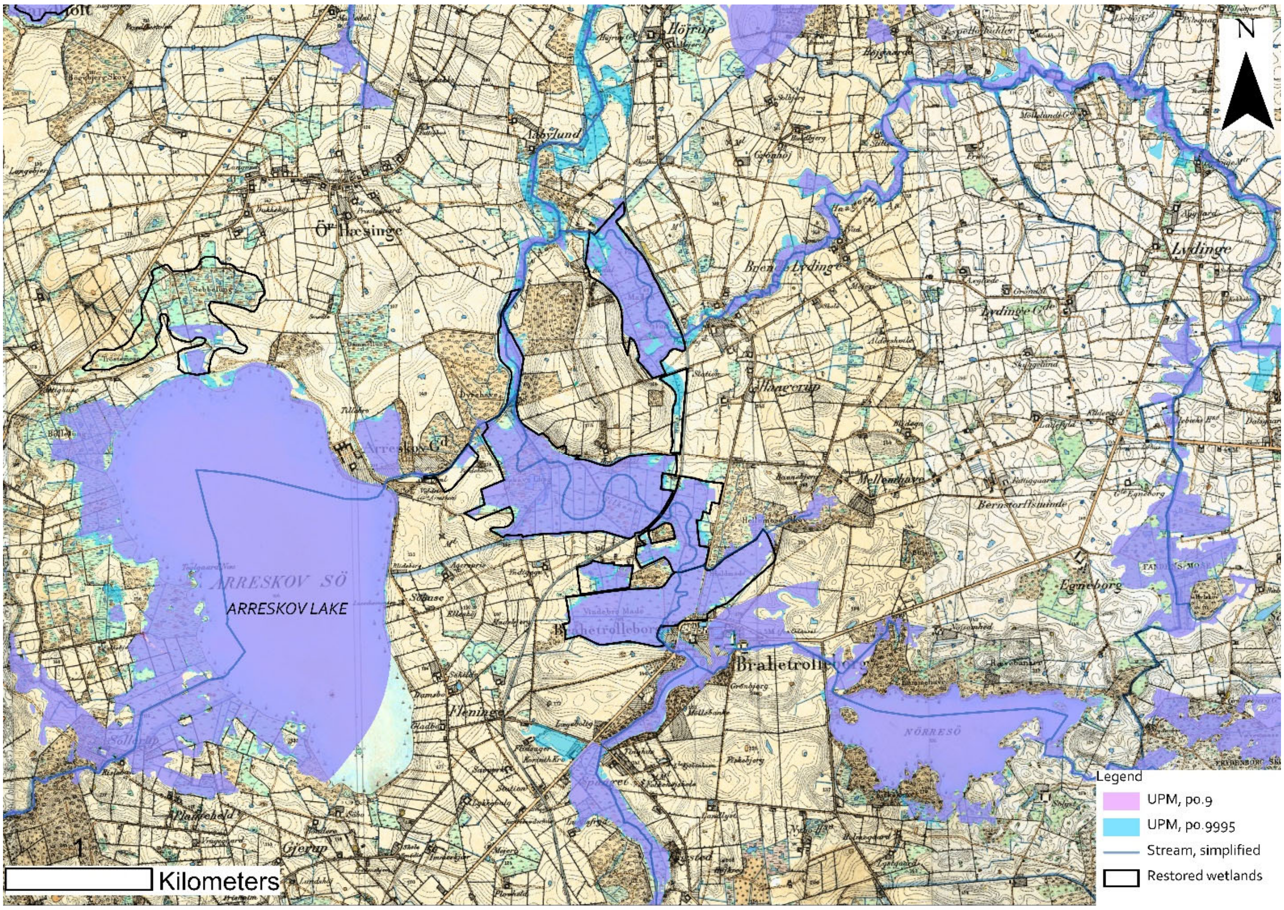


Figure 3.1.1.4. Close-up of the modelled flood based on the stream water levels as a function of the upstream area near Arreskov Lake and the restored wetlands of Silke River - VMPII/SVNI (WetID=3) and Brahetrolleborg Gods – VMPII (WetID=7) with Høje Målebordsblade as background. Wetlands are displayed in HM as green areas with stylised grass signature. The purple colour is caused by overlapping areas of UMP po.9 and UMP po.995 flooding.

As can be seen in Figure 3.1.1.5, the modelled flood fits well further upstream. Also here, the simulated flood follows the shape of the wetlands in Høje Målebordsblade. In many areas, there are only negligible differences between the 0.9 and 0.9995 percentiles in terms of flooded area. For example, within the boundary of the Brahetrolleborg Gods restored wetland, the 0.9995 percentile yielded only an additional 1.12 ha of flooded area compared with the 0.9 percentile, resulting in a 2.7 % increase in flooded area. In the Odense River phase 2 project - VMPII / SVNI (WetID=6), an additional area of 58.47 ha was flooded with the 0.9995 percentile, resulting in an area increase of 31%. On the right side of the Brahetrolleborg Gods wetland, an area called Lundemose is flooded as well (see Figure 3.1.1.5).

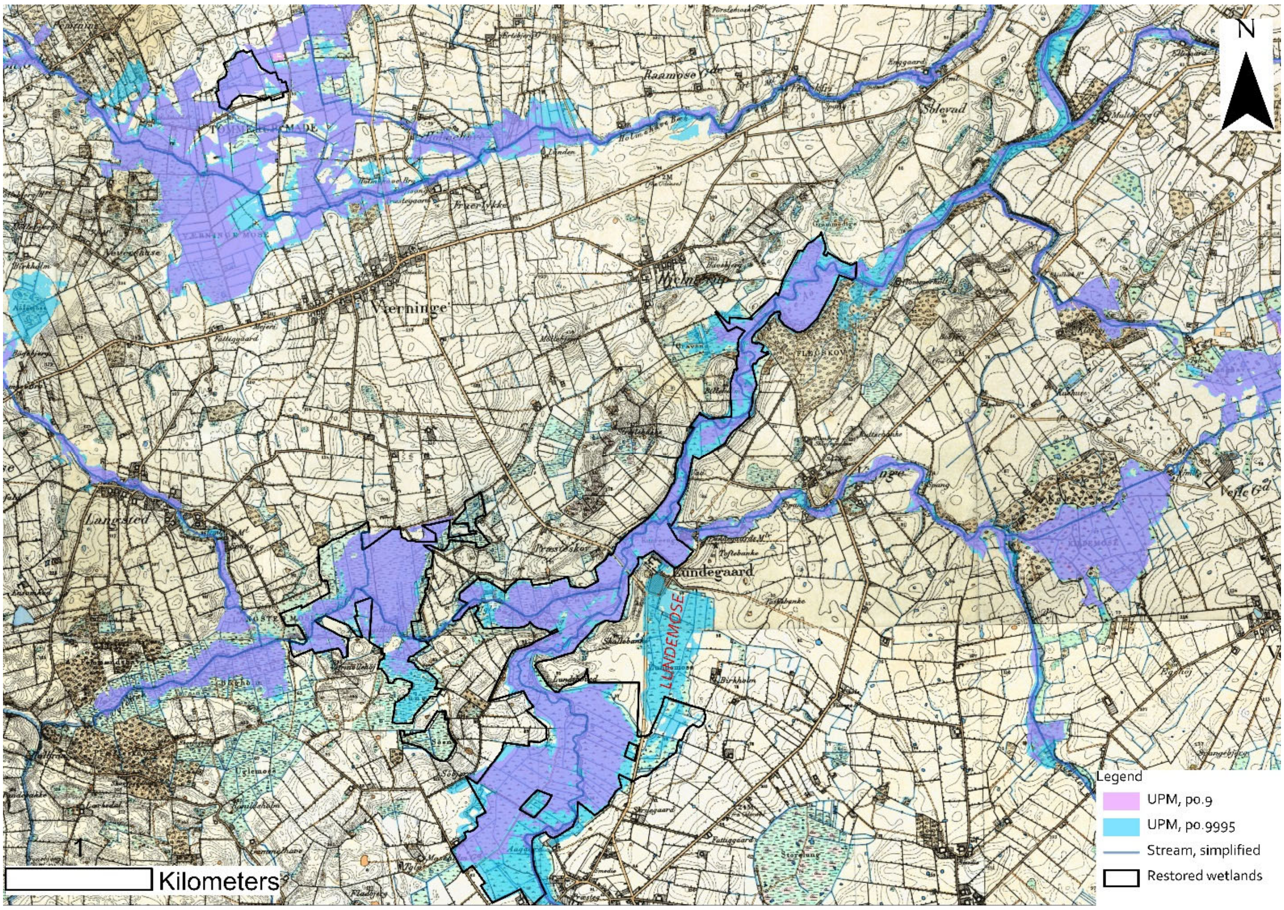


Figure 3.1.1.5. Close-up of the modelled flood based on the stream water levels as a function of the upstream length near Odense River phase 2 - VMPII/SVNI (WetID=6) with Høje Målebordsblade as background. This restored wetland is located further downstream than the area displayed in Figure 3.1.1.4.

3.1.2 Comparison of UPM and MIKE11

In general, the UPM and MIKE11 calculated floods for the 0.9995 percentile are very similar apart from Holmehave Bæk and River Haagerup where the MIKE11 values are highly overestimated (Figure 3.1.2.1), when compared to the other index layers (Høje Målebordsblade, Extended Wetlands, Slope). The overlapping area between AEW and the flood calculation is 176 ha (7.6%) smaller for the UPM than the MIKE11 calculated flood. The overlapping area between HM and the flood calculation is 67 ha (6.3%) smaller for the UPM than the MIKE11 calculated flood.

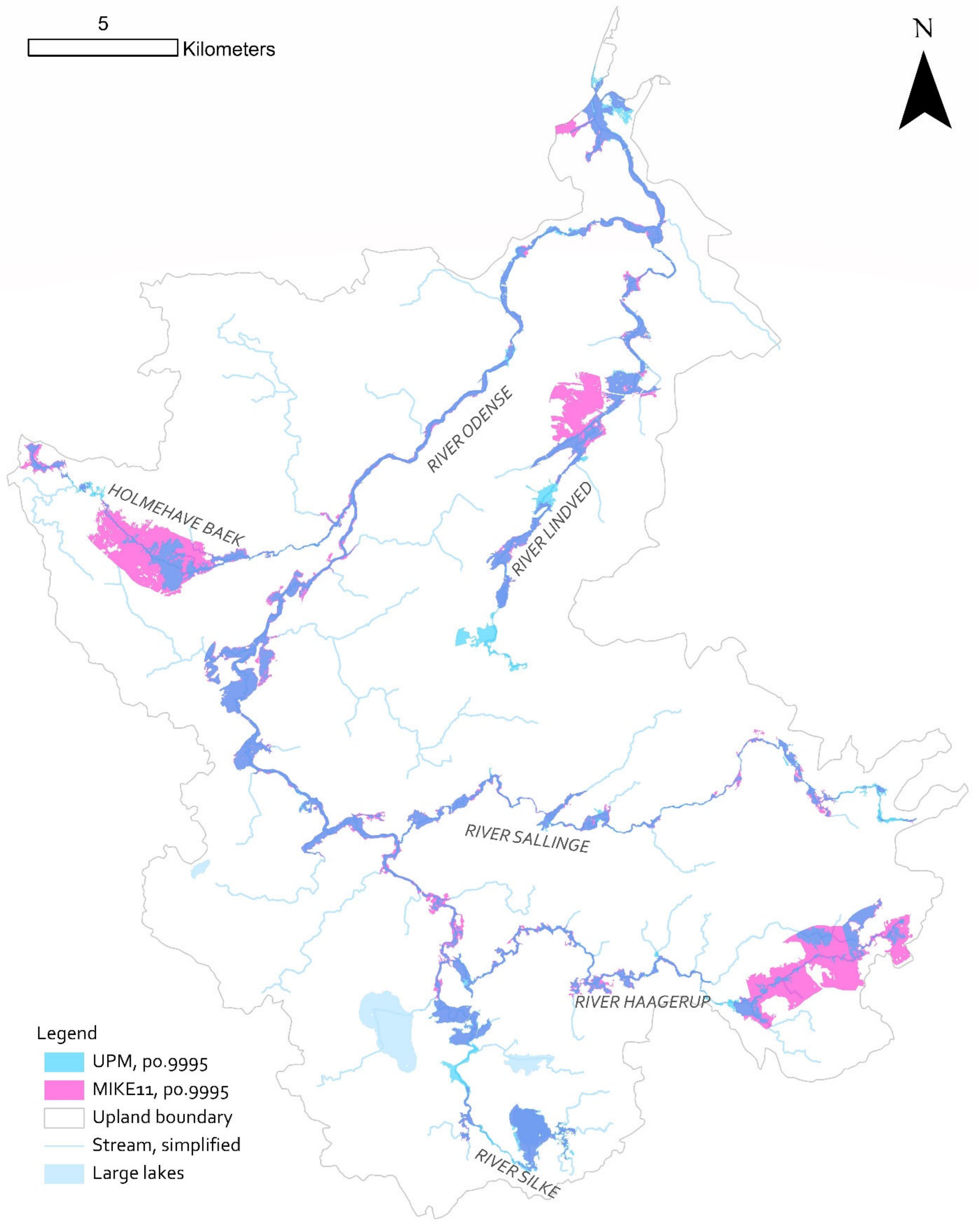


Figure 3.1.2.1. Comparison of the modelled flood based on stream water level elevations from MIKE11 and the Upstream River Length Model (UPM) for the 0.9995 percentile in Odense River, Lindved River, Silke River, Haagerup River, Holmehave Bæk and Sallinge River. The dark blue areas show an overlap between the floods calculated using UPM and MIKE11.

There is also extreme overestimation for Holmehave Bæk and River Haagerup regarding the MIKE11-calculated flood at the 0.9 percentile (see Figure 3.1.2.2). The overlap between the calculated flood and HM is 18.8 ha (2.3%) higher for UPM than MIKE11.

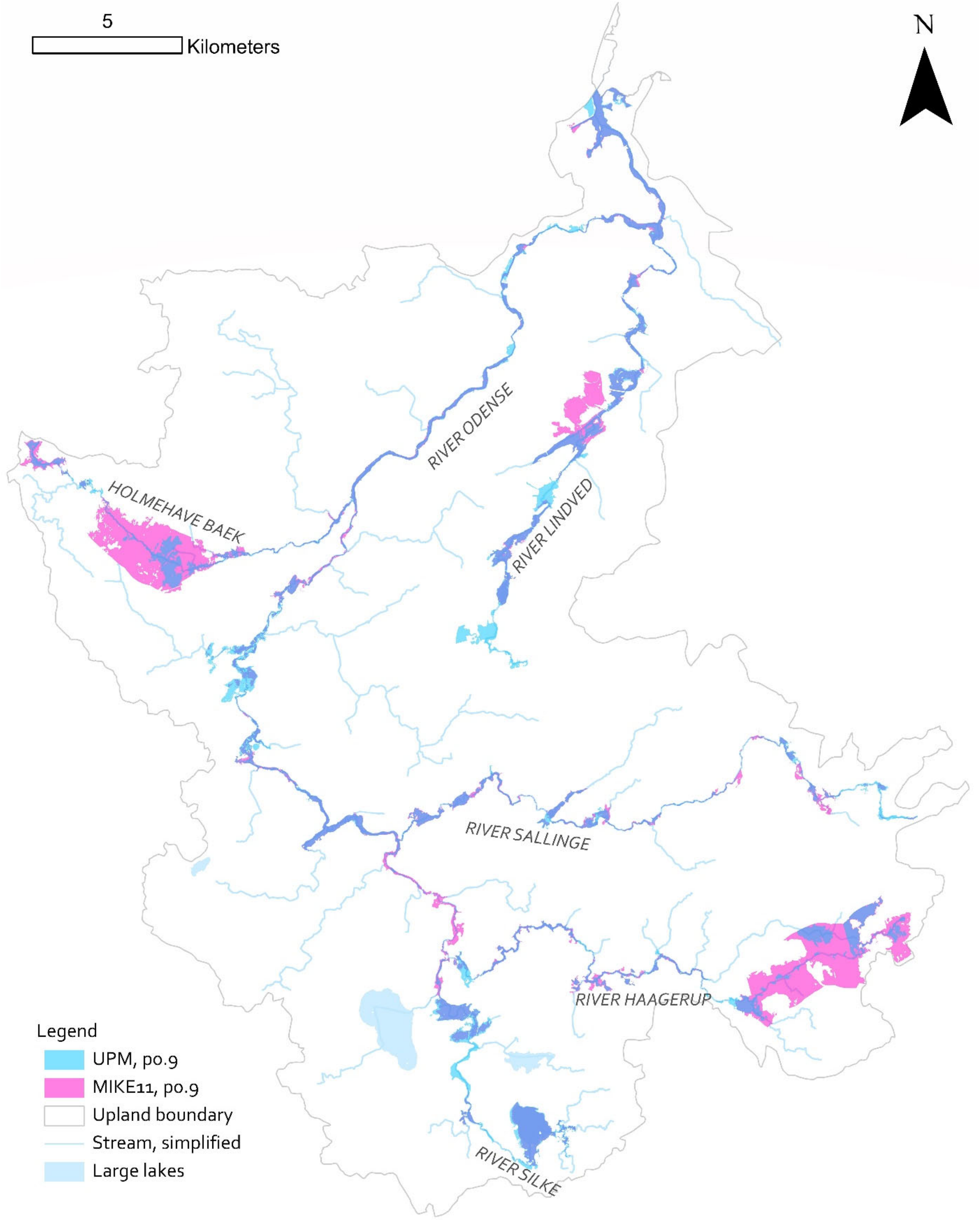


Figure 3.1.2.2. Comparison of modelled flood based on stream water level elevations from MIKE11 and the Upstream River Length Model (UPM) for the 0.9 percentile in Odense River, Lindved River, Silke River, Haagerup River, Holmehave Bæk and Sallinge River. The dark blue areas show an overlap between the floods calculated using UPM and MIKE11.

The extreme overestimation for Holmehave Bæk and River Haagerup when using the MIKE11-calculated flood occurs also for the 0.84 percentile (see Figure 3.1.2.3). The overlap between the calculated flood and HM is 40.4 ha (5.2%) higher for UPM than for MIKE11.

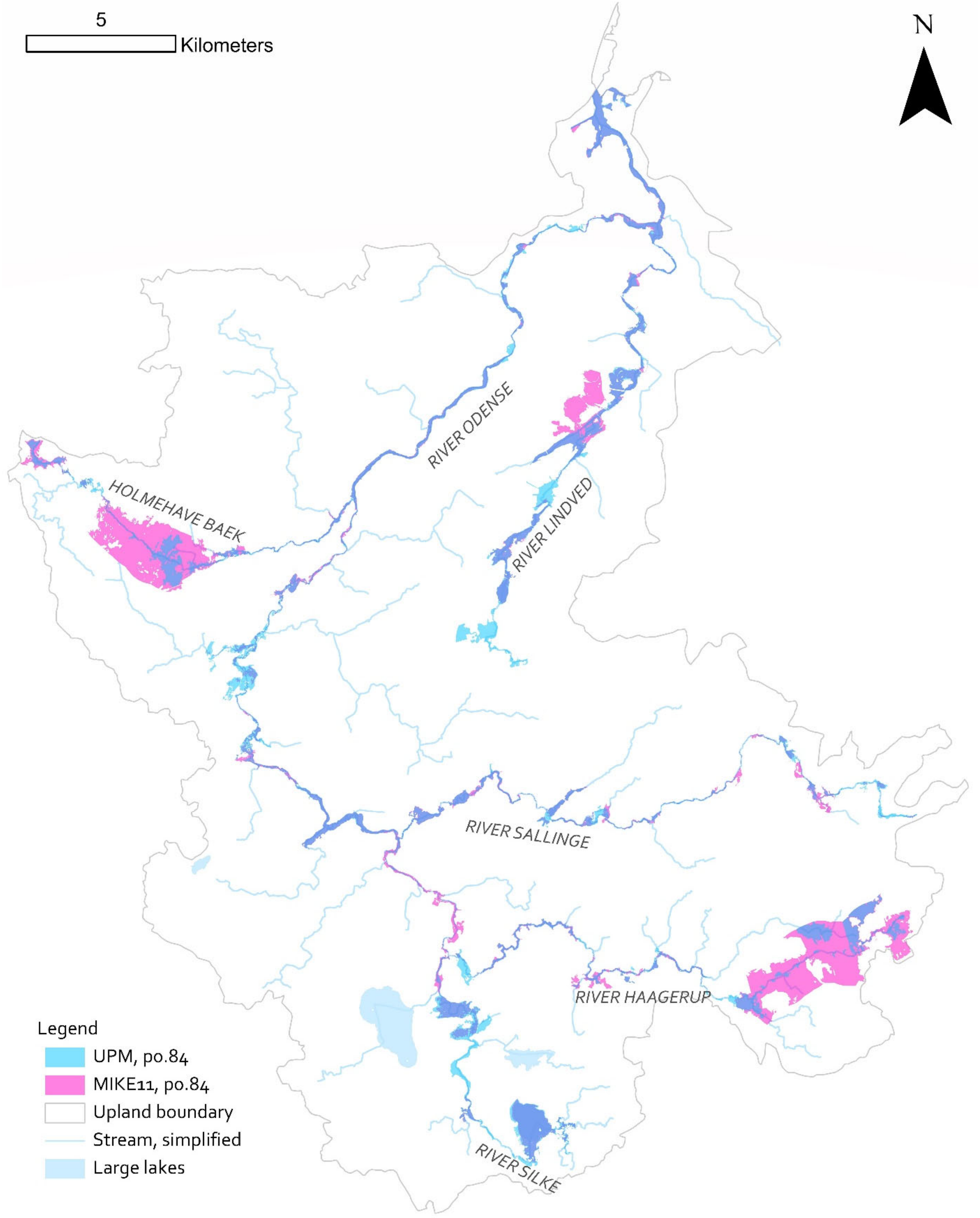


Figure 3.1.2.3. Comparison of modelled flood based on stream water level elevations from MIKE11 and the Upstream River Length Model (UPM) for the 0.84 percentile in Odense River, Lindved River, Silke River, Haagerup River, Holmehave Bæk and Sallinge River. The dark blue areas show an overlap between the floods calculated using UPM and MIKE11.

The high flood estimation of MIKE11 for Holmehave Bæk is displayed in Figure 3.1.2.4. For this specific stream, several stream elevation values were more than 5 m higher than the DEM, likely leading to flooding of a very large built-up area. Furthermore, the flooded area is cut off in the lower left corner as the upper limit for calculation was set to 1,000 m from the stream.

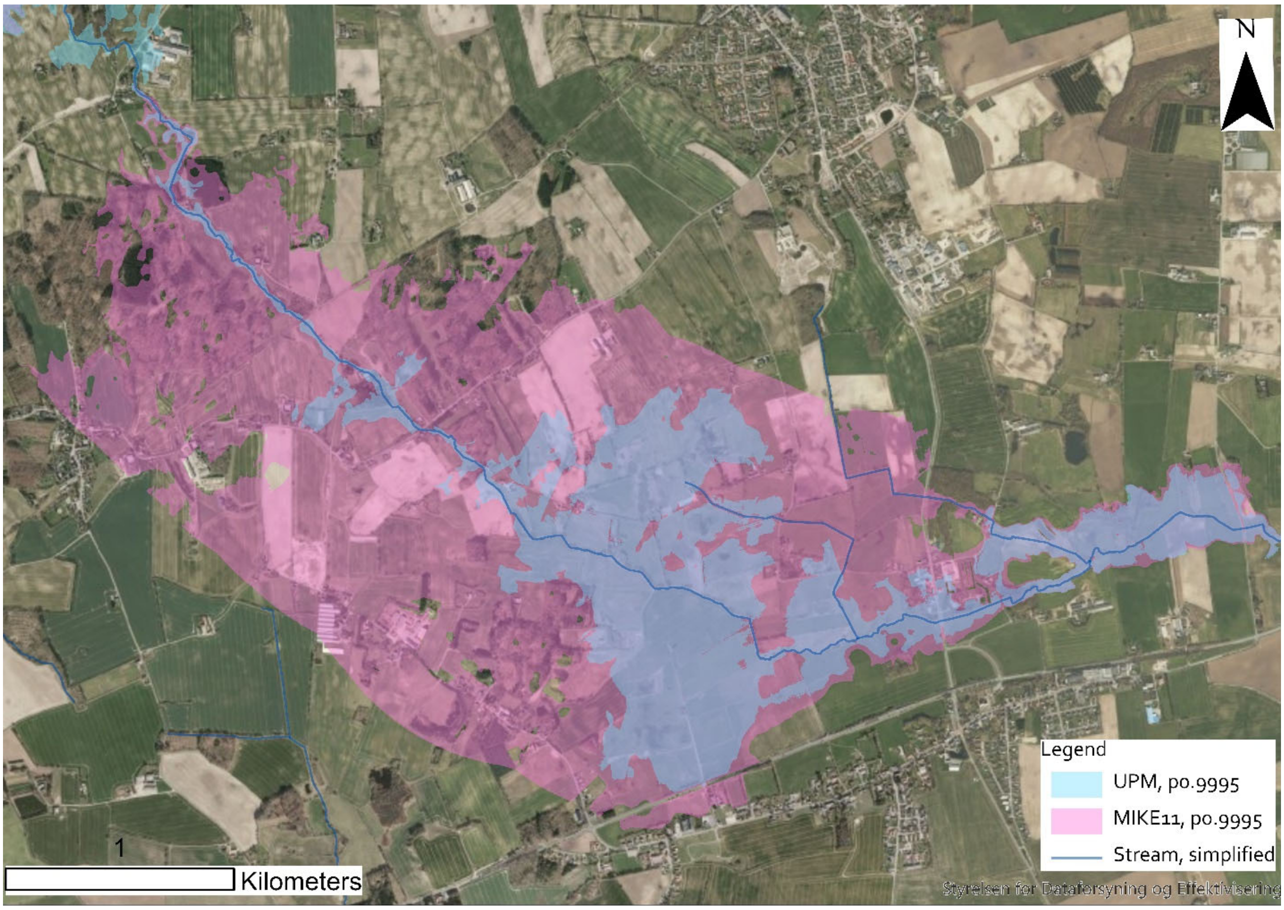


Figure 3.1.2.4. Flooding based on MIKE11 and UPM water elevation values with spring orthophoto as background. The stream is Holmehave Bæk.

On the other hand, for Holmehave Bæk, the UPM follows the shape of the wetlands shown in Høje Målebordsblade (see Figure 3.1.1.5 in the preceding paragraph), which is also the case for the upstream area of River Haagerup. Also here, the values calculated with MIKE11 are about 5 m higher than the DEM values. In fact, the highest DEM value at the River Haagerup source is approximately 99.97 m.a.s.l., while the MIKE11 value for the source elevation point is 104.63 m.a.s.l (0.9995 percentile).

In all three flood calculations, an area at Lindved River is flooded in MIKE11 but not in the UPM. This is due to the simplified stream applied for the UPM estimation where this particular stream branch was removed during the simplification process. Nonetheless, the elevation values in this stream section are up to 80 cm higher than the DEM values, resulting in flooding of the nearby town (see Figure 3.1.2.5).

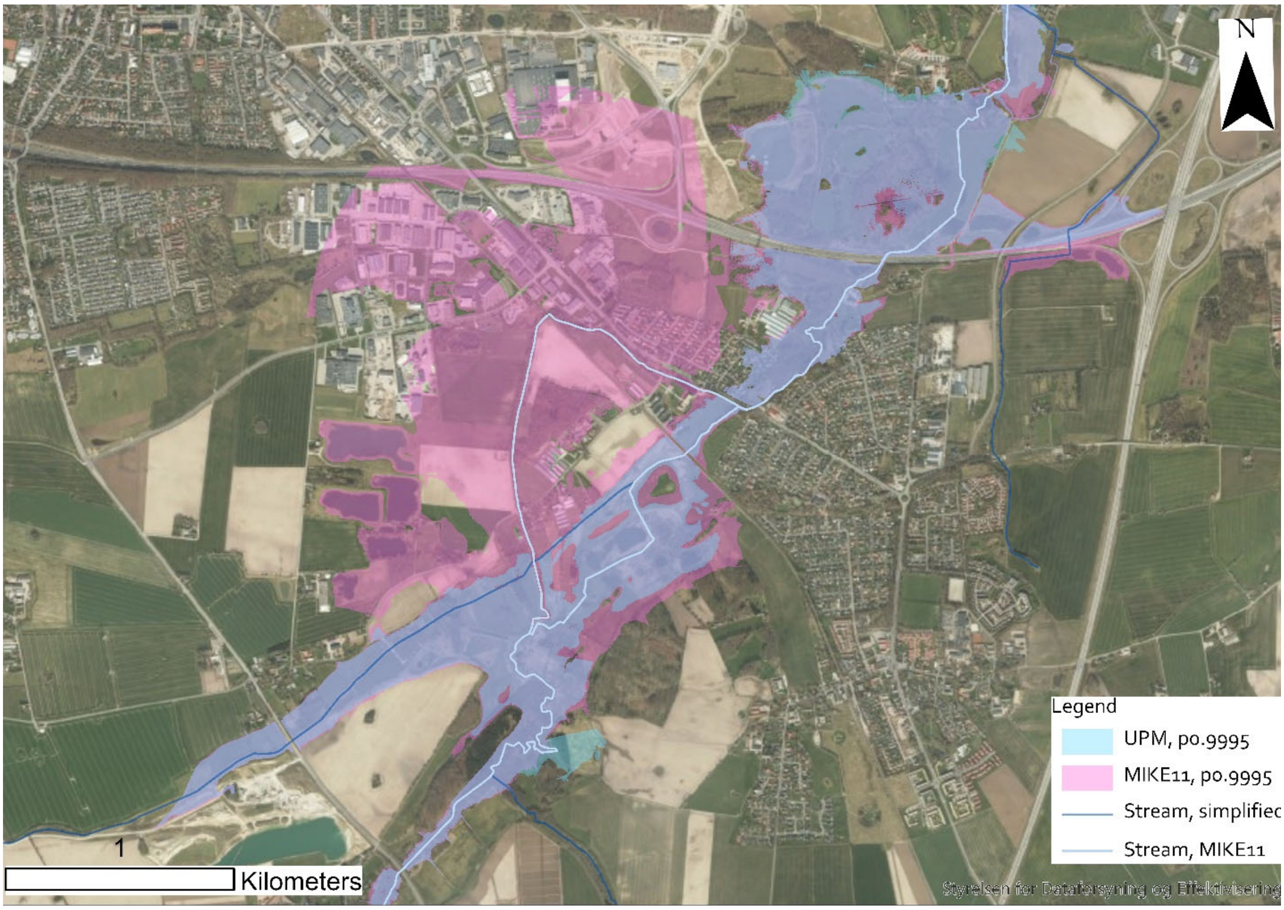
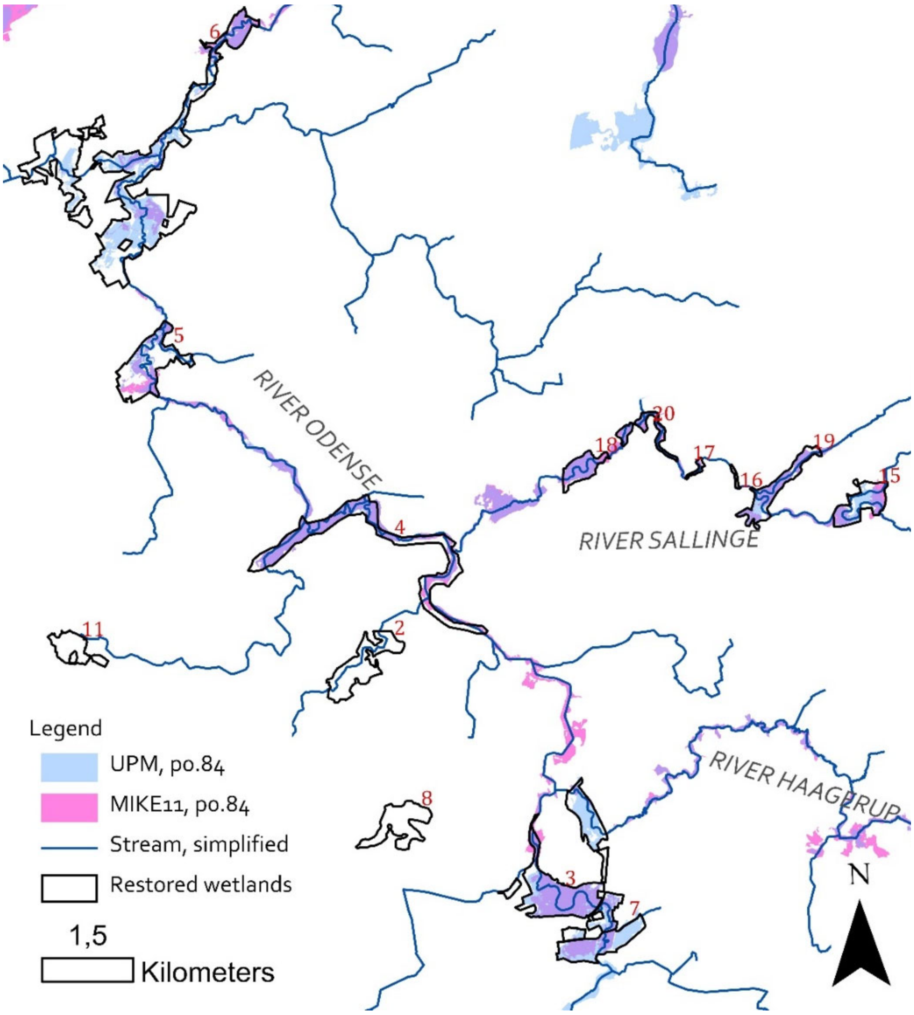


Figure 3.1.2.5. Flooding based on MIKE11 and UPM water elevation values with spring orthophoto as background. The stream flooding the town is Lindved River.

Generally, the floods calculated with UPM and MIKE11 overlap well at the 0.9995 percentile; thus, the differences between UPM and MIKE 11 are most prominent at the lower percentiles. As shown in Figure 3.1.2.6 and Table 3.1.2.1, there are differences in flood coverage between the two flood calculations at the 0.84 percentile.

Figure 3.1.2.6. Differences in flooded area coverage between the UPM and MIKE11 calculated floods based on stream water levels at the 0.84 percentile in several restored wetlands.



Especially the Silke River wetland (WetID=3), Odense River Phase 2 (WetID=6), Brahetrolleborg Gods (WetID=7), Sallinge River northwest near Boltinge (WetID=13), Sallinge River near Findinge (WetID=15), Sallinge River near Dalsmøllevej (WetID=17) and Sallinge River near Gestelevlundevej (WetID=19) exhibit large differences between the UPM and the MIKE11 calculated flood coverage at the 0.84 percentile, while flooding is similar at the 0.9995 percentile (see Table 3.1.2.1).

Table 3.1.2.1. Percentage of wetland area as defined by Høje Målebordsblade compared to flood calculated from UPM and MIKE11 elevation values for the 0.84 and 0.9995 percentiles.

WetID	PROJEKT	% of wetland area flooded, MIKE11, p0.84	% of wetland area flooded, UPM, p0.84	% of wetland area flooded, MIKE11, p0.9995	% of wetland area flooded, UPM, p0.9995
1	Maebækken	100.0	61.1	100.0	78.7
3	Silke River	46.7	74.4	82.7	87.2
4	Odense River near Brobyværk	67.7	57.9	81.0	74.2
5	Odense River Phase 1	38.8	44.3	97.5	95.5
6	Odense River Phase 2	18.5	45.7	79.7	76.5
7	Brahetrolleborg Gods	41.5	89.8	89.6	93.9
9	Karlsmosen	73.1	72.0	76.4	80.7
12	Sallinge River southwest near Boltinge	51.5	49.2	58.3	55.8
13	Sallinge River northwest near Boltinge	61.2	49.4	69.1	65.3
14	Sallinge River east near Boltinge	55.8	43.5	70.2	60.1
15	Sallinge River near Findinge	48.1	62.6	80.4	82.4
17	Sallinge River near Dalsmøllevej	69.4	52.7	82.1	78.1
18	Sallinge River near Sallinge	86.8	76.8	94.0	91.7
19	Sallinge River near Gestelevlundevej	64.8	77.3	82.6	83.4
20	Sallinge River near Sallingelunde	90.3	81.3	95.9	89.5

3.2 N and P retention

As can be seen in Figure 3.2.1 and Table 3.2.1, the majority of the restored wetlands are irrigated with drainage water and flooded. Hammerdam and Sallinge River near Præstebrogyden are expected to remove N via irrigation with drainage water only. In Sallinge River near Sallingelunde and in Sallinge River near Dalsmøllevej, N removal expectedly only occurs through flood inundation.

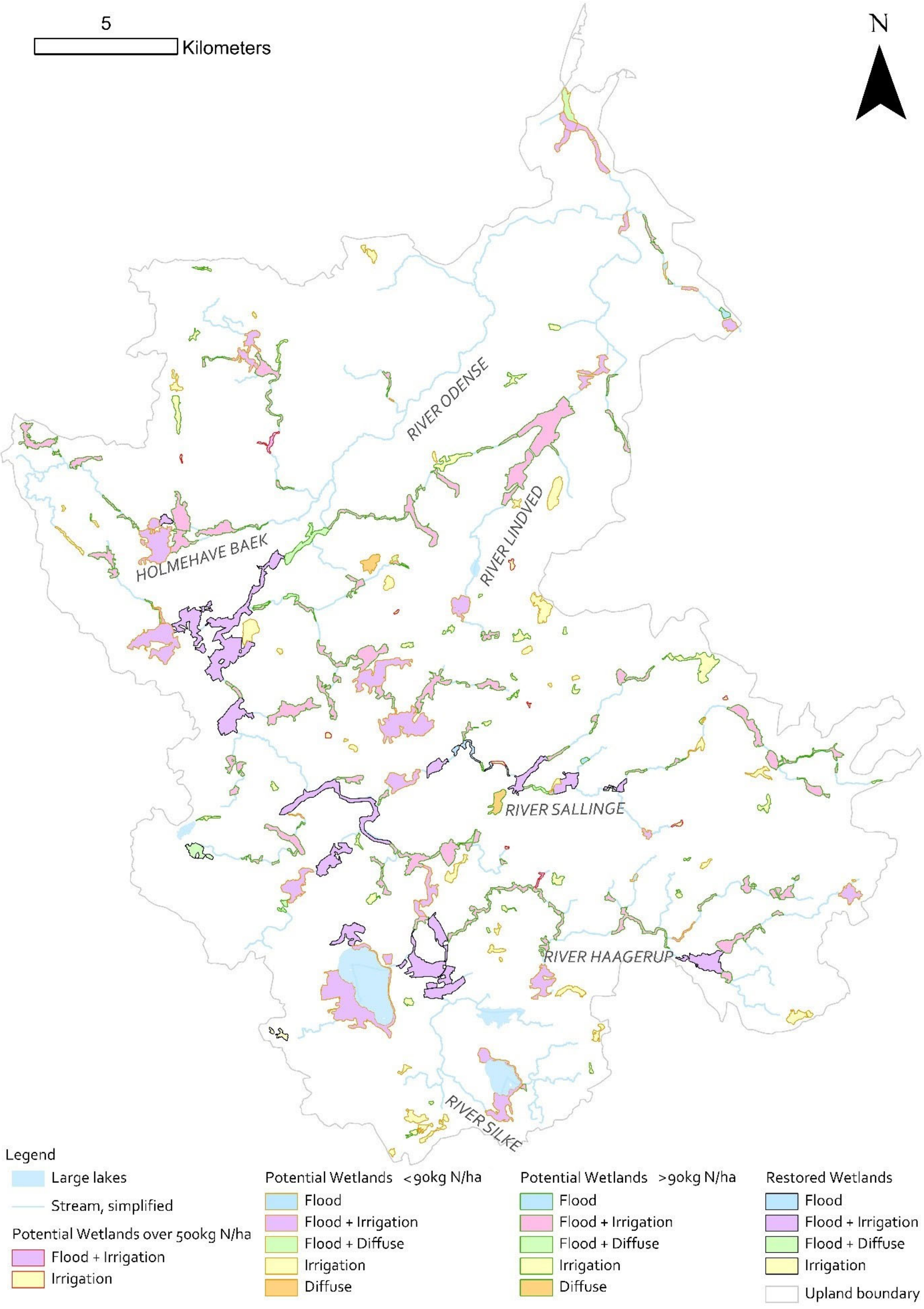


Figure 3.2.1. Potential and restored wetlands classified into flood-inundated wetlands (blue), flood-inundated + drainage water-irrigated wetlands (pink), flood-inundated wetlands with natural flow (also referred to as "diffuse", green), wetlands irrigated with drainage water (yellow), wetlands with only natural flow (also referred to as "diffuse", orange). The restored wetlands are marked with a black edge, the potential wetlands with a calculated N removal of more than 90 kg N/ ha with a green edge, the potential wetlands with a calculated N removal below 90 kg N/ ha with an orange edge and the potential wetlands with a calculated N removal through irrigation of more than 500 kg N/ ha with a red edge.

3.2.1 Already restored wetlands

The total already restored wetland area is 1,001 ha and N removal is calculated to 91.7 tons N per year (see Table 3.2.1.). The total load from the direct upland area is calculated to 81.7 tons N per year. Additionally the restored wetlands receives N load during flooding events. Calculating the flood N removal for 127 days (35% of the year, Table 3.2.1) would result in a total N removal in the restored wetlands of 127 tons N. The N removal in flooded wetlands would increase to 181 kg N per ha in Maebækken (WetID=1), 91 kg N per ha in Sandholt Møllebæk (WetID=2), 124 kg N per ha in Silke River (WetID=3), 159 kg N per ha in Odense River near Brobyværk (WetID=4), 105 kg N per ha in Odense River, Phase 1 (WetID=5), 104 kg N per ha in Odense River, Phase 2 (WetID=6), 103 kg N per ha in Brahetrolleborg Gods (WetID=7), 135 kg N per ha in Karlsmosen (WetID=9), 337 kg N per ha in Posens Mose (WetID=11), 463 kg N per ha in Sallinge River southwest near Boltinge (WetID=12), 179 kg N per ha in Sallinge River northwest near Boltinge (WetID=13), 155 kg N per ha in Sallinge River east near Boltinge (WetID=14), 128 kg N per ha in Sallinge River near Findinge (WetID=15), 97 kg N per ha in Sallinge River near Dalsmøllevej (WetID=17), 243 kg N per ha in Sallinge River near Sallinge (WetID=18), 168 kg N per ha in Sallinge River near Gestelevlundevej (WetID=19) and 150 kg N per ha in Sallinge River near Sallingelunde (WetID=20). Additionally, the restored wetlands are expected to retain approximately 2,750 kg P per year.

Table 3.2.1. The restored wetlands, their classified removal type, wetland area, direct upland area, calculated N load from the direct upland area, calculated N removal expressed as kg N per year, calculated N removal expressed as kg N per ha per year and calculated P deposition in kg P for 36 days per year.

ID	Project	Type	Area, ha	Direct upland area, ha	N load from direct upland area, kg N year	N removal, kg N year	N removal, kg N ha year	N removal including 127 days of flooding	P deposition, kg P, 36 days per year
1	Maebækken	F + Ir	11	40	1,927	1,872	172	181	-
2	Sandholt Møllebæk	F + Ir	55	83	3,037	3,339	61	91	-
3	Silke River	F + Ir	147	261	8,036	11,378	77	124	262
4	Odense River near Brobyværk	F + Ir	104	234	10,736	11,654	112	159	597
5	Odense River, Phase 1	F + Ir	69	91	2,663	4,656	68	105	635
6	Odense River, Phase 2	F + Ir	296	734	20,733	22,719	77	104	674
7	Brahetrolleborg Gods	F + Ir	46	76	1,117	3,127	69	103	38
8	Geddebækken	F + Ir	44	85	3,024	1,748	40		-
9	Karlsmosen	F + Ir	63	171	5,720	5,839	93	135	32
10	Hammerdam	Ir	10	75	1,479	847	86		-
11	Posens Mose	F + D	26	465	10,306	8,660	331	337	1
12	Sallinge River southwest near Boltinge	F + D	3	60	1,405	1,181	417	463	52
13	Sallinge River northwest near Boltinge	F + Ir	3	10	360	408	134	179	56
14	Sallinge River east near Boltinge	F + Ir	8	21	620	884	105	155	99
15	Sallinge River near Findinge	F + Ir	37	81	2,627	3,165	86	128	102
16	Sallinge River near Præstebrogyden	Ir	2	58	1,414	713	396		-
17	Sallinge River near Dalsmøllevej	F	3	18	599	131	46	97	52
18	Sallinge River near Sallinge	F + Ir	23	128	4,965	3,996	174	243	-
19	Sallinge River near Gestelevlundevej	F + Ir	36	139	3,656	4,174	115	168	140
20	Sallinge River near Sallingelunde	F	16	60	2,688	1,199	73	150	12
Total			**1,001**	**2,890**	**87,113**	**91,691**	**-**		**2,750**

F = flood inundation;

F + IR = flood inundation + irrigation with drainage water

F + D = flood inundation + diffuse transport (also referred to as natural flow)

I = irrigation with drainage water

D = diffuse (also referred to as “natural flow”)

3.2.2 Potential wetlands

There are five types of potential wetlands – “flood”, “flood +irrigation”, “flood + diffuse”, “irrigation” and “diffuse” – of which flood + irrigation with drainage water is the most dominant; a total of 2.803 ha fall within that category. A total of 42 ha wetlands are expected to remove N only through flood inundation. 105 ha of potential wetlands are expected to be flood inundated and receive their hydrological load through soil infiltration by water from the direct upland (and possibly groundwater). Potential wetlands where only irrigation with drainage water is expected cover an area of 636 ha. Lastly, diffuse – i.e. groundwater flow - transport through the soil is expected for a total area of 53 ha, and there is thus a possibility of groundwater flow.

Table 3.2.2. Wetland area, direct upland area, N load from direct upland area, calculated N removal and P deposition across the five wetland types. The results are further subdivided into three categories: Potential wetlands with calculated N removal above 90 kg N/ha, potential wetlands with calculated N removal below 90 kg N/ha and potential wetlands with calculated N removal above 500 kg N/ha through irrigation.

	Type	**Wetland area, ha**	**Direct upland area, ha**	**N load from direct upland area, kg N**	**N-removal, kg N per year**	**P deposition, kg P, 36 days per year**
N removal below 90 kg N/ha	Flood	9	170	2,461	692	14
	Flood + Irrigation	1,222	2,352	69,542	69,639	631
	Flood + Diffuse	31	23	577	1,869	-
	Irrigation	356	1,004	32,123	24,143	-
	Diffuse	26	53	1,128	1,154	-
	Total	**1,644**	**3,603**	**105,832**	**97,496**	**644**
N removal above 90 kg N/ha	Flood	12	34	1,265	1,294	-
	Flood + Irrigation	1,567	8,393	329,523	245,963	2,736
	Flood + Diffuse	74	427	13,060	13,380	148
	Irrigation	258	1,852	73,691	44,644	-
	Diffuse	27	95	2,908	2,692	-
	Total	**1,937**	**10,802**	**420,447**	**307,971**	**2,885**
N removal above 500 kg N/ha (through irrigation)	Flood + Irrigation	14	623	19,292	9,856	21
	Irrigation	22	684	33,161	18,756	-
	Total	36	1,308	52,453	28,613	21
Total		**3,617**	**15,713**	**578,731**	**434,080**	**3,551**

As seen in Table 3.2.2, there are 1,937 ha of potential wetlands with a calculated N removal of at least 90 kg N per ha per year. The total calculated N removal in these wetlands amounts to 307,971 kg N per year and the calculated P sedimentation is 2,885 kg P per year.

1,644 ha of the potential wetlands have a calculated N removal below 90 kg N per ha per year. These areas have a calculated total N removal of 97,296 kg N per year and the calculated P sedimentation is 644 kg P per year.

Additionally, there are 36 ha of irrigated potential wetlands where N removal through irrigation exceeds 500 kg N / ha; for these, total removal is estimated to 28.6 tons N per year. Using instead a maximum removal of 500 kg N / ha via irrigation, the calculated removal in these wetlands is 19.3 tons N, and the total N removal is 424.8 tons N rather than 434.1 tons N.

The calculated N removal in potential wetlands without separation into N removal levels is shown in Table 3.2.3 below.

Table 3.2.3. Wetland area, direct upland area, N load from the direct upland area, calculated N removal and P deposition summed across the five wetland types.
The data include irrigated wetlands with a calculated N removal through irrigation exceeding 500 kg N per ha. The N removal in these wetlands has been corrected to removal through irrigation of 500 kg N per ha.

Type	Wetland area, ha	Direct upland area, ha	N load from direct upland area, kg N	N removal, kg N per year	P deposition, kg P, 36 days per year
Flood	21	204	3,726	1,986	14
Flood + Irrigation	2,803	11,369	418,357	315,610	3,367
Flood + Diffuse	105	450	13,638	15,248	148
Irrigation	636	3,540	138,976	80,553	-
Diffuse	53	148	4,036	3,845	-
Total	**3,617**	**15,713**	**578,731**	**424,755**	**3,551**

3.3 Land use

For a total of 165 ha of the potential wetlands, 70% of the area is classified as wet nature, with a total removal of 10,633 kg N. For 1,482 ha of the potential wetlands, 30-70% of the area is classified as wet nature, with a total removal of 132,930 kg N. Lastly, for 1,970 ha of the potential wetlands, less than 30% of the area is classified as wet nature, with a total removal of 290,518 kg N. The presence of wet nature types in the potential wetlands are visualised in Figure 3.3.1.

As can be seen in Table 3.3.1, a total of 1,018 ha of the potential wetland area is classified as wet nature, covering 28.2% of the area. 86% of the wet nature area is under extensive agricultural use. The remaining 71.8 % of the area is agricultural land

Table 3.3.1. The area and proportion of the potential wetland area classified as wet nature (with or without extensive agricultural use) within the potential wetlands with a calculated N removal above 90 kg N/ha, potential wetlands with a calculated N removal below 90 kg N/ha and potential wetlands with a calculated N removal above 500 kg N/ha through irrigation.

Potential wetland category	Land use	Area, ha	% of total area
Above 500 kg N/ha	Nature, open, wet	0.4	1.0
	Nature, open, wet, agriculture, extensive	3.5	9.7
	Total	**3.9**	**10.7**
Above 90 kg N/ha	Nature, open, wet	236.5	12.2
	Nature, open, wet, agriculture, extensive	173.6	9.0
	Total	**410.0**	**21.2**
Below 90 kg N/ha	Nature, open, wet	259.8	15.8
	Nature, open, wet, agriculture, extensive	344.7	21.0
	Total	**604.5**	**36.8**
Total		**1,018.4**	**28.2**

Additionally, protected nature areas according to Section 3 of the Danish Nature Protection Act constitute 5.7 ha of the potential wetlands with an N removal of more than 500 kg / ha through irrigation (15.8% of total area), 514.5 ha of the potential wetlands with an N removal of more than 90 kg N / ha (26.6% of total area) and 743.6 ha of the potential wetlands with an N removal below 90 kg N / ha (45.2% of total area).

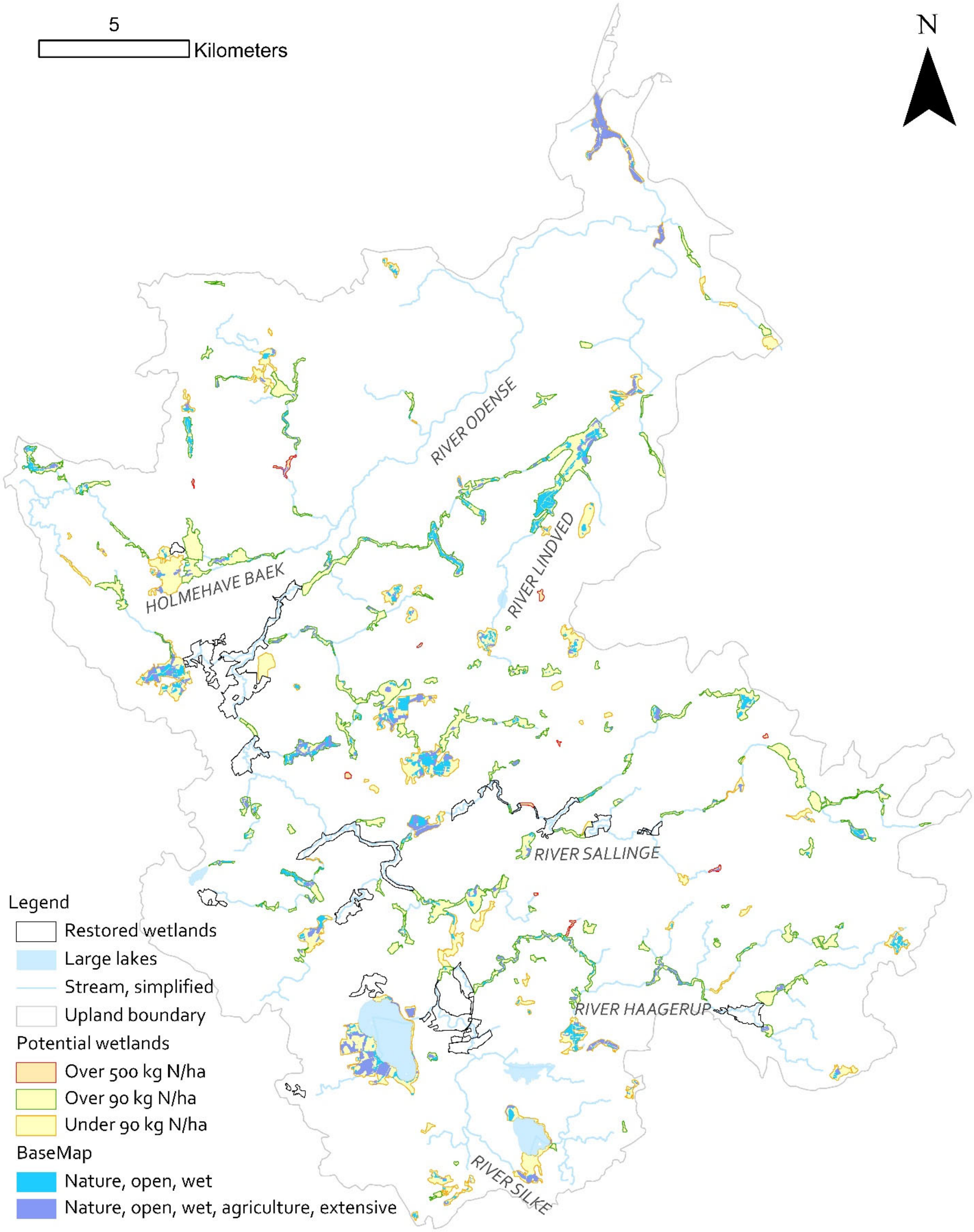


Figure 3.3.1. Location of areas classified as wet nature (with or without extensive agricultural use) within the potential wetlands. Potential wetlands with a calculated N removal above 90 kg N/ha are marked with a green edge, potential wetlands with a calculated N removal below 90 kg N/ha with an orange edge and potential wetlands with a calculated N removal above 500 kg N/ha through irrigation with a red edge. The already restored wetlands are marked with a black edge.

4 Discussion

4.1 Flood calculation

The UPstream length flood Model (UPM) predicted unrealistic flood events at the upstream end of small streams in some areas. As described (chapter 3), the DEM elevation in these areas was lower than at the elevation points up to 100 m downstream. The extremely flooded small streams were either located in forested areas or occurred as straight channels in agricultural landscapes. Therefore, in the stream simplification process, extra attention should be paid to these types of streams. Moreover, it is difficult to explain the high flooding found in the middle of the stream section in Figure 3.1.1.2.

Apart from the above reservations, UPM has a good fit with Høje Målebordblade and Agrosinks Extended Wetlands both upstream and downstream considering the fact that it is based on data from only 13 measuring stations covering the past 10 years (for some of the stations water level measurements were only available for one year) and upstream river length. In comparison with MIKE11, UPM has a smaller overlap with Agrosinks Extended Wetlands (AEW) and digitalised Høje Målebordsblade (HM) at the 0.9995 percentile, suggesting that MIKE11 has a better fit with the past wetland area. However, as shown in chapter 3.1, MIKE11 predicts a large flooding event in Holmehave Bæk and River Haagerup by estimating a water level more than 5 m above the DEM, i.e. a very steep increase, the highest water level increase revealed by the measuring station data being 1.5 m at station 45000003 compared with DEM.

The higher overlap of MIKE11 can rather be attributed to overestimation, as it covers a larger area, than to a better fit. Additionally, for the 0.84 and 0.9 percentiles, UPM has a higher overlap with HM and AEW in that the UPM flood covers a larger area at these percentiles.

The MIKE11-modelled stream level elevation is a result of many input variables and includes stream water levels as well as water flow measured at stations 45000003, 45000004, 45000043, 45000036, 45000080 and 45000047 (stations not shown). Furthermore, the model contains stream slope, cross-sectional area and cross-sectional profiles. The water elevation in MIKE11 also accounts for the for the plant biomass cutting regime in the stream (no removal, 1 removal or 2 removals per year) (Thodsen, 2010). Cutting of plant biomass reduces the water level and increases the water flow (Hoffmann et al., 2005). The cross-sectional profile also plays a role in the stream water elevation as a shallow and wide cross-section is more prone to overbank flooding than a narrow, deep stream channel profile (Şen, 2018). The cross-sectional area also provides information about water flow (Şen, 2018). Moreover, streams with a low slope are more likely to exhibit increases in stream water level than streams with a higher slope due to the slower flow (Şen, 2018).

For the above reasons, one would expect the MIKE11-calculated flood to be more accurate than the UPM-calculated flood. In fact, in the linear regression used to calculate the UPM flood R^2 is 0.64 at the 0.84 percentile,0.7 at the 0.9 percentile, whereas, R^2 is 0.85 at the 0.9995 percentile. This implies that 85% of the variation in stream level elevation is explained at the 0.9995 percentile, while only 64% of the variation is explained at the 0.84 percentile. This suggests that the stream elevation increase is more evenly distributed at the 0.9995 percentile, while there is more local variation at the lower percentiles. As the flooded area decreases only negligibly with decreasing percentiles and the amount of explained variance decreases as well, the UPM-calculated flood seems to be overestimated at the lower percentiles (not shown).

As demonstrated (Table 3.1.2.1), flood coverage within the restored wetlands varies significantly between the UPM- and MIKE11-calculated floods at the 0.84 percentile, while the flooded areas are very similar at the 0.9995 percentile. The restored wetlands, where the difference in flood coverage varied notably between the UPM- and the MIKE11-calculated flood, are those where the stream was re-meandered after 2006. Therefore, the MIKE11-calculated stream level values might not be accurate. Additionally, the manual placing of the elevation points (water level) also poses a challenge as several stream sections did not have any fixing points. Incorrect placement of the elevation points might corrupt the elevation raster and give inaccurate flood calculations. Considering the high amount of input data, the MIKE11 flood estimation should be more accurate than the UPM. However, the extreme overestimation for Holmehave Bæk, River Haagerup and River Lindved reduces the credibility of the MIKE11 flood estimates. The UPM is easy to use and provides good flood estimates distributed across the whole catchment. However, the accuracy of the UPM is limited to the high percentiles.

4.2 Restored wetlands

4.2.1 N retention

The direct upland to Karlsmosen reportedly covers an area of 140 ha, but the GIS analysis estimated the topographical upland area to 171 ha (Hoffmann et al., 2003). This may be explained by higher accuracy of the reported area, probably due to occurrence of 18 disconnected drains and a known tile-drained area. A part of the calculated upland may be drained with outlets located outside of Karlsmosen. This suggests an error in the N load calculation: if the actual direct upland area is smaller than the estimated upland, the calculated N load to a wetland and the estimated N removal will be flawed as well. No measurements of the actual N load from drains in Karlsmosen are available and comparison of the estimated and actual N load and removal from the direct upland is thus not possible (Hoffmann and Baattrup-Pedersen, 2007).

Gedebækken has a reported upland of 229 ha (Hoffmann et al., 2018a), while the direct upland area estimated in the GIS analysis is 85 ha. The reported upland area includes both the direct upland area and the stream upland area since the area around Gedebækken contains a lake that removes N from both the direct upland and the stream upland. According to Hoffmann and Baattrup-Pedersen (2007), Gedebækken has an upland of 284 ha, including the through-flowing stream. The estimated N load is 272 kg N / ha / year, while the measured load is 230 kg N / ha / year (Hoffmann and Baattrup-Pedersen, 2007). The N load estimated in the present GIS analysis is 68.5 kg N / ha / year as it is only based on the direct upland area. Consequently, the estimated N removal by irrigation is 34 kg N / ha / year and total N removal including flooding is 40 kg N / ha / year. According to Hoffmann and Baattrup-Pedersen (2007), the measured N removal in Gedebækken was 90 kg N / ha / year in contrast to the expected 215 kg N / ha / year, while Hoffmann et al. (2018a) reported an N removal of only 24 kg N / ha / year. The latter, however, accounts for only 20 ha of the project area, and according to Hoffmann et al. (2018a) only two small ponds seem to have active N removal. The stream Gedebækken in the Gedebækken upland was excluded in the process of stream simplification and the calculated flood therefore only limitedly covers the Gedebækken stream. If it had been included in the flood calculation, total removal would be higher.

It is known that Karlsmosen (WetID=9) is flooded 45% of the year (Hoffmann et al., 2006). Therefore, use of the 0.84 percentile provides inadequate knowledge of the amount of N removed by flooding events as it only covers flooding during 16% of the year. In Denmark, the highest precipitation occurs in winter (DMI, 2019). To obtain a more realistic and accurate flood removal estimate, lower percentiles should be used for low-lying areas such as Karlsmosen. However, the amount of variance explained decreases when flood is modelled for longer periods of time – at the 0.65 percentile R^2 is only 0.57. As R^2 is 0.85 at the 0.9995 percentile and 0.7 at the 0.9 percentile, the UPM-calculated flood is overall expected to be accurate at the high percentiles, while there is more local variation at the lower percentiles. Accordingly, use of the UPM-calculated flood for the lower percentiles should be restricted to areas like Karlsmosen for which it is known that the estimated flood is likely to occur.

Karlsmosen is estimated to remove only 93 kg N / ha / year (60 days), which contrasts the official estimate of 270 kg N / ha / year and the 337 kg N / ha / year measured in 2003 (Hoffmann et al., 2006). Using the flood calculated for 35% of the year, the total calculated N removal in Karlsmosen is 135 kg N / ha / year, which still is far from both the official estimates and the measurements. However, the N removal in Karlsmosen is variable since high hydraulic loads together with high N loads are necessary for high N removal. In fact, Karlsmosen was found to remove only 93 kg N / ha / year in 2002 (Hoffmann et al., 2003). It is unknown whether Karlsmosen is the only wetland in the Odense catchment that is flooded for longer periods of time. In 2005, the calculated removal in flood-inundated wetlands was 256 kg N / ha / year, on average (Hoffmann et al., 2006). Applying the high removal rate of 1.5 kg N / ha / day, the wetlands are inundated for 171 days, i.e. 47% of the year. However, many restored rivers are flooded for shorter periods of time – for instance, in Danish River Brede, flood inundation after restoration lasted 33 days, and in River Cole in England the flooding lasted 10 days after restoration (Kronvang et al., 1998).

Odense River Phase 2 (WetID=6) has an estimated removal of at least 150 kg N / ha / year (Naturstyrelsen, 2008), the types of removal including flood inundation, shallow lakes and drainage irrigation. According to the GIS analysis, the N removal is 77 kg N / ha / year or 104 kg N / ha / year in flood calculations covering 60 and 127 days, respectively. However, the duration of wetland flooding and the accuracy of the 127-day flood calculation are uncertain; 104 kg N / ha / year is still far from the officially estimated amount. If N removal in shallow lakes could be calculated, the estimate would probably be closer to the official figure.

The remeandered part of Silke River (WetID=3) has a reported N removal of 150 kg N / ha / year (Naturstyrelsen, 2014), while the calculated N removal in the GIS analysis is 77 kg N / ha / year for 60 days and 124 kg N / ha / year for 127 days. Also here, the actual flooding period is unknown and the accuracy for 127 days uncertain.

The calculated N load from the direct upland to Sallinge River near Præstebrogyden (WetID=16) is 786.4 kg N/ha/year and the calculated removal is 396 kg N/ha/year. The upland area might be overestimated as it happened for the Karlsmosen wetland. In fact, most of the upland area is estimated to be drained, which implies that a part of the upland area could be overestimated if some of the drains have an outlet outside of the restored wetlands. Therefore, the actual load and removal possibly deviate from the calculated values.

The values estimated in the GIS analysis do not always fit well with the measured values or the official estimates. There are only two project areas allowing comparison of the estimates, one of which includes a lake. Furthermore, due to lack of measurement data it is unsure how well the official estimates fit with the actual N removal. Therefore, consistency between the calculated N removal and the official N removal estimates cannot be regarded as a sign of compliance with the actual N removal.

The total N removal by the 1001.3 ha restored wetlands in the Odense River catchment has been calculated to 92 tons N/year for a 60-day flood period and 127 tons N/year for a 127-day period. Windolf et al. (2016) estimated that the restored wetland area of 860 ha resulted in an N load reduction of 124 tons N/year. Thus, the estimate based on flood calculated for 127 days is closer to the estimate by Windolf et al. (2016)) but should be regarded with caution due to uncertainty and possible inaccuracy of the flood calculation. Additionally, an unknown portion of the removed nitrogen is not accounted for as it is impossible to calculate the N removal without knowledge of the lake residence time. However, the majority of the lakes are small ponds with no connection to the stream network, which limits their direct upland area and the N load, and only small amounts of nitrogen are, therefore, expectedly removed.

4.2.2 P retention

The calculated P retention in the restored wetlands is 2,750 kg PP per year. Kronvang et al. (2016) estimated P retention in the Odense River catchment to 3,700 kg P per year based on P mass balance measurements in Karlsmosen (Hoffmann et al, 2011). Basing instead the calculation on P deposition measurements from Brynemade (in situ measurements from 2003 – 2013), Kronvang et al. (2016) estimated P retention in the Odense River catchment to 15,000 kg P. The water quality measurements from the Odense River catchment suggest a reduction in the nutrient transport of 5,600 kg TP per year and 3,600 kg DRP per year and 2,000 kg PP per year (Kronvang et al., 2016). The estimates by (Kronvang et al., 2016) apply to 860 ha of wetlands, and the P retention may well be higher. Accordingly, the calculated P deposition of 2,750 kg PP per year appears to be realistic.

Ideally, the P loss from each stream upland area should be calculated for each wetland individually; this was not the case, however, as the weighted average of the model-calculated P loss from smaller sub-catchments was used for each stream upland. If the P loss from the upland area were calculated individually for each wetland, different P deposition rates would probably be obtained for some of the wetlands.

Additionally, P deposition was calculated for 36 days, but ideally the average time period of flooding should be used for each wetland. As discussed in section 4.1., uncertainty is associated with the calculated flood, especially for longer periods of time. The calculated P deposition would expectedly be more precise with more accurate flood data. Lastly, in the formula for calculating P loss from the catchment R^2 was 0.75, and even if the other parameters were accurate, the results might still not reflect the actual P deposition.

4.3 Potential wetlands

4.3.1 N retention

The N removal to be gained by restoring additionally 3,167 ha wetlands is estimated to 434 tons N per year, which includes, however, the highest calculated values in wetlands with an N removal of more than 500 kg N / ha / year through irrigation. Using a maximum removal of 500 kg N / ha / year, the total calculated N removal in potential wetlands is 425 tons N per year. However, the actual N removal in irrigated wetlands may still deviate from the calculated values. In 2002, the irrigated wetland of Ulleruplund had a measured removal of 133 kg N / ha / year out of an N load of 198 kg N / ha / year, resulting in a removal efficiency of 67% (Hoffmann et al., 2006). The Lindkær wetland was found to remove 64% of the N load, or 191 kg N / ha / year in 2004-2005 (Hoffmann et al., 2006). The N removal efficiency in the Egeskov wetland was 43% and 75% of total N during the periods 2007-2008 and 2008-2009, respectively. The total load was 282 kg N / ha / year in 2007-2008 and 37 kg N / ha / year in 2008-2009 (Hoffmann et al., 2012). N removal efficiency in the irrigated wetland of River Stor was 32% in 1996-1997 and 26% in 1997-1998. However, the loads were 719 and 626 kg N / ha / year, respectively, and the monitored N removal was 219 and 150 kg N / ha / year (Hoffmann et al., 2012). This suggests that many irrigated wetlands with high N loads expectedly remove less than 50% of the N input. On the other hand, irrigated wetlands with low N input likely have an N removal efficiency higher than 50%.

N removal in shallow lakes has not been calculated in this analysis, and the actual removal could therefore be higher. Monitoring results from re-established lakes elsewhere in DK have shown that N removal amounting to 182 kg N / ha / year in Ødis Lake, 252 kg N / ha / year in Aarslev Engsø, 125 kg N / ha / year in Nakkebølle Inddæmningen, 117 kg N / ha / year in Wedellsborg Hoved, 125 kg N / ha / year in Skibet Enge, 244 kg N / ha / year in Slivsø, 100 kg N / ha / year in Gødstrup Engsø and 40 kg N / ha / year in Hals Lake (Hoffmann et al., 2006). These removal rates were measured during the first year after restoration, and in many of the lakes N removal was lower than expected due to the lower than expected N load. Nevertheless, Kronvang et al. (1999) suggest that shallow lakes may be permanent nutrient sinks and therefore be an important part of nutrient removal in river basins. A total of 91 ha lakes were found within the potential wetland area of which many are small ponds that likely have small upland areas and hence low N inputs. However, if the residence time is at least a week, an N removal of 11.5% can be expected (Naturstyrelsen, 2014).

The N removal in wetlands depends on the N load from the direct upland area, which again is highly dependent on the area used for agricultural purposes since the classification into agricultural rotation will eventually influence the calculated N removal. Permanent grass fields are not classified as agriculture because they have lower N leaching compared with annual agricultural crops (Bondgaard and Zacho, 2016). The N_{loss} equation (section 2.5.2.4) calculates the N loss to be approximately 6 kg N per ha per year when there is no agricultural rotation in the upland area. However, an N loss of 15-

30 kg N per ha per year can be expected from permanent grass fields (Poulsen and Knudsen, 2018). Therefore, the N load to the potential wetlands can be higher than calculated in the analysis, leading to a higher N removal.

Many stream sections did not flood at all, which is a result of stream channelisation conducted to prevent flooding. Many streams could be re-meandered in the process of restoration, resulting in flooding of more areas and thereby additional N removal.

The flood calculation shows theoretical flooding with the current stream morphology. Therefore, areas shown to be flooded presumably already are flooded during winter and N removal already occurs, restoration may, therefore, be unnecessary. However, many potential wetlands for which flood is predicted have a high probability of being drained. As discussed earlier, there are several uncertainties associated with the flood calculation used to estimate flood N removal. The duration of the flood estimated by UPM may not coincide with the actual flood duration. Drainage affects the water discharge in streams, and the purpose of drainage is to lead water away from the soil and increase the oxygen content to improve plant production (Clausen, 1988; (Hohlmann Bennetzen and Susgaard Filsø, 2017). Denitrification rates decrease with increasing oxygen content, reducing N removal (Burgin and Groffman, 2012, Groffman, 1994). Consequently, the current N removal via flood in these areas may be lower than the calculated removal, and the conditions for N removal via flood may improve if drainage is disconnected.

N removal through flooding was assumed to be 1.5 kg N / ha / day, which is a valid estimate for N concentrations of 5 mg / L and above, and at lower concentrations lower removal, 1 kg N per ha per day, should be assumed (Naturstyrelsen, 2014). In the last 5 years (2014 / 2015 – 2018 / 2019), in the period December-March, the average nitrite-nitrate concentration measured at the downstream Kratholm measuring station in River Odense was 4.7 mg / L (data available for download at https: / / odaforalle.au.dk). Using the N removal estimate of 1 kg N / per ha per day, total N removal would be 30 tons N lower.

4.3.2 P retention

The calculated P retention in potential wetlands was estimated to 3,551 kg P per year. As the stream in many areas has been channelised and straightened, additional areas could be flooded and more P could be deposited. Additionally, as discussed earlier in section 4.1., the actual occurrence of flood and its duration may differ from the flood estimate. If the actual flooding has a shorter duration or covers a smaller area than in the flood calculation, less P is deposited.

The model-calculated P loss from the catchment area depends on the presence of wetlands in the catchment. The P retention is calculated for the current wetland area. If more wetlands are restored in an upstream area of a catchment, more P will be deposited upstream, resulting in a lower P loss to a wetland located downstream in the catchment. Thus, less P will expectedly be deposited in the downstream-located wetlands. Consequently, the calculated P sedimentation may be an overestimate.

Even though flood-inundated wetlands are an effective way to capture particle-bound P, wetland restoration may have an adverse effect on P retention. Rewetting of previously drained soils is associated with P release to the stream (Kinsman-Costello et al., 2014). Before conducting a restoration, the soil in the project area should be analysed for P content to estimate a potential risk of release (Hoffmann et al., 2018b). If there is a substantial risk of P loss from the wetland, restoration should be abandoned as wetland restoration for the purpose of either N or P removal or preservation of low-lying soils should not lead to additional P release (Miljøstyrelsen, 2018).

4.3.3 Land use and restoration potential

Downstream of River Odense, near Odense Fjord and outside the investigated Odense River catchment area, lies a potential wetland area which has a high drainage probability, but at the same time the entire area is classified as wet soil with extensive agriculture. Back in time the area has likely been under agricultural use as the Prob Drain (i.e. the GIS layer; Olesen, 2009) layer only covers areas used for agricultural purposes. The direct upland area appears to be undrained and the wetland is predicted to be flooded. The tile drains might have been broken, allowing wetting of the area and hence classification as wet soil. The wet soil classification in BaseMap02 (Levin et al, 2017) is based on protected nature types according to Section 3 of the Danish Nature Protection Act. Nature type classification is based on whether the area is drained, either by tile drains or ditches, and if vegetation typical for wet soils is present. A wet nature type may to some extent be affected by previous drainage as long as vegetation typical of wet soil is prominent (Fredshavn et al., 2010). Whether the area in question is in a natural hydrological state or affected by previous land management is uncertain. According to the Danish Environmental Protection Agency, the wetland area in the upland to Odense Fjord has been reduced by 70% since the 1940s (Miljøstyrelsen). More than half of the remaining wet nature areas are affected by drainage or lowering of the water level due to regulation of adjacent public streams (Miljøstyrelsen). The current N removal in the wetland is unknown. The hydrological state of the area may be good enough to render restoration efforts unnecessary. The area consists of 26 ha and has a calculated N removal of 1,492 kg N.

Many potential wetlands contain small patches classified as wet nature even though the surrounding area does not belong to this nature type. Considering the fact that natural areas need to be large and continuous in order to support diverse plant and animal species, restoration could be extremely beneficial in terms of biodiversity and natural value (Hendrickx et al., 2007) (Miljøstyrelsen). In fact, one of the efforts conducted to ensure improvement of the ecological status in the Natura 2000 habitat in Odense Fjord was to expand the wet nature types to ensure their continuity (Miljøstyrelsen), including specific areas in the Odense River upland: Odense Fjord , Odense River , Sallinge River , Haagerup River , Lindved River , Arreskov Lake , Brahetrolleborg , Store Øresø and Storelung .

One might expect that potential wetlands in these nine above-mentioned areas are more likely to be restored due to their nature value as one of the aims of Natura 2000-protection is to ensure “clean water, natural river course and a river profile with varying stream bottom and depth” (Naturstyrelsen, 2016). In many areas, restoration may be necessary to achieve these goals as several streams have been modified.

Many of the potential wetlands may be restored if they are close (i.e. distance < 100m) Natura 2000-protected area and the calculated N removal is below 90 kg N/ha/year (Miljøstyrelsen, 2020). As shown in Section 3.3., in potential wetlands with an N removal below 90 kg N / ha / year a higher proportion of the area is classified as Section 3-protected nature compared with potential wetlands with an N removal above 90 kg N / ha / year (45% vs. 27%). This is because a lower proportion of the potential wetland area is under agricultural rotation in wetlands with a calculated removal below 90 kg N / ha / year, the changes in land use causing lower N retention. The Danish government has recently devoted an additional 10 million DKK to so-called synergy projects combining climate adaptation, N removal and nature protection (Naturstyrelsen). There is thus particular interest in areas that remove N as these have increased natural value, and wetlands located in areas designated as protected nature are therefore ideal candidates for restoration.

Several potential wetland areas are undrained and classified as wet soils but have a drained direct upland. Restoration would entail disconnection of the upland drains, allowing nitrate-rich water to irrigate the soil surface. These areas are not eligible for restoration if the protected nature will suffer from increased nutrient inputs according to Section 3 of the Danish Nature Protection Act that prohibits modifications causing deterioration of an area's ecological status (Miljøministeriet, 2009).

5 Conclusions

The Odense River catchment has been subject to intensive wetland restoration to mitigate the loss of nitrogen. Candidate wetland areas for potential additional restoration in the Odense River catchment were identified with an index model. The direct upland area to each wetland was determined in ArcGIS and from each upland N loss and N removal from the direct upland were estimated based on soil type and drainage probability. The calculations of N removal by flood inundation were based on a flood estimate accounting for flooding 16% of the year, this estimate being based on data on stream water level increases derived from monitoring stations and predictions by the upstream river length model (UPM). The UPM-predicted flooding provided a good estimate of a flood distributed evenly between upstream and downstream and minimum data inputs were required. The UPM performed best at the 0.9995 percentile (R^2=0.85) and had higher uncertainty at lower percentiles (R^2=0.7 at the 0.9 percentile, R^2=0.64 at the 0.84 percentile). The UPM flood estimate was compared with flood estimates based on MIKE11 stream water level elevations. The flood estimates were comparable at the 0.9995 percentile but differed at the 0.9 and 0.84 percentiles. This might be attributed to the higher accuracy of the MIKE11 stream water levels due to the higher amount of input data. However, MIKE11 overestimated the flood in some areas, thus reducing its accuracy. Several areas, which were overestimated by the UPM can be further improved during the stream simplification process, which is a necessary step to provide a satisfactory interpolation of the elevation raster used in the ArcGIS flood calculation. Even so, the level of accuracy of UPM will expectedly be lower with increasing duration of the calculated flood.

N removal by the restored wetlands was calculated to 91.7 tons N per year when flooded for 60 days and 127 tons N per year when flooded for 127 days. The 127-day flood estimate being, however, uncertain. The comparison between the calculated N removal and the measured data from restored wetlands showed an underestimation of calculated values. However, it should be noticed that the amount of available monitoring data is highly limited. Additionally, many restored wetlands contain shallow lakes for which N removal cannot be calculated without data on lake residence time. Also, uncertainties exist regarding the actual flood duration in the various restored wetlands.

The restoration of additional 3,617 ha of potential wetlands was calculated conservatively to remove 425 tonnes N per year. 636 ha of irrigated wetlands were estimated to remove 80,553 kg N per year, and 2,803 ha of irrigated wetlands that were also flood inundated were estimated to remove 315,610 kg N per year. Wetlands with diffuse water transport covered a total area of 53 ha and had an estimated N removal of 3,845 kg N per year, and potential wetlands with diffuse transport and flood inundation had a calculated N removal of 15,248 kg N per year distributed on 105 ha. Wetlands with flow inundation as the only removal type covered an area of 21 ha with a total removal of 1,986 kg N per year. Several uncertainties exist concerning the N removal calculation regarding, for instance, the actual flood duration and the lack of calculations for shallow lake N removal. Additionally, in irrigated wetlands the N removal falls below the standard removal rate of 50% at high N loads, but at low N loads the N removal rises above the standard rate of 50%. There are also several streams that are not currently flooded due to channelisation, but which might be flooded after remeandering, increasing the N removal.

P sedimentation in restored wetlands was estimated to 2,750 kg P per year. P sedimentation in potential wetlands for restoration was estimated to 3,551 kg N per year, which may be an overestimation as possible P retention in the potential upstream wetland areas is not taken into account. Such retention would lead to a reduction of the total amount of P deposited downstream. Again, several stream sections could be remeandered to allow flooding, thereby increasing the potential for P sedimentation.

The restoration value of the potential wetlands found in the analysis is uncertain. Various potential wetlands contain wet nature types. Even though the wetlands appear to be drained and / or have drained direct upland areas, it is uncertain whether these already function as wet soils or if their properties can be improved by drainage disconnection. Additionally, disconnection of the drains in the direct upland area would expose the Section 3-protected nature types to high N loads, which could deteriorate their natural value. Yet, wetland restoration improves the natural value of an area and is important for biodiversity.

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7 Appendix

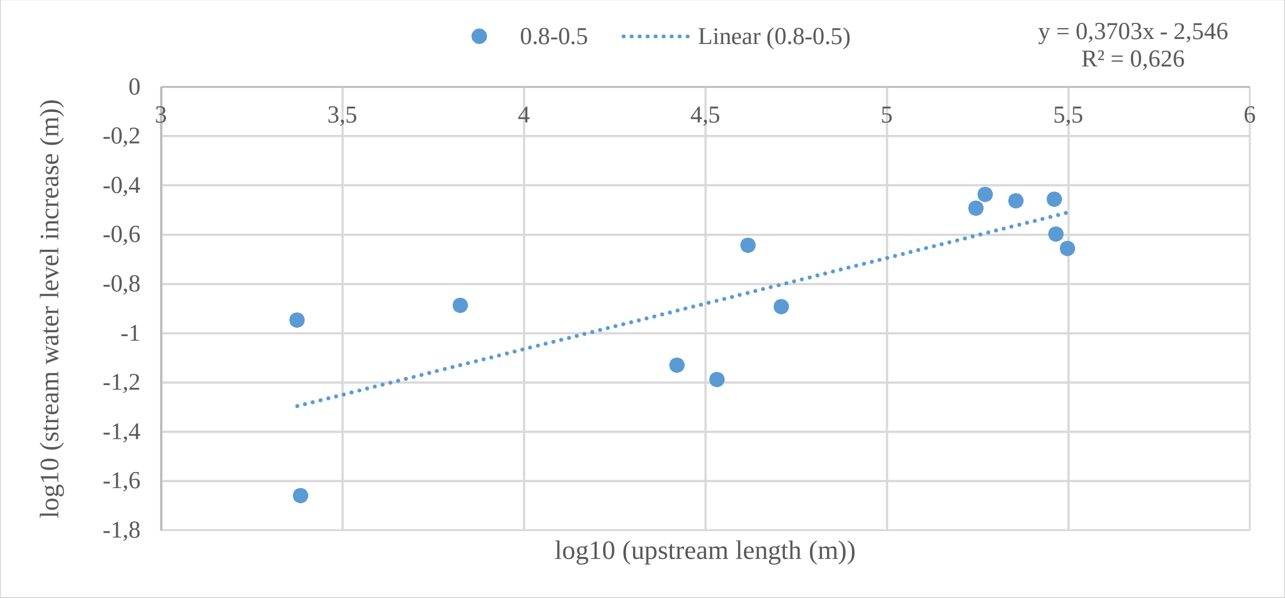

Figure 7.1. Linear relationship between the log10-transformed upstream length and the log10-transformed stream water level increase between the 0.5 and the 0.9 percentiles. The R^2 of 0.7 shows that 70% of the variation found in the dependent variable (log10-transformed stream water level increase) is explained by the explanatory variable (log10-transformed upstream length).

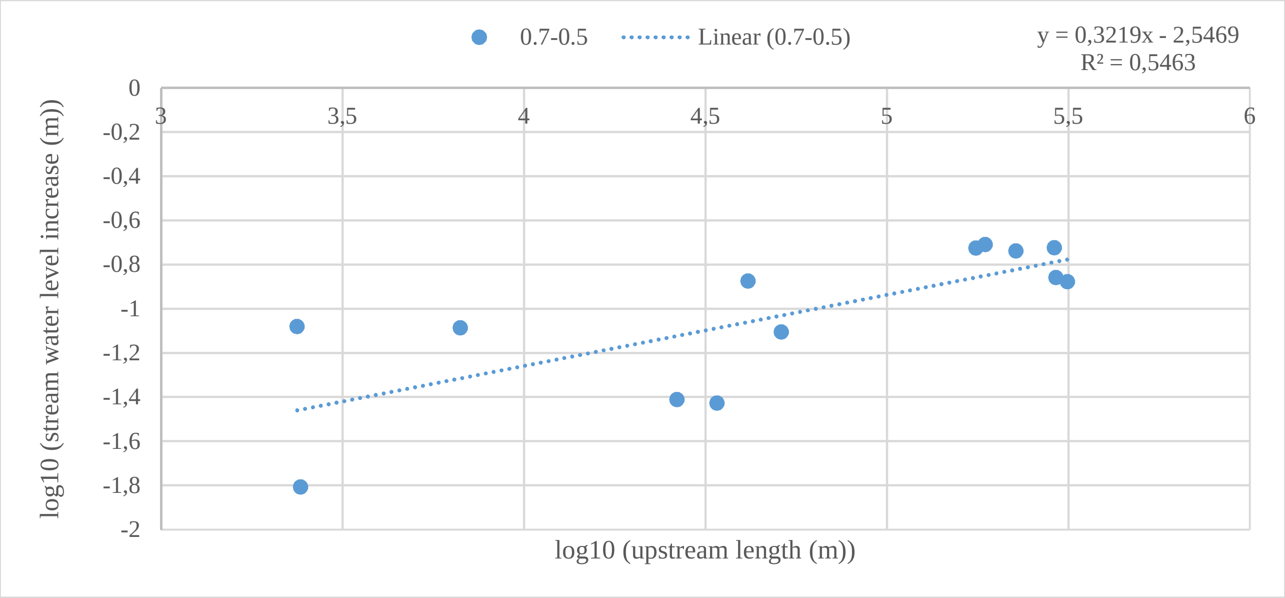

Figure 7.2. Linear relationship between the log10-transformed upstream length and the log10-transformed stream water level increase between the 0.5 and the 0.9 percentiles. The R^2 of 0.7 shows that 70% of the variation found in the dependent variable (log10-transformed stream water level increase) is explained by the explanatory variable (log10-transformed upstream length).

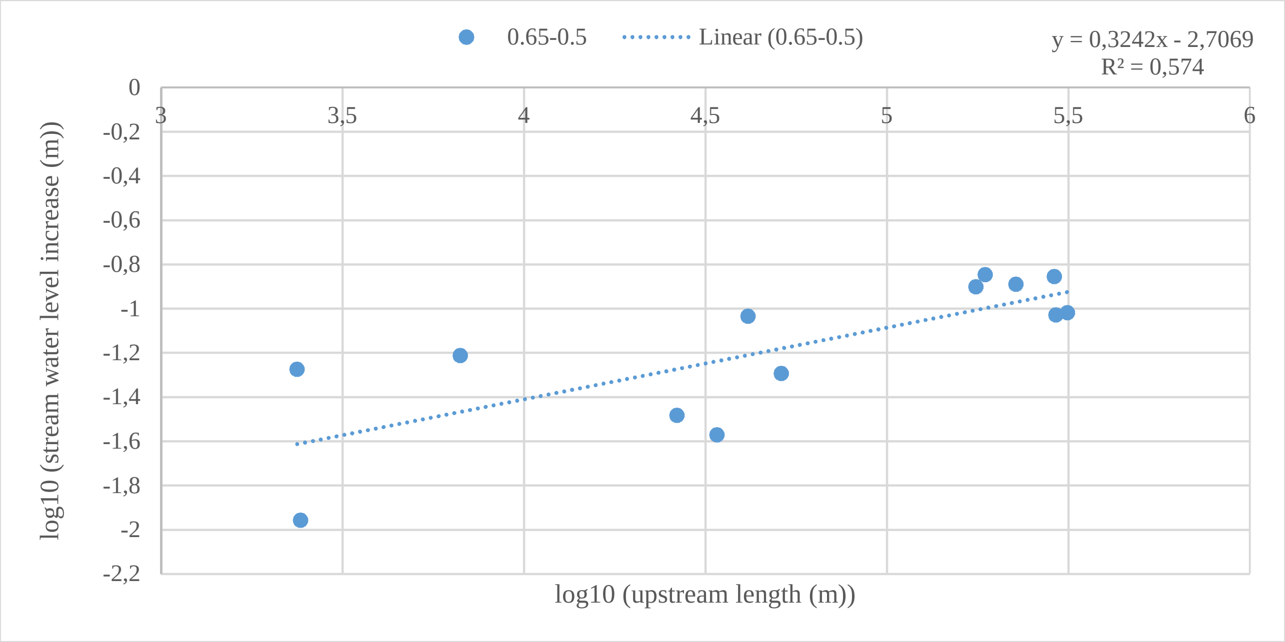

Figure 7.3. Linear relationship between the log10-transformed upstream length and the log10-transformed stream water level increase between the 0.5 and 0.9 percentiles. The R^2 of 0.7 shows that 70% of the variation found in the dependent variable (log10-transformed stream water level increase) is explained by the explanatory variable (log10-transformed upstream length).

POTENTIAL FOR FURTHER WETLAND RESTORATION IN THE ODENSE RIVER CATCHMENT AND NITROGEN AND PHOSPHORUS RETENTION

We have used ArcGIS to map already existing wet buffer zones as well as new potential wet buffer zones along the Odense River system, Funen, Denmark. We have developed a screening tool on how to identify wet buffer zones and calculate nitrogen removal and phosphorus retention in wet buffer zones. Further it also includes a tool on how to identify and map wet buffers which may be flooded by river water at peak flow events

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