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TRANSPORT OF NITROGEN AND PHOSPHORUS FROM LAND TO SEA AROUND YEAR 1900

Scientific Report from DCE – Danish Centre for Environment and Energy No. 498 2022

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

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Data sheet

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Abstract: The nutrient loads from land to sea around year 1900 in Denmark are estimated using a delta change modelling approach considering the numerous factors affecting the nutrient inputs and transport. The estimates are based on available data from that time, literature, comparative analysis methods and modelling tools. The main factors investigated are climate, hydrology, land use, agricultural practices and drainage, urban developments and landscape (e.g. nutrient retention in groundwater, wetland, lakes and streams). Nutrient loads around the year 1900 were affected by human activity, with total nitrogen and phosphorous loads being approx. 40% and 25-40% less than present-day loadings, respectively.

Keywords: Nutrient transport, nutrient load, nutrient concentration, nitrogen, phosphorus, water discharge, reference condition, point source, urban development, year 1900, climate, land use, retention.

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Contents

Preface

In order to assess the status and set environmental goals for waterbodies under the WFD, it is necessary to determine the border between "good" and "moderate" ecological status of the waterbody. The boundary is set by defining a "reference condition" reflecting an undisturbed / pristine condition, adding to this an acceptable deviation to allow for some human impact. The WFD describes the reference conditions as: *The values of the biological quality elements for the surface water body reflect those normally associated with that type under undisturbed conditions, and show no, or only very minor, evidence of distortion (WFD, Annex V. p 38 (https://eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0004.02/DOC_1&format=PDF)*

The ecological status in coastal waters is based on the status of the "ecological quality elements", here eelgrass and chlorophyll-a. For eelgrass, historical information from around the year 1900 has been used to establish the reference condition. This type of information is not available for chlorophyll-a, hence it has been necessary to use models to estimate a reference situation. As the concentration of chlorophyll-a is tightly linked to the concentration of nutrients in the water, reference load of nutrients from land to the sea are needed in order to run the models.

In October 2017, Aarhus University published the report "Estimation of nitrogen concentrations from root zone to marine areas around the year 1900" (Jensen (ed.) 2017)[1], which investigates the factors that could influence the annual mean nitrogen (N) concentrations from source to sea around the year 1900 and provides an estimation of the nitrogen concentration level in stream runoff to the sea at that time in Denmark. The main factors investigated were climate, hydrology, land use, agricultural practices, drainage and landscape (retention). The result was provided as a range of concentrations for the whole country but did not include point sources and the contribution of organic nitrogen. However, if the results are to be used in modelling studies for target setting for, for instance, chlorophyll-a, a more detailed spatial distribution of N concentrations and water runoff is required.

Therefore, the Danish Environmental Protection Agency (Danish EPA) requested that DCE, Aarhus University initiated a follow-up project where the analysis and estimations are made at a more detailed spatial scale and include an in-depth analysis of the contribution of nutrients from the larger cities in Denmark (point sources) to the modelled N concentrations. Furthermore, there was a wish to include phosphorus in the analysis. The goal of the project was to obtain a geographically distributed dataset of nutrient inputs to the sea from around the year 1900 with the hope that it could be used in defining the reference condition for target setting according to the WFD.

The project was initiated in 2019 but has, due to difficulties in obtaining reliable climate data for the years around the year 1900 and thus reliable modelled water discharge, been delayed several times. However, by early 2020 the first preliminary results from the project were presented at the national event "Plantekongres" in January 2020, showing that nutrient concentrations around year 1900 were significantly influenced by agricultural activities, urban wastewater etc. Based on the presentations, it was concluded that the estimated supply of nutrients to the sea around the year 1900 cannot be assumed to have been unaffected or only slightly affected by human activity (Timmermann, 2020[2]). Hence, the nutrient concentration and load around year 1900 in Denmark cannot be associated with an undisturbed situation such as required when establishing reference conditions in relation to the WFD. One of the main reasons for this conclusion is that the nutrient concentration levels estimated in this study are significantly higher compared with the current measurements of nutrient concentrations in streams with low human impact. Consequently, DCE recommended using an alternative approach to estimate nutrient loads representing reference conditions regarding the WFD (Timmerman, 2020[2]).

The current report documents the substantial work that has been carried out in this project and for the first time presents detailed analysis of agricultural practices, point source pollution and model-based estimates of climate conditions, water discharge and nutrient flows around the year 1900 in Denmark.

During the project period, meetings with an advisory group of external interested parties were organized by the Danish EPA. At these meetings results from the project were presented and discussed. Further, several project status meetings were held with the Danish EPA.

In June 2022 a draft report was sent in international scientific review. The reviewers were Dr. Markus Venohr from the Leibniz-Institute of Freshwater Ecology and Inland Fisheries in Germany and ir.EMPM Erwin van Boekel from Wageningen Environmental Research, in the Netherlands. Following the review a draft report was send to the Danish EPA who provided written comments to the report.

Acknowledgement:

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[1]Jensen P.N. (ed.), 2017. Estimation of nitrogen concentrations from root zone to marine areas around the year 1900. Scientific Report from DCE No. 241. Aarhus University, Danish Centre for Environment and Energy.

[2]Timmermann, K. (2020). Referencetilførsler af kvælstof til brug for Vandplan 3. DCE – National Center for Miljø og Energi

Summary

Background

The current report aims to describe the nutrient loads from land to sea around the year 1900. The nutrient loads are calculated considering the various factors affecting the nutrient inputs and transport based on available data from that time, literature, comparative analysis methods and modelling tools. The main factors investigated are climate, hydrology, land use, agricultural practices and drainage, urban development and landscape (e.g. nutrient retention in groundwater, wetlands, lakes and streams). The ambition was to use as much data and information from the time as possible, taking into consideration the quality and representativeness, and use modelling and GIS tools to provide a geographically distributed estimate of total nitrogen (TN) and total phosphorus (TP) concentrations and loads from the root zone to the sea. To be able to do this, the datasets on climate and hydrology were analysed and expanded as part of the project, and runoff was modelled using the national water resources model (DK- model).

The agricultural practices and land use in different areas of the country were analysed in detail, and the root zone concentration of nitrogen was determined for different land use categories. This was based on old farmland statistics from Denmark and Northern Germany, which at the time included land areas that are now Danish, and root zone nitrogen concentrations extracted from farming experiments resembling year 1900 farm management practices. Phosphorus inputs to the surface waters from the landscape, including agricultural activities, were estimated for the main input categories: soil drainage, land reclamation, grazing animals, soil erosion and manure storage.

Furthermore, a detailed analysis of the contribution of nutrients from cities (point sources) was included. This analysis estimated nitrogen as well as phosphorus inputs.

To model the concentration and transport of nitrogen in the freshwater load to the sea, the national nitrogen model (NMN) was used. The model requires geographically distributed input of climate variables, such as temperature and water runoff, the input of nitrogen from the root zone and point sources as well as data on the depth of groundwater and the proportion and location of wetlands, lakes and streams, to estimate the retention in the surface water system.

The phosphorus analysis used an approach of ”background” or ”nature” water concentration levels of phosphorous, on top of which the relevant additional diffuse and point sources were added and retention in lakes subtracted. The transport of phosphorus through the catchments was simulated using the same water discharge as for the nitrogen modelling, but the model as such is much simpler than the nitrogen model because of the way phosphorus behaves in the environment.

Among other things, the analysis showed that in the year 1900, weather conditions were colder and drier than today, more land was in agricultural use but less was tile drained, and due especially to a larger proportion of wetlands the retention of nutrients in the landscape was higher.

The conclusion from the chapters on climate, hydrology, nutrient input nutrient transport from land to sea and uncertainties are given in the synthesis of results in chapter 11 and are also presented below.

Climate

The climate was colder and drier around year 1900 compared with the present-day. The estimated average annual precipitation around year 1900 was about 60 mm, or 7% lower than today. Digitized climate data from around year 1900 at observation points across the country, including temperature, wind and rainfall, were used to find monthly values of bias-corrected precipitation. The correction approach was evaluated for the period 1917-1950 using water balance modelling of discharge. At national level, a water balance error of 3% indicated reasonable correction estimates, but large regional differences in error level was found. In order to obtain spatially distributed corrected precipitation for the period 1890-1910 a delta change climate factor approach was used. In this approach national monthly correction factors were calculated based on corrected precipitation for 1890-1910 compared with 1989-2010. These national factors were then applied to the present daily corrected precipitation assuming a similar geographical distribution of precipitation around year 1900 as in the present time reference period (1989-2010) to provide a spatially distributed daily time series of precipitation for the period 1890-1910.

To be able to model nitrate leaching, global radiation and potential evapotranspiration must be calculated. By using the measured minimum and maximum air temperatures for 1890-1950, the global radiation and potential evapotranspiration can be calculated and used in the simulation of nitrate leaching in this period. The modelled global radiation and potential evapotranspiration around year 1900 are in good agreement with values measured at Foulum from 1987-2013.

Hydrology

The total discharge based on the precipitation estimates and drainage density estimated for the historic time was in average 292 mm / yr for the period 1890-1910 compared with 333 mm / yr for the present period (1990-2010) as calculated by the hydrological model (DK model, chapter 3). Subsequently, applying a delta change method, the total discharge was recalculated to 335 mm / yr for the present period and 297 mm / yr for the year 1900 period (chapter 8). This means that for the total average, annual discharge was about 11% lower around year 1900 compared with the present time. The change in discharge for the two periods largely reflects the changes in precipitation, but is amplified in some areas by the lower density of drainage in the historical period. The calculated change in discharge when comparing the present time to the time around year 1900 ranged between 0 and 20% for most of the country, which agrees with the trend analysis of long discharge time-series presented in Jensen (ed.) (2017). However, for the western part of Zealand, the data indicate an increase in discharge between the two periods of approximately 30%, while the simulation resulted in a decrease in discharge of approx. 5%. The methodology used implies that the total discharge to the sea may resemble the conditions around year 1900, but it cannot be expected to reproduce the local conditions at that time.

Nutrient inputs

The nutrients reaching the sea from the land mainly originated from agricultural activities and dwellings across the country around year 1900. In addition, runoff from erosion along the streams contributed to the nutrient content in freshwater, particularly phosphorus.

Agriculture

The area in agricultural use increased dramatically during the last half of the 19th century and accounted for close to 3/4 of the area under Danish administration around year 1900. Crop production differed significantly from current agriculture for virtually all growth factors: inferior crop varieties, higher weed pressure, lack of chemical crop protection and inferior plant nutrient supply, including the absence of mineral fertiliser. The main sources of nutrients were solid farmyard manure, liquid manure and nitrogen fixation by legume crops. The number and categories of livestock as well as the farm structure and management practices around year 1900 also differed from today's practices.

Parish-level statistics from around year 1900 for the area under current Danish administration were unified into eight categories (winter and spring crops, grass, root crops, fallow, nature and forest), and for each category a nitrogen concentration was ascribed to the root zone percolate. The nitrogen root zone concentrations were set using data from studies of organic farming as a proxy for the past time situation. Literature data were found for the remaining categories. These values were applied in the nitrogen modelling. The calculation of the area-weighted average nitrogen concentration for land in agricultural use (78% of the land area) resulted in a value of 12 mg N/l, while the value for the entire land area was 9.6 mg N/l in root zone percolate (inorganic nitrogen).

The estimation of agricultural sources for phosphorus considered factors such as soil drainage, land reclamation, grazing animals, soil erosion and manure storage. These factors were difficult and uncertain to determine, leading to an estimated range from 56 to 196 ton P annually around year 1900.

Point sources

Sewer systems were increasingly implemented in towns, but wastewater treatment did not exist in year 1900. Therefore, towns were significant point sources around year 1900, with 4,261 ton N/yr and 764 ton P/yr emitted in excrements from humans and animals and industrial wastewater. The findings indicate that the majority of the nutrients from point sources discharged directly to receiving waters (55%), but emissions to landfills (20%) and agricultural soil (25%) were significant as well. The total contribution from inland and direct point sources to water was estimated to 471 ton P, about 65–70% of the present-day value (704 ton P, average 2014–2018) and 2,531 ton N, about 47% of the present-day TN point sources (5,400 ton N, 2020).

Other sources, including background nutrient concentration

Nitrogen inputs from the atmosphere were estimated by multiplying EMEP simulations for year 2000 by 0.3 (Jensen (ed.), 2017). Organic nitrogen originating from landscape sources and internal surface water sources was included to be able to calculate total nitrogen concentrations. Estimates based on literature studies assume that the organic nitrogen concentration around year 1900 was about 20% below the current levels. Furthermore, it is assumed that the current geographical distribution of organic N is valid for the time around year 1900.

A literature review and measurements from largely undisturbed streams were used to estimate background TP stream concentrations. An area-weighted TP median value at 0.052 mg/l was estimated.

Nutrient transport to the sea

Nitrogen percolates through the soil and reaches the groundwater where reduction of nitrogen under oxygen-free conditions (retention) can take place before the remaining nitrogen ends up in surface waters (wetlands, lakes, streams). The National Nitrogen Model simulates transport and retention in groundwater based on water discharge and nitrogen percolate input. The surface water component calculates the nitrogen retention in wetlands, streams and lakes, while also considering point source inputs, atmospheric inputs and the contribution of organic nitrogen. Landscape changes between the time around year 1900 and the present time were handled by modifying the current landscape maps based on various information sources on the past landscape related to rivers and lakes. For wetlands, different maps were used.

The phosphorus analysis was based on total phosphorus considerations and used an approach of a ”background” or ”nature” concentration level, on top of which the relevant additional agricultural and point sources were added and retention in lakes was subtracted. The transport and routing of phosphorus through the catchments were simulated using the same water discharge as in the nitrogen modelling.

The nitrogen retention in inland surface water was shown to be higher in the present period (28,000 ton N) than in the 1900 period (26,000 ton N) due to a larger present-day nitrogen load. However, the relative nitrogen retention was higher around the year 1900, as 43% of the load was removed compared with 33% for the present period.

The total nitrogen load is modelled to be approximately 36,000 ton N/yr around year 1900, which is approximately 40% less than for the present period (59,000 ton N/yr). The nitrogen concentration is modelled to be around 2.8 mg N/l around year 1900 compared with 4.1 mg N/l in the present period. The national nitrogen model yields regional results, which are utilised for estimating regional year 1900 nitrogen and freshwater loads.

The estimated average stream water phosphorus concentration around year 1900 was 0.062–0.075 mg P/l, equivalent to 60–70% of the present-day stream water TP concentration (0.1 mg P/l). The TP values were calculated for nine geographical regions across the country. The total TP loading to the sea, including background, other diffuse sources, inland and direct point sources and subtracted phosphorus retention in lakes, was estimated to 1,200–1,340 ton P, 60–65% of (or 35-40% less than) the present-day phosphorus loading (2,021 ton/yr).

Uncertainties

Working with a period 120 years ago naturally makes most aspects of calculating the national nitrogen and phosphorus load more uncertain than when calculating it for the present period. An in-depth analysis of uncertainties of data layers, variables, model and model assumptions was not a part of the present study however, some considerations regarding uncertainty and sensitivity (the effect of a given parameter on the result) have been made.

Most of the parameters used to estimate the nitrogen loads around the year 1900 are considered to have “medium” uncertainty (on a three-step scale from low to high). The uncertainty of the nitrogen loads is influenced by a variety of factors, the most important being the uncertainty of the estimates of precipitation, run-off, root zone concentration of nitrogen and retention in surface and groundwater.

Overall, the model concept used to calculate the year 1900 nitrogen load is considered relatively robust and the overall uncertainty at national scale acceptable. However, the uncertainty increases with decreasing geographical- and timescales.

Most of the parameters used to estimate phosphorus loads are considered “medium” to “highly” uncertain. The uncertainty of phosphorous loads is especially influenced by the uncertainties of the estimates of precipitation, run off, P input from point sources and the background TP concentration. Despite the many uncertainties the results of this study are believed to be the best possible estimate of the year 1900 phosphorous loads. Furthermore, the results are supported by historical lake measurements that also find the historical TP-concentrations to be lower than today but considerably higher than the background concentration, though.

Perspectives

Many of the European studies that are compared with the present study report nitrogen concentrations around the year 1900 that are considerably lower than in the present study. The reasons for this are probably differences in landscape, land use, farming practices and runoff between the investigated areas and Denmark. It probably also reflects the degree to which agricultural practices and nutrient dynamics are included in the studies. In the present study, the year 1900 root zone leaching is calculated, and nitrogen fixation, the main source of nitrogen in Danish agriculture in the year 1900, is considered, which is not the case in most other studies.

Sammenfatning

Baggrund

Denne rapport har til formål at beskrive næringsstofbelastningen fra land til kyst omkring år 1900 under hensyntagen til de forskellige faktorer, der påvirker næringsstoftilførslen og transporten. Næringsstoftilførslen og transporten er beregnet ud fra tilgængelige data fra omkring år 1900, litteratur, komparative analysemetoder og modelleringsværktøjer. De vigtigste faktorer, der undersøges, er klima, hydrologi, arealanvendelse, landbrugspraksis og dræning, byudvikling og landskabsforhold (fx retention af næringsstoffer i grundvand, vådområder, søer og vandløb). Det var hensigten at bruge så mange data og oplysninger fra perioden som muligt, kvaliteten og repræsentativiteten taget i betragtning, og at anvende modellerings- og GIS-værktøjer til at give et geografisk fordelt skøn over total kvælstofkoncentration (TN) og total fosforkoncentration (TP) i det vand, der transporteres til havet, samt et skøn over næringstoftransporten fra rodzonen til kyst. For at kunne gøre dette blev datasæt om klima og hydrologi analyseret og udvidet som en del af projektet, og afstrømningen blev modelleret ved hjælp af den nationale vandressourcemodel (DK-modellen).

Landbrugspraksis og arealanvendelse i forskellige dele af landet blev analyseret i detaljer, og rodzonekoncentrationen af kvælstof blev fastsat for forskellige kategorier af arealanvendelse. Analyserne blev foretaget på baggrund af gamle landbrugsstatistikker fra Danmark samt for Nordtyskland, idet Nordtyskland omkring år 1900 omfattede arealer, der nu er danske. Desuden indgår for kvælstof målte rodzonekoncentrationer, der stammer fra landbrugsforsøg, hvor landbrugspraksis minder om den, der var gældende omkring år 1900. Tilførslen af fosfor fra landskabet til overfladevandet, herunder landbrugsaktiviteter, blev anslået for de vigtigste kilder: jordafvanding, landindvinding, græssende dyr, jorderosion og opbevaring af gødning.

Desuden indgik en detaljeret analyse af bidraget af næringsstoffer fra byer (punktkilder). Denne analyse estimerede kvælstof samt fosfortilførsel fra byerne.

Den nationale kvælstofmodel (NMN) blev anvendt til at modellere koncentrationen og transporten af kvælstof til havet. Modellen kræver geografisk distribueret input af klimavariabler, såsom temperatur og vandafstrømning, tilførsel af kvælstof fra rodzonen og punktkilder, data om grundvandets dybde og mængden samt placeringen af vådområder, søer og vandløb, for at vurdere den kvælstofretention, der forekommer i overfladevandsystemet.

Fosforanalysen anvendte ”baggrunds-” eller ”naturlig” -fosforkoncentration i vandløbsvandet, hvortil de relevante landbrugs- og punktkilder blev tilføjet, og tilbageholdelse i søer blev trukket fra. Transport af fosfor i oplandet blev simuleret ved brug af den samme vandafstrømning som for kvælstofmodelleringen, men modellen som sådan er meget enklere end kvælstofmodellen grundet den måde, hvorpå fosfor agerer i miljøet.

Analysen viste blandt andet, at vejrforholdene i år 1900 var koldere og tørrere end i dag, mere jord blev anvendt til landbrug, men mindre blev drænet, og især på grund af en større andel af vådområder var retentionen af næringsstoffer i landskabet højere. Konklusionerne fra kapitlerne om klima, hydrologi, næringsstoftilførsel og næringstoftransport til havet gengivet nedenfor stammer fra syntesen, kapitel 11.

Klima

Klimaet var koldere og tørrere omkring år 1900, end det er i dag. Den anslåede gennemsnitlige årlige nedbør omkring år 1900 var ca. 60 mm, eller 7 % lavere end i dag. Digitaliserede klimadata fra omkring år 1900, herunder temperatur, vind og nedbør, blev brugt til at beregne daglige værdier af bias-korrigeret nedbør. Korrektionsberegningerne blev evalueret ved at sammenligne simuleret og målt afstrømning for perioden 1917-1950. På landsplan indikerede en vandbalancefejl på 3 % rimelige estimater, men de regionale variationer i denne fejl viste sig at være for store. For at opnå rumlige estimater af korrigeret nedbør for 1890-1910 blev der i stedet defineret månedlige delta change klimafaktorer, som blev beregnet ved at sammenholde korrektionsfaktorer for 1890-1910 og referenceperioden 1989-2010. Det blev antaget, at disse faktorer er regionalt repræsentative. De nationale klimafaktorer blev herefter anvendt til at korrigere daglig nedbør for referenceperioden, idet det blev antaget, at den rent klimatiske regionale nedbørfordeling for denne periode er den samme som for nedbør omkring år 1900. For at kunne modellere nitratudvaskning skal den globale ind- og udstråling og potentielle evapotranspiration beregnes. Ved at anvende de målte minimums- og maksimumstemperaturer for 1890-1950 kan den globale ind- og udstråling og potentielle evapotranspiration beregnes og anvendes i simuleringen af nitratudvaskning i denne periode. Den modellerede globale ind- og udstråling og potentielle evapotranspiration omkring år 1900 stemmer godt overens med værdier målt på Foulum fra 1987-2013.

Hydrologi

Den samlede vandafstrømning beregnet med en hydrologisk model (DK-modellen) baseret på disse nedbørsestimater og ændringer i dræntætheden var i gennemsnit på 292 mm/år for perioden 1890-1910 sammenlignet med 333 mm/år for den nuværende periode (1990-2010) (kapitel 3). Efterfølgende er vandafstrømningen genberegnet ved brug af en “delta change”-tilgang, hvorved den samlede vandafstrømning opgøres til 335 mm/år for den nuværende periode og 297 mm/år for tiden omkring år 1900 (kapitel 8). Det betyder, at den årlige vandafstrømning i gennemsnit var ca. 11 % lavere omkring år 1900, end den er i nutiden. Ændringen i vandafstrømningen mellem de to perioder afspejler i vid udstrækning ændringerne i nedbøren, men forstærkes i nogle områder af den lavere dræningstæthed i den historiske periode. Den beregnede ændring i vandafstrømning i forhold til tiden omkring år 1900 var mellem 0-20 % for det meste af landet, hvilket er i overensstemmelse med analysen af lange tidsserier for vandafstrømning, der blev præsenteret i Jensen (ed.) (2017). For den vestlige del af Sjælland indikerer observerede data imidlertid en øget vandafstrømning mellem de to perioder på ca. 30 %, mens modelsimuleringen resulterede i et fald i vandafstrømningen på ca. 5 %. Den anvendte metode indebærer, at den samlede vandafstrømning forventes at afspejle forholdene omkring år 1900, hvorimod metoden ikke kan forventes at reproducere de lokale forhold på det pågældende tidspunkt.

Næringsstoftilførsel

De næringsstoffer, der nåede havet fra land, stammede hovedsagelig fra landbrugsaktiviteter og bebyggelser over hele landet omkring år 1900. Derudover bidrog afstrømning fra erosion langs vandløbene til næringsindholdet i ferskvand, især fosforindholdet.

Landbrug

Landbrugsarealet steg dramatisk i sidste halvdel af 1800-tallet og tegnede sig for omkring tre fjerdedele af det område, der var under dansk administration omkring år 1900. Afgrødeproduktionen afveg betydeligt fra det nuværende landbrug for stort set alle vækstfaktorer: ringere afgrødesorter, højere ukrudtstryk, manglende kemisk plantebeskyttelse og ringere næringsstofforsyning til planter, herunder fravær af mineralsk gødning. De vigtigste kilder til næringsstoffer var fast husdyrgødning, gylle og kvælstoffiksering ved bælgfrugter. Antallet og kategorierne af husdyr samt landbrugsstruktur og forvaltningspraksis omkring år 1900 afveg også fra praksis i dag.

Sognestatistikker fra omkring år 1900 for arealet under nuværende dansk administration blev samlet i otte kategorier (vinter- og forårsafgrøder, græs, rodafgrøder, brak, natur og skov). Hver kategori fik tilknyttet en rodzonekoncentration af kvælstof. For landbrugskategorierne blev kvælstofkoncentrationen i rodzonen fastsat med baggrund i data fra undersøgelser af økologisk landbrug, idet disse forudsættes at kunne anvendes som proxy for rodzonekoncentrationen omkring år 1900. For de resterende kategorier blev rodzonekoncentrationen fastsat ud fra litteraturdata. Disse værdier blev anvendt i kvælstofmodelleringen. Beregningen af den arealvægtede gennemsnitlige kvælstofkoncentration for arealer anvendt til landbrug (78 % af landarealet) resulterede i en værdi på 12 mg N/l, mens værdien for hele landarealet var 9,6 mg N/l i rodzoneudvaskning (uorganisk kvælstof).

Vurderingen af fosfortilførslen fra landbrugskilder tog hensyn til faktorer som dræning, landindvinding, græssende dyr, jorderosion og opbevaring af gødning. Der var en del usikkerhed tilknyttet disse faktorer, da de var vanskelige at fastslå, hvilket førte til et anslået interval for fosfortilførslen fra 70-200 ton P årligt omkring år 1900.

Punktkilder

Kloaksystemerne blev i stigende grad anlagt i byerne, men stadig uden spildevandsrensning omkring år 1900. Byerne var derfor vigtige punktkilder omkring år 1900, med 4.261 ton N/år og 764 ton P/år udledt med ekskrementer fra mennesker og dyr samt med industrielt spildevand. Resultaterne viser, at størstedelen af næringsstofferne fra punktkilder udledtes direkte til det modtagende vand (55 %), men tilførslerne fra lossepladser (20 %) og landbrugsjord (25 %) var også betydelige. Det samlede bidrag fra indirekte og direkte punktkilder til vand blev anslået til 471 ton P, ca. 65–70 % af den nutidige værdi (704 ton P, gennemsnit 2014-2018) og 2531 ton N, ca. 47% af nutidens TN-punktkilder (5.400 ton N, 2020).

Andre kilder, herunder baggrundsnæringsstofkoncentration

Kvælstoftilførsel fra atmosfæren blev estimeret ved at multiplicere EMEP-simuleringer for år 2000 med 0,3 (Jensen (ed.), 2017). Organisk kvælstof fra landskabskilder og overfladevandskilder blev medtaget for at kunne beregne de samlede kvælstofkoncentrationer. Skøn baseret på litteraturundersøgelser antager, at den organiske kvælstofkoncentration omkring år 1900 lå ca. 20 %

under det nuværende niveau. Desuden antages det, at den nuværende geografiske fordeling af organisk kvælstof er gyldig for tiden omkring år 1900.

En gennemgang af litteraturen og målinger fra stort set uforstyrrede vandløb bruges til at estimere baggrundskoncentrationen af TP i det vand, der strømmer til havet. En arealvægtet medianværdi på 0,052 mg / l TP blev anslået.

Næringsstoftransport til havet

Kvælstof siver gennem jorden og når grundvandet, hvor der under iltfrie forhold kan ske reduktion i kvælstofindholdet (retention), før det resterende kvælstof ender i overfladevand (vådområder, søer, vandløb). Den nationale kvælstofmodel simulerer transport og retention i grundvandet baseret på vandafstrømning og kvælstofudvaskning. Overfladevandskomponenten beregner kvælstofretentionen i vådområder, vandløb og søer, samtidig med at der tages højde for punktkildetilførsler, atmosfæriske tilførsler og bidraget fra organisk kvælstof. Landskabsændringer fra år 1900 og nu blev håndteret ved at ændre de nuværende landskabskort baseret på forskellige informationskilder om det tidligere landskab relateret til floder og søer. For vådområder blev der anvendt et andet kort.

Fosforanalysen anvendte ”baggrunds”- eller ”naturlig” -koncentration af fosfor i vandløbsvandet, hvortil de relevante landbrugs- og punktkilder blev tilføjet og retention i søer trukket fra. Transport af fosfor gennem oplandet blev simuleret ved brug af den samme vandafstrømning som i kvælstofmodelleringen.

Den absolutte mængde af kvælstof, der fjernes ved retention, viste sig at være højere i den nuværende periode (28.000 ton N) end i 1900-talsperioden (26.000 ton N), hvilket skyldes den større kvælstofbelastning i dag. Den relative kvælstofretention var imidlertid højere omkring år 1900, idet 43 % af belastningen blev fjernet sammenlignet med 33 % i den nuværende periode.

Den totale kvælstoftilførsel (TN) er modelleret til at være ca. 36.000 ton N / år omkring år 1900, hvilket er ca. 40 % mindre end i den nuværende periode. Kvælstofkoncentrationen er modelleret til at være omkring 2,8 mg N / l omkring år 1900 sammenlignet med 4,1 mg N / l i den nuværende periode. Den nationale kvælstofmodel giver regionale resultater, som anvendes til at estimere regionale kvælstoftilførsler samt kvælstofkoncentrationer i det vand, der strømmer til havet, omkring år 1900.

Den gennemsnitlige fosforkoncentration i vand fra vandløb omkring år 1900 blev anslået til at være 0,062–0,075 mg P / l, svarende til 60–70 % af den nuværende TP-koncentration (0,1 mg P / l). TP-værdierne er fastsat for ni geografiske regioner i hele landet. Den samlede TP-belastning til havet, herunder baggrundsbelastning, andre diffuse kilder, indirekte og direkte punktkilder og fratrukket fosforretention i søer, blev anslået til 1.200-1.340 ton P, 60–65 % af (eller 35-40 % mindre end) nutidens fosforbelastning (2,021 ton).

Usikkerhed

Arbejdet med en periode for 120 år siden gør naturligvis de fleste aspekter af opgørelsen af den nationale kvælstof- og fosforbelastning mere usikre, end når man opgør den for den nuværende periode. En grundig analyse af usikkerheder på datalag, variable, model- og modelantagelser var ikke en del af nærværende undersøgelse; dog er der foretaget nogle overvejelser om usikkerhed og følsomhed (effekten af en given parameter på resultatet).

De fleste af de parametre, der bruges til at estimere kvælstofbelastninger omkring år 1900, anses for at have en ”middel” usikkerhed (på en tretrinsskala fra lav til høj). Usikkerheden på kvælstofbelastningerne er påvirket af en række faktorer, hvor de vigtigste er usikkerheden omkring estimeret nedbør, afstrømning, rodzonekoncentrationen af kvælstof og retention af kvælstof i overflade- og grundvand.

Overordnet anses det modelkoncept, der er brugt til at beregne kvælstofbelastningen i år 1900, som relativt robust og den overordnede usikkerhed på nationalt plan som acceptabel. Usikkerheden stiger dog med en faldende geografisk og tidslig skala.

De fleste af de parametre, der bruges til at estimere fosforbelastninger, betragtes som ”middel” til ”meget”" usikre. Usikkerheden på fosforbelastninger er især påvirket af usikkerheden på estimaterne for nedbør, afstrømning, P-tilførsel fra punktkilder og baggrundskoncentrationen af TP. På trods af de mange usikkerheder menes resultaterne af denne undersøgelse at være det bedst mulige estimat for fosforbelastningen i år 1900. Yderligere er resultatet af denne undersøgelse understøttet af historiske målinger i søer, der også finder historiske TP-koncentrationer, der er lavere end i dag, men betydeligt højere end baggrundskoncentrationen.

Perspektivering

Mange af de europæiske undersøgelser, der sammenlignes med nærværende undersøgelse, rapporterer om kvælstofkoncentrationer omkring år 1900, der er betydeligt lavere end i nærværende undersøgelse. Årsagerne hertil er formentlig forskelle i landskabet, arealanvendelsen, landbrugspraksis og afstrømning mellem de undersøgte områder og Danmark. Det afspejler formentlig også, i hvilken grad landbrugspraksis og næringsstofdynamik indgår i undersøgelsen. I nærværende undersøgelse beregnes rodzoneudvaskning for år 1900, og kvælstoffiksering, hovedkilden til kvælstof i dansk landbrug i år 1900, tages i betragtning, hvilket ikke er tilfældet i de fleste andre undersøgelser.

Introduction

The current report aims to describe the nutrient load from land to sea around the year 1900 and builds upon a previous project in which different factors influencing the nitrogen content from the field to the sea around the year 1900 were investigated (Jensen (ed.), 2017)[1]. The main factors investigated in 2017 were climate, hydrology, land use, agricultural practices, drainage and landscape effects (retention). The analysis showed, among other things, that it was colder and drier in the year 1900, more land was in agricultural use but less was tile drained, and due to especially a larger proportion of wetlands the retention of nutrients in the landscape was higher. Combined, this resulted in a best estimate at the time of the nitrogen concentration in the water running to the sea of 1-2 mg N/l.

The aim of the current project was to further develop this analysis and expand it to also include phosphorus, enabling the calculation of a spatial distributed estimate of the nitrogen and phosphorus concentrations from the root zone to the sea and the resulting load to the sea.

To be able to do this, the datasets on climate and hydrology were expanded and the runoff was modelled using the national water resources model (DK-model).

The agricultural practices and land use in different areas of the country were analysed in detail, and the root zone-concentration of nitrogen was determined for different land use categories. Furthermore, a detailed analysis of the contribution of nutrients from cities (point-sources) was included.

To model the concentration and transport of nitrogen in the freshwater load to the sea, the national nitrogen model (NMN) was used. The model requires geographically distributed input of climate variables such as temperature and water runoff, the input of nitrogen from the root zone and point sources as well as data on the depth of groundwater and the amount and location of wetlands, lakes and streams in order to estimate the retention occurring in the surface water system.

The phosphorus analysis focused on assessing the total phosphorus concentrations and used an approach of a ”background” or ”nature” concentration level on top of which the relevant additional agricultural and point sources were added and the retention in lakes was subtracted. The transport and routing of phosphorus through the catchments were simulated using the same water discharge as for the nitrogen modelling, but the model as such is much simpler than the nitrogen model because of the way phosphorus behaves in the environment

In the following chapters (1-7) each of the different factors influencing the nitrogen concentrations around the year 1900 is described and discussed and finally incorporated into the NNM model (chapter 8) to model the nitrogen concentration and load to the sea.

The method used for estimation of the phosphorus concentration (chapter 9) differs from the approach used for nitrogen because the two nutrients and their behaviour in the environment are significantly different. Phosphorus is discussed in a separate chapter, but the analysis is based on the same climate, hydrology, landscape data and point source analysis as for nitrogen.

In the last common chapters (10-12), uncertainties of the chosen approaches, a synthesis of results, discussion and perspectives are presented.

Report structure

Chapter 1 and 2: Describe the climatic conditions, temperature and precipitation around the year 1900 as well as the evapotranspiration and global radiation at that time. The data are used as input to the models calculating water-runoff (DK model) and nitrogen-load (NNM-model).

Chapter 3: Describes the water run-off around the year 1900 modelled with the DK model. Stream discharge is used as input to the NMN model described in chapter 6-8 and to calculate P transport in chapter 9.

Chapter 4: Describes the nutrient input from the larger Danish cities and related activities around the year 1900 (point sources). The results of the analysis are used as input to the NNM (chapter 6-8) and to calculate the P-transport in chapter 9. Inland point sources are added to the surface water module of the NNM, along with N and P from other sources and retention is calculated on the total load. Coastal point sources are treated as loads directly to the sea and hence there is no retention on coastal / direct loads.

Chapter 5. Describes the land use and agricultural practices around the year 1900 and how the root zone concentration of nitrogen around that time is estimated. The results are used as input to the NMN model chapter 6-8.

Chapter 6: Describes the NMN model concept, and how the model is adjusted to represent conditions around year 1900 based on the results from chapter 1-5. Further, the input parameters atmospheric nitrogen deposition and the level of organic nitrogen in freshwater are estimated.

Chapter 7: Describes changes in the landscape since the year 1900, how it affects surface water retention and how the retention is calculated in the different types of surface water systems (lakes, streams and wetlands)

Chapter 8: Incorporates the results from chapter 1-7 into the NNM to calculate the concentration and transport of nitrogen to the sea.

Chapter 9: Describes the phosphorus concentrations and transport around the year 1900 and how the concentrations and loads to the sea are estimated.

Chapter 10: Describes the uncertainty analysis for the various factors and methods used.

Chapter 11: Presents a synthesis extracting the main results and providing an overall overview.

Chapter 12: Presents the perspectives and conclusion of the study.

[1]Jensen (ed.), 2017. Estimation of nitrogen concentrations from root zone to marine areas around the year 1900. Scientific Report from DCE No. 241. Aarhus University, Danish Centre for Environment and Energy.

1 Climate around year 1900: Temperature and precipitation

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Abstract

Purpose: In the present chapter, climate data for the year 1900 and a validation period 1917-1950 are established. Spatially distributed temperature and bias-corrected precipitation are used as input to the calculation of global radiation and evaporation in chapter 2 and of the modelling discharge to the sea in chapter 3.

Materials and Methods: Based on digitised observations, spatially distributed meteorological variables are provided to the hydrological modelling of stream discharge. Rain gauge observations were corrected for shelter effects and biases caused by wind and wetting loss. In order to calculate the bias correction, a number of simplifications and assumptions are necessary due to, for instance, the facts that rain rate and precipitation type are not measured. The corrected precipitation was validated by comparing the simulated and observed water discharge for the validation period 1917-1950 (see also chapter 3).

Results and discussion: A general water balance error of 3% for the verification period 1917-1950 suggests that the national values for corrected precipitation are realistic. However, large variations in the fit between observed and simulated discharge were seen at a regional scale. Since the true wind speed and shelter conditions at station level are unknown, various approaches for calculation of corrected precipitation were tested but with no reasonable results. This uncertainty could not be addressed within the current project; thus, a delta change approach was applied instead. Based on this, approach the spatial distribution of the amount of rainfall in the reference period 1989-2010 was transferred to the period 1890-1910 by using monthly climate factors (delta change) derived from the relations in corrected rainfall between the two periods.

Verification of climate data shows that monthly and annual values of temperature and precipitation are reasonably well in line with official climate values, but with a larger uncertainty at local level, however. It is difficult to verify wind speed, but it is known that manual observation can be a source of uncertainty. In a parallel project, manual wind speed observations have been corrected for homogeneity problems, and a trend adjustment has been applied using geostrophic wind speed.

Conclusions: Based on uncorrected wind data, delta change was calculated to 0.931 per year (773 mm yearly corrected rainfall which is 57 mm less than during 1989-2010). The corrected wind data show that the uncorrected wind around year 1900 was probably overestimated, resulting in a 2.7% too large value of delta change corresponding to 20 mm/yr., a reasonable level given the different assumptions and uncertainties.

1.1 Introduction

The objective of this chapter is to provide this project with spatially distributed estimates of required meteorological variables to support the hydrological modelling of water discharge. The detailed content of the chapter has been previously published in a scientific brief from DCE, AU (Vejen, 2021). As no discharge data are available before 1917, it is not possible to validate the modelled discharge around year 1900. Therefore, the period 1917-1950 is chosen as validation period.

A limited number of digitised daily or monthly data in the database of the Danish Meteorological Institute (DMI) has motivated digitisation of a large number of climate data. The specific goal of the climate data activity was:

1) to collect and digitise historical meteorological data from 1890 to 1950.
2) to develop an approach for bias correction of historical rain gauge data.
3) to establish data series of bias-corrected rainfall, air temperature and wind speed for a suitable number of inland stations evenly distributed in Denmark, also with data for Southern Jutland before 1920.
4) to validate the uncertainty of calculated climate variables around year 1900 and to compare the results with official monthly and yearly climate values from DMI.

Based on these data, 10×10 km^2 fields of bias-adjusted precipitation and 20×20 km^2 temperature fields are established for calculation of evaporation, which acts as climate data input to the hydrological model run for the period 1917-1950 for evaluation of the water balance (see chapter 3). Finally, the goal is to refine or develop a novel approach for bias correction of rain gauge undercatch if the modelled water balance is not sufficiently accurate.

Measurement of precipitation is recognized as a challenging task, and uncertainties regarding rain gauge measurements have been widely reported. Precipitation measurements are affected by systematic errors, which lead to underestimation of the actual precipitation for rain (e.g., Sevruk, 1979) and, especially, for snow (e.g., Groisman and Legates, 1994; Yang et al., 1995). Numerous field experiments have shown that wind speed is the most important environmental factor for this undercatch, or bias, of rain gauge measurements (e.g., Sevruk and Hamon, 1984).

The interaction between a rain gauge, the wind flow and liquid or solid particles falling through the air is complex. The design and geometry of a rain gauge are of great importance for its aerodynamic properties and ability to measure precipitation, e.g., demonstrated by wind tunnel experiments (Nespor, 1996), and modelling of the air flow around rain gauges also showed systematic differences related to gauge geometry (e.g., Colli et al, 2018).

Precipitation measured by a rain gauge is subject to other systematic errors such as evaporation and wetting losses, the magnitude of which depends on the type of rain gauge (Sevruk and Hamon, 1984).

Precipitation is an important parameter in hydrological modelling and studies of the water cycle, and sustainable water balance monitoring requires availability of accurate precipitation data. It is necessary to apply a correction for the different losses in measured precipitation to acquire reliable calculations of the water balance (e.g., Plauborg et al., 2002).

Organised by the World Meteorological Organization (WMO), great efforts are made to conduct field tests and establish models for correcting sources of error in measured precipitation. A comprehensive correction model was developed, which elegantly combines sub-models for rain, sleet and snow in the same equation (Allerup et al., 1997) by which bias correction is conducted if information is available about wind speed, rain intensity, dry air temperature and the proportion of precipitation fallen as snow.

An important part of the work is to apply bias correction to the observed precipitation, but several data required for this were not available around year 1900, such as shelter information at rain gauge stations and rain rate. Wind speed was manually observed, and the observation frequency was low. A method was developed to overcome these challenges. The corrected precipitation estimates included in the hydrological modelling are based on a range of meteorological data, including manually recorded wind speed. It was possible to correct the wind speed for a number of errors and the improved wind data was finally used to examine the sensitivity of the corrected precipitation estimates.

1.2 Material and methods

1.2.1 Data

Monthly wind speed and daily temperature data for the period 1890-1950, and daily rain gauge data for the period 1913-1950, were published in analogue form in monthly or annual weather reports (DMI 1890-1950), and it is assumed that these data were subject to quality assurance before publication, even though no documentation for methodology is found. Opposite to this, rainfall data from 1890 to 1913 are available in the form of original observer reports (Rigsarkivet). Experience at DMI shows that these data have not been subject to quality control. Quality assurance of such a huge amount of data is an extremely comprehensive task, which is beyond the scope of this project, so only simple checks have been carried out, i.e., values exceeding certain thresholds are automatically flagged as suspicious or in error. It is assumed that after this simple quality control, these data have required quality, i.e., observation errors and scanning mistakes have been identified and flagged.

Since about 20% of the stations are not registered in DMI's metadata database, the approximate position of the stations could only be determined from the station name. There is therefore minor uncertainty in the position of some of the stations. It is considered that this is acceptable as the alternative would be exclusion of data and increased uncertainty of estimated precipitation fields.

Daily values of maximum and minimum temperature and measured precipitation at rain gauge stations have been digitized. The framework of the project has not allowed digitization of the daily wind speed, but monthly mean values have been digitized.

While the precipitation stations are evenly distributed, the wind speed stations are primarily coastal stations. Until 1913, there were only eight stations where wind speed was measured, including one inland station. Later, the number increased to 11-12, of which approx. six inland stations are available. See example for 1900 and 1935 in Figure 1.1. Stations with temperature measurements are evenly distributed with both coastal and inland stations, and the number of stations is identical for almost the entire period – 15-17 – with up to nine inland stations (Figure 1.1). The number of digitized precipitation stations increases from approx. 80 in 1890 to about 130 in 1913, including stations from Southern Jutland, but already in 1919 there were about 270 stations, a number that remained almost constant until 1950. Figure 1.2 shows the spatial distribution of precipitation stations in the two periods 1890-1910 and 1914-1950. In 1890-1910, there is a lack of precipitation data on the northern part of Jutland, and there are regions with a relatively sparse rain gauge network. The rain gauge density is much higher in the period 1914-1950, but the network is slightly in-homogeneous with smaller areas of lower coverage.

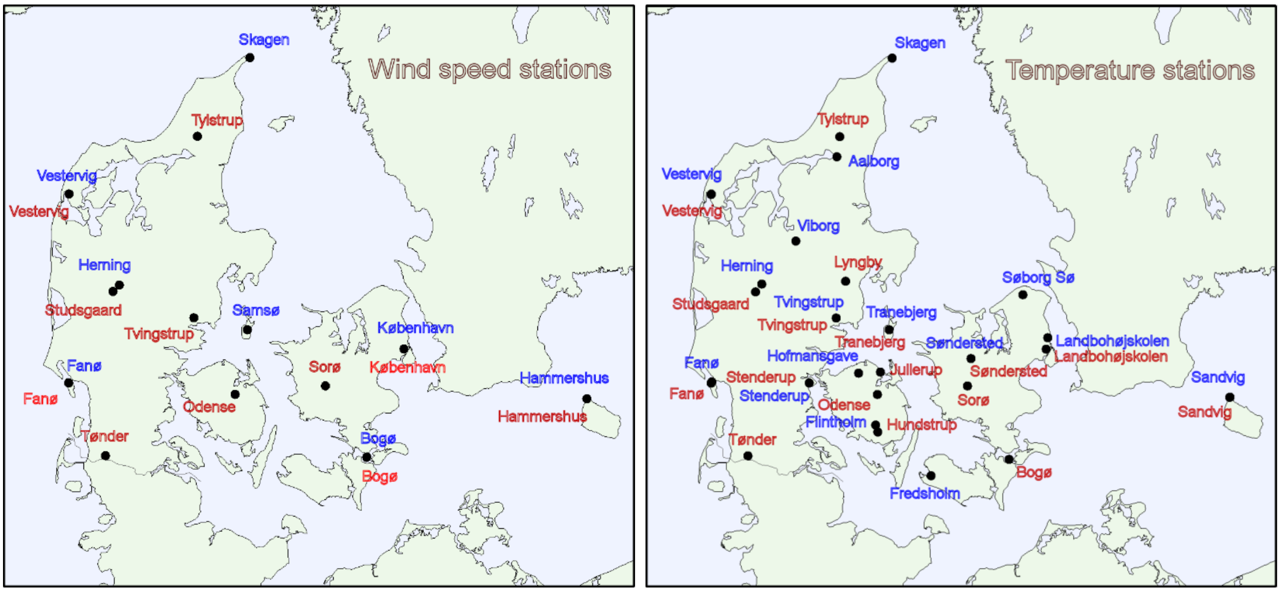


Figure 1.1. Stations with wind speed and temperature in 1900 (blue) and 1935 (red).

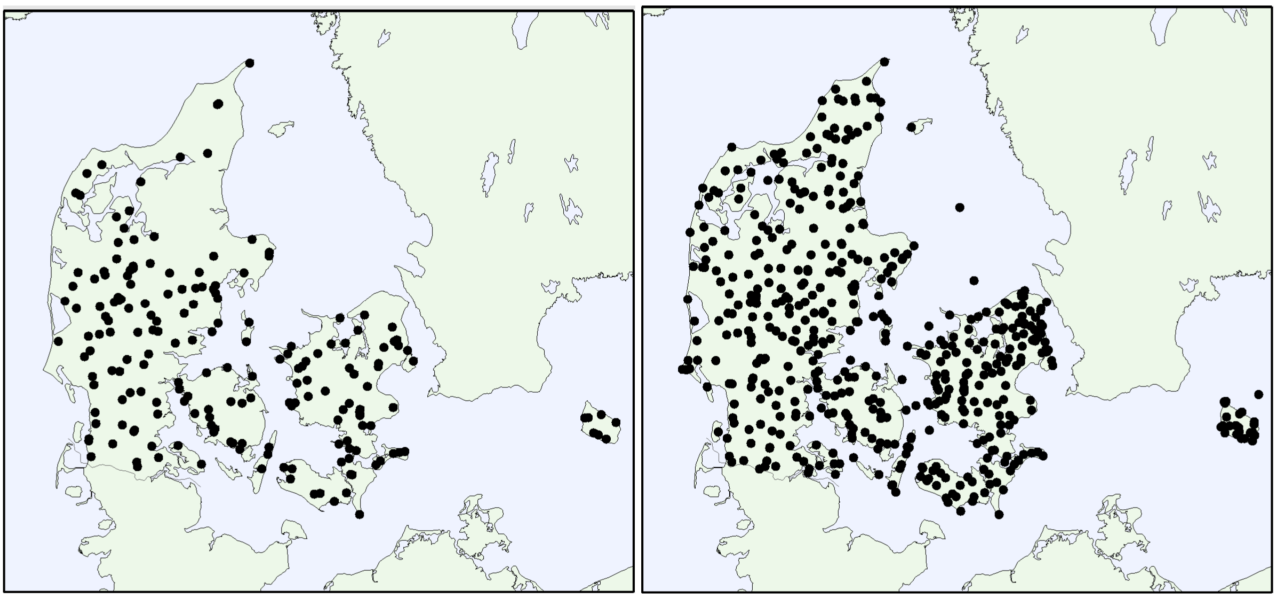


Figure 1.2. Stations with precipitation in the period 1890-1910 (left) and 1914-1950 (right). Maps are from Google Earth.

Up to the 1910s, the amount of precipitation was measured with the so-called Fjord rain gauge for measurement of rain, and for snow measurements, a zinc bucket was used (hereafter called snow gauge). In the period 1910-1925, the Fjord gauge was gradually replaced the Danish Hellmann gauge (Brandt, 1994), which functioned as the cornerstone of the DMI's rainfall network until 2011. For the Hellmann gauge the installation height was 1.5 m (Brandt, 1994), while the Fjord gauge was installed with its orifice placed at 2 m height above ground level (DMI, 1875). It is not known for how long time this practice continued, but presumably it gradually stopped during the transition to the Hellmann gauge.

Wind speed (V) was visually observed throughout the period. Until the end of 1910, it was indicated by the so-called Danish Land Scale, which has seven levels (0-6) (Kristensen and Frydendal, 1991). Hereafter, the well-known Beaufort Scale (level 0-12) was used. At DMI in Copenhagen, wind speed was given in m/s for the period 1890-1893. When correcting for wind-induced bias in precipitation measurement, V must be given in m/s. Therefore, a method was developed for conversion of Danish Land Scale and Beaufort to m/s (Vejen, 2021).

1.2.2 Adjustment, correction, and control of data

Several aspects and parameters need to be considered before the early observations are used to calculate the needed wind and temperature fields and precipitation field for the hydrological modelling. The methods and data used are briefly described in the following. The aspects considered in this work are listed in Table 1.1 where the topic and overall approach are mentioned. Detailed explanations are found in Vejen (2021).

Table 1.1. List of issues and overall approaches to tackle shortcomings of climatological data from the period 1890-1950. Further details in Vejen (2021).

Topic	Approach
Wind	
Conversion of wind speed measurements to m/s	Conversion model developed
Control of wind speed observation data	Homogeneity checks with observations from more recent times
Correction for shelter conditions	Assuming similar shelter practice in 1890-1950 as today
Adjustment of monthly wind speed to reflect precipitation days	Correction based on a monthly correction factor
Rain	
Estimation of wetting and evaporation loss	Evaporation and wetting loss according to the Hellman gauge (Allerup and Madsen, 1979, 1980)
Estimation of rain rate	Based on earlier climatological measurements
Calculation of precipitation type	Model based on air temperature
Bias correction of rain gauge observations	Argued not to cause too high uncertainty
Correction and control of rainfall measurements for wind-induced bias	Comprehensive model used in Denmark (Allerup et al., 1997)

For correction of precipitation measurements, in Denmark, a model combining the correction of solid, mixed and liquid precipitation into one expression is used (Allerup et al., 1997), where the correction factor K_α for the precipitation type a is given by the following correction model:

$$K_\alpha = \alpha \cdot e^{\beta_0+\beta_1 \cdot V+\beta_2 \cdot T+\beta_3 \cdot V \cdot T} + (1-\alpha) \cdot e^{\gamma_0+\gamma_1 \cdot V+\gamma_2 \cdot ln\, I+\gamma_3 \cdot V \cdot ln\, I+c}$$

Here, a = index indicating the proportion of precipitation fallen as snow (0=rain, 1=snow), V = wind speed at gauge level, T = air temperature, I = rain rate, β_0, β_1, β_2, β_3 = empirical constants for snow (Allerup et al., 1997) and $\gamma_0, \gamma_1, \gamma_2, \gamma_3$, c = empirical constants for rain (Allerup and Madsen, 1980; Førland et al., 1996). The corrected precipitation amount, P_c, is in principle given by $P_c = K_a P_m$ where P_m = measured precipitation, but also a wetting loss must be included in the correction (further details in Vejen et al., 2014). The design of a rain gauge is of importance for its aerodynamic properties (Sevruk and Klemm, 1989; Sevruk et al., 1989). The design of the Fjord and snow gauges is different from the Hellmann gauge. Despite the fact that their measuring ability may differs, it is assumed that the correction model can be used for both gauges.

For the Hellmann gauge, the wetting loss is a function of season and precipitation type (Allerup and Madsen, 1979, 1980; Vejen et al., 2000) and amounts to approx. 5% per year. The evaporation loss is negligible (1.5-2.0 mm / yr). The undercatch for the Fjord gauge due to wetting and evaporation is assumed to be the same as for Hellmann, although its design probably causes a larger evaporation loss than that of Hellmann.

Correction of precipitation requires input on wind speed and temperature at gauge level during precipitation, on rain rate, wetting loss and precipitation type, which is illustrated in the process diagram in Figure 1.3. For the period 1890-1950, there are certain data limitations. The wind speed is manually observed, and only monthly average values are digitally available. Air temperature is digitally available only as a maximum, T_{max}, and a minimum temperature, T_{min}. No information on rain rate and precipitation type is available.

Seasonal-dependent climatological values of rain rate, which are based on measurements of precipitation in Denmark over the period 1959-1974 at four stations (Madsen and Allerup, pers. comm.), are used and assumed representative of 1890-1950.

Daily average temperature, T_{avg}, is calculated using daily observations of T_{min} and T_{max} and is assumed to represent conditions during precipitation. A widely used model for the determination of precipitation type, *t*, uses the air temperature, or in our case daily average temperature, T_{avg}, as an indicator of precipitation type, i.e., t = snow if $T_{avg} \leq 0$ °C, t = rain if $T_{avg} > 2$ °C, and otherwise sleet, although this method may cause bias between estimated and observed *t* (e.g., Feiccabrino et al., 2015). A more realistic probability function for *t* can be obtained by including air humidity (e.g., Harder and Pomeroy, 2013), but this parameter is not available in the data set. Snow index *a* is calculated from T_{avg} by a=1 for snow, a=0 for rain and $a=-0.5\ T_{avg}+1$ for mixed precipitation.

Manually observed values of *V* are transformed to m / s based on information found in WMO (1970) Kaufeld (1981) and Kristensen and Frydendal (1991). From analyses of the general level of wind speed for manual observations before and automatic measurements after 1950, it seems reasonable to assume that V represents 10 m above ground level. *V* is adjusted down to the height of the rain gauge using the logarithmic wind law as recommended by the WMO (2008). As there is no information on the properties of the ground surface, the effective roughness length is used in the wind law in the form of a general value of 0.25 like that used in Refsgaard et al. (2011).

Monthly wind speed does not reflect the conditions during precipitation periods since it includes dry days and days with stable weather and low wind speed. Correction for this bias is applied using a seasonal-dependent adjustment factor (Vejen, 2021).

It is common practice to adjust the wind speed for local shelter conditions. The shelter adjusted wind speed, V_{shlt}, is found by adjusting the wind speed at gauge height *h*, V_h, by the expression $V_{shlt}=\lambda V_h$, where λ is a shelter correction factor given by $\lambda=1-c\cdot\eta$ (Sevruk, 1988; WMO 2008). Here, η = the average height angle to the top of the shelter given in degrees and c = a constant (c=0.024). At DMI, it is practice to use a weighted shelter index, η_{wgt}, which is calculated by weighting height angles with the statistical frequency of winds from eight directions. Thus η_{wgt} replaces η in the expression for λ.

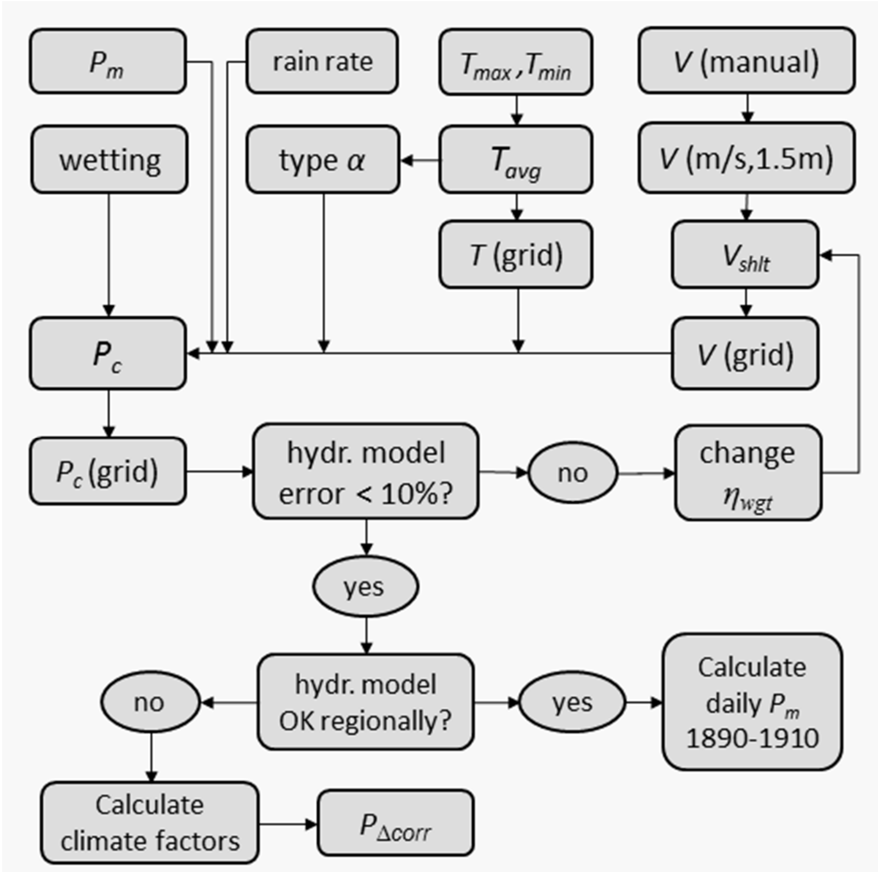


Figure 1.3. Process diagram for calculation of grid values of corrected precipitation, which is used as input to the hydrological modelling of chapter 3. P_m = measured precipitation, T_{max} and T_{min} = maximum and minimum temperature, V (manual) = manually observed wind speed, wetting = wetting loss, type α = index indicating precipitation type, T_{avg} = daily average temperature, T (grid) = gridded temperature, V (m/s, 1.5 m) = wind speed transformed to m/s and 1.5 m level, V(shlt) = shelter corrected wind speed, V (grid) = gridded wind speed, η_{wgt} = weighted shelter index, P_c = corrected precipitation, P_c (grid) = gridded corrected precipitation, η = shelter index, $P_{\Delta corr}$ = precipitation corrected using climate factors. See section 1.2.2 and 1.3.4 to 1.3.6 for explanation

DMI first began to measure height angles at rain gauge stations in the 1960s. Since shelter conditions can have great significance for the local wind speed and thus the correction level, it is necessary to make assumptions about height angles for the period 1890-1950. Already in the 19th century, the wind's effect on precipitation measurements and the importance of shelter were well known (Brandt, 1994). It is assumed that in the period 1890-1950, the same practice was used as today to ensure good shelter conditions at rain gauge stations (neither too open nor overprotected).

1.2.3 Calculation of 20×20 km² fields for wind speed and temperature

For consistency reasons, the same interpolation principles are used as in KlimagridDK where the weighting is calculated in relation to $1/r^2$. Here, r = the distance between a grid point and a weather station (Scharling, 1999).

For the period 1890-1950, however, the number of stations with wind and temperature data is quite limited, and especially for wind there are very few inland stations. Since calculation of the spatial distribution of V and T from so few stations is highly uncertain, the interpolated values of T and V are adjusted with a method inspired by Olesen et al. (2000), in which distributed variables are calculated even when the spatial resolution of the observation material is limited. The method combines observations with fields that for each month describe the normal relative spatial variation of V and T. These fields are incorporated into the interpolation technique by which daily 20×20 km^2 fields of *T*, and monthly values of *V*, are calculated.

The established relative normal fields, μ, in a 20×20 km^2 resolution are based on data for the period 1989-2017. The relative values, $\mu(i,j)$, are used to adjust interpolated values of temperature, $T(i,j)$, or wind speed, $V(i,j)$, in the formula below given as $F(i,j)$. In practice, the interpolated surface is lowered or raised depending on the pseudo-climatological value in an arbitrary point *(i, j)*. Especially for wind speed, it has the advantage that interpolation, which is largely based on coastal stations, is forced to lower values inland.

$$F_{(i,j)} = \mu_{(i,j)} \sum_{g=1}^{N} w_{g(i,j)} F_g \bigg/ \left(\sum_{g=1}^{N} w_{g(i,j)} \right)$$, where the weight $w_{g(i,j)}$ is given by:

$$w_{g(i,j)} = \left(\frac{1}{r^2_{(i,j)}} \right)$$

Here, w = a weighting function, g = a gauge station g, N = number of stations, F = measured (or observed) value of wind speed V, or temperature T at station g, $F(i,j)$ = value of T or V for a grid cell (i,j), and $\mu(i,j)$ = the weighting function for the relative spatial normal value for grid cell (i,j).

The weighting for the relative spatial distribution is given by:

$$\mu_{(i,j)} = \sum_{g=1}^{N} w_{g(i,j)} \frac{R_g}{R_{(i,j)}} \bigg/ \left(\sum_{g=1}^{N} w_{g(i,j)} \right)$$

Here, R_g = the relative climate value at gauge station of temperature T or wind speed V, $R(i,j)$ = the relative climate value of T or V for a grid cell (i,j), and w = the weighting function previously defined.

It is assumed that the relative spatial distribution based on data from 1989-2010 is consistent with the period 1890-1950 since the spatial distribution is determined by physical and meteorological factors as well as terrain conditions that are considered relatively unchanged over the period. Even though systematic changes in urbanisation and vegetation over the period are seen, the overall meteorological conditions are assumed to be relatively constant. However, the use of monthly normal fields for simulating spatial variations at daily level increases the uncertainty of the interpolated values.

1.2.4 Calculation of 10×10 km^2 fields of observed and bias-corrected precipitation

Almost the same interpolation method as previously described is used for wind and temperature. The only difference is that rainfall is not adjusted with a relative normal field because it is not needed due to the large number of rain gauge stations. The interpolated field value for precipitation sum, *P*, is given by:

$P_{(i,j)} = \sum_{g=1}^{N} w_{g(i,j)} P_g \bigg/ \left(\sum_{g=1}^{N} w_{g(i,j)} \right)$, where the weighting function $w_{g(i,j)}$ is given by: $w_{g(i,j)} = \left(\frac{1}{r_{(i,j)}^2} \right)$.

1.3 Results

This section analyses and evaluates the calculations of temperature, wind and precipitation, and the basic assumptions for bias correction of precipitation. The evaluation is a challenge as there is no independent data for testing the daily results. However, official national values of the meteorological variables (DMI database) are available; thus, the evaluation can be done by examining whether the interpolation of the meteorological variables can roughly reproduce the official monthly and yearly national climate values over the period.

At DMI, official national values of T and P_m were previously (from the 1950s up to 2006) calculated as a simple average of station values with data from Jutland weighted with 7/10 and data from the islands with 3/10, and after 2006 based on grid interpolation of station data (Cappelen, 2019). Before the 1950s, the methods used were not published. Since grid values calculated during this project are spatially distributed, in contrast to the official national values before 2006, minor differences between official values and grid calculations are expected. The possibility of assessing the calculations of P_m and T relative to climate values is greater than for V since P_m and T values are historically based on a larger network of stations those of V, for example the official normal for T for 1886-1925 is based on 30 evenly distributed stations (Det Statistiske Departement, 1964). The normal, or pseudo normal, for V for the periods 1931-1960 and 1961-1990 is based on a relatively limited number of coastal stations (Lysgaard, 1969; Cappelen, 2000), and official national values do not exist.

In the calculation of national averages of the meteorological variables in this project, grid cells in coastal regions are given lower weight depending on the fraction of land area.

1.3.1 Evaluation of temperature

While the official values are based on many stations available at that time (Cappelen, 2019), the grid method is based on a smaller number of stations. As the calculation method for the two datasets are quite different, the evaluation is used to determine whether this has an impact on the results. Official national daily values are not available for the period 1890-1950; thus, the grid estimates of T are evaluated monthly. Visual inspection of Figure 1.4 (left) leaves the expression that there is no obvious bias between official and gridded values, except a slight underestimation of the coldest months by the grid method. The monthly grid values of T are close to the official values. If the results are inspected carefully, an interesting difference between the two periods 1890-1919 and 1920-1950 is seen (Table 1.2 and Figure 1.4 (right)). The grid values before 1920 are biased towards higher values and those after towards slightly lower values. The explanation of the jump in the general temperature level is that the relatively warm southern part of Jutland was not a part of Denmark before 1920 and therefore not included in the official values, but it is included in the estimates of grid temperatures.

Table 1.2. Statistics on gridded and official national values of temperature *T* for the two periods 1890-1919 and 1920-1950; bias of *T* given as $T_{bias} = \sum(T_{grid} - T_{official})$ and absolute ias as $T_{bias} = \sum(|T_{grid} - T_{official}|)$.

	Year			Month	
Period	T_{grid}	$T_{official}$	T_{bias}	$T_{absbias}$	R^2
1890-1919	7.55	7.45	0.098	0.263	0.998
1920-1950	7.73	7.79	-0.055	0.228	0.998

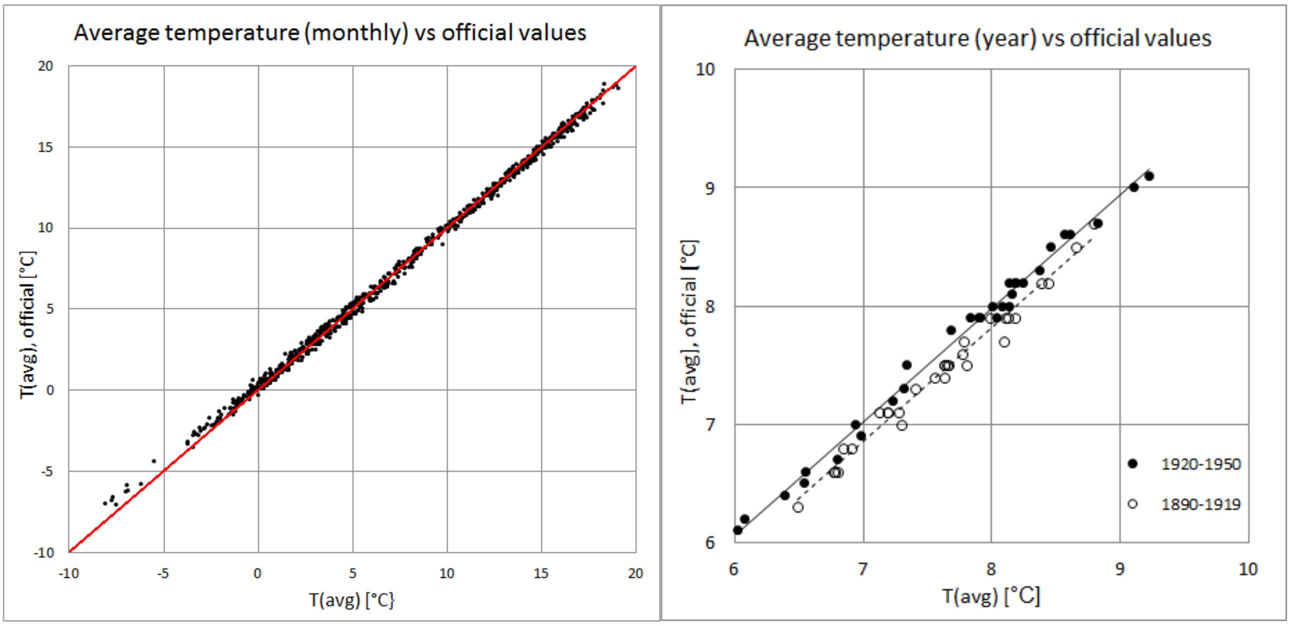


Figure 1.4. Left: National monthly grid values of temperature vs official climate values. Right: National yearly grid values of temperature vs official climate values.

1.3.2 Evaluation of measured precipitation

Figure 1.5 shows monthly and yearly gridded values of measured rainfall compared with official values. The scatter is probably due to differences in calculation methods. The annual values (Table 1.3) show that the grid values for the period 1890-1919 marginally underestimate the measured precipitation compared with official values by 0.56 mm per month and with an absolute bias of 2.9 mm.

Table 1.3. Statistics on gridded and official national values of measured precipitation P_m for the two periods 1890-1919 and 1920-1950. Bias of P_m given as $P_{m(bias)} = \sum(P_{m(grid)} - P_{m(official)})$ and absolute bias as $P_{m(bias)} = \sum(|P_{m(grid)} - P_{m(official)}|)$.

	Year			Month	
Period	$P_{m(grid)}$	$P_{m(official)}$	$P_{m(bias)}$	$P_{m(absbias)}$	R^2
1890-1919	643.0	646.8	-0.56	2.87	0.980
1920-1950	670.4	659.8	0.74	2.91	0.978

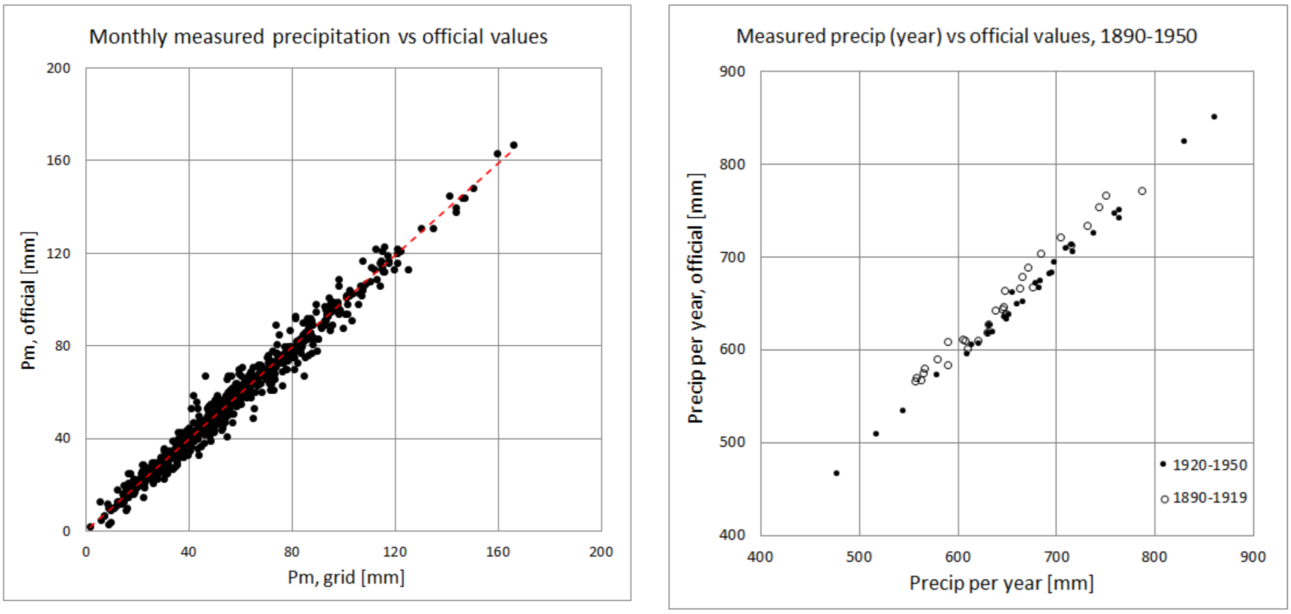


Figure 1.5. Left: National monthly grid values of measured precipitation vs official climate values. Right: National yearly grid values of measured precipitation vs official climate values.

1.3.3 Evaluation of wind speed

Like gridded temperatures, gridded wind speed is based on only few stations. The aim of an evaluation would be to investigate whether the calculation method results in biases compared with official national values, but this is not possible due to lack of official monthly or annual wind speeds.

Prior to 1953, practically all wind data were manually observed, and in the 1950s wind speed was measured in m / s only at a few stations, so evaluation can be done only based on a few long time series of V. Evaluation is done partly by looking at the continuity of V at the transition from Beaufort to m / s, and partly by considering the co-variation and trends in the manual series in relation to the geostrophic wind velocity, V_g.

The inherent uncertainty of manual wind observation is probably the cause of the homogeneity breaks detected for some of the wind series. An inter-comparison of the overall temporal trends in wind speed for the period 1890-1950 showed differences. Some series show increasing wind speed during the period, while others demonstrate a decreasing trend, and for many of the series a homogeneity break is also seen around the transition from manual to automatic measurement. This is a clear indication of the uncertainty of the manual observations, and adjustment for the homogeneity breaks using classical techniques is probably too uncertain.

Instead, the idea is to use geostrophic wind as an independent source for the general temporal trends during 1890-1950. After correction of precipitation and water balance was finished a project funded by DHI (www.dhigroup.com) made it possible to develop a methodology for homogenisation of all wind series in the period 1890-1950.

The method adopts that in Alexandersson et al. (1998) of using geostrophic wind as an indicator of trends in wind climate. Analyses of V_g were conducted to obtain a picture of the overall trend and to compare trends of V_g with the corresponding Beaufort / Danish Land Scale trends. The method is based on the assumption that a relation exists between geostrophic wind and the true wind near the ground, even though it is affected by, for instance, stability, friction and gradient winds (e.g., Luthardt and Hasse, 1981). Geostrophic wind is not a perfect measure of true wind (Alexandersson et al., 1998), and V_g is therefore used mainly for interpretation of trends.

Based on three long air pressure series, daily values of *Vg* were calculated for the period 1890-2010. Based on monthly values of *Vg*, a polynomial model was established, which describes, with good approximation, the temporal trends of *Vg*. Although uncertainty is associated with the calculation of V_g, and certain spatial differences between a point value of *Vg* and wind at individual stations would be expected, it is assumed that the model can give a reasonable impression of the overall trends in wind climate for all stations in the period 1890-1950. The model is then adapted to the level of wind speed for each individual wind series to ensure that the model, in addition to adjustment for the general trend errors, also adjusts for the break around the transition to automatic wind speed measurements.

Reasonable results have been obtained by adjusting all wind series as homogeneity breaks and trend errors are significantly reduced without changing the variability in monthly wind speed. Figure 1.6 shows the monthly values of *V* for Denmark with and without trend correction for 1890-1950 and 1989-2010. Because national grid values are not available in the intermediate period, representative wind series are shown for stations where *V* has been measured with anemometer since 1953. The stations chosen are all inland stations, while the grid estimates for Denmark are averaged over 20×20 km^2 grid cells. No obvious homogeneity break is seen at the transition from Beaufort to m / s in the 1950s.

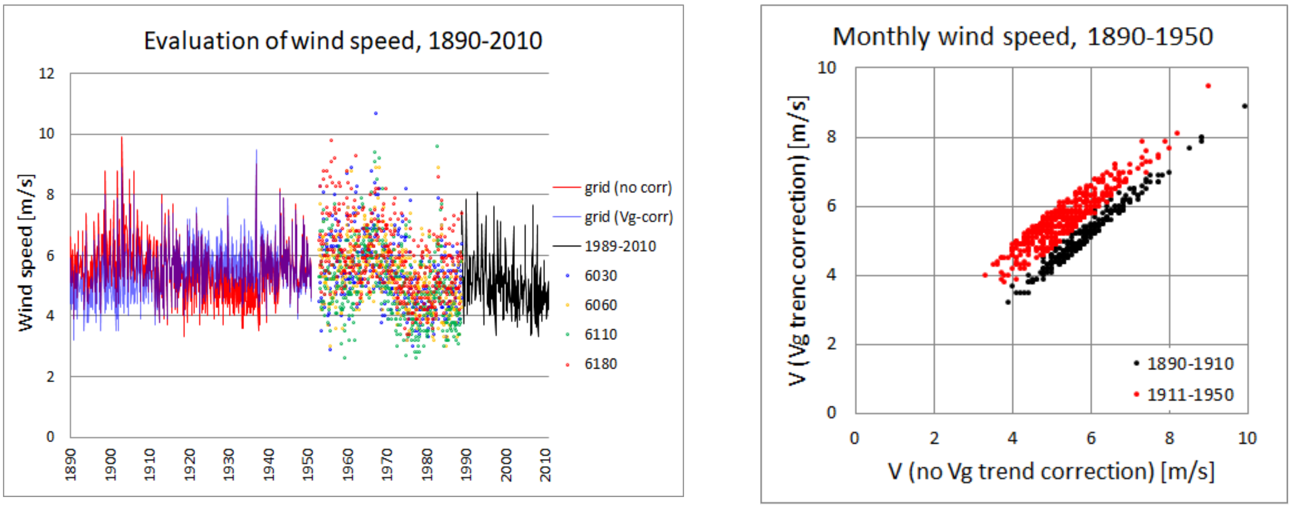


Figure 1.6. Left: Monthly wind speed for the period 1890-2010, national averages of 20×20 km^2 grid values and selected station values. Red line: Grid values not corrected for trends. Blue line: Grid values corrected for trends using analyses of geostrophic wind velocity, V_g. Black line: Grid values for the period 1989-2010. Coloured bullets: Station values. Stations are 06030 FSN Aalborg, 6060 FSN Karup, 6110 FSN Skrydstrup, 6180 Copenhagen Airport. Right: Comparison between averages of monthly national grid averages before and after correction for trend and homogeneity errors.

It seems from Figure 1.6 that Danish Land Scale (1890-1910) probably overestimates and the Beaufort Scale probably underestimates *V*, at least in parts of the period up to 1950. This underlines the importance of wind adjustments as the uncertainty of manual wind observations would otherwise deleteriously affect the bias correction of precipitation, as discussed later.

1.3.4 Evaluation of shelter assumptions

Of the parameters needed for bias correction of rainfall, the lack of information on shelter conditions is particularly critical as the wind speed at gauge height must be adjusted by the shelter correction index, η_{wgt}.

The shelter conditions were generally not known at rain gauge stations until the 1970s. Since shelter can have great significance for the local wind speed and thus the correction level, it has been necessary to make assumptions about shelter conditions for the period 1890-1950. Since the wind’s effect on precipitation measurements and the importance of shelter were well known already in the 19th century (Brandt, 1994), it is assumed that in the period 1890-1950 the same practice was used as today to ensure good shelter conditions (neither too open nor overprotected).

Assumption of a nationwide constant shelter index may result in significant over- or underestimation of bias-corrected rainfall, locally, regionally or nationwide. Streamflow values are calculated by the national water resource model, the DK model, for several catchments using input of bias-corrected precipitation data. To get an idea of what would be the most appropriate index, the calculation of bias-corrected precipitation is iterated over various assumptions about shelter index, η_{wgt} (see Figure 1.3). The effect on hydrological modelling is then evaluated using streamflow gauge stations, which are available for the evaluation period 1917-1950. The water balance error, which is the absolute difference between calculated and measured streamflow at several streamflow gauge stations, is calculated for several catchments and is compared for the different shelter index assumptions. The goal is to minimise the water balance error.

A variety of shelter indices have been used, ranging from nationwide values to more regionally variable indices. It was found that a value of η_{wgt}=12 nationwide for the period 1917-1950 led the total observed and simulated discharge at national scales to agree within a 3% error (Table 3.10).

Despite a good fit at national level, water balance calculations for the approaches showed major errors at regional scale with an excessive water deficit in Western Jutland and excess of water in the eastern part of Denmark (Table 3.10). The assumption of equal nationwide shelter conditions does not hold. A variety of experiments have been carried out with 40×40 km^2 modelling of regional shelter variations, but all approaches still yield large regional water balance errors.

Thus, more experiments are required, but this is beyond the framework of this project. Hence, it was decided to use a climate factor approach for calculation of precipitation climate around year 1900, since the corrected precipitation for 1917-1950 worked well at a national scale.

1.3.5 Definition of delta change climate factor for precipitation ($\Delta\phi_m$)

National values of corrected precipitation are used to calculate monthly delta change climate factors, $\Delta\varphi_m$, defined as the ratio of historical precipitation (1890-1910), P_{hist}, to present precipitation (1990-2010), P_{pres}:

$\Delta\varphi_m = P_{hist}/P_{pres}$

$\Delta\varphi_m$ is based on corrected precipitation for 1890-1910 calculated using the same bias correction method and the same model setup and assumptions as for 1917-1950. Historical and present precipitation is averaged over all grid cells, which have all been given equal spatial weight.

If it is assumed that the relative regional variations of the precipitation amount are identical for the two periods, it may be reasonable to use the delta change climate factors for projection of regional variations of the present climate to the period 1890-1910. This would imply that the temporal climate development is the same all over the country, which does not appear to be the case since the stream discharges change differently between regions. Thus, the use of a general delta change factor, Δϕm, results in regional variations of the uncertainty in the calculated rainfall climate for this period, and probably also around year 1900. Despite the differences in response, it seems reasonable to use the general Δϕm to adjust for the identified climate change. The use of the climate factor in the hydrological modelling is described in section 3.3.2.

1.3.6 Analyses of the effect of trend-adjusted wind speed on corrected precipitation

It is difficult to quantify how much the uncertainty of wind corrections (shelter, trends and homogeneity) contributes to the uncertainty of corrected rainfall. The results in section 1.3.3 suggest that the uncorrected *V* is somewhat too high during the period of Danish Land Scale observations (1890-1910). For the period of Beaufort observations (1911-1950) *V* is on average close to the level without trend correction, but with underestimation in certain periods. The idea of using geostrophic wind for correction of manually observed wind was introduced *after* the modelling of discharge was finished. Therefore, this section investigates how wind correction propagates the estimated climate factors.

It is clear that a higher trend-corrected wind speed will result in an increased amount of bias-corrected precipitation for the period 1917-1950 and that more precipitation will cause too high values of modelled discharge compared with the water balance error of 3% reported earlier. Since the wind speed is the only variable changed, the increased corrected precipitation can be counterbalanced by adjusting the shelter index until the precipitation amount 1917-1950 is approximately equal to the amount causing a water balance error of 3%.

The increase in corrected precipitation can be practically eliminated if the shelter index is changed from 12 to 15, i.e., the new index compensates for the changes in *V* and reproduces corrected precipitation close to the original values that resulted in a water balance error of 3%. As shown in Table 1.4 and Figure 1.7, this is true for the years after the 1910s but not for the periods 1890-1910 and 1900-1920. For approach 1 (no trend correction of *V* and η=12), P_c is much higher than for approach 2 (trend correction of *V* and η=15). For example, for the period 1890-1910, P_c is 793.1 mm for approach 1 but only 758.5 mm for approach 2.

An explanation of these results may be related to observation practice until the 1910s. Until the 1910s, rainfall was measured 2 m above ground level (DMI, 1875), but as for Hellmann the shelter index assumes that the orifice of the rain gauge is at 1.5 m height.

The different measurement heights may have caused the average shelter index to be lower than 15 up to the 1910s and the rain gauge more exposed to the impact of the wind. It can be calculated theoretically that for a typical garden, the shelter index, η_{wgt}, will change from 15 to 13 if precipitation is measured in 2.0 m level instead of at 1.5 m. It is presumably more correct to use η_{wgt} = 13 in the period 1890-1915 and then η_{wgt} = 15 in the period 1916-1950 (approach 3). The results of the three approaches are shown in Table 1.4 and Figure 1.7.

The question is whether the landscape was more open around year 1900, especially in the western part of Jutland, which would produce a lower shelter index. For example, a smaller number of plantations and lower height of the vegetation than today would be expected. Probably, the assumption of a constant shelter index in the whole period 1890-1950 does not hold. For example, it can be calculated that η_{wgt}=10 would practically eliminate the quite large changes in corrected precipitation occurring in the 1910s (Table 1.4).

Table 1.4. Measured annual precipitation (P_m) and results of corrected precipitation (P_c,) based on approach 1 (no trend correction of *V*, η=12), approach 2 (trend correction of *V*, η=15) and approach 3 (as approach 2 but with η=13 for the period 1890-1915, see text for explanation. The differences between approach 1 and 2 and 1 and 3 are also shown (mm and %).

Period	Measured precip, P_m	Corrected precip, P_c (approach 1-3)			Difference	
		1	2	3	1 vs 2	1 vs 3
1890-1910	634.1	793.1	758.5	769.7	-34.6 (-4.5 %)	-23.4 (-3.0 %)
1900-1920	645.5	794.5	772.7	781.2	-21.8 (-2.8 %)	-13.3 (-1.7 %)
1910-1930	674.9	801.8	798.8	801.9	-3.0 (-0.4 %)	0.1 (0.0 %)
1920-1940	673.0	789.8	793.8	793.8	3.9 (0.5 %)	3.9 (0.5 %)
1930-1950	665.3	786.5	786.2	786.2	-0.3 (-0.0 %)	-0.3 (-0.0 %)
1916-1950	671.9	794.1	794.7	794.7	0.5 (0.1 %)	0.5 (0.1 %)

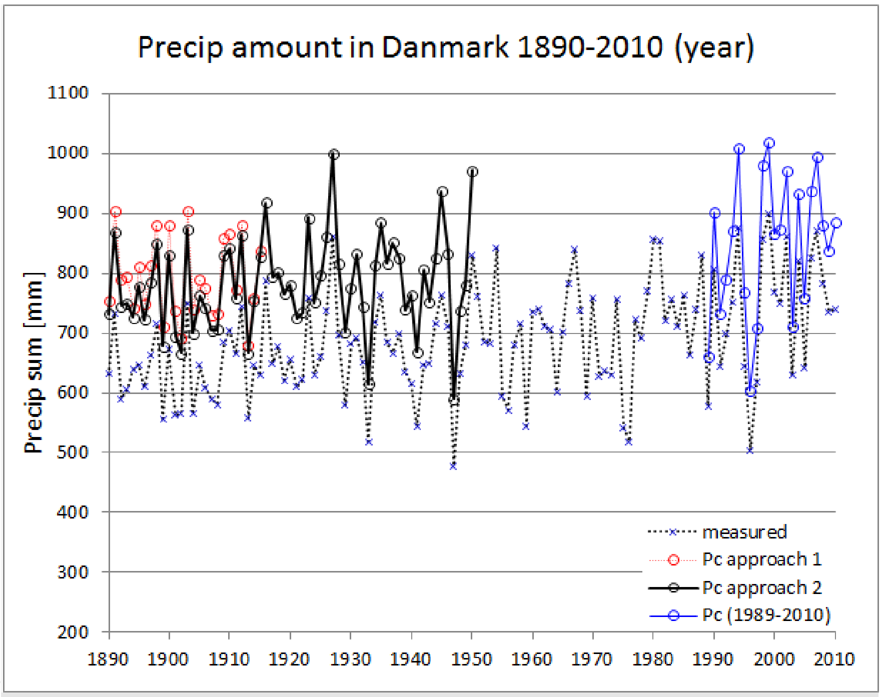


Figure 1.7. Measured and corrected annual rainfall in Denmark 1890-2010. Results of corrected precipitation are shown for approach 1 (no trend correction of *V* and η=12), approach 2 (trend correction of *V* and η=15) and approach 3 (trend correction of *V* and η=13). Corrected precipitation is also shown for the period 1989-2010 (Vejen et al., 2014).

P

Figure 1.8 shows a 20-year moving average of measured and corrected precipitation for shelter approach 1, 2 and 3 and for recent years. The trend curve is based on measured precipitation 1935-2010 and is extended backwards in time to 1890. The overall trend in both measured and corrected rainfall does not appear to be linear over the period 1890-2010. The amount of corrected rainfall seems to be relatively constant during 1915-1950, with a change towards a wetter climate in the years after 1950. Before 1915, the change in type of rain gauge and the lower shelter index caused higher uncertainty in the level of corrected precipitation. Calculation of measured and corrected grid precipitation for the period 1951-1988 are missing, but from a climate perspective it could be interesting to analyse the changes during this period to see when the corrected precipitation started to increase.

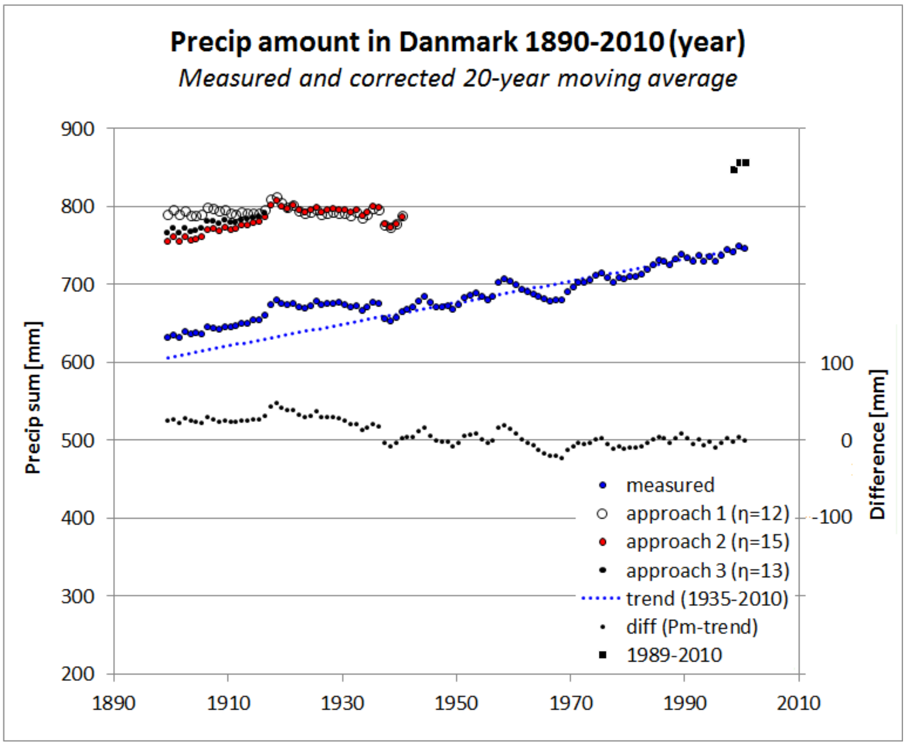


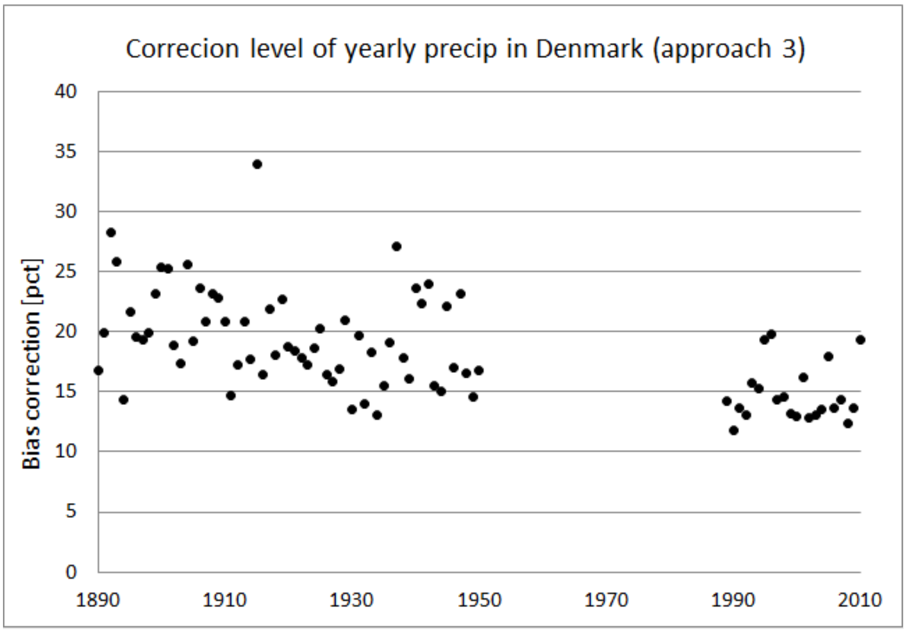
Figure 1.8. 20-year moving average of measured and corrected annual rainfall in Denmark 1890-2010. Note that each point indicates the middle of the time interval. Large blue dots: measured precipitation. Open black circles: approach 1, corrected precipitation using shelter index 12 and V_{mw}. Red dots: approach 2, corrected precipitation using shelter index 15 and V_{mw} corrected for trends according to geostrophic wind. Large black dots: approach 3, as approach 2 except that η=13. Black squares: P_c for 1989-2010. Small blue dots: trend line based on measured precipitation 1935-2010. Small black dots: difference between measured and expected precipitation according to the trend line.

1.3.7 Comparison of measured and corrected precipitation 1891-2010

Figure 1.9 and Table 1.5 summarize the change in measured and corrected precipitation over the period 1890-2010 given as (unofficial) 30-year climate normal. It is seen that the measured amount of precipitation has increased by approx. 97 mm from around 1900 (1891-1920) until today (1989-2010), whereas the corrected value only has increased by 53 mm (approach 1) or 70 mm (approach 3). At the same time, the annual correction level of bias corrected precipitation for approach 1 / approach 3 has fallen from 23.6 / 21.1% for 1891-1920 over 18.0 / 18.1% for 1921-1950 to 14.6% for 1989-2010, which primarily is coupled to changes in wind, temperature, and rain climate.

The amount of corrected precipitation has been at a rather constant level, at least throughout the period between 1910s and 1950, although the measured amount has increased. This is partly due to a short warmer period, especially in the 1930s, with relatively little snow and lower correction level. The changes towards a wetter climate thus seem to have occurred after 1950. As pointed out by Førland and Hanssen-Bauer (2000), the omission of bias adjustment of precipitation entails a risk of interpreting on virtual climate change. On the other hand, the reported uncertainties of the wind speeds are critical for the corrected precipitation estimates, especially for the period 1890-1910 where the Danish Land Scale was in use.

Figure 1.9. Annual correction level for Denmark 1890-1950 for approach 3 and for the reference period 1989-2010.



The trend in bias-adjusted precipitation and correction level is related to a change towards a gradually warmer climate with less observed snowfall. The changes in temperature, climate and precipitation type do not occur gradually at a constant rate but are complexly linked, creating large year-to-year variations in the correction level.

Table 1.5. Measured (P_m) and corrected precipitation (P_c) for approach 1 and 3 (for explanation see Table 1.4), and correction level K_α (%) for approach 1 and 3 for Denmark for different 30-year periods. In the calculation of national averages, grid cells in coastal regions are given lower weight depending on the fraction of land area.

	1891-1920	1901-1930	1911-1940	1921-1950	1931-1960	1961-1990	1989-2010
Measured, P_m	643.8	657.4	670.3	670.9	670.1	711.5	740.9
Corrected, P_c [1]	796.0	793.3	792.9	791.4	-	-	849.3
Corrected, P_c [3]	779.4	786.5	794.9	792.3	-	-	
K_α % [1]	23.6	20.7	18.3	18.0	-	-	14.6
K_α % [3]	21.1	19.6	18.6	18.1	-	-	

1.3.8 The climate around year 1900 and calculation of delta change climate factor ($\Delta\varphi_m$)

Table 1.6 shows estimated annual and monthly climate values around year 1900 (based on data from 1890-1910) compared with the conditions in 1989-2010. The measured precipitation has increased by 92.9 mm but the corrected one only by 57.2 mm (approach 1), corresponding to a decrease in the annual correction level from 22.9% to 15.0%. This change is related to several changes in climatic parameters. It has become warmer, which is particularly true during winter, where *T* for January and February has increased by approx. 2 °C. Opposite to this, the temperature change in the three summer months is only +0.4 °C. The temperature change in the winter months is associated with a marked decrease in the proportion of precipitation falling as snow. Around 1900, almost 50% of the corrected precipitation fell as snow in the three winter months, while the proportion of snow in 1989-2010 was approx. 26%. The climate has only changed marginally in the direction of lower wind speeds.

Table 1.6. The climate around 1900 (period 1890-1910) is compared with the reference period 1989-2010. Monthly and yearly values of measured and bias-corrected precipitation, P_m and P_c, and correction level K_a=100(P_c-P_m)/P_m (%) are shown for approach 1 (η_{wgt}=12). Also shown are temperature T_{month} and the proportion of corrected precipitation fallen as snow (%) and trend corrected wind speed, *V* (*), for the period 1890-1910 using geostrophic wind data. The delta change factor, $\Delta\varphi_m$, of each month for approach 1 used for calculation of water flow is also included. Note that due to rounding of the monthly values, the sum of these is not equal to the annual rainfall sum. K_α (%) is calculated as the average of individual months.

	1890-1910 (approach 1)						1989-2010						
	P_m	P_c	K_a (%)	*V* (*)	*T*	Snow %	P_m	P_c	K_a (%)	*V*	*T*	Snow %	$\Delta\varphi_m$
J	44.9	71.7	59.6	5.8	-0.3	52.0	61.0	74.4	22.1	5.9	1.7	18.3	0.963
F	33.1	54.6	64.6	5.6	-0.4	58.1	50.6	66.9	32.3	5.9	1.7	32.2	0.816
M	41.6	58.7	41.1	5.6	2.1	32.9	46.9	57.1	21.7	5.6	3.3	12.8	1.028
A	40.1	48.3	20.4	5.3	5.8	3.2	37.7	44.2	17.1	4.9	7.0	1.7	1.094
M	46.1	51.8	12.3	4.9	10.7	0.0	44.4	49.2	10.8	4.6	11.2	0.0	1.053
J	50.2	55.7	10.8	4.8	14.7	0.0	61.6	67.6	9.6	4.6	14.2	0.0	0.824
J	61.7	68.0	10.2	4,7	16.3	0.0	61.4	67.0	9.1	4.3	16.8	0.0	1.014
A	88.1	96.8	9.8	5.0	15.5	0.0	77.5	83.9	8.2	4.4	16.8	0.0	1.155
S	53.6	59.6	11.3	4.8	12.6	0.0	70.8	77.4	9.3	4.8	13.4	0.0	0.771
O	69.6	78.1	12.2	4.9	8.4	0.2	79.9	88.0	10.2	5.1	9.2	0.1	0.888
N	49.4	60.0	21.3	5.0	3.9	12.3	66.9	77.5	15.9	5.3	5.1	6.2	0.773
D	50.1	69.6	38.9	5.6	1.1	35.9	63.0	77.0	22.2	5.2	2.1	21.1	0.905
Year	**628.8**	**772.9**	**22.9**	**5.2**	**7.5**	**16.2**	**721.7**	**830.1**	**15.0**	**5.1**	**8.6**	**7.7**	**0.931**

It is interesting to study the annual variation in rainfall. As today, the spring months were also the driest around 1900, and the wettest months occurred in late summer or autumn. Around 1900, August was the wettest month of the year with 96.8 mm (corrected), while in 1989-2010 it was October with 88.0 mm. The spring months March-May were slightly wetter than today, while August had more precipitation. Almost all the other months were drier than in 1989-2010. These differences are reflected in the delta change climate factors ($\Delta\varphi_m$) shown in Table 1.6. As stated earlier, the magnitude of these factors may be affected by the uncertainty of wind speeds converted from Danish Land Scale.

1.4 Evaluation of uncertainty

For the period 1890-1910, absence of discharge measurements makes it impossible to use hydrological modelling for evaluation of the precipitation estimates, especially for spatial distribution. However, it is assumed that if the model setup and its assumptions work for 1917-1950, for which discharge measurements are available for verification, it does so for 1890-1910.

Figure 1.10 shows a comparison between T and K_a (%) for 1890-1910 relative to the reference period 1989-2010. There seems to be a tendency for the correction level 1890-1910 to be slightly higher than for the other two periods. This is especially true at the lowest temperatures, that is, primarily during the winter months.

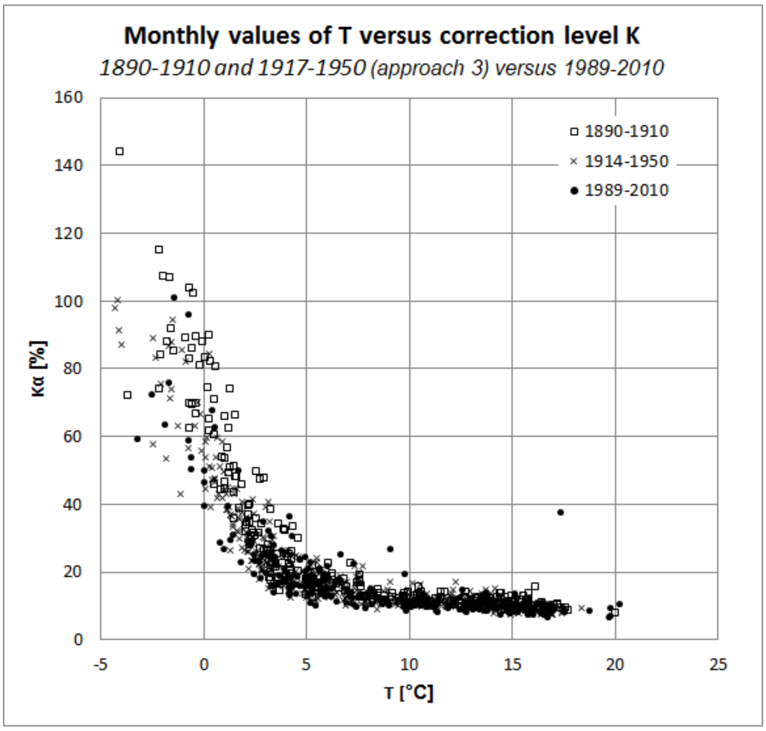


Figure 1.10. A comparison of temperature and correction level (%) for monthly values of bias-corrected precipitation between the reference period 1989-2010 and the periods 1890-1910 and 1914-1950.

Other factors that may affect uncertainty are the basic assumptions for the calculations.

A measure of the uncertainty of corrected rainfall is composed of several significant contributions, which are further elaborated upon in Vejen (2021):

- Stochastic uncertainty of the correction model.
- Spatial uncertainty (values of T, V and a) is allocated to a precipitation station from nearest grid cell.
- Spatial uncertainty of gridded precipitation due to in-homogeneity of rain gauge station network.
- Uncertainty of methods for calculation of meteorological variables.
- Other sources of uncertainty, for instance adjustment for shelter effect and trend correction of wind speed.

Due to the challenges of determining the shelter index (section 1.3.4), the climate factor, $\Delta\varphi_m$, was used as a pragmatic approach to calculate corrected rainfall for 1890-1910. The result in Figure 1.11 shows the regional distribution of corrected rainfall around 1900 compared with more recent values. In all regions, systematically smaller amounts of rainfall are seen. However, using a climate factor contributes to regional uncertainty as the change in the regional correction level depends on the magnitude of the corrected rainfall, as shown in Figure 1.12. The relative change is largest in the western part and lowest in the eastern part of Denmark.

The use of monthly delta change climate factors results in a fraction between the historical and recent precipitation that varies from relatively high values in the eastern part of Denmark to quite low values in the western part, i.e., there are regional variations in the percentage change in the precipitation amount (Figure 1.11). This variation is only between 6 or 8% lower than today, which is a rather small regional difference.

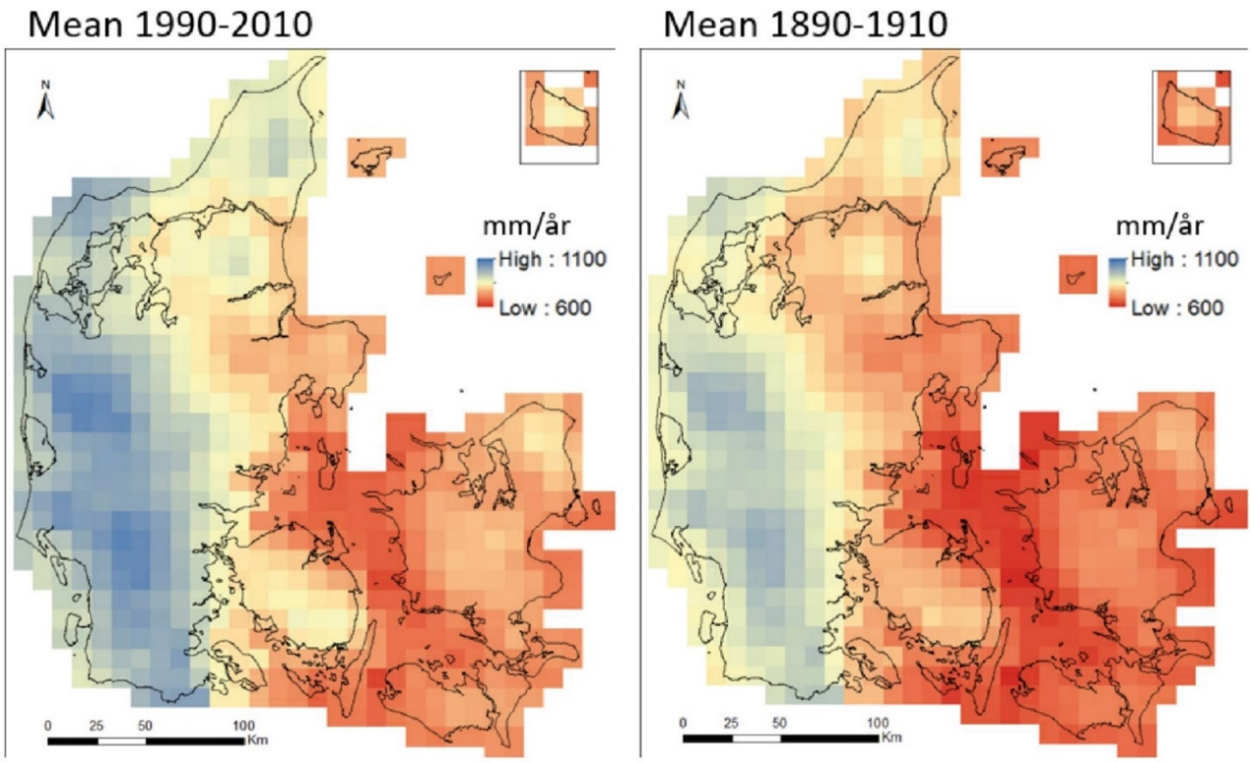
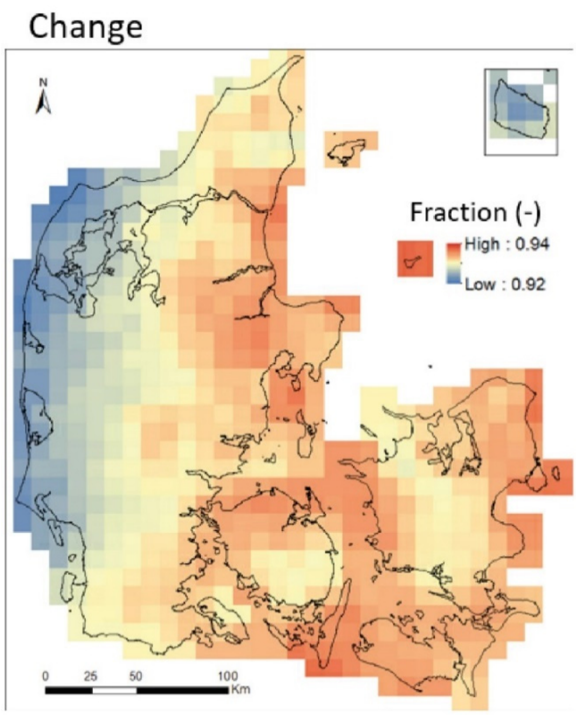


Figure 1.11. Left: Mean precipitation per year 1890-1910 based on approach 1. Right: Mean corrected precipitation per year 1997-2017.

Figure 1.12. Mean change in corrected precipitation between 1890-1910 and 1997-2017.



The use of a national delta change climate factor at a regional scale may result in systematic regional bias, which may have an impact on the uncertainty of runoff calculations at the spatial scale shown in the Figure (10×10 km²). It may be necessary to average for larger regions and to redefine the delta change climate factor, for example by incorporation of regional variability.

1.5 Conclusion

The objective is to provide this project with spatially distributed estimates of required meteorological variables to support the calculation of evaporation and hydrological modelling. To make this possible, historical meteorological data over the period 1890-1950 have been digitized. Furthermore, an approach for bias correction of historical rain gauge data has been developed, and based on data series of bias-corrected precipitation, air temperature and wind data, the climate around year 1900 has been estimated and validated. Various conditions contribute to the uncertainty of the corrected rainfall. Particular attention has been paid to the wind speed based on manual observations. Some of the wind series are affected by homogeneity breaks and deviation from the general trends in *V*.

The calculations and assumptions are evaluated for the period 1917-1950 using water balance modelling of discharge. At national level, a water balance error of 3% has been found, but this covers large regional differences in error level. Of the many assumptions, the use of a general shelter index seems to have a large impact on the regional uncertainty. Analyses of the relationship between monthly temperature and the correction level for the different periods support the impression of reasonable estimates at national level. However, it requires more model experiments with fine tuning of the different basic assumptions to reduce the regional uncertainty to an acceptable level.

It has therefore been necessary to calculate corrected rainfall for 1890-1910 by using a delta change climate factor. In this approach, national monthly correction factors were calculated based on corrected rainfall for 1890-1910 compared with 1990-2010. These national factors were then applied to the present daily corrected precipitation data to provide a spatially distributed daily time series of precipitation for the period 1890-1910.

Based on the assumptions in this study, a delta change value of 0.931 per year was found, which corresponds to approximately 773 mm per year or 57 mm (7%) less than the precipitation amount in the reference period 1989-2010. Much more of the precipitation around year 1900 consisted of snow, which is related to a colder climate; 16.2% of the total amount was snow compared with 7.7% in the reference period. This also explains the higher correction factor of 22.9% per year compared with 15.0% for the reference period.

The uncertainty of bias-corrected precipitation depends, among other things, on the reliability of wind speed data. Around year 1900, wind speed was observed with the so-called Danish Land Scale, which can be considered as a kind of half Beaufort. Manual wind observations are subject to different errors and larger uncertainty compared with modern automatic instruments. At the end of the project, tests could be made for correction of wind data for trend errors using a long time series of on geostrophic wind speed. It was found that the wind speed used for bias correction was probably overestimated. As a result, the corrected precipitation and delta change values were a little too high. Use of the corrected wind speed resulted in a delta change value of 0.906 (-2.7%,) which corresponds to around 20 mm less precipitation per year compared with the original precipitation estimate, which is an acceptable difference given the many assumptions and uncertainties.

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2 Climate around the year 1900: Calculation of global radiation and evaporation for historic sites

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Abstract

Since no data on global radiation and evapotranspiration were available for the period 1890-1950, they had to be calculated by using the measured minimum and maximum air temperature for the same period. Firstly, the air temperature and the distance to the nearest coastline were used to calculate the global radiation. The modelled global radiation was used to calculate the reference evaporation under Danish conditions. The modelled global radiation and reference evapotranspiration in the year 1900 are in good agreement with values measured at Foulum from 1987-2013.

2.1 Introduction

To be able to simulate the historical water discharge and nitrogen leaching, measurements of daily global radiation and reference evaporation are needed. However, the historical dataset of climate variables (chapter 1) does not have any recordings of such data. Therefore, these parameters must be estimated by using the available data (temperature and precipitation).

2.2 Materials and methods

2.2.1 Calculation of global radiation

To calculate the daily global radiation for the sites during the years in which no global radiation measurements were conducted, Hargreaves' radiation formula was used (Allen et al., 1998-FAO report 56, chapter 3, formula 50 therein):

$$R_s = k_{Rs}\sqrt{(T_{max} - T_{min})}R_a$$

R_s is the daily global radiation [MJ / m^2 / d], R_a is daily extra-terrestrial radiation [MJ / m^2 / d], T_{max} is maximum daily air temperature [°C], T_{min} is the minimum daily air temperature [°C], and K_{Rs} is the adjustment coefficient [°C^{-1}]. K_{Rs} ranges from ≈ 0.16 for inland locations to ≈ 0.19 for locations close to the coast, where the air mass is influenced by the water bodies (Allen et al., -FAO report 56, chapter 3). The extra-terrestrial radiation, R_a, can be calculated by using the latitude of the site (Allen et al., FAO report 56, chapter 3, formula 21 therein).

All analyses were conducted using the R statistical software v3.5.0 (R Development Core Team. R Foundation for Statistical Computing, 2018).

To determine the K_{Rs} values for Denmark, data from 10 sites from 1987 until 2013 were used (Figure 2.1). For all 10 sites, the minimum and maximum temperature and the global radiation were recorded and subsequently used in Hargreaves' radiation formula. To determine the K_{Rs} values based on the distance to the closest coastline for these sites, a linear regression is conducted.

The purpose of this regression is to calculate the K_{Rs} values for the historical sites based on distance to the coast. By using the K_{Rs} values and the air temperature, global radiation can be calculated.

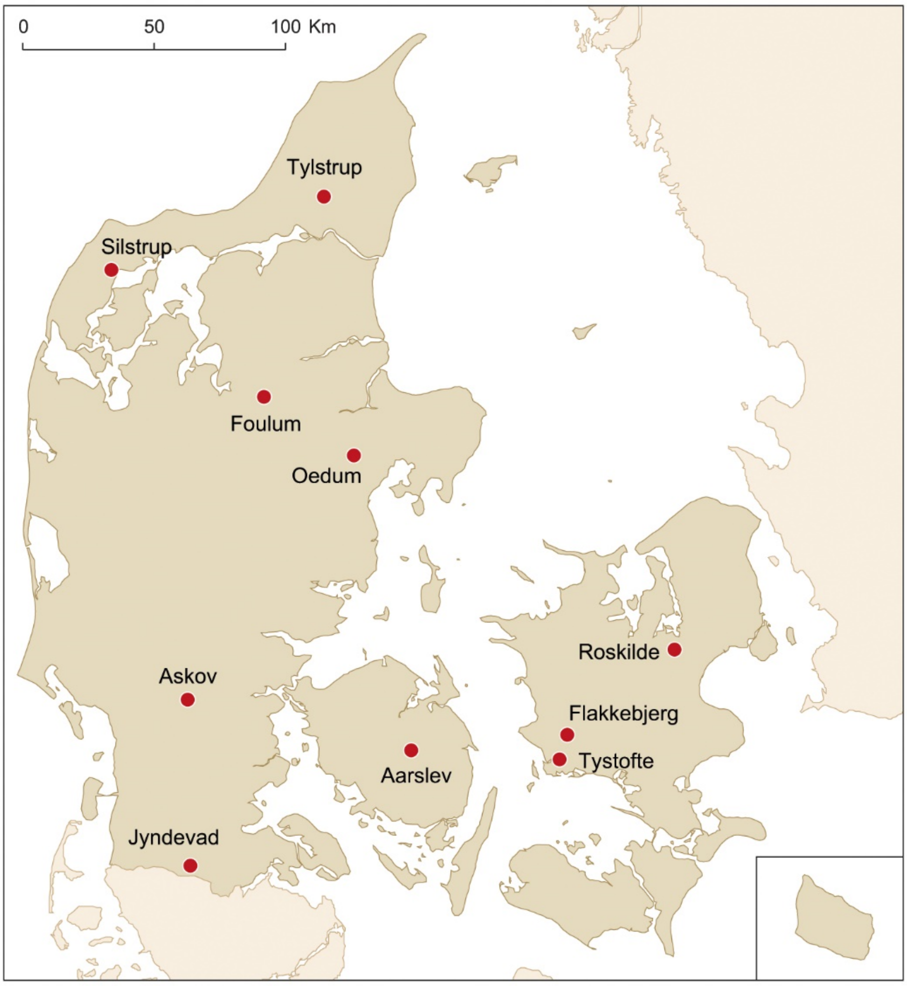


Figure 2.1. Location of the 10 sites used in this stud, where global radiation was measured over the period 1987-2013.

2.2.2 Calculation of reference evapotranspiration (ET0) for historical sites

The daily reference evapotranspiration was calculated by means of the Makkink formula calibrated for Denmark (Makkink, 1957; Mikkelsen and Olesen, 1991):

$$ET_0 = \beta_{M0} + \beta_{M1}\frac{sS_i}{\lambda(s+\gamma)}$$

where ET_0 is the daily reference evapotranspiration [mm], β_{M0} and β_{M1} are constants [unitless], λ is the latent heat of vaporisation [2.465 MJ/kg, γ is the psychrometric constant [0.667 mb/°C], s is the slope of the vapour pressure curve [mb/°C], and S_i is the daily global radiation [MJ/m^2/day]. The global radiation is calculated in the previous step, β_{M0} is set to 0, and β_{M1} is set to 0.7 calculated for Danish conditions (Aslyng and Hansen, 1982)

The slope of the vapour pressure curve (s) is calculated by using the formula defined by FAO (Allen et al., 1998):

$$s = \frac{4098\left[0.6108 exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+273.3)^2}$$

where T is the mean daily air temperature (°C).

2.3 Results

Table 2.1. Mean K_{Rs} values per site in the period 1987-2013.

Site	K_{Rs}
Aarslev	0.17
Askov	0.16
Flakkebjerg	0.17
Foulum	0.17
Jyndevad	0.15
Oedum	0.16
Roskilde	0.17
Silstrup	0.19
Tylstrup	0.17
Tystofte	0.18

These sites follow the previously described trend of K_{Rs} and distance to the closest coastline (Allen et al., 1998- FAO report 56, chapter 3); therefore, a linear model was fitted to the distance to the coast and the K_{Rs} value (Figure 2.2).

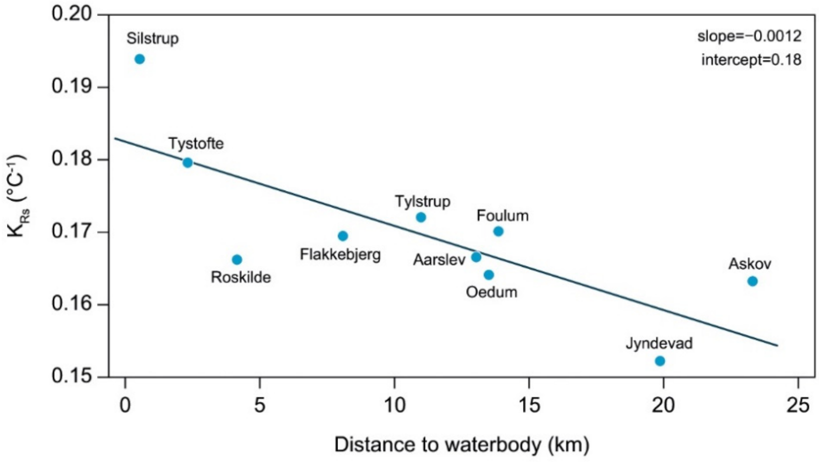


Figure 2.2. Relation between K_{Rs} values and distance to coast for all 10 sites.

The monthly average, minimum and maximum of the global radiation modelled for Foulum for the period 1890-1950 (Table 2.2) are slightly higher than the measured values for Foulum between the years 1987-2013 (Table 2.3); however, the range is the same as are the annual average and the seasonal fluctuations.

Table 2.2. Modelled monthly minimum, maximum and average global radiation ($MJ/m^2/d$) with standard deviation in the period 1890-1950 for Foulum**.**

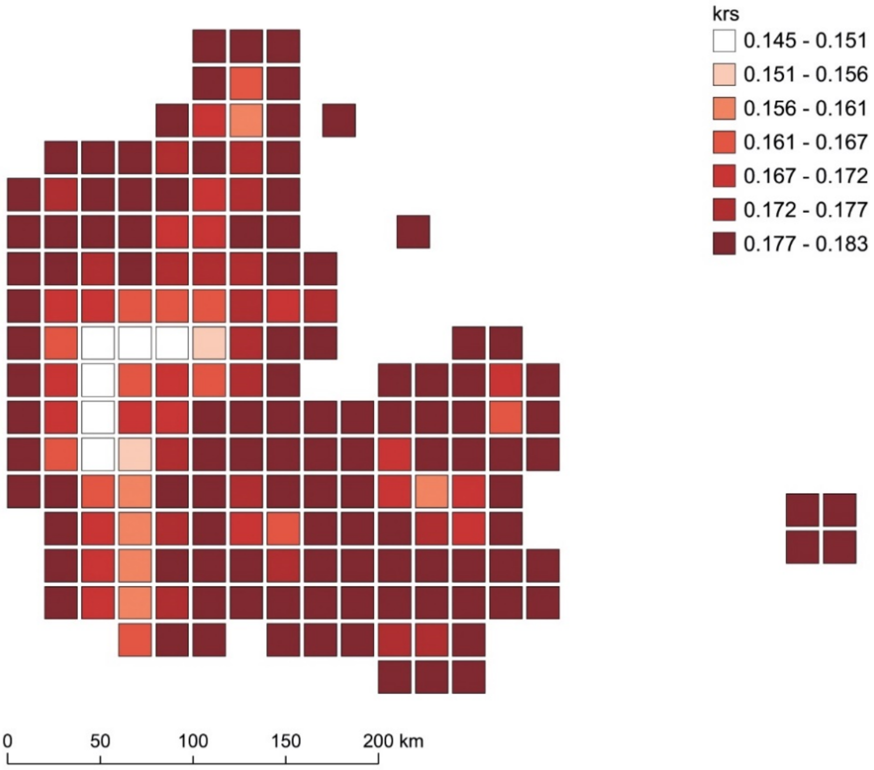
Month	Minimum	Maximum	Average	Standard deviation
January	5.8	51.3	20.3	6.6
February	11.3	95.9	42.0	13.2
March	27.9	167.1	84.9	23.8
April	56.5	240.4	146.5	31.5
May	83.9	301.2	202.1	34.4
June	90.9	311.4	217.9	35.2
July	110.1	295.9	203.0	34.4
Augustus	69.2	253.8	159.8	29.2
September	46.7	182.0	108.0	23.6
October	16.5	108.2	56.6	16.9
November	7.4	54.0	24.9	7.8
December	5.6	31.3	14.4	3.9
Annual	5.6	311.4	107.0	77.6

Table 2.3. Measured monthly minimum, maximum and average global radiation ($MJ/m^2/d$) with standard deviation in the period 1987-2013 for Foulum.

Month	Minimum	Maximum	Average	Standard deviation
January	0.9	59.6	14.8	10.6
February	4.3	96.8	32.6	20.0
March	8.6	165.0	70.8	37.2
April	18.1	215.1	115.8	50.4
May	25.1	265.2	159.4	59.8
June	21.6	270.4	167.1	62.8
July	21.6	262.7	159.7	55.9
August	16.4	220.3	127.8	44.6
September	7.8	167.6	83.8	36.2
October	0	104.5	44.2	23.7
November	1.7	55.3	18.3	11.7
December	1.7	38.0	10.9	7.5
Annual	0	270.4	84.0	70.3

The K_{Rs} for each grid cell was calculated based on the distance from the mid-point of the cell to the coast (Figure 2.3).

Figure 2.3. Distribution of K_{Rs} values on a 20*20 km grid.



The monthly measured and modelled reference evapotranspiration are in good agreement (Table 2.4 and Table 2.5). The annual values are also in good agreement with each other.

Table 2.4. Modelled monthly minimum, maximum and average reference evapotranspiration (mm/d) with standard deviation in the period 1890-1950 for Foulum.

Month	Minimum	Maximum	Average	Standard deviation
January	0.1	0.8	0.3	0.1
February	0.2	1.4	0.6	0.2
March	0.4	2.5	1.2	0.4
April	0.8	3.5	2.1	0.5
May	1.2	4.4	3.0	0.5
June	1.3	4.6	3.2	0.5
July	1.6	4.3	3.0	0.5
August	1.0	3.7	2.3	0.4
September	0.7	2.7	1.6	0.4
October	0.2	1.6	0.8	0.3
November	0.1	0.8	0.4	0.1
December	0.1	0.5	0.2	0.1
Annual	0.1	4.6	1.6	1.1

Table 2.5. Measured monthly minimum, maximum and average reference evapotranspiration (mm/d) with standard deviation in the period 1987-2013 for Foulum.

Month	Minimum	Maximum	Average	Standard deviation
January	0	0.6	0.2	0.1
February	0.1	1.2	0.4	0.3
March	0.1	2.5	1.0	0.5
April	0.3	4.2	1.9	0.9
May	0.4	6.2	3.0	1.2
June	0.4	5.9	3.3	1.3
July	0.4	5.7	3.4	1.2
August	0.3	5.0	2.7	1.0
September	0.2	3.4	1.6	0.7
October	0	2.0	0.9	0.4
November	0	0.9	0.3	0.2
December	0	0.5	0.1	0.1
Annual	0	6.2	1.6	1.5

2.4 Conclusion

Climate data are an important input to models. However, the required data have not always been measured. Examples of this are global radiation and reference evapotranspiration that are needed as input to hydrological models. By using the measured minimum and maximum air temperature from Danish meteorological stations for the 1890-1950, the global radiation and reference evapotranspiration can be calculated and used in the simulation of nitrate leaching over this period. Such calculated values of global radiation and especially reference evapotranspiration during 1890-1950 were found to be in good agreement with values measured at Foulum during 1987-2013.

2.5 References

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3 Modelling discharge to the sea

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Abstract

Purpose: In the present chapter, the groundwater flow and the stream discharge from land to sea around year 1900 are simulated. This simulation is used to estimate the historical recharge to the groundwater system and the groundwater transport between the root zone and the surface water system. The simulation is used as input to the national nitrogen model for assessing the total nitrogen load to the sea presented in chapter 8.

Materials and methods: The National Water Resources Model (the DK model) that describes groundwater and surface water flows, including the interaction between the two media, has been used to simulate the historical stream discharge. Simulation was carried out for the period 1917-1950, for which historical observations exist, and afterwards for the period 1890-1910. Comparison between observed and simulated discharges was used to evaluate the historical precipitation established from observations and corrected for wind and shelter effects.

The DK model is originally developed to represent current conditions, but in the present project it has been modified to represent historical conditions as well. This entailed use of historical climate data, adjustment of groundwater abstraction and point discharges and incorporation of land use, as described in chapter 5. Artificial drainage, being an important flow and transport pathway from the fields to the surface water system, has almost doubled since 1900. Using historical data on the estimated production of tile drains, drainage in the model was modified to represent the conditions around year 1900.

Results and discussion: Using precipitation established from observational data corrected for wind and shelter effects for the period 1917-1950 showed that the total observed and simulated discharge at national scale agreed within a 3% water balance error. However, large variations in the fit between observed and simulated discharges were observed for the different regions in Denmark. Alternative models for correcting the observed precipitation were tested but without a satisfactory result. Hence, use of observed and corrected precipitation data results in large regional uncertainty, but since the true wind speed and shelter index are unknown, addressing this uncertainty was beyond the framework of the current project. A delta change approach was therefore applied using national monthly delta change factors to correct current precipitation to a historical level. This approach is more robust at a national scale and is less dependent on the distribution of wind speed and shelter index. The inherent assumption is, however, that the relative change in precipitation has been the same for the entire country. Based on the delta change approach, it was estimated that the historical precipitation was 7% less on a yearly basis but with variations between the different months. With the

change in land use, evapotranspiration, and drainage, the change in precipitation resulted in a simulated discharge for 1900 that was approx. 12% lower than the present discharge.

Conclusions: Using a delta change approach to establish a historical time series of precipitation, the discharge to the sea was estimated using the national water resources model that was modified to represent the conditions around year 1900. The discharge estimate can be used to assess the change in discharge at the national scale but will not be valid at local scale.

3.1 Introduction

Nitrate leaching from the root zone is transported through the groundwater to the freshwater system and by the streams further to the marine recipients. Additionally, the amount of nitrate leaching to the root zone in the period around year 1900 is calculated from an estimated nitrate concentration (chapter 5) and the amount of water infiltrating the subsurface. A valid representation of the freshwater system, including estimates of the net precipitation, transport pathways and potential reduction of nitrate during transport is thus essential for calculating the total nitrogen load to the coast.

Previous analysis of long time series of observed stream discharge and precipitation indicates that there has been a significant change in the precipitation rate between the two periods considered (Jensen (ed.) 2017), with less precipitation / stream discharge for the historical period. To assess and quantify the effect of this change, a hydrological model is utilised to simulate the freshwater cycle for both the current and historical conditions. The model results are then used as input to the national nitrogen model to estimate the total nitrogen load to the coast in chapter 8.

3.2 Material and methods

Freshwater discharge to the sea is calculated by the national water resources model (DK model) (Højberg et al., 2013; Henriksen et al., 2003). The model construction represents the current conditions, i.e. current climate, groundwater abstractions, land use and farming practice, which together with model calibration and validation are described in detail in Højberg et al. (2015a) and will not be described further here. To represent the historical conditions around year 1900, several adjustments to the model have been made, which are described in the current chapter.

With the DK model modified to represent the historical conditions, climate data estimated in chapter 1 and 2 were used as forcing variables in the model to simulate the historical stream discharge. The simulation was compared with discharges observed at 41 stream discharge stations with data within the period 1917-1950. This comparison was used to evaluate the corrected precipitation data, i.e., observed precipitation corrected for wind and shelter effects. The focus of this comparison was how well the total discharge volume could be represented. When a model to correct the historical precipitation was developed, this was used to establish a time series for the period 1890-1910 that was used in the DK-model to calculate discharges for the same period.

3.2.1 DK model

The DK model is a physically based and fully distributed model describing both the groundwater and the surface water systems and their interlinkage (Højberg et al., 2013; Henriksen et al., 2003) (www.vandmodel.dk), and is developed in the model system MIKE SHE / MIKE11 (Havnø et al., 1995). Actual evapotranspiration and the amount of water that recharges the saturated zone are calculated using a two-layer water balance method based on a formulation presented in Yan and Smith (1994). Simulation of flow and transport in the groundwater system relies on a comprehensive three-dimensional interpretation of the subsurface hydrogeology, while one-dimensional approximation is used to describe the stream flow for which stream dimensions are characterised from stream cross-sections. The DK-model consists of seven sub-models as illustrated in Figure 3.1.

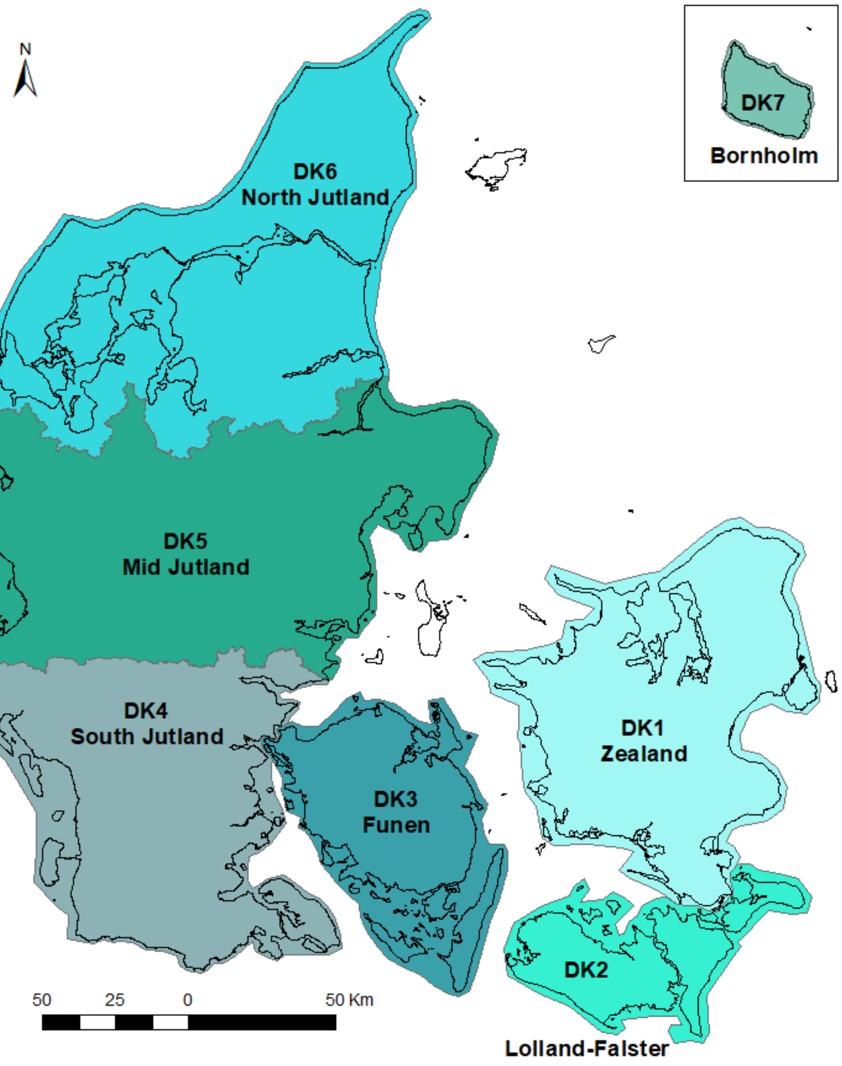

Figure 3.1. The seven sub-models in the national water resources model (DK-model).

The model has been developed continuously during the past 20 years, with focus on updating the model basis, i.e., detailing the input data – the hydrogeological interpretation that describes the water flow in the subsurface and model performance through improved parameterisation and calibration schemes. The model has been used and tested in numerous studies to analyse the impact of varying conditions that are central for the present study. These include climate change impacts as well as changes in land use and management. The model is regularly updated based on new data and knowledge. The model version applied in the present study is the DK-model2014 (Højberg et al., 2015a), which is the same model version used to develop the national nitrogen model (Højberg et al., 2015b).

3.2.2 Modification to the DK-model to represent 1900 conditions

Most data needed to construct and run the national hydrological model for present conditions can be obtained directly from national databases. This is not the case for the period around year 1900, and it has therefore been necessary to make some assumptions of how to represent the historical conditions in the hydrological model, as summarised in Table 3.7 and described below.

Table 3.7. Summary of modification to the hydrological model to represent the conditions around year 1900.

	Present*	Year1900
Climate	National data from the Danish Meteorological Institute (DMI).	Precipitation is estimated by the delta change approach and potential evapotranspiration calculated from temperature, see chapter 1 and 2.
Land use	Data on land use and vegetation on agricultural fields are obtained from national databases.	Land use is obtained from statistics at parish level, chapter 5
Drainage	All agricultural areas are assumed drained.	Drains are distributed in accordance with the total drained area, and the probabilities of drainage are determined from the physical properties
Abstraction	Abstraction for irrigation and drinking water/other uses are based on yearly data reported to national databases.	It is assumed that there was no irrigation and that all other abstraction was 20% of the current amount with the same geographical distribution as at present.
Point source discharge	Data on discharge to streams is obtained from national database.	It is assumed that the discharge by point sources was 20% of the current amount with the same geographical distribution as at present.

* (see Højberg et al., 2015a for details)

Climate

Development of the historical times series for precipitation and potential evapotranspiration is described in chapter 1 and 2. Time series for potential evapotranspiration calculated based on historical data have been used directly in the model setup.

The initial method for calculating precipitation, as described in chapter 1, was to develop an approach to correct the historical data and test this approach by using the data in the hydrological model and test the results of this against the observed discharge for the period 1917-1950, from which such data exist. By testing different approaches, it was found that, due to limited and uncertain historical data on wind speed and shelter index for rain gauge stations, calculation of distributed historical precipitation was beyond the resources of the current project. While the spatial pattern is very sensitive to the local temporal and spatial conditions, the national long-term estimate, i.e. the change in precipitation for the entire country averaged over a period, is a much more robust estimate. It was thus decided to apply a delta change approach using a national delta change factor per month. This was achieved by calculating an average total precipitation for the entire country for each month for the periods 1890–1910 and 1990–2010 as well as the monthly fractions between the two periods. A historical precipitation dataset was then generated by multiplying the present daily precipitation data with the corresponding monthly correction factors, i.e. all days in January are multiplied by the same factor, all days in February by another factor etc.

Land use

Land use was estimated on parish level statistics in which land use has been reduced to eight categories as described in chapter 5. Since only the statistics and not the exact locations are known, land uses have been distributed randomly within each parish. However, such random distribution may result in undesirable placements, with agricultural land being located in areas with upwelling groundwater, i.e. wet areas that are wetlands, meadows or similar and not cultivated farmland. The land uses have therefore been corrected to avoid such inconsistency. This has been achieved by identifying agricultural land uses in areas with upwelling groundwater and switching the land use code with the nearest grid cell with no upwelling groundwater and a land use code different from agriculture.

Under the current conditions, a large fraction of the precipitation can be routed directly to the sewage system and further to the streams in urban areas. This process is assumed much less important around year 1900. However, some impermeable surfaces existed in the larger cities. Direct runoff to the surface water system has thus been maintained in the larger cities. This has been achieved by assuming the structure of the larger cities to be identical with that of the present in terms of location and relative size, but with a much lower runoff fraction.

The crop development in terms of leaf area index (LAI) and root zone depth controls the actual evapotranspiration. It is assumed that a lower nitrogen application in the historical period resulted in a lower LAI, where the maximum LAI at full crop development was reduced from 5 to 3, while the maximum root zone depths were unchanged from present conditions.

Drainage

Drainage of the land can be achieved through natural drainage systems, such as ditches or by artificial tile drains. Due to the spatial resolution of the hydrological model (500 x 500m grids), it is not possible to represent all ditches directly in the model. Drainage by both ditches and tile drains are therefore represented in the model by model-drains to mimic the fast runoff from these areas, preventing accumulation of water on the surface.

In the version of the DK-model representing the current conditions, drainage is implemented in the entire model. However, drain flow is only generated if the groundwater table rises above the drain levels. The rationale for including drains in the entire model area is that the exact location of tile drains is largely unknown, and it is assumed that all agricultural areas are drained if the groundwater table is high during part of the year, thereby limiting access to the fields with heavy machinery. The same assumption is not valid for the period around year 1900, but drainage of agricultural land by tile drains was already significant with approximately 660,000 hectares in 1907 (Aslyng, 1980) and a distribution in the different regions as shown Table 3.8. No data are available for the southern part of Jutland, as this was under German administration up to 1920, and drainage has thus been estimated based on the drainage density in West and East Jutland as discussed further below.

Table 3.8. Tile drainage statistics from 1907 (Aslyng 1980).

	Zea-land	Bornholm	Lolland-Falster	Funen	East Jutland	West Jutland	North Jut-land	South Jutland	Entire country
Drained area (1000 ha)	235	19	85	109	127	33	51	32*	659

* No data are available for South Jutland, and the number has thus been estimated based on the drainage density in West and East Jutland, see text for further explanation.

The location of tile drains areas around year 1900 is unknown, and the following assumption was made for the distribution of tile drains:

1. Agricultural land in lowland areas are drained by ditches and not tile drains.
2. Agricultural land located in areas with a high density of ditches are solely drained by ditches and not tile drains.
3. Tile drains are sequentially distributed in the remaining agricultural land according to the area's need for drainage, i.e. areas with a high potential need for drainage are drained before areas with less need for drainage.

Agricultural land in lowland areas has been identified by combining the land use map with agricultural land and the national map of "extended" lowlands. Areas with a high density of ditches have been identified from the FOT GIS theme for streams, which has been combined with the numerical grid of the DK-model, Figure 3.2. Grids with more than five stream reaches and a total length of more than 1,500 m has been designated as areas where drainage was carried out by ditches.

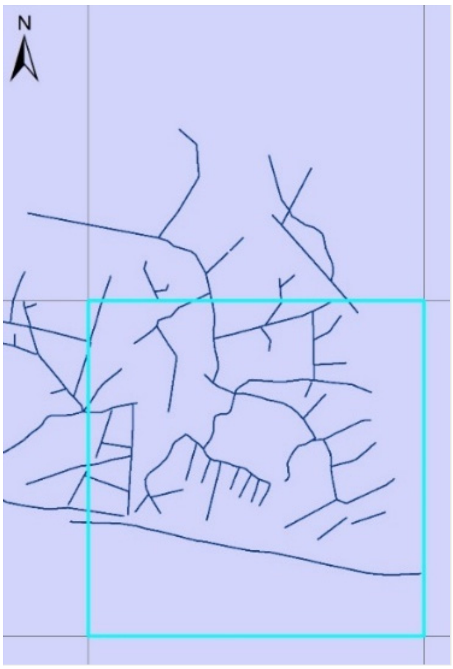

Figure 3.2. Illustration of a grid in the DK-model with a high density of streams in the FOT dataset where natural drainage by ditches has been assumed.

For the remaining agricultural land, tile drainage has been distributed in accordance to the drained area within each region. For the Danish islands, the delineation of the regions coincides with the land areas of the islands. The extent of the regions south-, west-, east- and north-Jutland is not reported in the drainage reference, i.e. Aslyng, 1980. The regions have thus been defined by:

1. South Jutland, the area between the border to Germany up to 1920 and the current border.
2. North Jutland, identical with the current region “Nordjylland”.
3. The Mid Jutland ridge was used to divide the remaining part of Jutland into an eastern and a western part. This division separates Jutland into a predominantly sandy part in the west, with generally low drainage intensity, and an eastern part dominated by clay / till and high drainage density.

The regions in Jutland are illustrated in Figure 3.3.

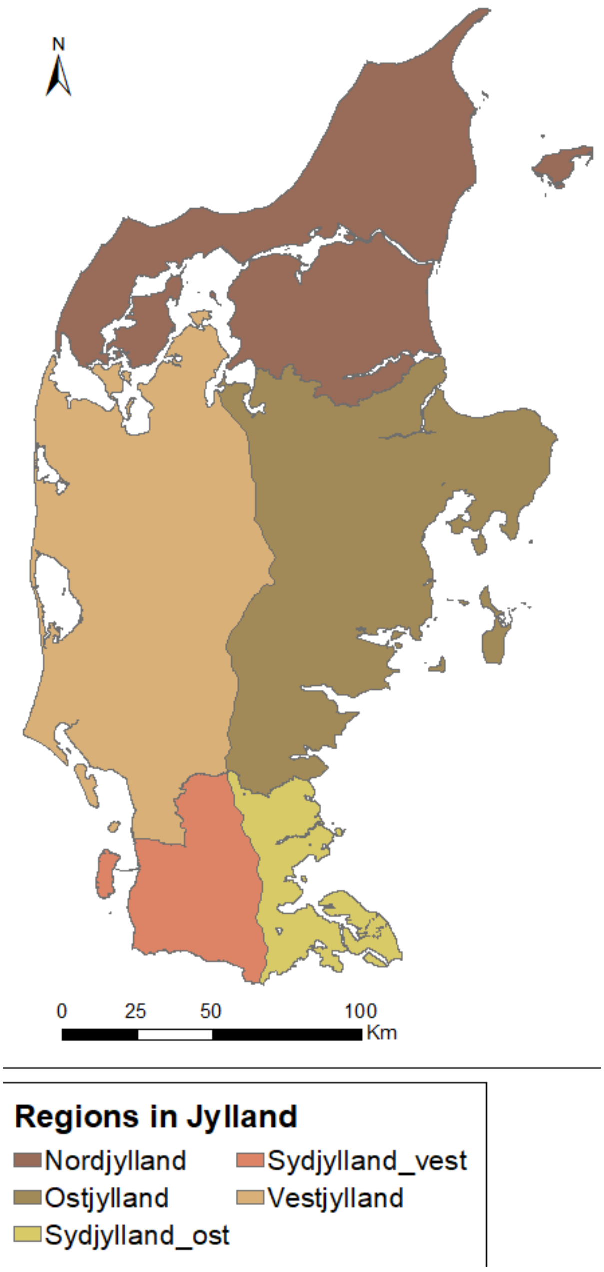

Figure 3.3. Regions in Jutland used to distribute historical tile drains.

No data on tile drainage area are available for the southern part of Jutland. The geologically east-west division in Jutland extends south to the present border to Germany. It was thus assumed that the drainage density in the western and eastern parts of South Jutland equalled that of West and East Jutland, representing 24 and 9% of the agricultural land, respectively.

Within each region, the tile drains were distributed by associating drainage with the areas with highest probability of being drained. For this purpose, the drainage probability map (Møller et al., 2018) was used, which is developed from statistical models describing the probability of an area being drained based on selected explanatory variables. The final distribution of the drainage into the three drainage categories is shown in Figure 3.4.

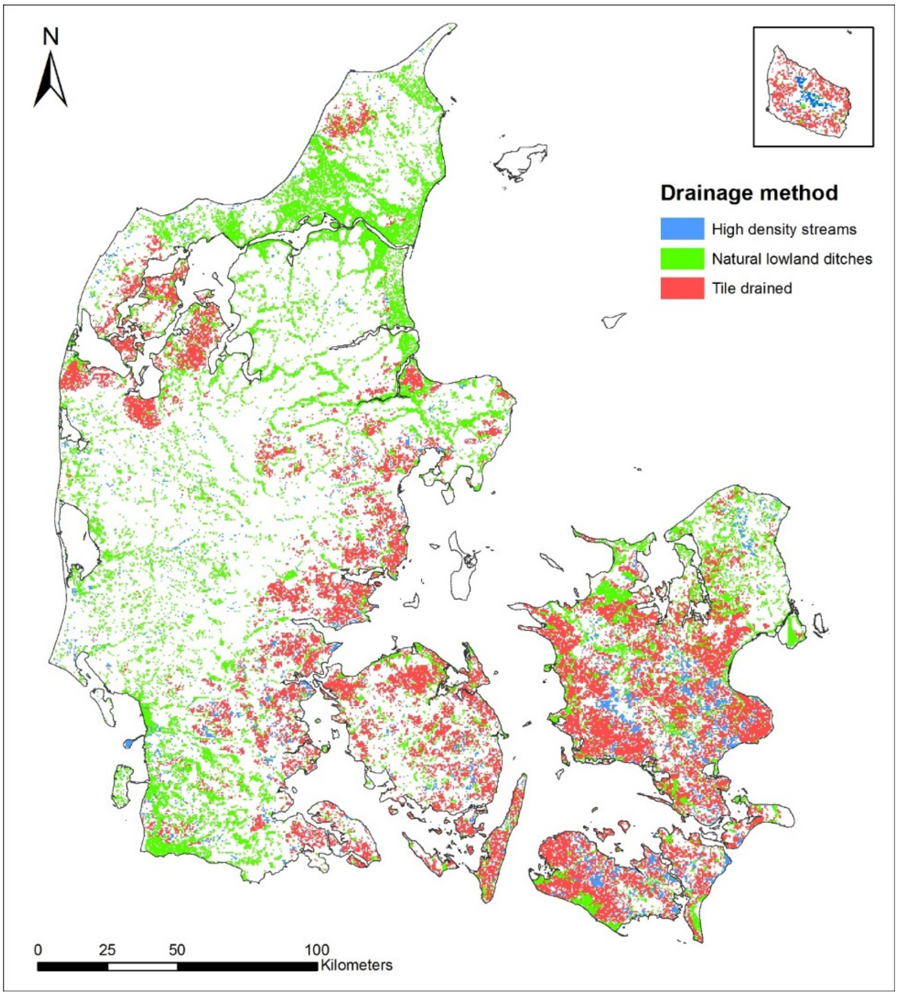

Figure 3.4. Final distribution of drains in the model representing year 1900.

Abstraction

All abstractions (locations and amounts) are reported to the national groundwater database JUPITER, from where data are extracted for the current situation. Around year 1900, waterworks started to become established in the larger cities. At that time, city development was rapid, including a growing number of waterworks. This project did not allow a detailed reconstruction of the development of waterworks in the country and the amount of water abstracted. It was therefore assumed that the water abstraction was 20% of the current level and that the structure of the abstraction has not changed, i.e. the city structure then and today is the same.

Discharge from point sources

Discharge from point sources such as wastewater treatment plants is included as a source to the simulated stream discharge. For the current conditions, the data are collected from national databases. No historical data are available, and it was therefore assumed that discharge, as abstraction, is 20% of the current amount and has a distribution identical to that of the present.

3.3 Results

The hydrological model was used to calculate the historical stream discharge based on the two approaches for establishing a historical dataset on precipitation: 1) correction of measured precipitation amounts based on estimates of wind speed and shelter index and 2) the delta change approach.

3.3.1 Historical precipitation from corrected observations

Test of the historical precipitation calculated by correcting observed data was achieved by comparing observed and simulated stream discharges for the period 1917-1950. Within this period, data were available from 41 stations having observations for two or more years. Basic statistics from the discharge stations are found in Table 3.3, and their spatial location is shown in Figure 3.5.

Figure 3.5. Location of stream discharge stations and catchments with data in the period 1917-1950.

Table 9.3. Stream discharge stations with data from the period 1917-1950.

Discharge station no.	Mean discharge (l/s)	Observations		
		First year	Last year	Years with data
50000050	103	1943	1950	8
52000025	130	1947	1950	4
52000029	442	1948	1950	3
52000189	483	1930	1948	15
55000017	660	1945	1950	6
55000018	1,604	1921	1950	29
56000006	81	1922	1950	27
56000007	779	1933	1950	16
57000049	383	1919	1950	31
57000050	3,728	1943	1944	2
57000058	5,068	1935	1950	16
57000121	387	1944	1950	7
59000006	852	1918	1950	33
61000012	181	1932	1950	19
44000034	220	1926	1950	20
44000035	133	1926	1950	19
45000002	4,421	1931	1950	20
45000004	2,726	1918	1950	33
46000030	555	1919	1950	31
31000044	6,261	1930	1944	3
32000001	3,542	1917	1950	34
35000142	255	1920	1950	24
38000024	6,920	1933	1950	18
40000001	2,971	1922	1950	29
21000084	15,456	1917	1950	34
21000085	2,370	1918	1950	33
21000634	876	1931	1939	7
21000792	275	1918	1939	22
21000794	2,591	1918	1950	33
24000001	538	1933	1950	18
25000018	1,316	1948	1950	3
25000082	13,431	1923	1950	26
25000249	97	1949	1950	2
26000082	1,042	1920	1950	31
3000003	1,451	1917	1950	34
7000003	895	1918	1950	33
11000012	2,667	1918	1931	14
11000016	1,226	1936	1950	15
14000022	2,297	1926	1950	25
17000018	1,344	1918	1949	26
66000014	300	1922	1950	29

Good agreement was found for several of the model domains, while a general water balance error was found for other domains, i.e. the model simulated too much or too little stream discharge, indicating that the historical precipitation was over- or underestimated.

Several alternative approaches to calculate precipitation was tested, see chapter 1 for a description of the alternative approaches to correct the precipitation. Table 3.10 shows the total water balances calculated for each of the model domains using the precipitation based on the assumptions expected to represent the historical conditions best (best estimate). The water balance error for Funen, South Jutland and North Jutland was less than 10%, which is considered acceptable given the uncertainty in estimating the historical period. On Zealand and Lolland-Falster, the water balance was 24 and 47% off, the simulated values were higher than the observed values (negative water balance), indicating that the estimated precipitation is overestimated. Furthermore, the stations on Zealand showed a clear trend as 11 out of 13 stations on Zealand showed a negative water balance. In the model domain Mid Jutland, the trend was opposite; there was a total water balance error of 17%, and eight out of ten stations showed a positive water balance, indicating too little precipitation under historical conditions. Finally, Bornholm also showed a high positive water balance error of 34%.

Within the framework of the project, it was not possible to improve the match between the observed and simulated water flow for all areas simultaneously by applying a different scheme to correct the precipitation for the entire country. As the nitrate leaching in 1900 is calculated from the amount of water recharging the subsurface and the nitrate concentrations estimated in chapter 5, an error in the water balance will invariably result in an error in the estimated nitrate leaching.

Table 3.10. Water balance error (%) for the seven model domains in the DK-model for the period 1917-1950 using "best estimate" and adjusted precipitation.

Precipitation scenario	Zealand	Lolland-Falster	Funen	South Jutland	Mid Jutland	North Jutland	Bornholm	Country
Best estimate	-24	-47	2	-6	17	9	34	3
Number of stations	13	1	5	5	10	6	1	41

3.3.2 Historical precipitation using the delta change approach

Using the delta change approach, precipitation is corrected to the period 1890-1910 at a monthly time scale. No stream discharge data are available, and the simulated discharge cannot be compared with the observed counterparts. It is thus assumed that the approach used to correct precipitation to the period 1917-1950, which provided a small water balance error at national scale, can also be used to correct precipitation to the period 1890-1910 with an acceptable national water balance.

The mean simulated discharge to the sea in the period 1890-1910 is shown in Figure 3.6 (middle) for fourth order streams, where also the present period, 1990-2010 (left) and – for comparison – the absolute difference between the two time periods (right) are displayed. As seen, the delta change approach preserves the overall national pattern with a higher discharge towards the west. However, the pattern is not fully identical for the two periods. This is due to differences in the local weather conditions. In the delta change approach, the present precipitation data are corrected using the same monthly correction factor for the entire country. The relative variation in monthly precipitation is nevertheless not the same all over the country, and the effect of the monthly correction will thus vary. Similarly, the calculated potential evapotranspiration may contribute to a different spatial pattern; here, a simple approach has been used based on daily minimum and maximum temperatures, which may not capture the local variations correctly and to the same degree as observed in the present potential evapotranspiration. Finally, the changes in agricultural practices, i.e. cultivated areas and drainage density, will have affected the water cycle and thereby also the stream discharge.

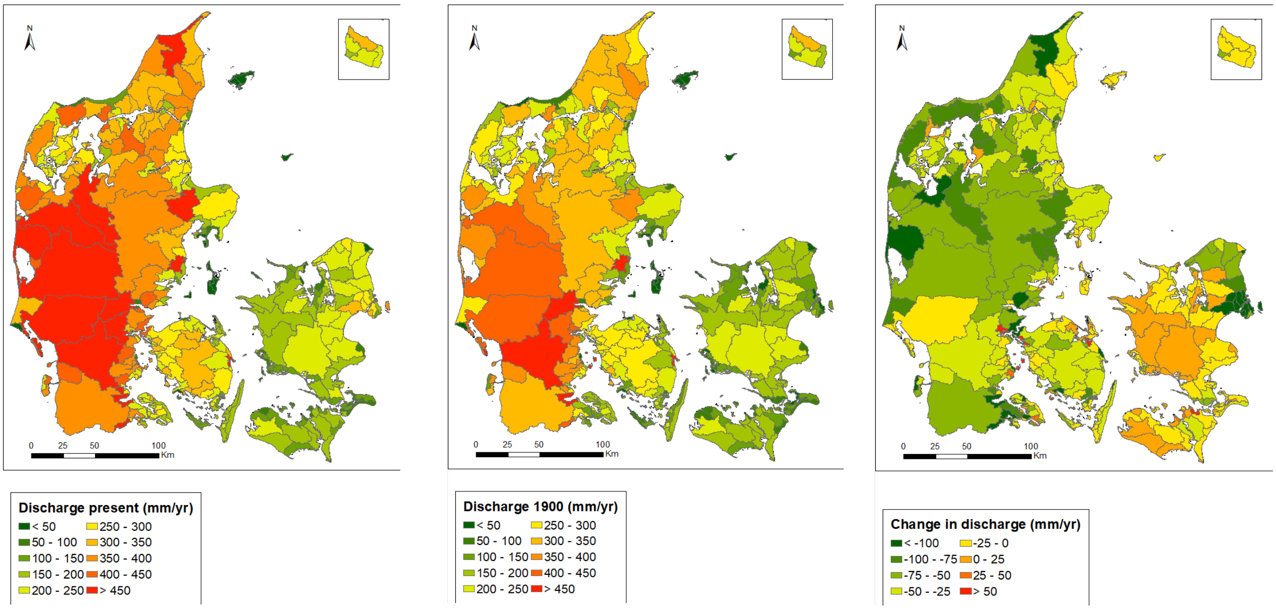

Figure 3.6. Simulated discharge to the sea aggregated to fourth order catchments for the period 1900 (left) and the present (centre). Right: Changes in discharge as mm/yr for the two periods.

Differences in the simulated historical and present stream discharge are shown in Figure 3.6 (right); negative values indicate an increase in stream discharge from 1900 until now. In the eastern part of the country (most parts of Zealand, Lolland, Falster and Bornholm), there is either no or a modest change the in stream discharge from 1900 until now, and in some areas a decrease is found. This is a combination of the changes in precipitation calculated by the delta change approach, where almost no increase is observed in the eastern part of the country (Figure 1.12), and the reduced drainage density results in a higher groundwater table and more evapotranspiration. Towards the west, the increase in precipitation is higher, which is also reflected in the enhanced stream flow.

A total discharge to the sea of 333 mm / yr is simulated for the present conditions, while a discharge of 292 mm / yr is simulated for the historical period. At national scale, the stream discharge is thus estimated to increase by 45 mm / yr, which corresponds to a 12% lower discharge than today. The percentage changes in stream discharge aggregated for fourth order catchments are shown in Figure 3.7. A negative increase in discharge is found for the western part of Zealand and Lolland, i.e. a decrease in the discharge, which is generally below a 5% change. For some of the smallest catchments, a decrease in stream discharge of more than 20% occurs. These small catchments are only covered by a single precipitation value (one climate grid) and are thus very sensitive to the local precipitation estimates. Expectedly, the calculated change in discharge is therefore more uncertain for small catchments.

Historical changes in discharge were previously estimated by Jensen (ed.) (2017) based on linear trend analysis of long time series with data from minimum 80 years. The results are given in Figure 3.7 (right), showing the calculated changes between 1935 and 2015 in mm / yr and as percentages. In Jensen (ed.) (2017), the statistical trend model was used to back-write discharge to the year 1900. However, the analysis in chapter 1 of the development of precipitation indicates that the largest change in precipitation probably occurred after 1950. Hence, it may be questioned if the discharge in year 1900 can be back-written to 1900 using a linear model based on data from 1935-2015. For this reason, the trend analysis for the period 1935-2015 has been used for comparing the results obtained by the delta change approach.

The simulated percentage changes in discharge for the main parts of Funen range between 0 and 20%, which corresponds well with the trend analysis. Close agreement is further seen for Mid and North Jutland, while the trend analysis indicates an up to 33% increase in discharge in the southern part of Jutland, where the simulated change is maximum 20%. Discrepancies between the two approaches are also seen for the western part of Zealand. Here, the trend analysis estimates an increase between 18-28%, whereas a decrease is simulated using the delta change-corrected precipitation data. No data are available for Bornholm preventing comparison with the simulation results.

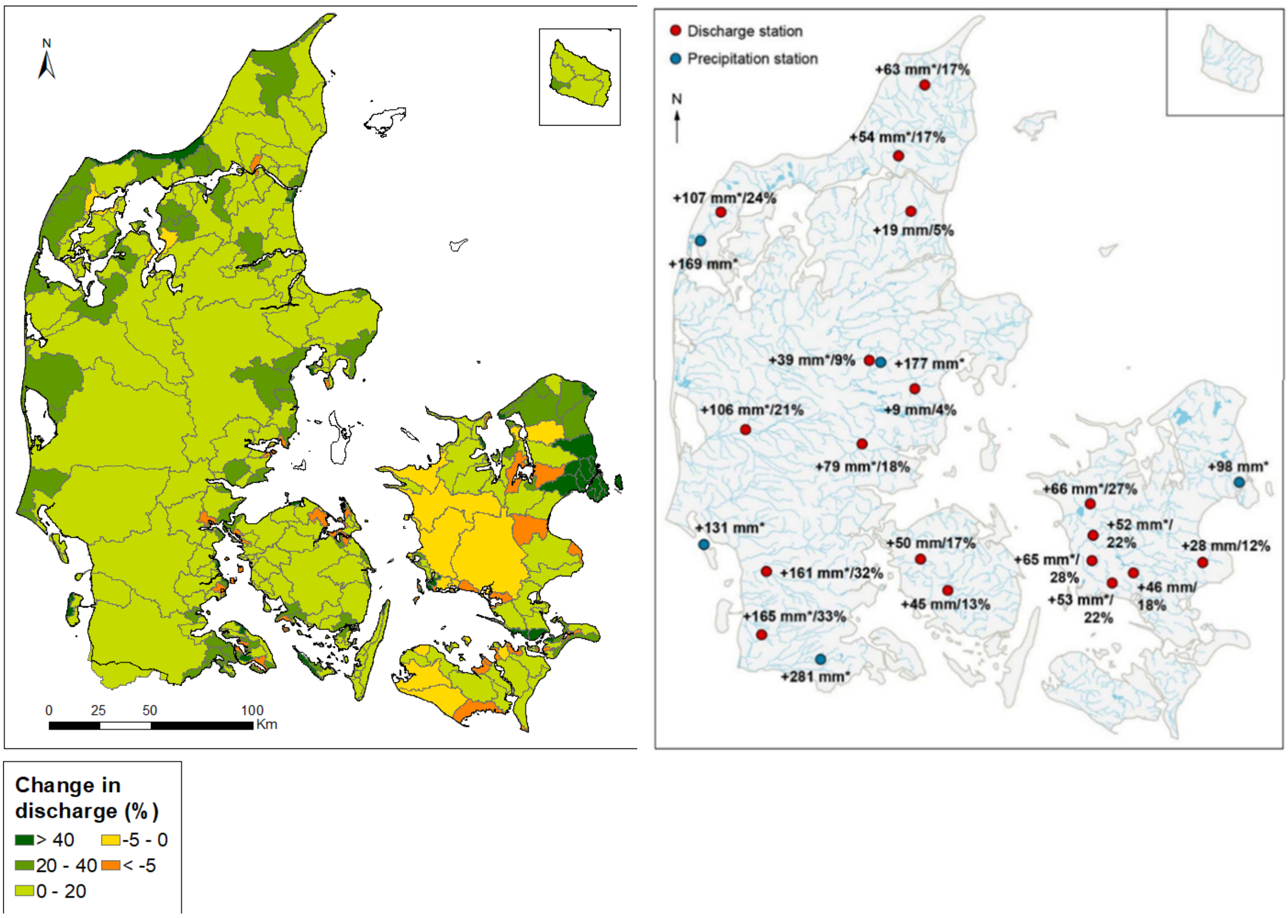

Figure 3.7. Change in simulated stream discharge from 1900 to the present as percentage (left) and calculated changes in precipitation and stream discharge from trend analysis of time series (right) (from Jensen (ed.), 2017).

3.4 Conclusion

Applying the historical precipitation calculated from observed data corrected for wind and shelter effects in the hydrological model resulted in only 3% difference in the total observed and simulated discharges for the period 1917-1950. The simulation similarly showed good agreement for several discharge stations, but for Mid Jutland and the eastern part of Denmark the historical discharge was under- and overestimated, respectively. Additionally, the water balance errors between observed and simulated discharges for streams within a region displayed noticeable variations. Despite the test of several alternative approaches to correct the historical precipitation data, no approach reproducing the spatial variation in stream discharge could be found. Therefore, it was decided to apply a delta change approach by which a historical time series of precipitation was established by adjusting the current precipitation values by a national monthly correction factor. In this way, the same factor, varying from month to month, was applied to the entire country. This approach exploits the fact that the national water balance was low, while simultaneously acknowledging that the spatial variation could not be reproduced.

Using the delta change approach, the total discharge was found to increase from an average value of 292 mm / yr for the period 1890-1910 to 333 mm / yr for the present period (1990-2010). This change in discharge between the two periods largely reflects the changes in precipitation, but for some areas it is amplified due to the lower density of drains in the historical period. The calculated change in discharge from 1900 to the present ranged between 0 and 20% for most of the country, which agrees with the trend analysis of long discharge time-series conducted by Jensen (ed.) (2017). However, for South Jutland, the discharge development is underestimated as the observed data indicates an increase in discharge just above 30%. For the western part of Zealand, the development in stream discharge is similarly underestimated as the discharge observations indicate an increase of up to 28%, while the simulation resulted in a decrease in discharge of approx. 5%. With the delta change method it is thus assumed that the total discharge to the sea resembles the conditions around year 1900, but local conditions cannot be reproduced.

Estimation of precipitation is crucial as this, together with evapotranspiration, is the driving force for calculating the recharge to the groundwater. Uncertainty regarding the estimated recharge will result in uncertainty as for the groundwater pathways and, thus, the transport pathways of nitrate from the root zone to the sea. Even more critical is it that the total mass of nitrate leaching from the root zone is calculated from the root zone concentration estimated in chapter 5 multiplied by the estimated recharge. Uncertainty regarding the recharge will thus translate to the estimated total nitrogen load to the subsurface in year 1900. From this follows that the estimates of nitrate leaching, in accordance with the estimated stream discharges, cannot be used at local scale.

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4 Point source emissions of nutrients from urban areas in 1900

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Abstract

Purpose: The purpose of this chapter is to quantify nitrogen and phosphorous emissions to water and soil from Danish towns around the year 1900.

Materials and methods: Based on an extensive literature review, qualitative information regarding discharge paths is translated into quantitative mass flow charts. The resulting emissions to different environmental compartments are then calculated using adjusted current measurements of nutrient contents in human and animal faeces and industrial wastewater.

Results and discussion: Total nutrient emissions are estimated to 4,261 ton N / yr and 764 ton P / yr in 1900. The largest fraction was discharged to water (2,531 ton N / yr and 462 ton P / yr), followed by landfills (811 ton N / yr and 143 ton P / yr) and agricultural soil (919 ton N / yr and 159 ton P / yr).

4.1 Introduction

Large parts of the Danish population migrated to towns in the second half of the 19th century, and industries centred around towns were growing (Statistics Denmark, 2000). By 1901, 39% of Denmark's 2.45 million population lived in towns (Matthiessen, 1985). Even though agriculture was not the main source of income for the majority of the town population, animals were often held for self-supply in the beginning of the 20th century (Mikkelsen, 2012, 2010; Statistics Denmark, 1969). Industries and factories developed around the towns. With this growing pressure on towns, hygiene and sanitation gained increasing attention in the 19th century, and efforts were put into limiting human contact with excrements and waste (Iversen, 2004).

However, this development varied significantly between towns. While underground sewers were largely installed in Copenhagen by 1900, smaller towns still had buckets for human waste, and wastewater was discharged in open gutters along the roads. The use of artificial fertiliser was still very limited around year 1900 (Statistics Denmark, 1968), and human and animal excrements were a valuable resource that was used as fertiliser on farms. Emissions from industries were largely unregulated, and wastewater treatment did not exist (Engberg, 1999). Discharges around year 1900 of excrements and waste from humans, animals and industries in Danish towns have not been quantified until now, and the magnitude of nutrient emissions to streams and marine waters is largely unknown. Here, a first estimate of total nitrogen (N) and phosphorous (P) emissions from Danish towns around the year 1900 is provided. The assessment is based on national upscaling based on representative towns for which detailed historical data have been collected and detailed estimates of nutrient mass flows are made.

4.2 Materials and methods

Individual assessment of each town lies outside the scope of this report. Instead, three model towns with representative characteristics were chosen and analysed in more detail to derive typical conditions. Total emissions from Danish towns with more than 5,000 inhabitants are then calculated by upscaling the assessed characteristics of the model towns. The chosen cut-off is based on the assumed demographic difference that smaller towns with less than 5,000 inhabitants were more rural and less developed in terms of sanitation than larger towns. Towns larger than 5,000 inhabitants covered approximately 80% of the urban population in 1900. 24 out of 29 towns larger than 5,000 inhabitants around year 1900 are coastal towns.

Copenhagen was assessed separately as it was distinctively different from all other Danish towns as to size and level of industrialisation. Almost 500,000 people lived in Copenhagen around 1900, which accounts for 45% of the Danish town population (19% of the total population) (Matthiessen, 1985). Apartments were scarce and overcrowded and industries were growing, which led to faster development of organised waste disposal and underground sewer systems than in the remaining part of Denmark (Iversen, 2004).

Besides Copenhagen, three model towns were selected to reflect the typical population growth and the fraction of population working in agriculture among Danish towns around year 1900. Towns with more than 5,000 inhabitants showed widely varying characteristics regarding these two parameters, population growth ranging between -6% and +773% between 1880 and 1901 (median; +58%) and the fraction of the town population working in agriculture ranging between 1% to 18% in 1890 (median: 6%) (Dansk Center for Byhistorie, n.d.; Matthiessen, 1985). Towns and settlements with less than 5,000 inhabitants had a markedly lower population growth (29%), and occupation was dominated by agriculture and fishery (62%) (Dansk Center for Byhistorie, n.d.; Matthiessen, 1985).

Besides proximity to calculated median values for both population growth and occupational pattern (appendix 4.1), geographical distribution was considered, and based on this, Svendborg (Funen), Helsingør (Zealand) and Randers (Jutland) were selected as model towns (Table 41). All three towns, like most larger towns at the time, were connected to the railway, enabling trade and industrial growth (Fertner, 2012). Furthermore, access to the sea was an important factor for growth and industrialisation, which was the case for most larger towns (Figure 4.1).

Table 4.1. Median characteristics of Danish towns with more than 5,000 inhabitants, of three Danish model towns and of Copenhagen.

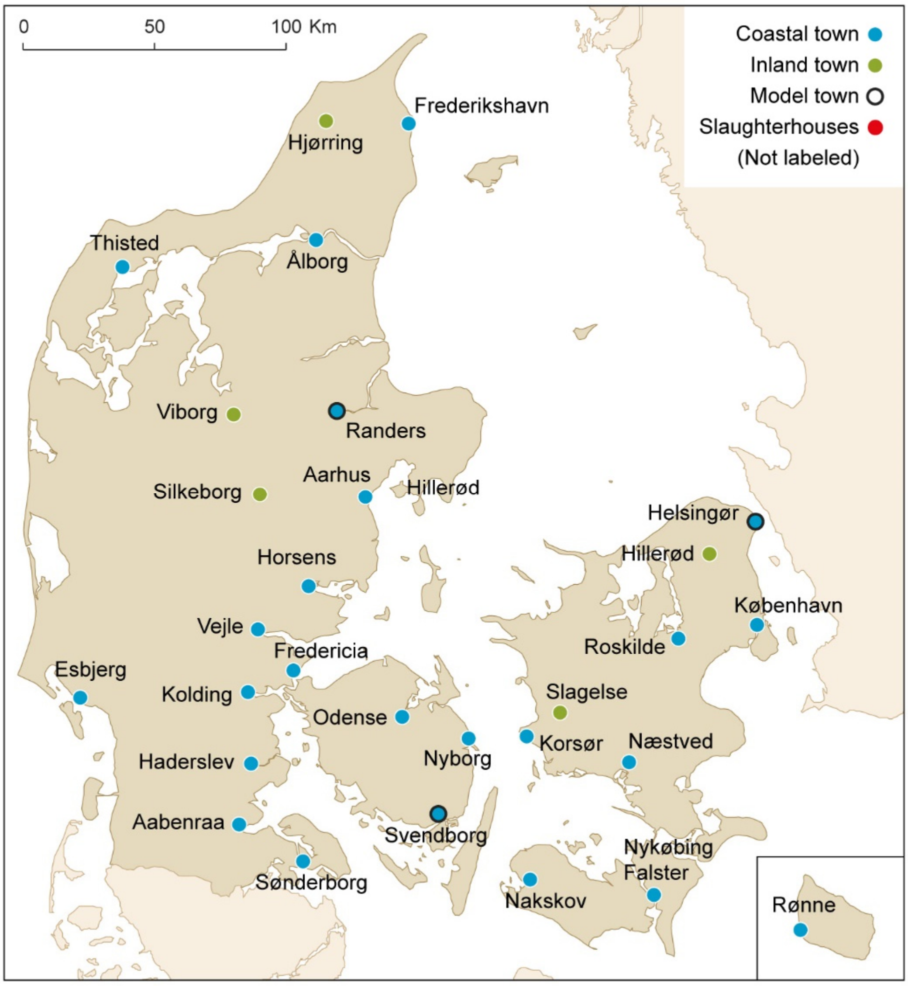
	Population size 1900 (Matthiessen, 1985)	Population growth between 1880 and 1901 (Matthiessen, 1985)	Fraction of the population working in agriculture or fishery in 1890 (Dansk Center for Byhistorie, n.d.)	Location
Median	8,958	+58%	6%	-
Svendborg	11,543	+61%	7%	Funen
Helsingør	13,902	+55%	8%	Zealand
Randers	21,377	+49%	11%	Jutland
Copenhagen	491,278	+74%	1%	Zealand

The inhabitants of the 29 towns with more than 5,000 inhabitants (Table 4.1) cover 80% of the population living in towns (34% of the total Danish population) (Matthiessen, 1985). Data on the numbers of cattle, pigs and sheep held within the towns were gathered (Trap, 1906). For the three model towns, information regarding the infrastructure, regulations and processes to collect and dispose of waste from humans, animals and industry was collected from historical documents.

Slaughterhouses, dairies and tanneries existed in all three model towns and Copenhagen. Other types of industry and factories varied between the towns and are not analysed in detail in this report. Tanneries were assumed to mainly emit toxic substances, especially chromium, and were therefore not considered as a significant nutrient source. Current data on wastewater quantity and quality from slaughterhouses and dairies were used to estimate emissions around year 1900. In addition to emissions from larger towns, the emissions from slaughterhouses in more rural areas of Denmark were also assessed. Slaughterhouses were mainly located in smaller towns with less than 5,000 inhabitants and were therefore included as separate point sources in the assessment (appendix 4.1). In general, food production resources were used as efficiently as possible, and by-products were often reused. For instance, the organic waste of breweries was fed to cows, and the skimmed milk was redistributed from dairies to farms as feed for animals (Iversen, 2017; Statistics Denmark, 1969). This is assumed to limit the nutrient emissions of industry around year 1900. Finally, a distinction was made between coastal and inland towns, where coastal towns were characterised by access to a major water body and thereby easy access to discharge of sewage.

Based on the collected information, the flows of nutrients from humans, animals and industries were compiled in flow charts for coastal and inland towns and for Copenhagen. Randers and Odense can be considered inland towns, but their proximity to large water bodies led to their categorisation as coastal towns. In the following, initial concentrations refer to the direct nutrient discharge from humans and animals, i.e. what was emitted in excrements. The initial concentrations of nitrogen and phosphorous from humans and animals and in wastewater from industry were based on current values reported in the literature and adjusted by the assumed change in nutrient intake since the time around year 1900 (appendix 4.1). Based on the developed flow charts, the resulting emissions to water, landfills and agricultural soil were calculated for each town, including dairies and each slaughterhouse.

Figure 4.1. Danish towns with more than 5,000 inhabitants in 1900. Odense and Randers are considered to have the characteristics of coastal towns because of their close proximity to major water bodies.



4.3 Results and discussion

4.3.1 Latrines and dumpsites

Most Danish towns changed from simple pit latrines to collect human excrements (Danish: *grubelatrine*) towards a bucket system in the 19th century (Danish: *tøndelatrine*) (Gædeken et al., 1894; Kongstad, 2016). In 1899, 44 Danish towns (including all three model towns) had, at least partially, introduced a bucket system, with only 29 still using pits (Carlsen, 1900). Collection of the buckets was rarely organised and regulated. Buckets were often emptied at small dumpsites within the towns (Danish: *mødding*), where also animal excrements were disposed. The transport of excrements to the dumpsites often resulted in significant spills (Steensberg, 1964), which were included as emissions to soil (Figure 4.2). The dumpsites were emptied by the surrounding farmers only one to two times per year (Gædeken et al., 1894). Only some towns, for instance Randers, had organised bucket collection and disposal by private companies that sold the buckets to surrounding farmers (Hyldegaard, 2002).

Water closets (WC) were not common around year 1900, with only 44 WCs reported in Helsingør (Pedersen, n.d.) and approximately 100 in Randers. They were connected to septic tanks that often overflowed (Hyldegaard, 2002). In Copenhagen, it was legalised to connect WCs to the subsurface sewer system in 1897, which led to a faster technology uptake, resulting in around 5,000 WCs in 1900 (Lützen, 1998). The majority of the Copenhagen population still relied on buckets that were collected at night, transported to four dumpsites outside of Copenhagen and sold to farmers (Iversen, 2017). The fraction of sold buckets decreased steadily at the end of the century; thus, less than 10% of approximately 30,000 buckets were sold in 1900 (Gædeken et al., 1894).

4.3.2 Gutters and pipes

We assume that the preferred way of disposal was direct discharge to water preventing the hygiene and odour problems caused by landfills. Wastewater was mainly discharged to receiving water bodies in gutters, which replaced ditches in the 19th century in order to reduce infiltration of wastewater (Hyldegaard, 2002; Kongstad, 2016). The installation of pipes began at the end of the 19th century in most Danish towns, including all three model towns (Bro-Jørgensen, 1959; Hyldegaard, 2002; Kongstad, 2016). This was often done in combination with the construction of water works and water distribution pipes. Around year 1900, 62 water works had been constructed in larger towns, including all the three model towns (Foreningen af Vandværker i Danmark, 2012; Trap, 1906). The construction of sewer pipes often started in the town centre and in connection with specific problematic industries, as for instance reported for Esbjerg (Esbjerg Kommune, 2019). The update of this technology varied widely in 1900 between complete absence of sewers to complete coverage, for example in Roskilde (Fang, 2017; Kongstad, 2016). Pipes and gutters were often connected to the nearest surface water body, for instance to the River Gudenå in Randers (Jensen, 1989). Direct discharges to water, especially from industries, were very common in the 19th century, as documented, for example, for tanneries and slaughterhouses (Christensen, 1912; Iversen, 2017). If direct connection to surface water was not feasible, the wastewater was discharged to dumpsites outside the town as was the case for the town of Svendborg (Bro-Jørgensen, 1959).

Copenhagen had an extensive sewer system already around year 1900, into which human waste and industrial wastewater were discharged (Eriksen, 2007; Hanne Lindegaard, 2001). Even before it was legalised to discharge human excrements to the sewers in 1897, it was estimated that 75% of the excrements was discharged illegally by either disposing of excrements through kitchen pipes or by throwing them on the streets (Hanne Lindegaard, 2001; Iversen, 2017). The pipes and gutters discharged into canals, lakes and the harbour with a direct connection to the open sea (Gædeken et al., 1894). The canals and lakes were malodorous, and the sea between Køge and Copenhagen was so polluted that it was brown at that time (Andersen, 2012; Hilden, 1973).

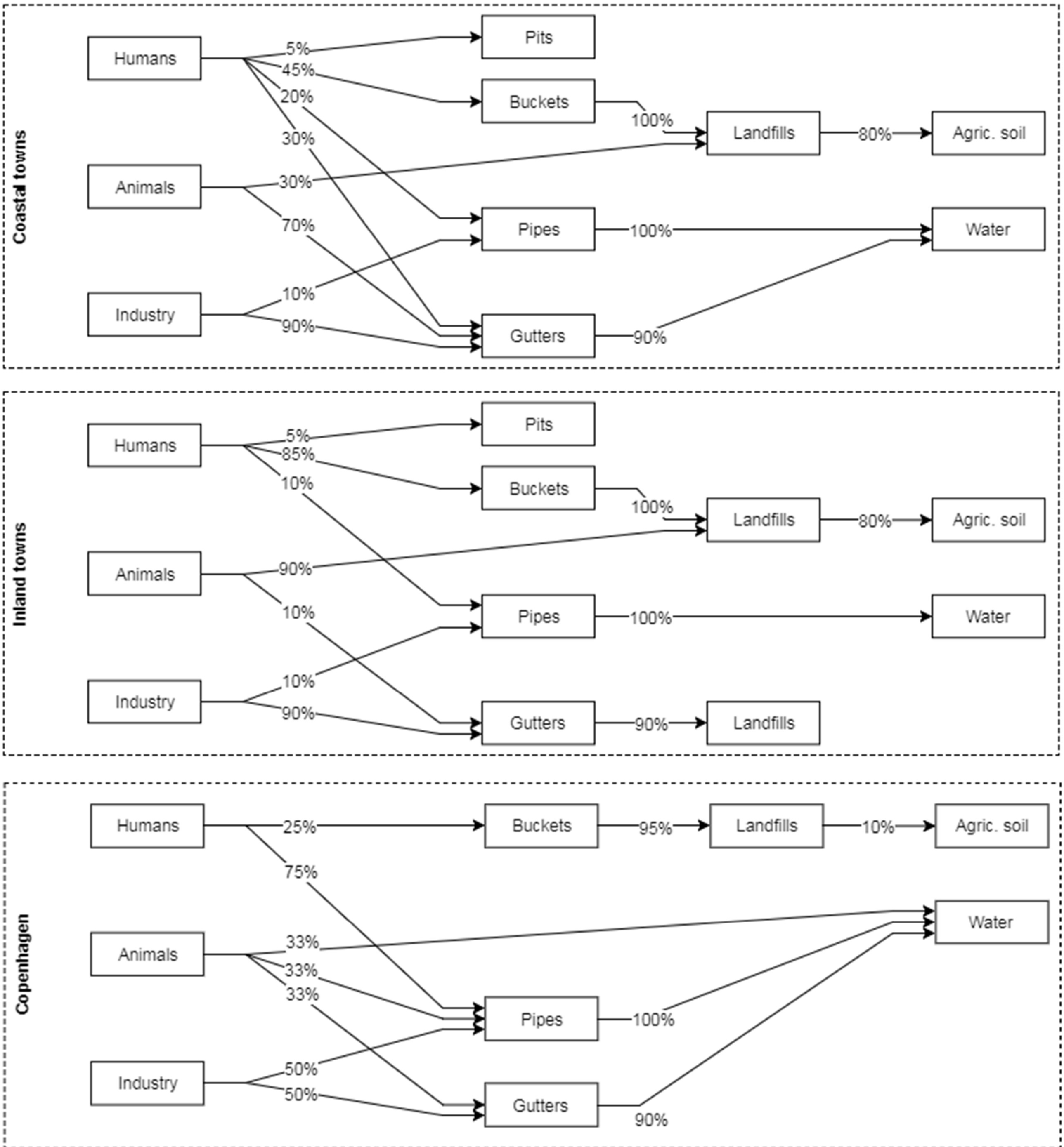


Figure 4.2. Flow charts of nutrients in human, animal and industry waste in Danish towns in 1900. Losses are considered emitted to soil on-site due to spill and infiltration (emissions to soil) or disposed of in landfills without further export to agricultural soil. For example, town landfills would lose 20% nutrients to soil on site, and for Copenhagen landfills 90% of nutrients was lost on site.

4.3.3 Initial emissions

Initial emissions refer to nutrients excreted by humans, animals and industries. Reported emissions of nutrients in human excrements are around 4 kg N / pers. yr and 0.7 kg P / pers. yr (Hevesy et al., 1939; Holtze and Backlund, 2003; Rose et al., 2015; Wrisberg et al., 2001). Nutrition was significantly less varied, and the calorie intake was around 25% lower than today (Roser and Ritchie, 2019; Staun, 2002), which also resulted in lower intake of nutrients (appendix 4.1) The historical values were therefore adjusted, and nutrient emissions per person was assumed to be 25% lower around year 1900 than today (Table 4.2).

The excretion of nutrients from animals depends on the ability to process nutrients and the feed. Protein-rich feed reduces the nitrogen demand and excretion, which such feed was not known or applied around year 1900 (Manitoba, 2015). We therefore also assume a 25% decrease in addition to using the minimum emissions reported for present-day conditions (Table 4.2) (Hong et al., 2012).

As piped systems were not yet implemented, wastewater production at slaughterhouses and dairies was assumed to be limited. Therefore, the lowest wastewater production reported in the literature for present conditions combined with the highest reported nutrient concentrations was used (Table 4.2) (Rad and Lewis, 2013; Verheijen et al., 1996). Emissions from single slaughterhouses were calculated by evenly distributing the mass of all slaughtered animals in 1900 over all 29 slaughterhouses, with the exception of Randers, Esbjerg and Odense. These towns had larger slaughterhouses, twice the throughput was therefore assumed (appendix 4.1) (Krak, 1950; Statistics Denmark, 1969). To derive the emissions from dairies, the per person consumption of milk were calculated by dividing the total production by the total population (Matthiessen, 1985; Statistics Denmark, 1969). As there were in total approximately 1,000 dairies in Denmark, it was assumed that there was a dairy processing milk for all inhabitants in every town (spreadsheet appendix) (Christensen, 2012).

Table 4.2. Estimated emission of nutrients from humans, animals and industry in 1900 based on present-day values reduced by 25% to account for differences in nutrition and animal feed.

	Nitrogen	**Phosphorous**
Human excrements	3.0 kg/pers./y.	0.5 kg/pers./yr
Animal excrements		
Cattle and horses	45.0 kg/animal/yr	7.5 kg/animal/yr
Pigs	6.8 kg/animal/yr	2.3 kg/animal/y.
Sheep and goats	6.5 kg/animal/yr	1.3 kg/animal/yr
Industry		
Dairies	0.3 kg/pers./y.	0.1 kg/pers./yr
Slaughterhouses	27 kg/slaughterhouse/yr	2 kg/slaughterhouse/yr

4.3.4 Point source nutrient emissions 1900

The total nitrogen emissions from towns and slaughterhouses were 4,261 ton/yr, and the total phosphorous emissions were 764 ton/yr. Most of the emissions was discharged to water (2,531 ton N/yr, and 462 ton P/yr.. Emissions to landfills and soil (811 ton N/yr and 143 ton P/yr) and agricultural soil (919 ton N/yr and 159 ton P/yr) are significant (Table 4.3). The estimated emission of nutrients from humans, animals and industry around year 1900, based on present-day values, was reduced by 25% to account for differences in nutrition and animal feed. Slaughterhouses contributed insignificantly to total emissions (Table 4.3).

Table 4.3. Nutrient emissions to water, landfill or soil and agricultural soil from coastal towns, inland towns, Copenhagen and slaughterhouses around year 1900. Emissions to landfills or soil include spills during transport and overflows.

	Emission to water [ton/yr]		**Emission at landfill or on site soil (not reaching agricultural soil) [ton/yr]**		**Emission to agricultural soil [ton/yr]**		**Total [ton/yr]**	
	N	P	N	P	N	P	N	P
Coastal towns	1,182	218	309	54	600	102	2,091	374
Inland towns	13	2	114	21	280	50	407	73
Copenhagen	1,336	242	388	68	40	7	1,764	317
Slaughterhouses	1	0	0	0	0	0	1	0
SUM	2,531	462	811	143	919	159	4,261	764

In 2017, the estimated level of phosphorous in domestic wastewater was 0.7 kg P/pers./yr in Denmark (Arildsen and Vezzaro, 2019) This is mainly due to the increased use of phosphorous in products like detergents, while around year 1900 only excrements contributed to the emissions of phosphorous from humans. While more than 80% of phosphorous is removed in wastewater treatment plants today (Danish Nature Agency, 2014), a large fraction of human excrements was discharged directly to water around year 1900 (Figure 4.3). The resulting per capita emissions for discharges of phosphorous from humans to water were estimated to 0.11 kg P/pers. yr today. For the time around year 1900, it was found that, after losses (Figure 4.3,) discharges to water were 0.05 kg P/pers./yr from inland towns and 0.24 kg P/pers./yr from coastal towns.

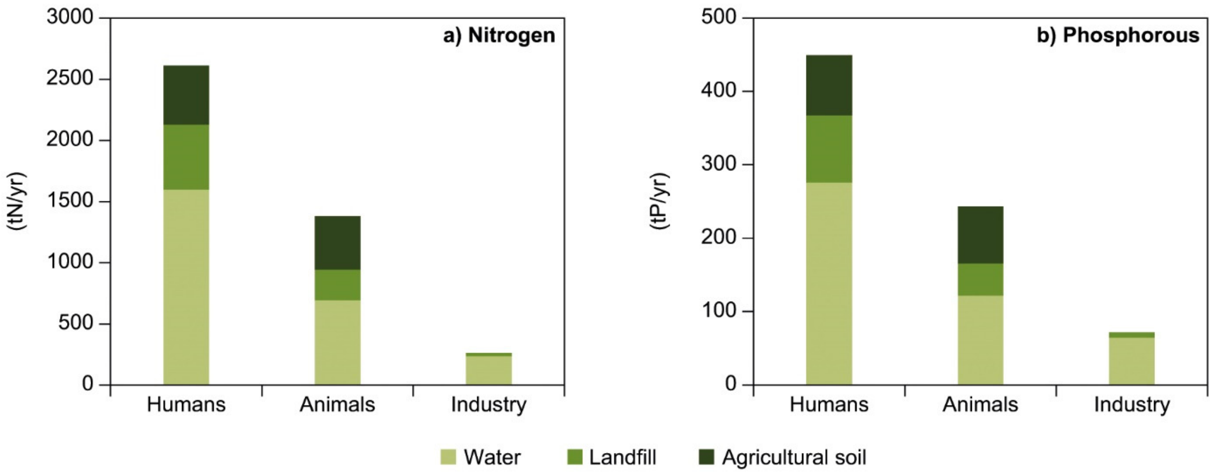
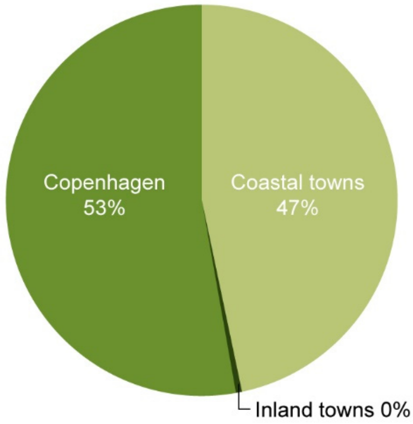


Figure 4.3. Total nitrogen and phosphorous emissions from humans and animals in towns with more than 5,000 inhabitants and industry (slaughterhouses and dairies) to water, landfill (emissions to soil and not reaching agricultural soil) and agricultural soil around year 1900.

Most nutrients were emitted in human waste, contributing almost twice as much as animal excrements. The emissions from industry were one order of magnitude lower than the emissions from humans or animals (Figure 4.3). Copenhagen was the largest single point source of nitrogen and phosphorous (53%), followed by coastal towns (47%). Less than 1% of the total nutrient emissions stemmed from inland towns (Figure 4.4).

Figure 4.4. Nutrient emissions to water from coastal and inland towns with more than 5,000 inhabitants and Copenhagen (including humans, animals and industry).



4.3.5 Main uncertainties

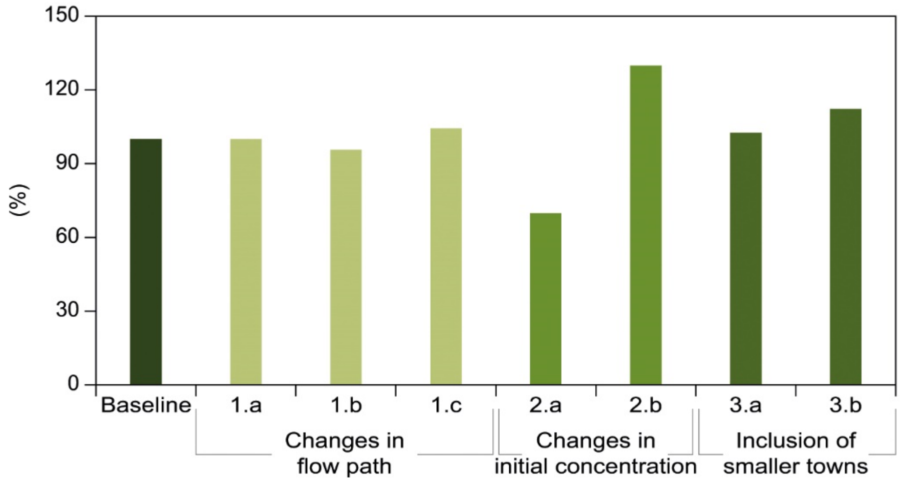
The flow paths of nutrients, the initial load of nutrients from human and animal excrements and the minimum population for inclusion of towns in the assessment were identified as the main sources of uncertainty. For each source, alternative scenarios and assumptions were tested and the resulting nutrient emissions compared with the baseline scenario (Table 4.4, results given in appendix 4.2).

Table 4.4. Tested alternative scenarios for selected parameters.

Source of uncertainty	Parameter	Baseline	Alternative
1. Flow paths of nutrients	1.a Fraction of buckets from Copenhagen sold to farmers	10%	80%
	1.b Fraction of waste disposed to pipes	10-20% of human excrements 10% of industrial wastewater	50% decrease
	1.c Same as 1.b	Same as 1.b	50% increase
2. Initial load of nutrients from human and animal excrements	2.a Initial load of nutrients from human and animal excrements	75% of present values	50% of present values
	2.b Same as 2.a	Same as 2.a	100% of present values
3. Minimum population for inclusion of towns in the assessment	3.a Towns with less than 5,000 inhabitants	Excluded	Included as inland towns
	3.b Same as 3.a	Same as 3.a	Included as coastal towns

Changes in the initial load of nutrients in animal and human excrements was the most significant factor affecting the resulting nutrient emissions. The excretion of nutrients correlates directly to the nutrient intake, which is a highly uncertain parameter as no measured values exists or the time around year 1900. In the baseline scenario, a 25% reduction of the values reported for the present conditions was assumed. Assuming no reduction of initial loads results in a 30% increase in emissions. Assuming an even more significant reduction of 50% of initial loads decreases the emissions by 30%. The inclusion of smaller towns with less than 5,000 inhabitants leads to a maximum increase of 12% in the resulting emissions to freshwater. Flow path changes did not cause significant changes in the subsequent nutrient emissions to water (-4% to +4%). However, the flow paths for solid and liquid waste, carrying different fractions of the initial nutrient loads, were not differentiated. Infiltration of urine possibly led to higher emissions of nitrogen than of phosphorous to soil, but a detailed assessment of the different paths lies outside the scope of this assessment.

Figure 4.5. Relative change in nutrient emissions to water compared with the baseline of seven alternative scenarios listed in table 4.4.



The calculated emissions are based on the assumed average conditions in Danish towns around year 1900. However, towns were developing very differently, and the source and fate of emissions varied widely. It was not the scope of our study to conduct a detailed mapping of nutrient emissions and routing for each individual town, and our results must therefore be interpreted with caution for individual towns. The values are, as such, a qualified indication of the magnitude of nutrient loads from point sources around year 1900 and a robust national estimate of emissions. A more detailed assessment of each individual town and industry could be made based on specific mass balances. This would improve the assessments of emissions to local surface waters but is not expected to significantly affect the calculated national estimate.

4.4 Conclusion

The disposal of excrements and wastewater differed widely between Danish towns around year 1900. Hygiene and sanitation had gained increasing interest, but sewer systems were still limited, and a large fraction of waste was discharged in gutters. Discharges to receiving water bodies were not regulated or treated, and a large fraction of waste was disposed of at landfills in and around towns. The fate of nutrients differed between coastal and inland towns, with more direct discharges to water along the coast and more discharges to dumpsites and application on agricultural soil inland.

Towns were significant point sources around year 1900 with 4,261 ton N / yr and 764 ton P / yr emitted in human and animal excrements and industrial wastewater. These emissions are one order of magnitude lower than the estimated emissions from agriculture. Our findings indicate that the majority of the nutrients from point sources was discharged directly to receiving waters (55%), but emissions to landfills (20%) and agricultural soil (25%) were significant as well. The contribution from slaughterhouses and dairies was found to be negligible (<1%). 45% of the town population lived in Copenhagen in 1900, which led to large point source emissions (1,764 ton N / yr, 317 ton P / yr) from. Most larger towns (>5,000 inhabitants) were located along the coast, and the resulting total emissions (2,091 ton N / yr and 374 ton P / yr) were consequently higher here than from inland towns (407 ton N / yr and 73 ton P / yr).

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5 Land use, agriculture and nitrate concentrations in root-zone percolates around year 1900

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Abstract

Purpose: The purpose of this chapter is to provide estimates of the concentration of N in water leaving the root zone of land under agricultural use around year 1900. At that time, agricultural management and land use differed significantly from current practices.

Materials and methods: The chapter relies on literature addressing agricultural management around year 1900, on official agricultural statistics and on N concentrations in root zone percolates measured in well-defined field experiments with year 1900-relevant management. Estimates of concentrations of nitrate-N in root zone percolates were established for eight categories of land uses derived from detailed parish-level statistics recorded for land areas under Danish and German administration in 1896 / 1900.

Results and discussion: Parish level statistics for the area under Danish administration included 34 land use categories (termed DA), while the area under German administration included 51 categories (termed TY). These were unified into 26 land uses (termed S) and finally into eight DK categories to comply with model requirements. For each DK category, an N concentration was ascribed to the root zone percolate: winter crops (DK-1, 18 mg N / l), spring crops (DK-2, 13 mg N / l), grass (DK-3, 9 mg N / l), root crops (DK-4, 12 mg N / l), fallow (DK-5, 20 mg N / l), nature (DK-6, 1 mg N / l), forest (DK-7, 2 mg N / l) and other land use (DK-8, 0 mg N / l). These categories account for 8, 23, 36, 4, 6, 14, 7 and 3% of the area, respectively.

Conclusions: Using the derived estimates, the area-weighted average N concentration for land in agricultural use (app. 78% of the land area) is 12 mg N / l, while the value for the entire land area is about 9.6 mg N / l. This is in accordance with previous preliminary estimates reported in Jensen (ed.) (2017).

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5.1 Introduction

For the time around year 1900, measurements of N concentrations in streams are extremely few (Westermann, 1898), and their representativeness is uncertain. Consequently, the N load of coastal waters around year 1900 remains currently unknown.

Bøgestrand et al. (2014a) deduced the N concentration in water reaching the coastal area around year 1900 from current N concentrations in streams from minimally disturbed catchments (Kronvang et al., 2015; Bøgestrand et al., 2014b) and national N balances for agriculture established for year 1900 Kyllingsbæk, 2008). However, Christensen et al. (2017) subsequently demonstrated that this approach was not valid. One reason is the lack of correlation between field N surplus and N leaching from the root zone (Blicher-Mathiesen et al., 2014; Eriksen et al., 2015; Hansen et al., 2015). In an analysis of 39 streams from Danish catchments with between 0 and 90% of the area in agricultural use, Kronvang et al. (2015) found a good correlation between the percentage of land in agriculture and the flow-weighted N concentration in streams without incorporating the field N surplus. Further, current and year 1900 land use and agricultural management differ substantially. This affects the interpretation of farm and field N balances, including the proportion of the N surplus contributing to leaching.

In this chapter, we establish -for the time around year 1900- estimates of concentrations of nitrate-N in root zone percolates for eight categories of land uses. The land use is derived from parish-level statistics recorded in 1896/1900 and N concentrations in root zone percolates measured in well-defined field experiments with time around year 1900-relevant management.

5.2 Agriculture around year 1900

In the period 1861-1896, the area in agricultural use increased dramatically and accounted in 1896 for ´nearly 3/4 of the area under Danish administration. For instance, heathlands and sand dunes declined by 656,000 ha during 1850-1907 (Mortensen, 1969). Large areas of land had been included in rotational cropping in the decades preceding year 1900, and there was widespread use of bare fallow where the vegetation-free land subject to frequent tillage throughout a year. Tile drainage, first introduced in Denmark in the 1850s, covered 26% of the agricultural area by year 1907. The activity peaked during 1860-1880 where 15,000 to 30,000 ha were drained annually (300,000 ha were drained during the decade 1871-1881). For the agricultural area on the islands Zealand and Funen, 45% was tile drained by 1907, mainly the more clayey soils (Jensen, 1988; Olesen, 2009).

The agricultural and land use statistics reported in this section relates to the area under Danish administration. From 1864 to 1920, the southern part of Jutland (northern part of Schleswig) was under German administration. Data based on parish statistics include areas under Danish and German administration around year 1900 (see section 5.2) and thus covers the current Danish territory.

5.2.1 Plant production and nitrogen use

Crop production around year 1900 differed significantly from the current agriculture for virtually all growth factors: inferior crop varieties, higher weed pressure, lack of chemical crop protection and inferior plant nutrient supply, including the absence of mineral N fertiliser. The main sources of N were solid farmyard manure, liquid manure and N_2 fixation by legume crops.

The annual average (1900-1904) input of N with animal manure was estimated to 21 kg N/ha when corrected for 15% loss of N during storage of feedstuffs and stable feeding and 25% loss of N during storage (Danmarks Statistik, 1968). Subsequent losses of N in the field were not included. In 1896, the number of storage tanks for liquid manure was 28,000 (Iversen, 1944); manure heaps with roof covers accounted for 16,500 in 1907. Statistics for 1895 show a total number of 237,000 farms and smallholdings and 35,000 holdings without land (Christensen, 1985). Thus, only a small proportion of the agricultural holdings had proper storage facilities, leaving room for substantial losses of manure-N from the site. Around year 1900, most of the manure was applied during the period late summer, autumn and early winter, partly due to soil tillage requirements and establishment of autumn-sown crops, the availability of farm labour and the lack of manure storage capacity. Application of animal manure during this period leads to poor N use efficiency with a substantial leaching potential of mineral N present in the manure or derived from mineralisation of organically bound N outside the growing season.

The grain yields for oats, barley, rye and wheat around year 1900 averaged 14, 18, 20 and 28 hkg / ha, respectively (Iversen, 1942; Danmarks Statistik, 1968). The grain yields are comparable to those achieved in the period 1894-1904 in the Askov long-term experiments and currently obtained in plots kept unmanured for more than 120 years (Christensen et al., 2019) and only slightly lower than yields of cereal crops grown under unmanured conditions in ongoing organic farming experiments (Olesen et al., 2002). For hay produced on rotational and permanent grassland (incl. meadows), the around-year 1900 yield was 24 and 27 hkg / ha, respectively (Danmarks Statistik, 1968). Even though contemporary textbooks prescribed generous use of liquid manure to meadows, permanent grasslands and grass-clover crops in rotation in late autumn and again in the spring (Christensen, 1898), the yield level of grasslands around year 1900 was below that obtained currently for rotational grass-clover grown under unmanured conditions (Christensen et al., 2019).

According to Christensen (1898), the typical crop rotation around year 1900 was spring cereals (mainly oats) undersown with grass-clover, three to five years in grass-clover followed by one year in bare fallow and, finally, autumn sown cereals (mainly cereal rye) and / or a root crop. On the more fertile soils, one or more crops of spring-sown oats could follow until the soil became nutrient exhausted and a new grass-clover crop was established.

5.2.2 Animal production

Animal husbandry around year 1900 also differed significantly from current Danish agriculture for most production factors: livestock composition, feed quality and rate of feeding, grazing intensity and periods, and productivity per animal unit. Converted into livestock units, the agricultural sector included 2.6 million units in 1898 (Danmarks Statistik, 1969) with 54% cattle, 16% pigs, 15% horses, 8% poultry and 7% sheep and goats. Although the number of cattle around year 1900 and today is just slightly different, the productivity per livestock unit has increased 3- to 4-fold since 1900 (Kristensen et al., 2015). Around year 1900, grass ingested in fresh condition was the dominant source of ruminant forage (49%), while root crops, hay and cereal straw accounted for 19%, 18% and 13%, respectively (Danmarks Statistik, 1968). Kristensen et al. (2015) estimated that for cows, grazing accounted for more than 70% of the feed intake. In terms of digestible protein in homegrown forage (the source of N ending up in animal manure), grass accounted for 67%, hay for 24% and root crops for just 4.5%.

5.2.3 Farm structure

Compared with today, the distribution among different animal categories was very different around year 1900. This is also true for the farm structure. Most farms were small in terms of acreage and production volume. Thus, cattle herds encompassing 1 to 14 cows accounted for 70% of all cows. When calculated in livestock units (1 unit = cow), the animal density in 1898 was 0.89 unit / ha on land under agricultural use; this ranged from 0.69 in West Jutland to 1.14 unit / ha on Zealand (Danmarks Statistik, 1969). In 1900, farm sizes were measured in hartkorn (Hkt.), a unit that combined land area, land use and soil quality in providing an estimate of the production of individual farms. Based on this unit, smallholdings (< 1 Hkt.) and smaller farms (1 to 8 Hkt.) accounted for 74% of the total agricultural crop production in 1895 (Christensen, 1985).

5.2.4 Land use and agriculture- based on parish level statistics

To establish an area-distributed account of land use and agriculture around year 1900 covering the current Danish area, the parish unit appeared most relevant. The boundaries of the church parishes have remained almost unchanged since year 1900, and the parish thus probably represents the most conservative land area unit. The church parish was also an important administrative unit with detailed information on land use and agriculture being recorded for each parish every five to ten years. The present study relies on statistical information collected in 1896 for the area under Danish administration and around year 1900 for the area under German administration, the latter accounting for 1 / 11 of the current Danish territory. Matching parish boundaries and parish land use statistics called for some minor adjustments (see Appendix 5.1). Thus, the present study relies on 1,766 individual parish units of which 1,702 and 64 are from parishes under Danish and German administration, respectively.

For each parish, in 1896 the Danish administration allocated the area to 34 land use categories, here coded DA (Table 5.1). The land use categories encompassed not only the area in agricultural use but also accounted for the total area within the parish. In 1900, the German administration allocated each parish area to 51 land use categories designated by numbers (45 categories) or by letters (six categories). These are coded TY (Table 5.2). The Danish and German land use categories were somewhat different. Using the Danish categories as template, the two sets of categories were therefore merged into one new set of categories, coded S and encompassing 26 categories (Table 5.3).

For each land use category, Table 5.3 also shows the area adapted to the water catchment map anno 2015 (see Appendix 5.1 for details). Next, the 26 S-coded land use categories were condensed into eight DK categories (Table 5.4). The reduction of the number of categories was made to facilitate the establishment of N concentrations in root zone percolates from major land uses based on current year 1900-relevant data and facilitate their subsequent use in the DK-model (National Nitrogen Model). Table 5.4 shows that the grass-covered area and the area of spring-sown crops and nature accounted for 36, 23 and 14% of the current Danish territory, respectively.

Table 5.1. Land-use data collected in 1896 in parishes under Danish administration (3,880,000 ha; Statens Statistiske Bureau & Danmarks Statistik, 1898).

Code	Land use category	% of total area
DA1	Wheat	0.9
DA2	Cereal rye	7.6
DA3	Barley	7.4
DA4	Oats	11.6
DA5	Mixed cereals (mature)	3.1
DA6	Buckwheat	0.3
DA7	Pulses	0.2
DA8	Spurrey (mature)	0.2
DA9	Caraway and oil-seed rape	0.0
DA10	Seed production (clover, grass, beets, lupines)	0.1
DA11	Potatoes	1.4
DA12	Sugarbeets and chicory	0.3
DA13	Carrots	0.2
DA14	Fodder beets	1.8
DA15	Green forage (mixed cereals, spurrey, lucerne)	1.3
DA16	Flax, hemp and tobacco	0.0
DA17	Garden crops	0.0
DA18	Black fallow (vegetation-free)	5.1
DA19	Black fallow (green manure before ploughing)	0.1
DA20	Semi-black fallow (early summer-crop)	1.4
DA21	Cultivated grass for hay	6.9
DA22	Cultivated grass for grazing	17.9
DA23	Meadows	6.0
DA24	Fens and commons	2.5
DA25	Moors and peatland	2.0
DA26	Hedgerows and shelters	0.2
DA27	Gardens and plant nurseries	0.9
DA28	Forest area (planted)	6.3
DA29	Forest area (unplanted)	0.7
DA30	Heathland	9.2
DA31	Sand dunes and shifting sands	1.1
DA32	Swamp, foreshores, stone fields etc.	0.4
DA33	Roads, building sites and storage areas	2.3
DA34	Lakes, ponds, streams (outside sea territory)	0.3
Total		100.0

Table 5.2. Land use data collected in 1900 in parishes under German administration.

Code	Land use category	% of total area
TY1	Winter wheat	1.6
TY2	Spring wheat	0.0
TY3	Winter rye	5.6
TY4	Spring rye	0.0
TY5	Winter barley	0.0
TY6	Spring barley	4.4
TY7	Oats	8.9
TY8	Mixed cereals (winter)	0.0
TY9	Mixed cereals (summer)	2.1
TY10	Buckwheat	0.7
TY11	Peas	0.1
TY12	Fava bean	0.0
TY13	Vetch	0.0
TY14	Mixed cereals	0.4
TY15	Mixed pulses	0.0
TY16	Other types	0.0
TY17	Potatoes	1.0
TY18	Sugar beets	0.0
TY19	Fodder beets	0.6
TY20	Carrots	0.1
TY21	Fodder radish	0.1
TY22	Swedes	1.3
TY23	Field herbs and caddish	0.0
TY24	Other types	0.0
TY25	Winter rape and radish	0.0
TY26	Leindotter (Camelina sativa)	0.0
TY27	Flax	0.0
TY28	Other types	0.0
TY29	Clover (for forage)	1.0
TY30	Lucerne	0.0
TY31	Seradel	0.0
TY32	Spurrey	0.0
TY33	Seed production (clover, grass-clover)	4.2
TY34	Maize	0.0
TY35	Vetch	0.0
TY36	Lupines (for forage)	0.0
TY37	Mixed legumes	0.2
TY38	Mixed vegetables (for forage)	0.0
TY39	Mustard	0.0
TY40	Lupines	0.0
TY41	Mixed vegetables	0.0
TY42	Mustard	0.0
TY43	Fallow	3.3
TY44	Cultivated grass	25.0
TY45	Gardens and fruit plantations	0.7
TYG	Meadows	10.7
TYH	Pastures	11.1
TYI	Forests	3.6
TYJ	Buildings and yards	0.7
TYK	Uncultivated land	5.8
TYL	Roads and lakes, ponds, streams	6.7
Total		100.0

Table 5.3. DA and TY land use categories and distribution merged into 26 S-categories.

Code	Land use category	Area (ha)	% of total area	DA code	TY code
S01	Wheat	41,428	1.0	1	1, 5
S02	Cereal rye	315,998	7.3	2	3
S03	Barley	301,057	7.0	3	6
S04	Oats	479,084	11.1	4	7
S05	Mixed cereals	129,831	3.0	5	2, 4, 8, 9
S06	Buckwheat	14,530	0.3	6	10
S07	Pulses	11,600	0.3	7	11, 12, 13, 14, 15, 16
S08	Spurrey	7.641	0.2	8	32
S09	Caraway and rape	525	0.0	9	25, 39, 42
S10	Seed production	25,028	0.6	10	29, 30, 31, 33
S11	Potatoes	56,743	1.3	11	17
S12	Sugar beets	13,583	0.3	12	18
S13	Carrots	6,535	0.2	13	20
S14	Fodder beets	76,910	1.8	14	19, 21,22
S15	Green forage	51,277	1.2	15	23,24, 35, 36,37, 38, 40
S16	Flax, hemp and tobacco	293	0.0	16	27, 28
S17	Garden crops	37,549	0.9	17, 27	45
S18	Fallow	267,843	6.2	18, 19, 20	43
S19	Cultivated grass	1,053,714	24.5	21, 22	44
S20	Meadows, fens and commons	407,621	9.5	23, 24	G, H
S21	Moors, peats and heathland	587,555	13.7	25, 30, 31, 32	K
S22	Forest	295,580	6.9	26, 28, 29	I
S23	Roads and building sites	88,336	2.1	33	No code
S24	Lakes, ponds and streams	13,086	0.3	34	No code
S25	Buildings and yards	2,967	0.1	No code	J
S26	Roads and water areas	17,441	0.4	No code	L
Total		4,303,762	100.0		

5.3 Estimating the N concentration in root zone percolates

The N concentrations in water leaving the root zone remain unknown for the specific land uses adopted around year 1900 due to lack of measurements. Christensen et al. (2017) discussed factors affecting the N leaching around year 1900 and provided a preliminary estimate of N concentrations in root zone percolates in year 1900. Based on year 1900-relevant management, the N concentrations in leachate from the root zone ranged between 5 and 15 mg N/l for most of the land, with concentrations exceeding 20 mg N/l for land under bare fallow, land subject to prolonged grazing periods and soil left bare after ploughing of grasslands. The average concentration of N in water leaving the root zone was set to 12 mg N/l from land subject to agricultural use.

To estimate N lost from different crop types (DK-1, DK-2, DK-4) and grassland (DK-3) around year 1900, results of recent studies with conditions similar to those around year 1900 (in terms of farming practice, nutrient supply etc.) were compared.

For the eight land use categories shown in Table 5.4, current measurements from well-controlled agricultural experiments with year 1900-relevant management were employed. This allows us to link specific and well-known management with N concentrations measured in root zone percolates. For forest-covered areas, we adopt measurements of N concentrations in soil solutions from samples retrieved from the bottom of the root zone. The fate of N supplied with residues of N_2-fixing crop remains uncertain because organic N in the residue must first be mineralised to become available to subsequent crops. Mineralisation outside the growing season provides a substantial potential for N leaching. For unfertilised grassland, terminated in the spring and then seeded to spring barley, Eriksen et al. (2008) found an annual flow-weighted nitrate concentration of 36 mg N / l in drainage collected during the leaching period following the barley crop. Leaching of N from grazed grasslands can be substantial, in particular grass-clover swards subject to long grazing periods. Around year 1900, grasslands were amended with liquid manure in the early spring and after having delivered a first cut of hay, they were used for grazing until late autumn (Christensen, 1898). Urination by grazing animals creates locally high inputs of mobile N. For a four-year old grass-clover field, subject to grazing from late April to late October, Hansen et al. (2012) estimated that one-third of the area became affected by urination and that the N concentration in percolate from this area was 23 mg N / l. When first exposed to a grass cut in the spring and then subjected to grazing, the N concentration was 19 mg N / l.

A study of different organic farming practices was initiated in 1997 at three sites varying in climate and soil type (Jyndevad, sand; Foulum, loamy sand; Flakkebjerg, sandy loam; see Olesen et al., 2000). One four-year crop rotation included grass-clover ley, winter cereals, spring cereals and either a potato or a grain legume crop. Animal manure was applied at an average annual rate of 70 kg total-N / ha (Olesen et al., 2000). Nitrate leaching was measured using porous ceramic suction cups situated at the bottom of the root zone (Jyndevad, 60 cm; Foulum and Flakkebjerg, 100 cm; Askegaard et al., 2011). The average flow-weighted nitrate-N concentration of the leachates was remarkably constant across the different sites and the three rotation cycles in the period 1997 to 2008. The nitrate-N concentration averaged 11.7 mg N / l, with a variation from 7.4 to 14.9 mg N / l. Percolation was 637, 362 and 238 mm at Jyndevad, Foulum and Flakkebjerg, respectively, and considerable differences thus occurred between sites as to the amount of N lost by leaching.

Eriksen et al. (1999) provide results from an organically managed rotation addressing cattle production. The total nutrient addition in liquid and bedding-rich farmyard manure and from grazing cattle corresponded to 0.9 animal units / ha. The six-course rotation was spring barley undersown with grass-clover, two years with grass-clover, barley / pea, winter wheat and beetroots. The grass-clover was subject to one cut early in the growth period and then exposed to grazing. Except for the lack of bare fallow, the rotation and its management, including nutrient load, corresponded well with a year 1900 scenario. The average flow-weighed nitrate-N concentrations measured by ceramic cups extracting water leaving the root zone were 13 mg N / l for spring sown crops (barley undersown with grass-clover and barley / pea mixture), 18 mg N / l for winter wheat, 9 mg N / l for grass-clover (first- and second-year grass-clover) and 12 mg N / l for the root crop. These values are associated with DK-codes 1 to 4 and inserted in Table 5.4.

Table 5.4. DK-model codes merged from S codes: Land use, areas and nitrate-N concentrations in root zone percolates for each DK-model category. Area adjusted to the total area of parish maps around year 1900.

DK-Model	DK-Model: Land use and area				Nitrate-N concentration
Code	**Land use category**	**1,000 ha**	**%**	**S land use codes**	**mg N/l**
DK-1	Winter crops	357	8.3	1,2	18
DK-2	Spring crops	982	22.8	3,4,5,6,7,8,9,16,17	13
DK-3	Grass	1,538	35.7	10,15,19,20	9
DK-4	Roots	154	3.6	11,12,13,14	12
DK-5	Fallow	268	6.2	18	20
DK-6	Nature	588	13.7	21	1
DK-7	Forest	296	6.9	22	2
DK-8	Other land use	122	2.8	23,24,25,26	0
total		4,305	100.0		

Several studies show significant leaching losses of N from soil under bare fallow (DK-5). In a lysimeter experiment at Askov Experimental Station, the annual average N leaching over a four-year period corresponded to 104 kg N / ha for unmanured bare fallow (Thomsen et al., 1993). The average percolation during the experimental period was 504 mm / yr, and the concentration of nitrate in the leachate was 21 mg N / l. This is in accordance with measurements of N leaching in lysimeter experiments with undisturbed soil columns conducted in 1870 at Rothamsted Experimental Station. This experiment showed an average nitrate-N concentration of 19 mg N / l during the first seven years under permanent fallow (Addiscott, 1988). Therefore, the nitrate-N concentration was set to 20 mg / l for fallow (Table 5.4).

For non-forest areas with natural vegetation (DK-6), an N concentration of 1 mg N / l is applied as previously reported (see Jensen (ed.), 2017). This reflects the assumption that in areas without net gain in standing vegetation biomass and soil N storage, the leaching of N reflects deposition of N. The first systematic measurements of N in rainwater were made in the period 1921-1926 at Askov, Blangstedgaard (near Odense), Spangsbjerg (near Esbjerg) and Hornum research stations and showed an annual deposition of N in ammonium and nitrate of between 6 and 11 kg N / ha (Hansen, 1931). Measurements made in the period 1880-1885 at the Royal Veterinary and Agricultural University's experimental field near Copenhagen showed an average annual deposition of just under 14 kg N / ha (Tuxen, 1890).

For N lost from forest (DK-7), we rely on studies of differently sized forest areas (Callesen et al., 1999) and forest of different age (Hansen et al., 2007). The average concentration of N in soil solutions extracted from 75-100 cm soil depth in forests with an area of < 10 ha, 10-50 ha and > 50 ha were 3.0, 2.0 and 1.3 mg N / l, respectively. For coniferous stands younger than 45 years grown at a nutrient-poor location, the N concentration in 90 cm soil depth was typically between 0.5 and 1 mg N / l. The concentration in percolate from deciduous forests at a more nutrient-rich locality varied around 4 mg N / l, generally with the smallest values under younger stands. The concentrations of N increased with increasing stand age for coniferous as well deciduous stands residing on the more nutrient-rich soils. Based on this information, the value for forest was set to 2 mg / l (Table 5.4).

For the category other land use (DK-8), we do not estimate a concentration. Any losses of N related to this land use code categorise as loss from point sources.

Appendix 5.1 describes how the data on N in root zone percolates are used in the hydrological models.

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6 The National Nitrogen Model and other Nitrogen Sources

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Abstract

In this chapter, the NNM model structure is described as well as the modifications of the model that are performed to represent the year 1900 conditions. Further additional nitrogen sources, besides leaching from soils and point sources, are evaluated.

6.1 The national nitrogen model

The national nitrogen model (NNM) was developed in a collaboration between GEUS and the departments of Ecoscience and Agroecology at Aarhus University. The model development is described in detail in Højberg et al. (2015), while only a brief description is provided here. The model is constructed by coupling three existing modelling systems describing nitrogen transport and -reduction in the root zone; groundwater; and surface waters (Figure 6.1):

1. Root zone. N-leaching from the root zone is estimated by the NLES4 model for agricultural areas (Kristensen et al., 2008). For non-agricultural areas, land use specific values are used (Højberg et al., 2015). NLES is a statistical model developed on the basis of data from field trials where nitrate leaching has been measured one metre below the surface. Root zone leaching is calculated at the same 500 m grid used in the hydrological model (see chapter 3).

2. Groundwater. Flow and transport from the root zone to the surface water system is simulated by the DK-model (see chapter 3). The transport is simulated using the particle tracking approach. By this approach, particles are tracked through the groundwater system from the root zone until it is removed by a sink, such as streams, wells, drains or the sea.

3. Surface water. Statistical models are applied to describe retention and reduction of nitrate in streams, wetlands and lakes.

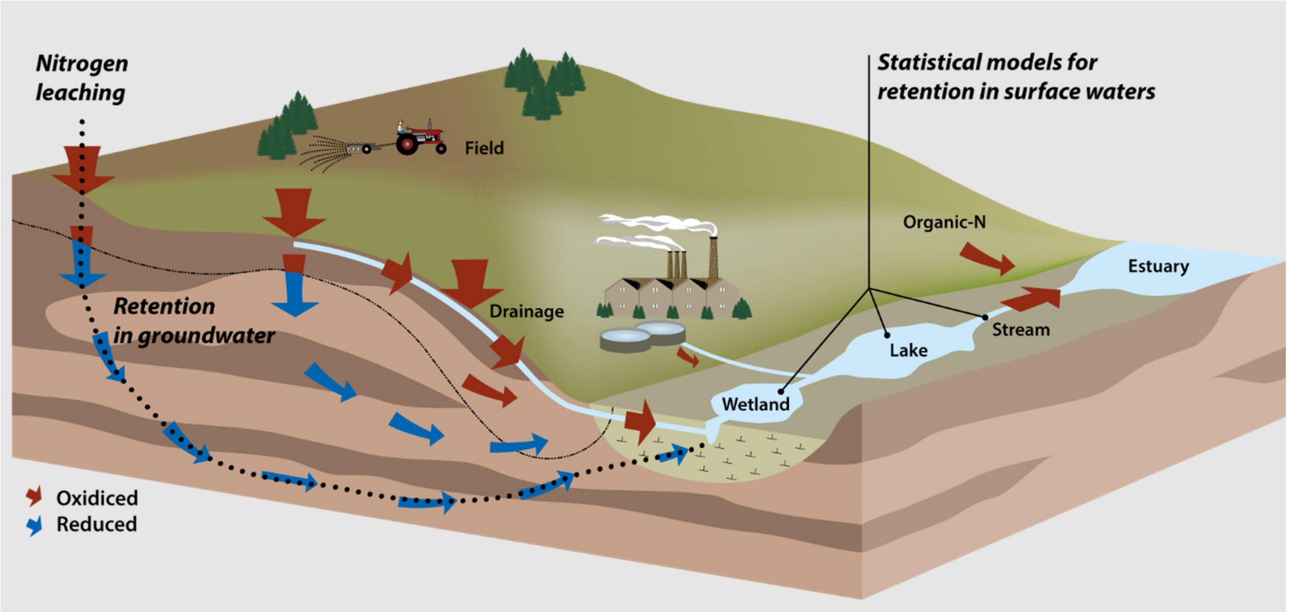


Figure 6.1. Sketch illustrating the model system combined in the national nitrogen model (NNM).

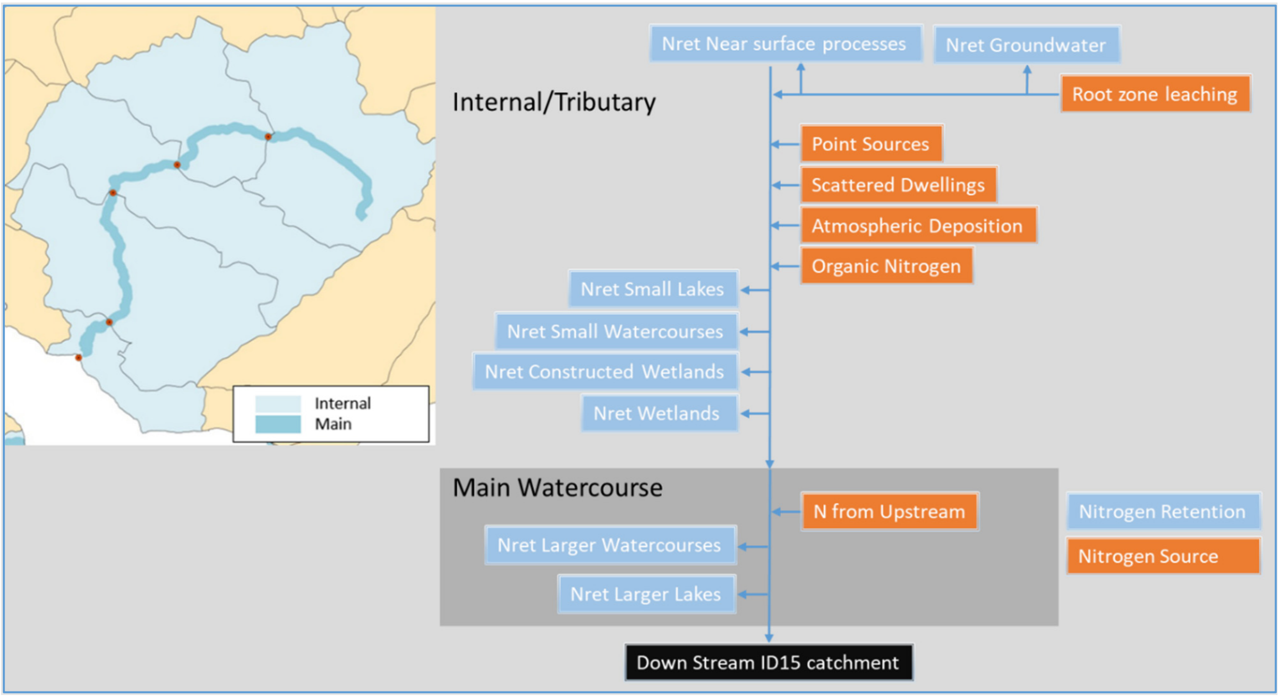


Figure 6.2. Schematic illustration of NNM. Orange is nitrogen sources. Blue is nitrogen sinks.

The conceptual structure of the NNM is illustrated in Figure 6.2. Transport and retention / removal of nitrate is calculated at sub-catchment scale (ID15 catchments) defined by topographic catchments with a mean area of approx. 15 km^2 (for ID15 map see Figure 6.5). Conceptually, each ID15 catchment is divided into two compartments: an "Internal" part and a "Main" part. The "Main" part accounts for processes in the main river reach that flows across the catchment (Figure 6.2, left-hand side), which is included in the hydrological model. The Internal part accounts for tributaries to the main river and associated surface water features. Within each ID15 catchment, a mass balance is calculated from the different nitrogen sources entering the catchment and sinks accounting for nitrogen retention. Diffuse ID15 nitrogen load is first added to the internal compartment, which also receives nitrogen from point sources, atmospheric deposition and organic nitrogen. The total nitrogen amount in the system is then subject to retention in accordance with the reductive capability of the internal surface water system. Excess nitrogen is routed to the Main part, which also receives nitrogen from upstream ID15 catchments, before reduction in the main river and associated larger lakes is accounted for (Figure 6.2). The order and content of the different steps in the model are:

1. Root zone leaching: The diffuse source of nitrogen leaching from the root zone, primarily in the form of nitrate
2. Reduction in groundwater: During transport in the subsurface, nitrate may be subject to removal, with reduction of nitrate to free nitrogen gas by denitrification being the most important process. The redox conditions of the subsurface in Denmark are generally characterised by an upper oxic part and a lower reduced part that is separated by a redox interface. Estimating the nitrate reduction in the subsurface is thus accomplished in the NNM by establishing whether particles are crossing the redox interface. Particles transported by tile drains will usually not have crossed the redox interface. Nitrate entering the lower reduced environment in the subsurface is thus assumed to be removed by denitrification.
3. Reduction in groundwater-surface water interactions (Nret Near surface processes in Figure 6.2): The nitrate reduction processes in the groundwater-surface water interface have not been included directly in the model but are accounted for by specifying reduction proportionally to the number of small streams / ditches, with a higher reduction potential in sandy areas. In the following, this part is called “the conceptual reducer” (e.g. Table 7.10).
4. Addition of other nitrogen sources: This accounts for point sources that are discharged directly to streams, atmospheric nitrogen deposition on lake surfaces and most importantly the organic nitrogen fraction originating from the landscape and aquatic environment.
5. Internal surface water retention in ID15: The internal retention is calculated based on the lengths and sizes of the tributaries as well as the number and area of small lakes and wetlands in the ID15 sub catchment. The actual retention is calculated in a lumped process, i.e. the sources in pt. 4 is added to the internal diffuse load (pt. 1 minus pt. 2 and pt. 3), after which the calculated internal retention is subtracted, considering that the nitrogen mass cannot be negative. The approach to calculate the internal reduction capacity is detailed in Højberg et al. (2015).
6. Addition of N from upstream: The main rivers receive nitrogen from the internal part of the ID15 catchment and from associated upstream ID15 catchments.
7. Retention in main rivers and lakes: This includes the retention in the main river and associated larger lakes.

For NNM results from the year 1900 period and the present period see Table 7.10.

6.1.1 Modifications of the national nitrogen model (NNM) to represent year 1900 conditions

The NNM was developed and calibrated to the present conditions (1990-2011) (Højberg et al., 2015). The present project has not included an update or recalibration of the model to new data, and the model structure and parameters have thus been reused from Højberg et al. (2015), with only a few modifications. These modifications are related to the representations of the small streams and the organic nitrogen model as described in section 6.4 and chapter 7. Furthermore, a new module to describe the effect of natural wetlands has been developed (chapter 7) and included in the NNM for both the present and the year 1900 period.

N leaching from the root zone

The nitrate leaching model NLES4 (Kristensen et al., 2008) has been used to estimate the present period nitrate leaching. The model was set up to reflect 2011 agricultural practices and was run with climate data from the period 1990 to 2011, i.e. using the same agricultural practice each year but with the actual climate. Afterwards, the model results were averaged across the period 1990-2011 to avoid the impact of year-to-year variations on the climate (Troldborg et al., 2016). Output from the model is a "climate-normalised" nitrate leaching in kg N / ha / yr. The yearly data have been disaggregated to monthly values, forming the temporal basis of the NNM, by calculating monthly nitrate leaching fractions based on daily nitrate leaching time series from 1990-2011 included in the original NNM (Højberg et al., 2015). This is done at the 500 m grid, geographical level.

NLES4 is a statistical model and can thus not be applied directly to estimate historical conditions. Instead, the year 1900 soil water concentrations estimated in chapter 5 have been multiplied with the net precipitation for year 1900 calculated by the national hydrological model, chapter 3. To similarly utilise the year-to-year climatic variation for the historical period, average monthly net precipitation was calculated during the period 1890-1910, prior to calculating the nitrate leaching in kg N / ha / month. The 1890-1910 net precipitation is calculated from the "delta change" 1990-2010 precipitation described in chapter 1.

In both periods, a climate-normalised monthly nitrate leaching has thus been used as input for the NNM, while transport in the subsurface reflects the actual climatic variability in the two periods.

Groundwater reduction

Reduction of groundwater is calculated by the same approach for the two periods, where particle tracking is used to describe the nitrate transport from the root zone to the surface water system, keeping track of particles crossing the redox interface. Particle tracking is based on groundwater flow calculations from 2000 to 2017 to represent the current climate, while flow calculations from 1890 to 1910 have been used for the historical period.

The reducing capacity of sediments is slowly consumed, resulting in a vertical movement of the redox interface. Observations of this movement have been reported by Postma et al. (1991), who found a vertical migration rate of 0.34 cm / yr in a sandy aquifer, while an even lower migration of 0.04cm / yr has been found in till areas (Robertson et al., 1996). In the 120 years since 1900, the redox interface can thus be expected to have moved vertically between 4 and 34 cm, which is much less than the accuracy by which the location of the redox interface can be determined for the present conditions. The same national map of the redox interface developed by Ernstsen and von Platen (2014) has thus been used in both periods. This map was also applied in the development of the nitrogen model.

6.2 Point sources

The point sources applied for the present period are the inland point sources presented in Miljøstyrelsen (2019). Point sources applied for the year 1900 period are described in detail in chapter 4.

6.3 Atmospheric nitrogen deposition year 1900

Atmospheric nitrogen deposition is a nitrogen input to lake surfaces in the NNM (Højberg et al., 2015; Jensen (ed.) 2017). Three different model estimates of the nitrogen deposition for year 1900 were examined in Jensen (ed.) (2017). The three modelling approaches gave nearly similar results and estimated that the nitrogen deposition in 1900 was about 30% of that in 2000. The nitrogen deposition applied for year 1900 in the NNM is based on the 28% of the EMEP depositions calculated for year 2000, which represents the present time. A deposition in the time around year 1900 of 28% of that in 2000 was estimated based on the difference found using the Danish Eulerian Hemispheric Model (DEHM) for freshwater surfaces. EMEP and the MATCH model show indexes close to 30% for the year 1900 when year 2000 =1 (Jensen (ed.), 2017).

For the present time, gridded deposition time series from EMEP were applied (Højberg et al., 2015).

Nitrogen deposition on land surfaces is included as part of soil leaching.

6.4 Organic nitrogen concentrations

The organic nitrogen (OrgN) fraction found in rivers consists of both particulate and dissolved organic nitrogen. It originates from both landscape sources and surface water sources, such as rivers and lakes. Landscape sources can be relatively fresh organic matter (e.g. fallen leaves and grasses) reaching the freshwater system from the surface. Older organic soil particles might reach the surface water through bank erosion, surface erosion or dissolved organic matter through tile drains or leaching. Sources within the freshwater system originate mainly from the primary production within lakes and rivers but depend to some degree on landscape sources of nitrogen, for example aquatic vegetation uptake of dissolved inorganic nitrogen originating from the landscape.

The organic nitrogen fraction found in rivers does not originate directly from the nitrogen applied to cropped fields and the leaching of this nitrogen. Therefore, the NNM needs a module specifying the amount of organic nitrogen from landscape sources transported in rivers.

The organic nitrogen (OrgN) model included in the original NNM was improved as a part of this study. As OrgN is not measured directly, monthly flow-weighted OrgN concentrations were calculated from measured values of total nitrogen (TN) and fractions of DIN as: TN – NH_x –NO_x = OrgN (Figure 6.3). Monitoring stations with at least 96 monthly (eight years) loads from the period 1990-2017 were used. Monitoring stations downstream larger lakes influencing the OrgN concentration were excluded. For areas upstream monitoring stations (for river catchments with more than one monitoring station, only the most downstream station was used) the average monthly flow-weighted OrgN concentration at the monitoring station was used in the NNM.

For ungauged areas (ID15 catchments see section 7.1), monthly flow-weighted averages of monitoring station concentrations in 12 regions were used (Figure 6.3) for OrgN concentrations, see Figure 6.5.

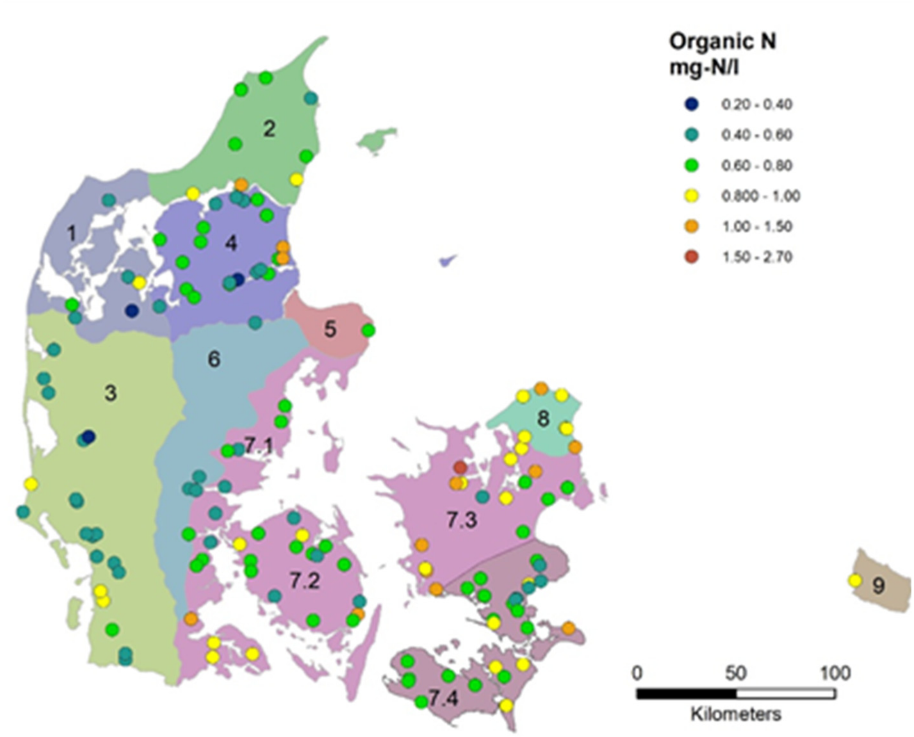
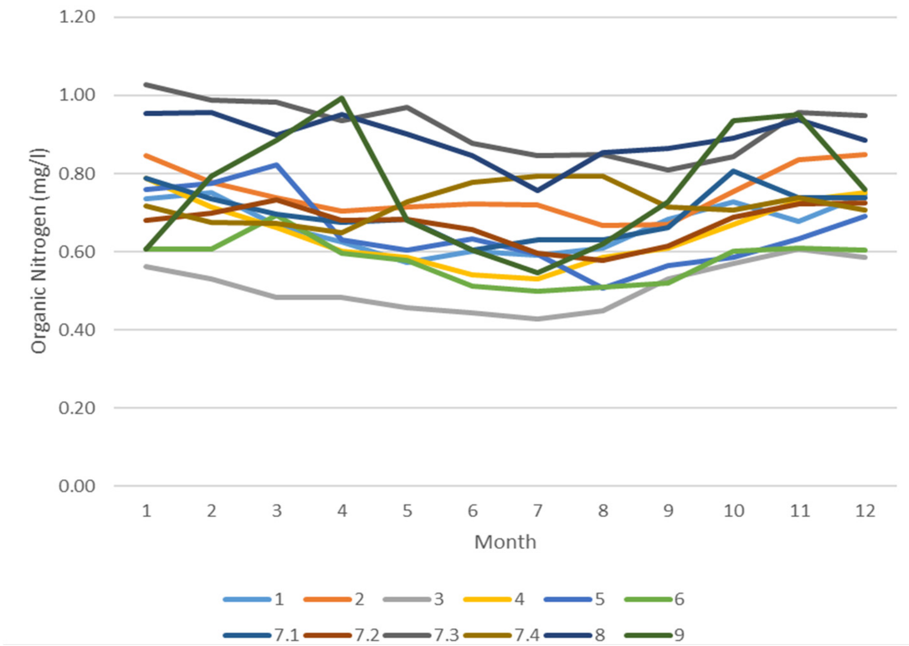


Figure 6.3. 12 regions (original region 7 is split into four subregions). Dots are monitoring stations with mean organic nitrogen concentrations.

After these concentrations were calculated and applied in the NMN model, it was established that OrgN concentrations for the period 2011-2015 and for some stations also for 2009-2010 were underestimated due to the application of an erroneous laboratory analysis method. Therefore, the presented OrgN concentrations are somewhat underestimated (Larsen et al., 2021a, 2021b). It was beyond the scope of this project to rerun the entire NNM with recalculated OrgN concentrations.

The regional average monthly flow-weighted OrgN concentrations used for the present period are shown in Figure 6.4. Some geographical differences were found, for example between the low OrgN concentrations in western Jutland (region 3) and the high concentrations in central and northern Zealand (region 7.3 and 8).

Figure 6.4 Average monthly OrgN concentrations (1990-2017) in 12 regions (original region 7 is split into four subregions, see Figure 6.3).



ID15-specific mean annual OrgN concentrations used in the NNM for the present period are shown in Figure 6.5.

For the period around the year 1900, a few studies estimate the OrgN concentrations and compare the results with modern values. Goolsby and Battaglin (2001) found that total OrgN concentrations in the lower Illinois River were 21% lower during the period 1897-1902 than between 1980-1998. They found that the difference was 15% for the Upper Mississippi River (US) near Grafton (below Illinois R. and above Missouri R.) between the periods 1899-1900 and 1980-1998. For the lower Missouri river (US), OrgN concentrations fell from 1.8 mg/l in 1899-1900 to 1.1 mg/l in 1979-1981 and 1995-2007, this reduction is, though, primarily due to impoundment of the river (Blevins et al., 2014). Green et al. (2004) estimated that in the temperate climate zone (global scale), the OrgN concentrations in pre-industrial times were half of those of the 1990s. However, in a Danish context, the period around year 1900 cannot be perceived as pre-industrial, and the change is, therefore, likely smaller. Based on these earlier studies and the Danish context, a 20% OrgN concentration reduction around the year 1900 period compared with the present period is assumed.

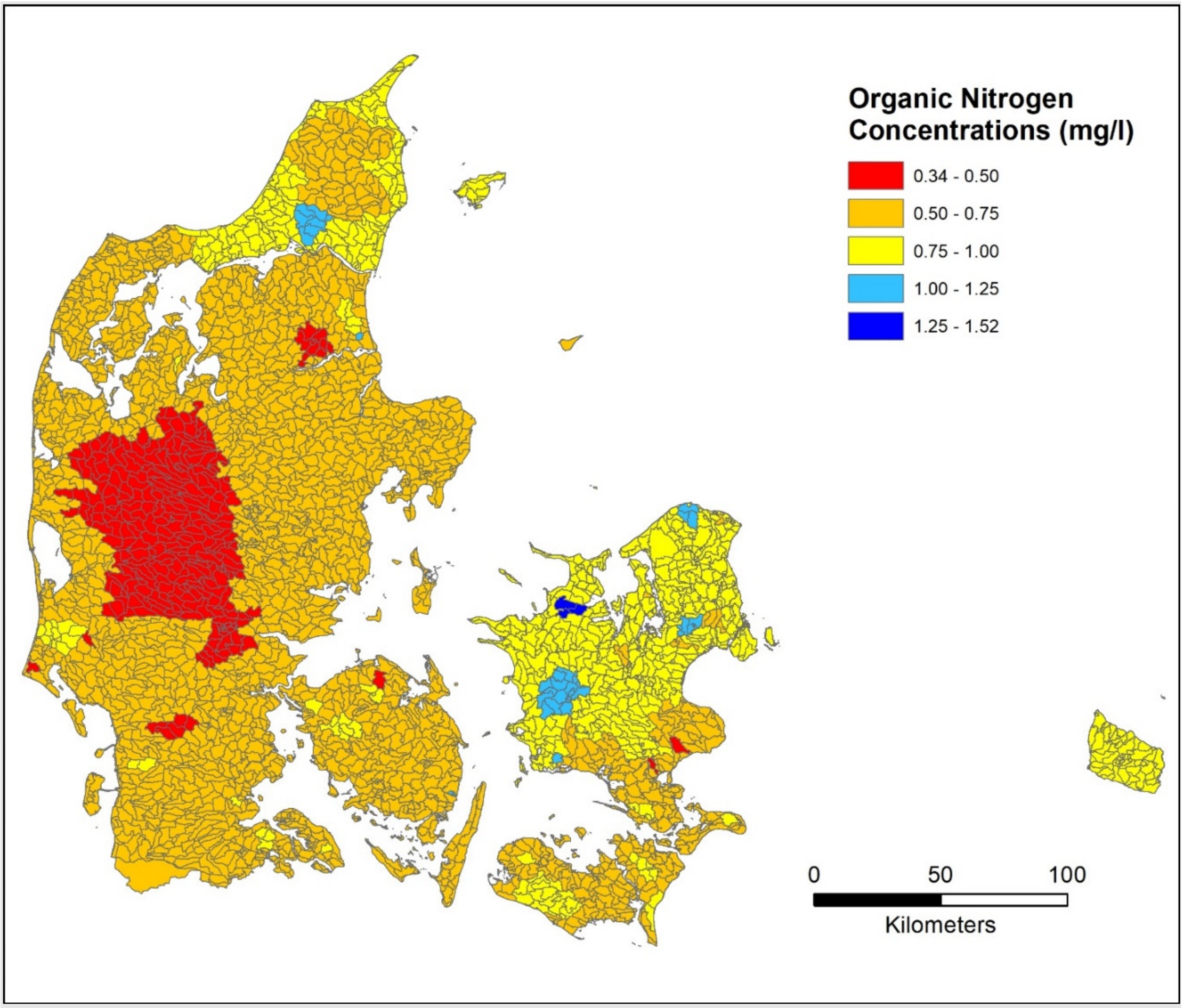


Figure 6.5. Areas (ID15 catchments) with similar mean annual OrgN concentrations (present period).

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7 Modelling nitrogen retention in surface waters

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Abstract

Purpose: The purpose of this chapter is to analyse the difference in landscape nitrogen (N) retention between the current period and the period around the year 1900. This was done by analysing the major elements of N retention during both periods.

Materials and methods: The National Nitrogen model (NNM) is used for calculating N retention (Nret) in surface freshwater (Højberg et al., 2015a; Højberg et al., 2020). The NNM has routines calculating Nret in wetlands, constructed wetlands, small watercourses (streams and ditches), small lakes, larger watercourses and larger lakes. For a more detailed description of how historic climate / weather data is used see chapter 1, 2 and 3. As for climate, the present period is represented by the period 1990-2010.

For all surface water environments, except wetlands, a present period map is used as the basis to derive the year 1900 period conditions. For example, the 20% increased length of year 1900 larger rivers is distributed through manipulating the length of each present period river stretch. For wetlands, the parish land use survey from 1896 / 1900 (see section 5.1) was used for the time around year 1900, and a land use map from 2016 was used for the present period (Levin et al., 2017).

As there has been some development in the numbers, functions and areas of aquatic environments during the two periods, for example due to restoration or drainage of larger lakes during the period around year 1900 to 2017, a standard year was chosen for both periods. The year 1900 was chosen for the year 1900 period and 2017 for the present period. Thus, a lake restored in, for example, 2008 and present in 2017 is included in the model for the entire present period. This approach was chosen to make the year 1900 period estimates as comparable to the present as possible.

Results and discussion: Mean monthly nitrogen retentions were calculated for each aquatic environment at the ID15 geographical level for each of the two periods. On this basis, mean annual absolute and percentage changes between the present period and the period around year 1900 were calculated.

Conclusions: The absolute Nret amount was shown to be higher in the present period (28,000 ton N) than around the year 1900 period (26,000 ton N) due to a larger load. However, the relative Nret was larger during the year 1900 period, where 43% of the load to freshwater was estimated to be removed compared with 33% for the present period.

7.1 Introduction

The aim is to calculate mean monthly Nret for all environments represented in the NNM for the period around year 1900 and the present period and to present the differences between the two periods.

7.2 Materials and methods

NNM includes a surface water nitrogen retention (Nret) part consisting of six separate modules describing Nret in six different aquatic environments. The modules are divided into two groups, one (Internal/Tributary) handling small-scale retention at tributary level and one (Main Watercourses) handling Nret at the larger main river level (Figure 7.1). The Internal Nret group handles Nret in streams, small lakes, constructed wetlands and natural wetlands. The larger-scale group handles Nret in rivers and larger lakes and receives water and nitrogen from upstream sub-catchments. Compared with other North European countries, there is little modern hydropower in Denmark and rivers are almost not used for navigation, and hence there are no inland canals for navigational use. Therefore, almost no flow-regulating structures are needed for these activities. Most weirs are historical relics from closed old water mills, and mill ponds were generally small with a short water residence time. The Danish database for river restoration activities lists “replacing old weirs with riffles” as a clear no. 1 activity during the 1980s and 1990s, and as a result the number of mill ponds has decreased since 1900 (Iversen and Andersen, 1997). The effect of this process on nitrogen retention is thought to be small but almost certainly would have meant a slightly higher retention rate in year 1900 (see Jensen (ed.) (2017) for more information).

All modules can be altered to represent year 1900 conditions.

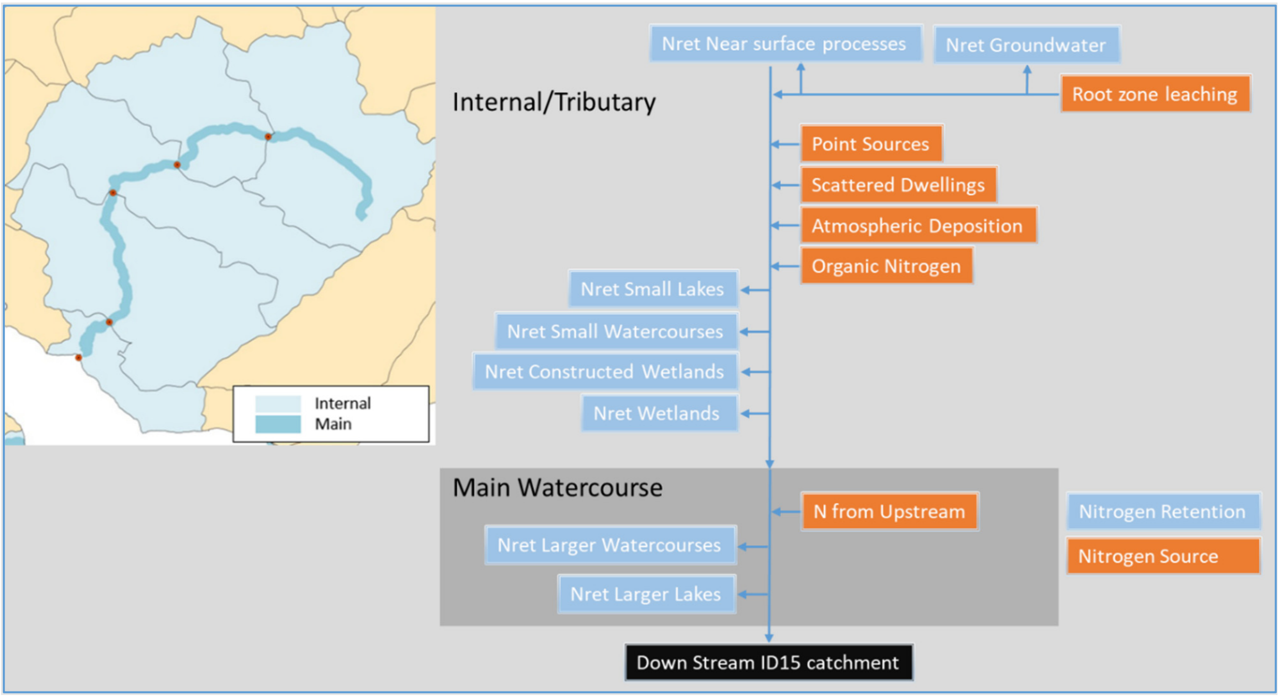


Figure 7.1. Schematic flow diagram of the National Nitrogen Model, N source (orange) and N retention (blue).

Because of the methodology applied in assessing the load to the sea in year 1900 (see chapter 8), neither the total mass balance nor the change in nitrogen retention in each environment presented in this chapter is completely comparable to the calculated load for year 1900 (chapter 8). However, the changes in nitrogen retention in each environment are described below to provide some indication of the changes between year 1900 and the present.

7.3 Nitrogen retention in natural wetlands

Nitrogen retention in natural (non-constructed) wetlands was not included in the original NNM (Højberg et al., 2015a). A new model was developed and included in the NNM, calculating Nret for each ID15 with a wetland area. Wetland Nret is calculated based on the internal load generated in each separate ID15, which consequently does not receive any load from upstream ID15 catchments. This will be the case for most wetlands.

The wetland retention model depends on the wetland area of each ID15 catchment and a monthly outflow concentration from the wetland. The load to the wetland is an area-weighted fraction of the load generated within the ID15. Through a national scale calibration procedure, the wetland area multiplied by 3 is estimated as the source area to the wetland. The wetland source area cannot be larger than 75% of the ID15 area.

Wetland source area load = ID15 load × (wetland area x 3) / ID15 area)

Wetland outflow load = wetland outflow N concentration x wetland source area (+wetland area) runoff.

Wetland retention = Wetland source area load - Wetland outflow load (if Wetland outflow load > Wetland source area load then is set to Wetland outflow load = Wetland source area load).

The monthly wetland outflow N concentrations were calculated based on measurements from three natural wetlands in Denmark – one in East and two in West Denmark. From these measurements, two sets of wetland outflow concentrations were generated (Table 7.1), where one set was applied to wetlands in western Denmark and the other to wetlands in eastern Denmark. It is assumed that the two sets of outflow concentrations are more suitable for East and West Denmark than an average would be for the entire country. The same monthly outflow concentrations are used for year 1900 and the present period, respectively.

The wetland data from eastern Denmark originate from a riparian wetland along River Stevns. The land use in the upland catchment to this wetland is dominated by agriculture. Nitrogen discharge data were generated from three outflow stations situated approximately 2 m from the river. The data include concentrations measured at several depths below terrain (15-600 cm).

The wetland data from western Denmark originate from two riparian wetlands that are both situated along River Gjern. The land use in the upland catchments to the riparian wetlands was dominated by agriculture. Data were generated based on several outflow stations and included nitrogen concentrations from several depths (0-500 cm) (Hoffmann et al., 1993; Hoffmann, 1998; Hoffmann et al., 2000).

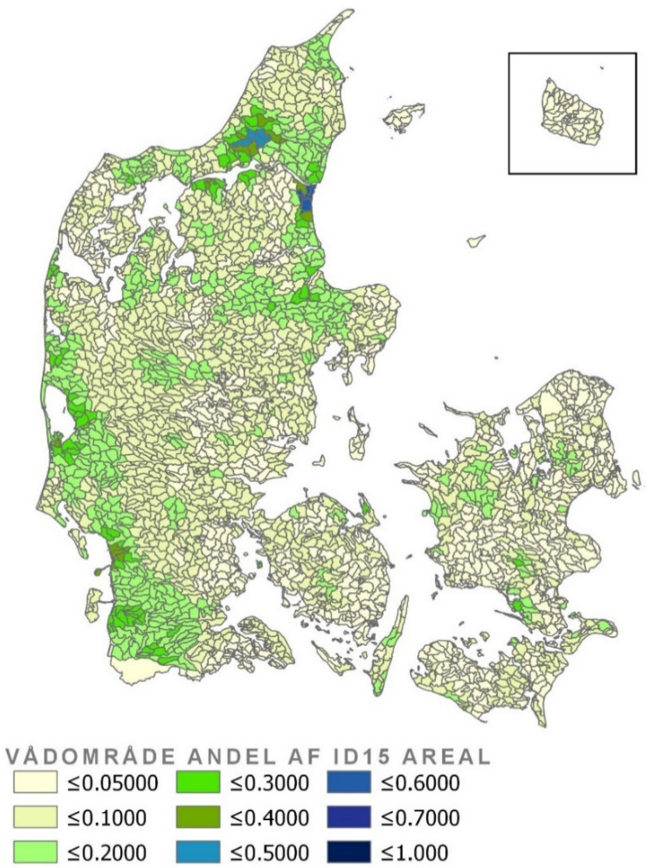
Wetland areas for each ID15 catchment from both the period around year 1900 and the present period were applied in the NNM.

Table 7.1. Wetland outflow total nitrogen concentrations. Based on (Hoffmann et at. 1993, Hoffmann 1998, Hoffmannet al. 2000).

Month	Eastern Denmark (mg/l)	Western Denmark (mg/l)
January	0.75	1.64
February	0.60	1.59
March	0.48	1.17
April	0.99	1.29
May	1.55	1.48
June	1.46	0.97
July	1.92	0.61
August	2.47	0.58
September	1.72	0.72
October	0.99	0.99
November	0.73	0.81
December	0.76	0.93

Data on wetland areas for 1896 / 1900 were collected from the land use assessment made for each parish (n = 1766) and are the same data used in the assessment of crop distributions (section 5.2.4). The land use categories used in estimating the wetland area were meadow and peat bog. Comparable statistical land use assessments were found for the southern part of Jutland that in 1900 was part of Germany where the category meadow was used (section 5.2.4). The national wetland area for 1896 / 1900 (used unaltered as wetland area in 1900) is reported to be 3,483 km^2. The parish land use survey is a statistical survey and not a map survey; hence, the location of each wetland within a parish is not known. Therefore, the wetlands were treated as being equally distributed within each parish and transferred to ID15 catchments with a parish-specific area weight. The spatial distribution is seen in Figure 7.2.

Figure 7.2. Fraction of wetland area in each ID15 catchment year 1900.



For the present period, the 2016 Basemap (Levin et al., 2017) was applied using the category "Nature open wet" (grid code 802). The total wetland area is 1,132 km². Thus, the wetland area today is estimated to be 67% smaller than that around year 1900. ID15 catchment wetland areas are calculated directly by overlaying with the Basemap. The spatial distribution is shown in Figure 7.3.

Figure 7.3. Fraction of wetland area in each ID15 catchment year 2016.

The methods for estimating ID15 wetland areas are not the same as there is no digitised map from year 1900. This introduces small differences in the Nret estimations between the two periods.

Table 7.2 Nitrogen retention and change in national wetlands between the present and year 1900.

Period	Wetlands nitrogen retention (ton/yr)	Change in wetlands nitrogen retention – from 1900 to present % – (from present to 1900 %)
Year 1900	8,100	
Present	3,300	-60 (147)

As shown in Table 7.2, the area-specific retention is about 29 kg N / ha in the present period and 23 kg N / ha around year 1900.

Nitrogen retention is modelled to have been 147% larger around the year 1900 than at present. This is due to the substantially larger area of wetlands around at that time, which was approximately three times larger than at present. The fact that the present increased nitrogen load to the remaining wetlands also increases the retention in these cannot counterbalance the loss in wetland area from year 1900 to the present.

7.4 Nitrogen retention in constructed wetlands

Constructed wetlands, aiming at maximising nitrogen retention, is a recent invention and was not in use around year 1900. Therefore, this module is turned off for this period and only active for the present period. For the present period, the NNM was updated with new wetlands constructed no later than 2017.

The Nret model for constructed wetlands is based on measurements from a 0.8 ha constructed wetland monitored between 1990 and 2005 (Fuglsang, 2006; Hoffmann et al., 2006). The Nret model has a summer (May - October) and a winter (November – April) stage as monitoring data show higher area-specific Nret rates during summer than during winter. Hoffmann et al. (2006) found lower area Nret rates for constructed wetlands in sandy areas (120 kg N / ha / yr. than in loamy / clayey areas (190 kg N / ha / yr). Therefore, there are separate versions for both soil types. However, the area-specific retention is markedly higher for constructed than for natural wetlands, which was calculated to 29 kg N / ha in the present (section 7.3). The constructed wetland Nret models are simple power functions yielding monthly area-specific Nret rates (kg N / ha / month) as a function of wetland runoff (mm / month). As constructed wetlands need to meet minimum estimated Nret rates (kg N / ha) to receive subsidies for construction, the load to the constructed wetland must be large enough to ensure such Nret rates. Therefore, there is a fairly constant ratio between the area of the constructed wetland and the upstream source area. In this way the runoff entering the constructed wetland can be estimated knowing the size of the constructed wetland (Højberg et al., 2015b). Modelled nitrogen retention in constructed wetlands is given in Table 7.3.

Table 7.3. Nitrogen retention in constructed wetlands.

-	Nitrogen retention in constructed wetlands (ton/yr)
Year 1900	0
Present	265

The location of constructed wetlands is depicted in Figure 7.4.

After the modelling process was completed, a modelling mistake was discovered. The constructed wetland area used for the present period should have been that of 2017. Instead, the actual area of constructed wetlands of each year between 1990 and 2010 was used, thereby including too few constructed wetlands for too short a period, leading to underestimated retention. On the other hand, during the latest work with the NNM (Højberg et al., 2021), it was discovered that the maps representing the constructed wetlands included the whole project area and not only the constructed wetlands area. Besides this, the project area often included areas with natural wetlands and lakes that are also included in other modules of the NNM. This led to an overestimation of the retention. In Højberg et al. (2021), the average N retention between 1990 and 2010 is reported to be about 100 ton N / yr (0.1×10^3 ton N / yr), which is lower than it would be for 2017. Therefore, and because the retention in constructed wetlands is of minor importance in all cases, it was decided to keep 265 ton N / yr as the retention in constructed wetlands.

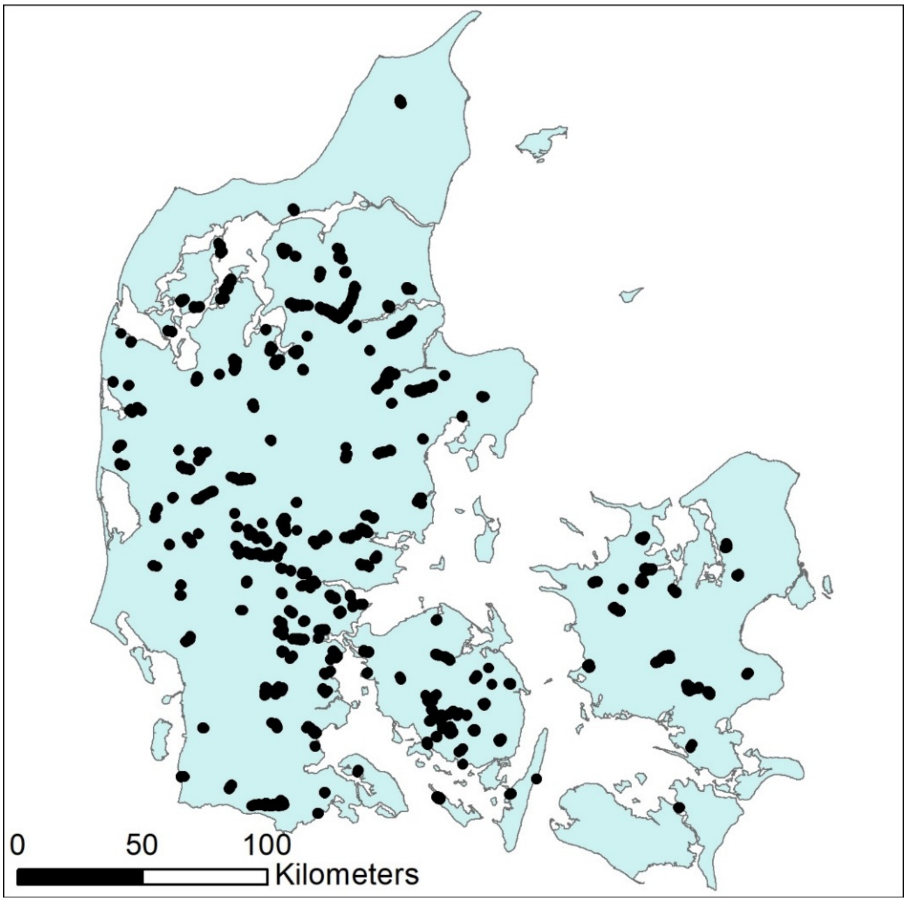


Figure 7.4. Location of constructed wetlands (sizes are exaggerated for the sake of visibility).

7.5 Nitrogen retention in small watercourses

For calculating Nret in both small and larger watercourses, a residence time approach suggested by Seitzinger et al. (2002) is applied in the NNM (see section 7.2). To represent both summer and winter conditions (in-stream vegetation growing and non-vegetation seasons) and different watercourse size categories, seasonally different depths and flow velocities are applied. Besides this, a scaling factor considering that a drop of water will not run through the entire lengths of all watercourses (all tributaries) in a subbasin is introduced. The scaling factor is calculated based on ID15 catchment watercourse density (km / km^2) (Højberg et al., 2015b).

In Jensen (ed.) (2017), the total length of small watercourses (<2.5 m width), (streams / ditches) was estimated to have been 20% longer for the year 1900 period. This was mainly due to the existence of more open ditches that were later converted into tile drains or irrigation canals, which are not in use in the present period, and because many small watercourses have been straightened, from a natural meandering to a straight planform, since 1900. However, the process of straightening small watercourses is believed to have started before 1900 but continuing well into the 20th century. This increases the total length from 46,610 km at present to 55,930 km in year 1900. The national watercourse GIS layer used in the original NNM was cleaned for watercourses located in marine areas and other errors (Højberg et al., 2015a). Besides this, in earlier work with the NNM some forested areas were observed to have a very high density of streams that in reality were dry most of the year, thus creating unrealistically high retention values. Therefore, small watercourses in forest areas were omitted from the analysis.

Table 7.4. National small watercourse nitrogen retention and change between the present and year 1900.

Period	Small watercourse nitrogen retention (ton/yr)	Change in small watercourse nitrogen retention – from 1900 to present % – (from present to 1900 %)
Year 1900	7,500	
Present	10,400	39 (-28)

Nitrogen retention in smaller watercourses is shown to have been about 28% lower in the year 1900 period than at present. This is due to the lower load but despite the estimated 20% longer small watercourses around year 1900. The longer watercourses will have longer residence times, yielding higher nitrogen retention percentages.

7.6 Nitrogen retention in larger watercourses

For a description of the modelling approach see section 7.2 and Højberg et al. (2015a,b).

In Jensen (ed.) 2017, the total length of larger watercourses (>2.5 m width) was estimated to have been 20% longer for the year 1900 period. This was mainly because many larger watercourses have been straightened from a natural meandering to a straight planform since 1900. Because of the straightening, larger watercourses are more technologically demanding and have benefitted more from the invention of heavy earth moving machinery than small straightened streams. The straightening process took place later for large than for small streams. The process of straightening meandering watercourses accounts for the entire 20% decrease in the length of large watercourses, increasing total length from 12,480 km at present to 14,970 km in year 1900.

Table 7.5. National large watercourse nitrogen retention and change between the present and year 1900.

Period	Larger watercourse nitrogen retention (ton/yr)	Change in larger watercourse nitrogen retention – from 1900 to present % – (from present to 1900 %)
Year 1900	2,700	
Present	4,400	61 (-38)

Nitrogen retention is modelled to have been 38% lower around year 1900 than at present (Table 7.5). This is due to the higher load in the present period (which results in higher retention) and despite the shorter length and shorter residence time of the larger watercourses in the present period (which results in lower retention).

7.7 Nitrogen retention in small lakes

Small lakes are defined as smaller lakes with an outflow. Smaller lakes are assumed located on tributaries and not receiving water or nitrogen from upstream ID15 catchments. As small lakes are located inside the ID15 catchments and as there often is >1 small lake in an ID15, the specific load of water and nitrogen to each of these lakes is unknown (un-modelled), as is the catchment area of each small lake. The mean water depth is also unknown. Therefore, the retention in the >27,000 small lakes (Højberg et al., 2015b) cannot be estimated using a water residence time approach as for larger lakes (section 7.8), and which is often recommended as the best approach by, for instance, Saunders and Kalff (2001).

Nitrogen retention in small lakes is believed to have been different (in amount) around year 1900 than during the present period due to two factors. The first factor is that many small lakes and ponds have been filled or drained, and the total area is thus smaller today. The same estimation as that used by Jensen (ed.) (2017) is applied, increasing the national area of small lakes by 100% for year 1900 (170 km^2) compared with the present area (85 km^2). The second factor is that the nitrogen load to small lakes would also have been different. The load estimate (for description see Højberg et al., 2015a, b) is changed with the same proportion as the total N leaching at the national scale, which is modelled to have been 13% lower in the year 1900 period than in the present period (see Table 7.10). Assuming that Nret follows the load to small lakes, the area retention rates decrease by 13% for the year 1900 period as well (Table 7.6).

Nitrogen retention values in Table 7.6 are derived from mass balances for 13 Danish lakes, with an average Nret of 320 kg / ha (lake surface area) per year. Soil type and land use are calculated from a buffer around each lake, with an area 5-10 times the lake area (Højberg et al. 2015b).

Table 7.6. Small lake nitrogen retention rates (kg/ha lake surface area) used for the year 1900 and the present period.

Soil type	Land use (present)	1900 nitrogen retention rate kg/ha	Present nitrogen retention rate kg/ha
Clay	>60% agriculture	348	400
Clay	30-60% agriculture	148	170
Clay	<30% agriculture	70	80
Sand	>60% agriculture	261	300
Sand	30-60% agriculture	109	125
Sand	<30% agriculture	52	60

Table 7.7. National small lake nitrogen retention and change between the present and year 1900.

Period	Small lakes nitrogen retention (ton/yr)	Change in small lakes nitrogen retention – from 1900 to present % – (from present to 1900 %)
Year 1900	2400	
Present	1500	-36 (56)

The nitrogen retention in small lakes is shown to have been 56% larger around year 1900 than at present. This is due to the larger area of the lakes (estimated to be 100% larger than at present) during the earlier period. The retention in year 1900 is larger despite a smaller load to the lakes in this period compared with the present.

7.8 Nitrogen retention in larger lakes

Larger lakes are defined in the same way as in the NNM (Højberg et al., 2015b; Windolf et al., 1996)). The model used to calculate Nret in larger lakes is the same as in the original NNM. All lakes are connected to the river network and have an outflow. Monthly lake nitrogen retention is simulated by adding water and nitrogen load to each lake at each time step (month) and multiplying this by a dynamic monthly retention factor (Eq.1 and Eq.2).

$$Eq1 \quad N_{lake(t+1)} = (1 - FN_{ret}) \times \left(N_{lake(t)} + N_{load(t)}\right) / \left(lake\ volume + Q_{load(t)}\right)$$

$N_{lake(t+1)}$ is lake N concentration in month t+1.
FN_{ret} is the relative monthly N retention in month t.
$N_{lake(t)}$ is lake N concentration in month t.
$N_{load(t)}$ is the N load to a lake in month t.
$Q_{load(t)}$ is the water load to a lake in month t.

FN is calculated either by Eq2 or Eq3 depending on residence times (T_w) < 1 year (Eq2) and one for T_w > 1 year (Eq3). Eq2 from Windolf et al. (1996).

$$Eq2 \qquad FN_{ret} = \alpha \times \theta^{T-20}$$

α is 0.455 (± 0.074 C.L.).
θ is 1.087 (± 0.014 C.L.).

T is monthly average water temperature (°C) for Danish lakes calculated from mean monthly air temperature (T_{air_t}) in the current month and the previous month (T_{air_t-1}), C.L. is confidence limits.

$T = 1.517 + 0.3034 \times (T_{air\_t}) + 0.1909 \times (T_{air\_t-1}) + 0.6347 \times (T_{air\_t}) \times \mathrm{Sin}\ (\pi \times \mathrm{month}(1\text{-}12)\ /\ 13)$

$$Eq3 \qquad FN_{ret} = 0.01 \times \left(K \times M_{05} - T_{air\_t}\right)$$

K is 6.117
M_{05} is a month-specific value (Jan=1, Feb=2…Dec=1) (1,2,3,4,5,6,6,5,4,3,2,1)

This model will automatically respond to changed flows, nitrogen loads and air temperature.

In the period from 1900 to the present, lakes have been drained, and new lakes have been created. Some have even been both drained and restored during this period. A full overview of which lakes have disappeared or been created does not exist; nor are GIS layers available showing the surface areas of many of these lakes. The NNM includes a functionality applying starting and end years of the Nret calculation. For lakes with known (by the authors) history, this information is included. Thus, lakes known to exist only in the year 1900 or at present (2017) are only included during this period. All other lakes are included for both periods. The bulk of the lake draining in Denmark happened before 1900 (Figure 7.5). More than 2,700 ha of lakes have been restored since 1990 (Thodsen, unpublished data). Therefore, the lake area is larger in the present period than it was around year 1900. In total 569 lakes (366 km²) are included for the year 1900 and 611 (422 km²) for 2017 (present).

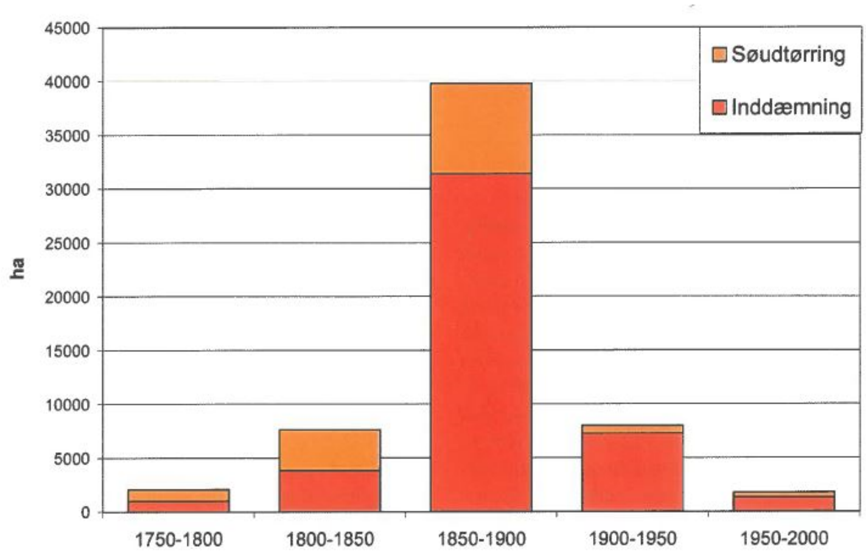


Figure 7.5. Lake area drained (Søudtørring) and reclaimed marine area (inddæmning) in Denmark during different eras (Hofmeister ed., 2004).

Table 7.8. National large lake nitrogen retention and change between the present and year 1900**.**

Period	Larger lakes nitrogen retention (ton/yr)	Change in larger lakes nitrogen retention – from 1900 to present % – (from present to 1900 %)
Year 1900	5,000	
Present	8,200	64 (-39)

Nitrogen retention in larger lakes is modelled to have been about 39% smaller in year 1900 compared with the present period (64% larger in the present compared with year 1900). This is primarily due to an increase in the nitrogen load to the lakes and, to a lesser extent, due to a slight increase in the number and surface area of lakes because of lake (re)construction in the later part of the period since 1900. Because of the generally lower runoff in the year 1900 period and consequently larger lake water retention time, the N retention percent is calculated to have been higher (Eq.1-3).

7.9 Total surface water nitrogen retention around year 1900 compared with the present period

The total amount of surface water nitrogen retention around year 1900 and the present period is calculated in ton per year (Table 7.9). The total surface water retention have been 8% lower around year 1900 than for the present period. This is because of a higher load of nitrogen in the present period compared with the time around year 1900, which means that the absolute amount of nitrogen removed is higher in the present period.

Table 7.9. Estimated (NNM) changes in national surface water nitrogen retention between year 1900 and the present period.

Period	Surface water nitrogen retention (ton/yr)	Change in surface water nitrogen retention – from 1900 to present % – (from present to 1900 %)
Year 1900	26,000	
Present	28,000	9 (-8)

However, when calculating the relative (percent) nitrogen retention of the load entering streams and rivers around the year 1900, 43% is removed in the surface water system compared with 33% in the present period.

7.10 National Nitrogen Model – nitrogen mass balance

NNM nitrogen balances for the present period and the period around 1900 were calculated. This was done to ensure that the balance is closed and to provide an overview of the size of each source and sink (Table 7.10). The N balance is calculated at national scale. The overall nitrogen mass balances of the two NNMs are shown to be very close to zero (Table 7.10 – bottom row), meaning that all nitrogen is routed through the models. The only parts of the NNM storing nitrogen between time steps are the groundwater routing module and the larger lakes module.

It is important to notice that the loads to the sea given in Table 7.10 are not directly comparable to the real loads given in chapter 8 (see section 7.2 for detailed explanation).

The national root zone leaching is found to be 15% higher in the present period than around year 1900 (Table 7.10). The total national land-based nitrogen sources, of which the root zone leaching is by far the largest source, are found to be 18% higher in the present period than during the year 1900 period (Table 7.10). The groundwater retention is modelled to be only 3% larger in the present period despite a 15% larger root zone leaching, resulting in a lower groundwater retention percentage of 58% compared with 64% around year 1900. This is primarily due to the smaller tile-drained area and the lower precipitation in 1900. Both circumstances promote a larger fraction of the rainfall recharging to the groundwater and thereby higher groundwater nitrogen retention. For surface water retention, the largest sink around year 1900 is modelled to be natural wetlands, but due to a large reduction in the wetland area the largest retention in the present period is modelled to be that in smaller watercourses. The total surface water retention is 4% higher in the present period than around 1900, mainly because of the larger load. However, the total source to surface waters is modelled to be 41% higher, resulting in a larger surface water retention percentage around year 1900, 43%, compared with 33% in the present period. The land-based nitrogen load to the sea is modelled to be 65% larger in the present period than around 1900, corresponding to an about 22,000 ton N increase (Table 7.10). The larger load in the present period is caused partly by an 18% larger total source and a lower retention percentage in both groundwater and surface waters, however.

The year 1900 point sources are in Table 7.10 shown to be 679 ton N / yr. In chapter 4, the inland point sources from towns with >5,000 inhabitants are given as 407 ton N / yr. The difference originates from additional point sources estimated for smaller towns.

Table 7.10. National Nitrogen Model, nitrogen balance for the present and the year 1900. The nitrogen amount removed through the conceptual reducer has added to the groundwater retention component (for "conceptual reducer" see, Højberg et al. (2015a,b) and section 6.1)). The presented model output values are rounded to the nearest ton of nitrogen to show the model nitrogen balance. However, the uncertainty of the individual values is much larger than this.

Source/sinks	Present period ton N/yr	1900 period ton N/yr	Percent change – from 1900 to present – (from present to 1900)
Source			
Root zone leaching	167,702	146,432	15% (-13%)
Groundwater & tile drains	70,707	52,275	35% (-26%)
Point source	3,607	679	431% (-81%)
(Not including point source loads directly to the sea)			
Organic nitrogen	9,559	6,555	46% (-31%)
Atmospheric deposition (deposition on lake surfaces)	527	251	110% (-52%)
Total sources	181,395	153,917	18% (-15%)
Total sources to surface waters	84,440	59,760	41% (-29%)
Sinks/Retention			
Groundwater	96,995	94,157	3% (-3%)
Groundwater Nret %	58%*	64%*	
Smaller lakes	1,527	2,376	-36% (56%)
Smaller watercourses	10,441	7,523	39% (-28%)
Constructed wetlands	265	0	-
Natural wetlands	3,268	8,087	-60% (147%)
Larger watercourses	4,382	2,715	61% (-38%)
Larger lakes	8,201	5,013	64% (-39%)
Total surface water sinks	28,084	25,712	9% (-8%)
Total sinks	125,079	119,869	4% (-4%)
Surface water Nret %	33%**	43%**	
Total Nret %	69%	78%	
Load to the sea			
Sources – sinks	56,316	34,048	65% (-40%)
Modelled load to the sea	56,283	34,026	65% (-40%)
N balance error			
Ton nitrogen	33	22	
% of load to the sea	0.06%***	0.07%***	

* Nret groundwater % is percent of leaching removed by retention in groundwater.
** Total surface water Nret % is percent total surface water N source removed as total surface water N retention.
*** N balance error percentage of load to sea is the percent difference between the N load to sea calculated through the mass balance and the "modeled load to sea" calculated by summing the NNM outlets to the sea.

7.11 References

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8 Calculating the nitrogen load to the sea

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Abstract

Purpose: The purpose of this chapter is to calculate the nitrogen and freshwater load to the sea for the period around year 1900. Additionally, the mean annual year 1900 riverine nitrogen concentration is calculated.

Materials and methods: The calculation of the year 1900 nitrogen and freshwater load to the sea is done using a delta change approach, with the official load estimate from the period 2008–2019 as the baseline (Thodsen et al., 2021). Regional, monthly delta change factors are calculated from the results presented in chapters 7 (Table 7.10) and 3, point sources transported directly to the sea are added from chapter 4.

Results and discussion: The year 1900 freshwater load to the sea is modelled to be 297 mm / yr compared with 335 mm / yr in the present period (2008-2019), and it was thus 11% lower in the period around year 1900. The nitrogen load is modelled to be approximately 36,000 ton N / yr around year 1900, which is about 40% less than during the present period, 59,000 ton N / yr. The mean annual river nitrogen concentration is modelled to be around 2.8 mg N / l around year 1900 compared with 4.1 mg N / l in the present period.

Conclusion: The freshwater load to the sea was lower around year 1900 than during the present period. The nitrogen load to the sea and the nitrogen concentration are modelled to be about 40% and 32% lower during the year 1900 period than during the present period, respectively.

8.1 Introduction

The landscape has changed significantly during the last 120 years, with the present having a higher drainage density, fewer and shorter streams as well as fewer small lakes and especially wetland areas. The natural removal of nitrate and total nitrogen during transport from agricultural fields to the sea has thus been reduced. This was also found by Andersson and Arheimer (2003) in their analysis of a Swedish catchment. The present chapter describes the approach taken to assess the nitrogen load around year 1900, taking the changes in climate, landscape, agricultural practise, point source loads and their spatial variations into account.

8.2 Material and methods

The national nitrogen model (NNM) (Højberg et al., 2015) is applied to estimate a spatially distributed nitrogen load to the sea for the entire country (not including point sources discharged directly to the sea). No data on the nitrogen load to the sea exist for the period around year 1900, which prevents a direct evaluation of the accuracy of the estimates provided by the model. The approach taken in the study has therefore been to use the model to estimate the relative difference in the load, invoking a common assumption that a model is better at estimating the relative change between two contrasting conditions rather than providing an absolute estimate. The nitrogen model has thus been used to estimate the relative difference in the nitrogen load for the current and historical conditions. This relative change is then forced upon the official national load estimate for Denmark (point sources applied directly to the sea excluded) (Thodsen et al., 2021). Thus, the National Nitrogen Model (NNM) was run for both the present period and for the period around year 1900 (Højberg et al., 2015). Subsequently, the relative difference between the two NNM runs was used in calculating the total nitrogen load to Danish coastal waters in the period around year 1900 with the average load (Point sources directly to the sea excluded) between 2008 and 2019 as the baseline load (Figure 8.1) (Thodsen et al., 2021). Point sources directly to the sea are added subsequently to calculate the total load to the sea. This approach is parallel to the delta change approach often used in hydrological climate change studies where climate model-generated climate / weather estimates are not directly comparable to observed climate values. However, climate model data from different periods are mutually comparable and the relative difference can be used in changing observed climate time series to represent the future climate (e.g. van Roosmalen et al., 2010).

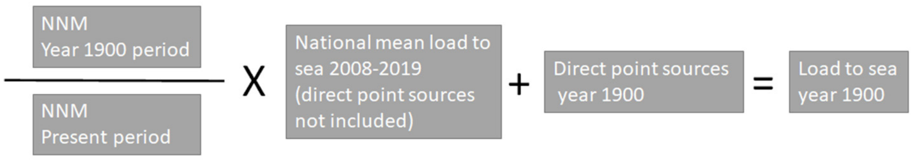


Figure 8.1. Concept for calculating the nitrogen load to the sea year 1900. NNM is the National Nitrogen Model. The official load to the sea as calculated in Thodsen et al. (2021).

The comparison between the two NNMs was carried out at a mean monthly scale. The $NNM_{present}$ was run on climate / weather data for the 21-year period 1990–2010 (both years included). The NNM_{1900} was run with delta-changed precipitation input baselined from the period 1990-2010, representing the climate around year 1900 (se chapter 1 for background and method regarding the delta change method).

The NNM_{1900} mimics the year 1900 as closely as possible, while the $NNM_{present}$ mimics the year 2017 as closely as possible but with year 2011 agricultural leaching. 2011 is used as it is the most recent year modelled with the 2015 version of the NNM, on which the present period NNM is based (Højberg et al., 2015).

It was chosen to model a period of 21 years, for both NNMs, to base the analysis on long-term climate / weather series rather than single-year climate series that tend to be unusual in some way for some parameters. In this way, the load estimates are based on a robust climate foundation.

The NNM results are aggregated at the fourth order coastal catchment level (Figure 8.2).

8.2.1 Present period

The $NNM_{present}$ was run for the period 1990-2010. The target year (year of the general conditions of the NNM) is 2017, except for the nitrogen leaching from agricultural fields which is 2011 as it utilises the data set also used in Højberg et al. (2015).

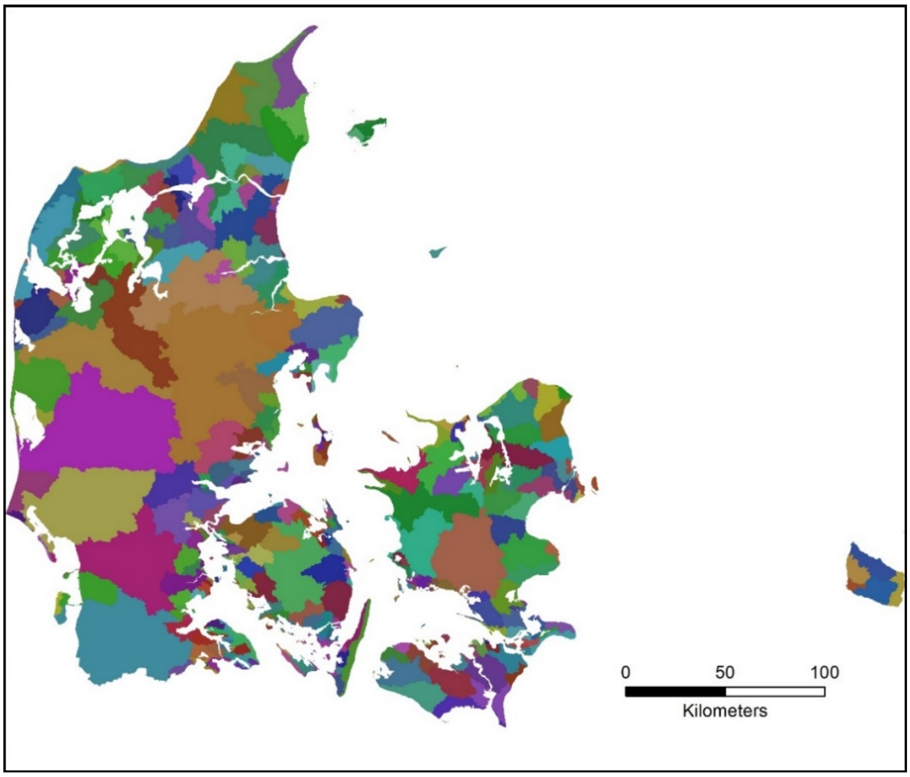


Figure 8.2. Fourth order catchments (n=315).

8.2.2 Year 1900

The NNM_{1900} was run for the period 1890-1910 but based on delta-changed climate data for the period 1990-2010. The target year is 1900.

8.2.3 The national nitrogen load estimate

The baseline for the year 1900 nitrogen load estimation is the national annual nitrogen load estimation for 2008-2019 (Windolf et al., 2011; Thodsen et al., 2021). Originally, the national nitrogen load estimate has a monthly time step and is based on the fourth order coastal catchment scale (Figure 8.2) (Thodsen et al., 2021).

The national nitrogen load estimate is reported annually and is based on both measured water discharge and measured total nitrogen concentrations as well as modelled values of water discharge and empirically modelled total nitrogen concentrations (Windolf et al., 2011; Thodsen et al., 2021).

8.2.4 Calculating delta change factors

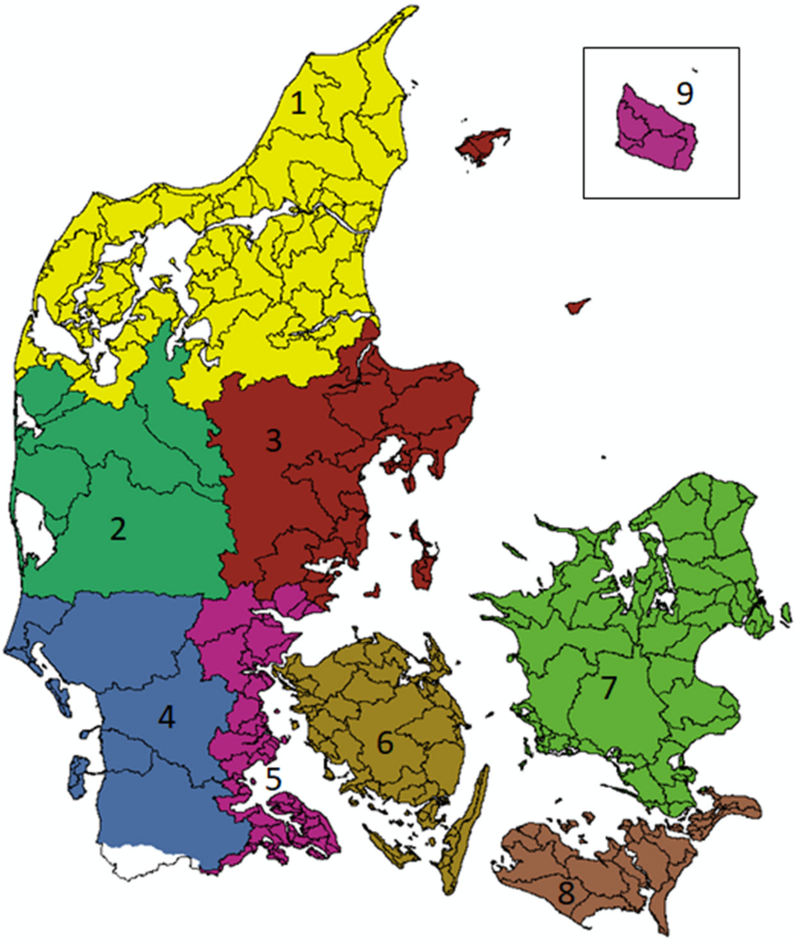
Delta change factors for runoff and nitrogen loads need to be calculated to transfer the differences found between the $NNM_{present}$ and NNM_{1900} to the national nitrogen load estimate. It was found that utilising the individual fourth order catchment scale for calculating delta change factors introduced too much uncertainty in some usually small fourth order catchments. Therefore, it was decided to calculate area-weighted mean delta change factors for both runoff and nitrogen loads on a subset of fourth order catchments in the nine regions, shown in Figure 8.3, and use these nine delta change factors on all fourth order catchments within a region.

Fourth order catchments on which the regional delta change factor calculation was based were chosen in the following way:

Fourth order catchments with the 20% highest and lowest values were excluded.

a. Minimum 50% of the region area is covered.
b. Minimum three fourth order catchments are included in a region.
c. All fourth order catchments >300k m^2 are included.

Figure 8.3. Nine delta change regions and fourth order coastal catchments.



8.3 Results

8.3.1 NNM_{1900} and $NNM_{present}$

Percent differences in runoff, nitrogen load and nitrogen concentration at national and mean annual level have been calculated based on the regional monthly delta change factors. The regional monthly delta change factors for runoff (Figure 8.4) and for nitrogen loads (Figure 8.5) are presented below. The change in single regions is less certain than at the national scale, both because of the smaller scale and because of the national-scale delta change procedure used for year 1900 precipitation.

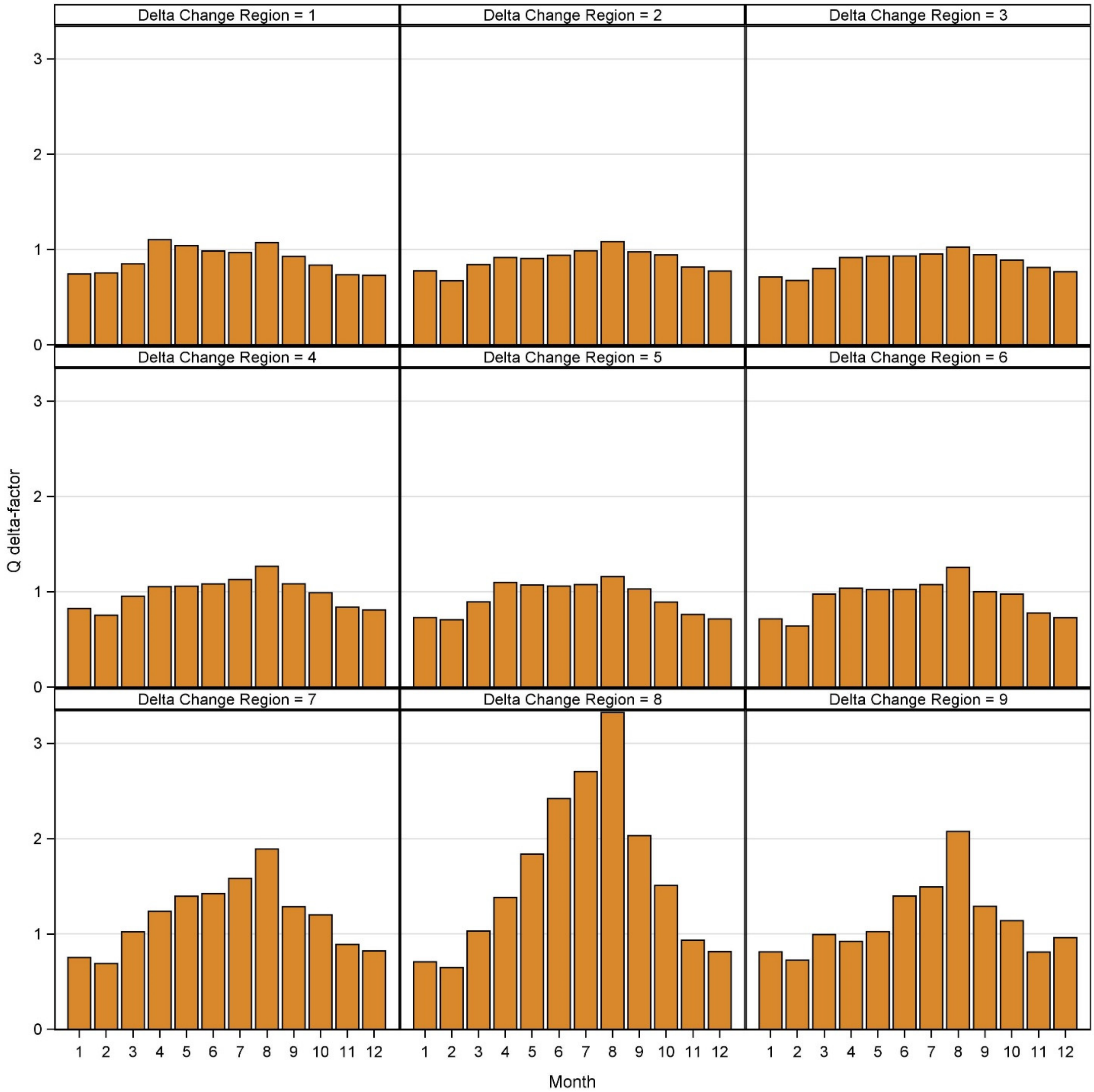


Figure 8.4. Monthly delta change factors for regional runoff (Q) between the present period (baseline) and the around year 1900 period.

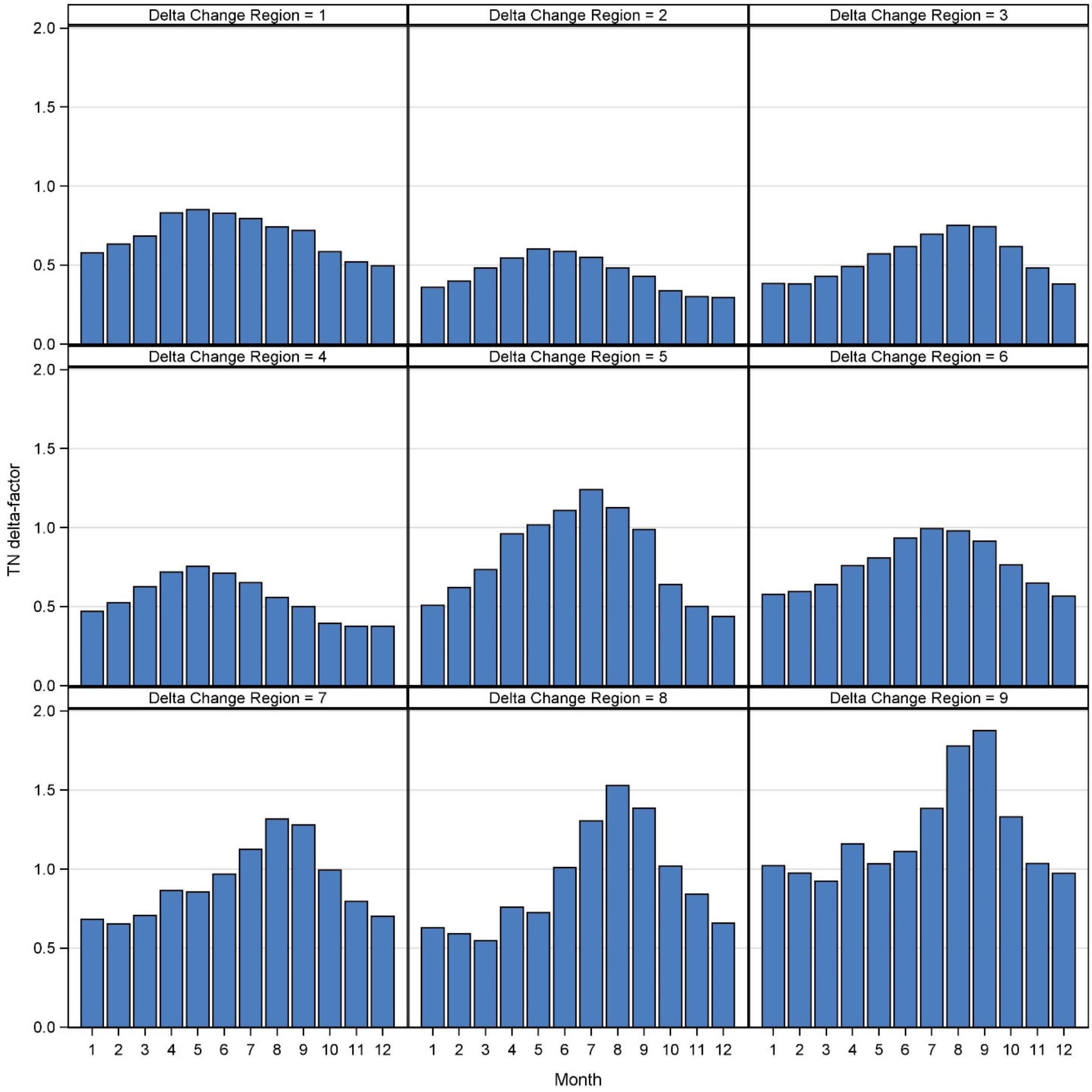


Figure 8.5 Monthly delta change factors for regional nitrogen loads between the present period (baseline) and the year 1900 period.

The runoff delta change factors from the western and central part of the country show lower winter runoff and similar summer runoff for the period around year 1900 compared with the present. For the eastern part, summer runoff is markedly larger around year 1900 compared with the present period, while winter runoff is lower. As for the nitrogen loads, region 1-4 show markedly lower loads around year 1900 compared with the present period, with winter loads being mostly below half of present period loads. For region 5, 7, 8 and 9, summer and early autumn loads are higher during the year 1900 period than during the present period, while winter loads are lower. Only for region 9, the island of Bornholm, around year 1900 loads are similar (winter and spring months) or higher (July – October) than the present period loads.

At the national and mean annual scale, the two NNMs yield the results presented in Table 8.1.

Table 8.1. Mean national differences (absolute and in %) in mean annual runoff, flow-weighted nitrogen concentration and nitrogen load between the year 1900 period and the present period as calculated by NNM_{1900} and $NNM_{present}$.

	NNM_{1900}	$NNM_{Present}$	Percent difference
Runoff (mm/yr)	292	333	14% (-12%)
Flow-weighted total nitrogen concentration (mg-N/L)	2.7	3.9	45% (-31%)
Total nitrogen load (ton N/yr)	34,026	56,283	65% (-40%)

8.3.2 Year 1900 total nitrogen and freshwater load to the sea

The monthly, regional delta change factors for runoff (Fig 8.4) and nitrogen loads (Figure 8.5) were used in calculating the year 1900 runoff, flow-weighted nitrogen concentrations and nitrogen loads at the fourth order catchment level and mean monthly and mean annual level. The fourth order mean monthly national nitrogen load estimate for 2008-2019 is used as the baseline for the calculations (Thodsen et al., 2021). However, utilisation of the fourth order coastal catchment scale is limited by the national-scale delta change method used for year 1900 precipitation and by using the regional rather than the fourth order coastal catchment scale for the Q and TN delta change factors (Figure 8.4 and 8.5). This method transfers a mean regional difference in runoff and nitrogen load, between the year 1900 and the present, to each fourth order catchment, with the national nitrogen load estimate as the baseline (Thodsen et al., 2021). As the results presented in Table 7.10 and Table 8.1 are aggregated from the ID15 scale, and the year 1900 results in Table 8.2 are based on the regionalised delta change factors, the ratios between the year 1900 and the present period nitrogen loads and runoffs (presented in Table 8.1 and 8.2) cannot be expected to match completely.

Mean annual year 1900 national freshwater and nitrogen loads as well as flow-weighted nitrogen concentrations are calculated (Table 8.2) based on fourth order catchments and on the principals shown in Figure 8.1.

Table 8.2. Mean national differences (absolute and in %) in mean annual runoff, direct point sources to the sea, total inland nitrogen load, flow-weighted nitrogen concentration and nitrogen load between the year 1900 period and the present period (Present = 2008-2019) after applying the delta change parameters (Figure 8.4 and Figure 8.5) to the NNM_{1900} values.

	1900	Present/baseline	Percent difference
Runoff (mm/yr)	297	335	13% (-11%)
Point sources directly to the sea (ton N/yr)	2,518	2,710	8% (-7%)
Total inland nitrogen load (ton N/yr)	33,550	56,310	68% (-40%)
Flow-weighted total nitrogen concentration (mg N/L)	2.8	4.1	47% (-32%)
Total nitrogen load (ton N/yr)	36,068	59,020	66% (-40%)

The geographical pattern (fourth order catchments) of flow-weighted nitrogen concentrations (Figure 8.6), area-specific nitrogen loss (Figure 8.7) and runoff/freshwater load (Figure 8.8) are shown below.

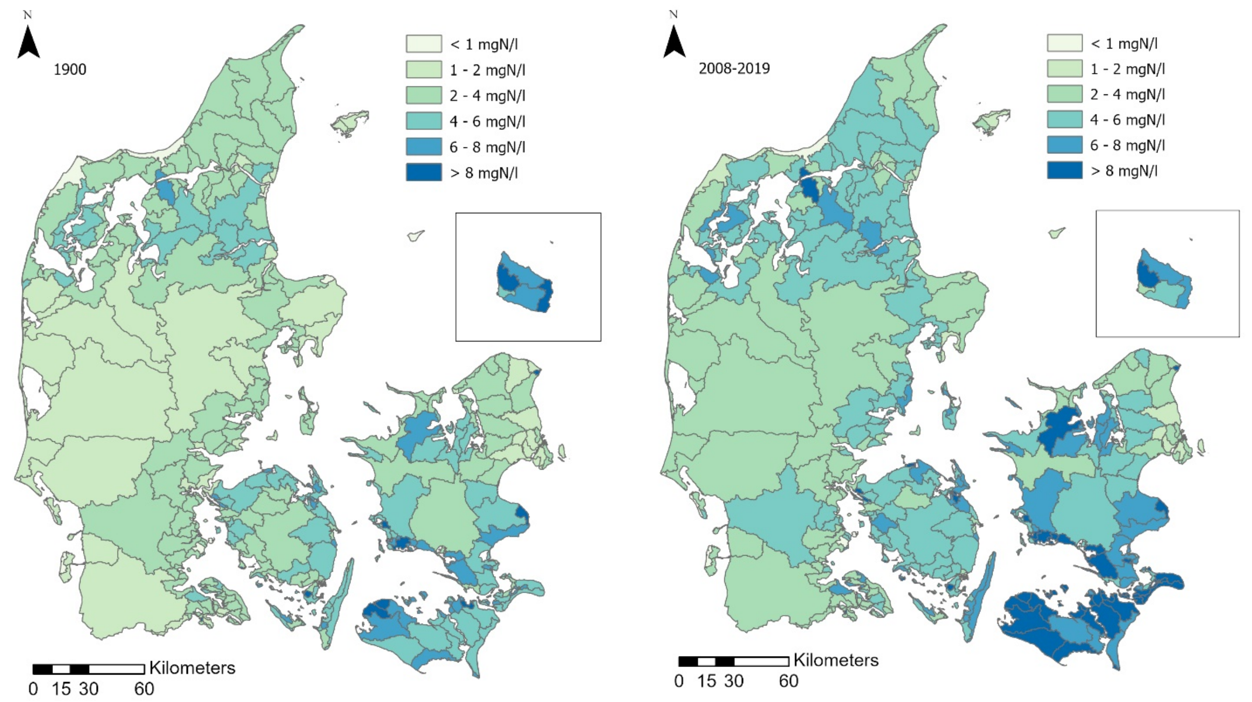


Figure 8.6. Mean flow-weighted nitrogen concentration for fourth order catchments. The change in single 4th order catchments is less certain than at the national scale, both because of the smaller scale and because of use of a similar national delta change procedure for around year 1900 precipitation.

The flow-weighted nitrogen concentration in most fourth order catchments is shown to be lower or in the same category in 1900 as in present. In both periods, the highest concentrations are seen on the islands and in the northern part of Jutland. Large parts of central and western Jutland are shown to have concentrations below 2 mg N / L, but also northeastern Zealand has low concentrations (Figure 8.6). In 1900, most of the country lost 5-10 kg N / ha, while during the present period the most common class is 10-20 kg N / ha (Figure 8.7).

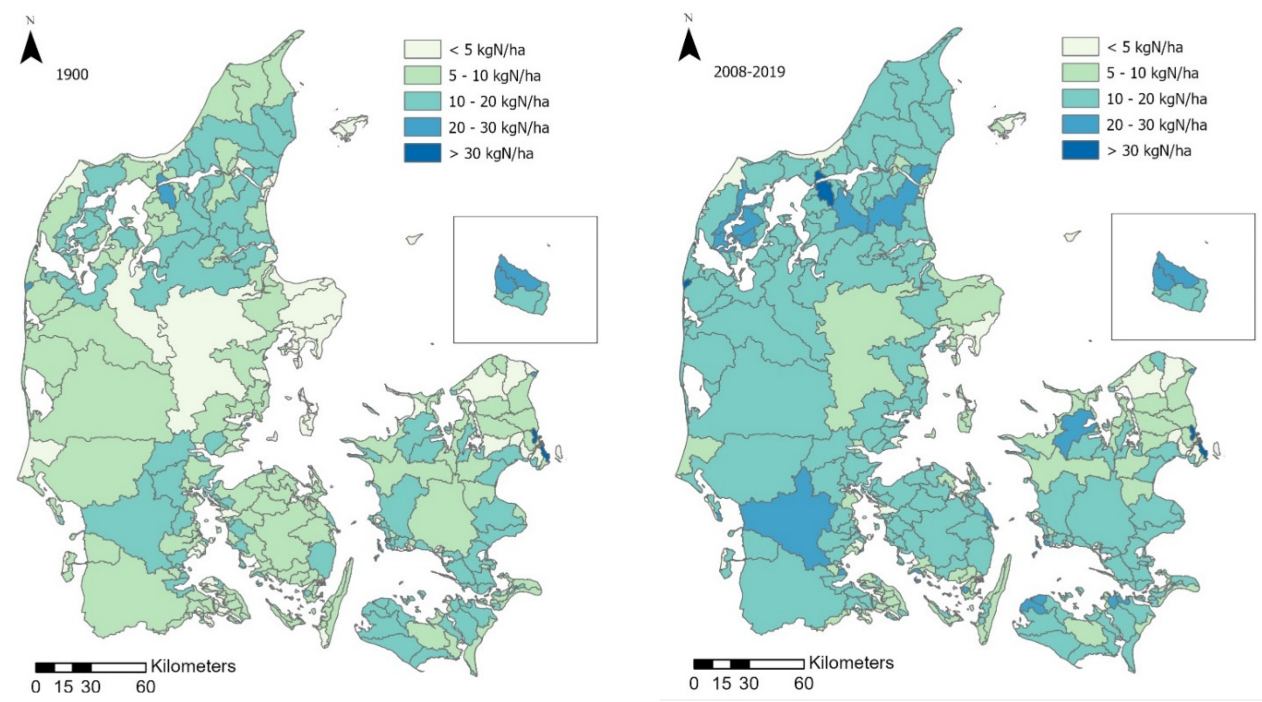


Figure 8.7. Mean area-specific nitrogen loss for fourth order catchments. The change in single fourth order catchments is less certain than that at the national scale, both because of the smaller scale and because of use of a similar national delta change procedure for around year 1900 precipitation.P

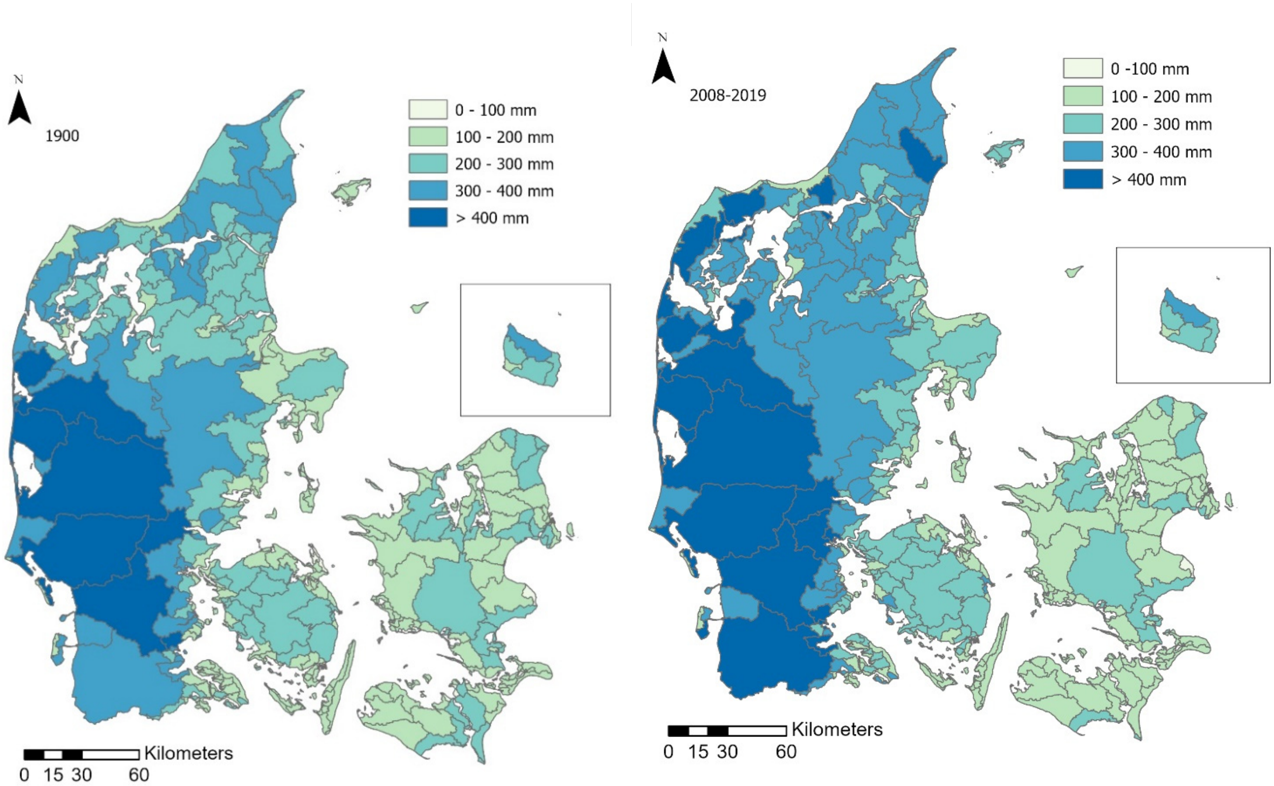


Figure 8.8. Mean runoff (mm/yr) for fourth order catchments. The change in single fourth order catchments is less certain than at the national scale, both because of the smaller scale and because of use of a similar national delta change procedure for around year 1900 precipitation.

The runoff (Figure 8.8) has generally increased since year 1900 due to increased precipitation. The increase is shown to be larger in the western than in the eastern part of Denmark. A few eastern catchments show decreases. However, the regional pattern is very uncertain because of the similar national delta change procedure (single monthly value for the whole country) used for calculating the year 1900 precipitation.

If the ratio between the whole-country NNM_{1900} and $NNM_{present}$ (shown in Table 7.10 and Table 8.1) of 0.60 is multiplied with the baseline nitrogen load to the sea of approximately 56,000 ton N / yr (Table 8.2) and adding to this the direct input to the sea from point sources of approximately 2,500 ton N / yr, the resulting year 1900 nitrogen load to the sea is approximately 36,000 ton N / yr.

8.4 References

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9 Phosphorus losses from the Danish land area to the sea around year 1900

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Abstract

Purpose: We aim to estimate the total P load to the sea around the year 1900 including contributions from background, other diffuse sources, inland and direct point sources and taking P retention in lakes into account.

Materials and methods: The stream water background concentration of total phosphorus is derived from present-day measurements in natural streams. Other diffuse phosphorus sources are sought quantified using historical information and expert judgements and are added to the background contribution. Around the year 1900, discharge is calculated by the National Water Resource Model forced by historical climate data. Water is routed through a network of connected catchments. The streams in each catchment are assigned specific geo-regional year 1900 stream water TP concentrations. P retention is included for larger lakes. Finally, contributions from direct point sources are added to the calculated phosphorus transport, thus arriving at estimates of total phosphorus loading to the sea around the year 1900. The available data only allow calculations at a geo-regional scale (Denmark subdivided into nine geo-regions).

Results and discussion: Around year 1900, the stream water TP concentration is estimated to 0.062-0.075 mg P/l, including contributions from natural background sources, other diffuse sources and inland point sources. The year 1900 TP concentration is equivalent to 60-70% of the present-day stream water TP concentration (0.1 mg P/l). The contribution from inland and direct point sources is estimated to 471 ton P, 65-70% of the present-day contribution from point sources (704 ton P, average 2014-2018). The total around year 1900 P loading to the sea including background, other diffuse sources, indirect and direct point sources and subtracted P retention in lakes is estimated to 1200-1340 ton P, which is 60-65% of the present-day P loading (2,021 ton, average 2014-2018).

9.1 Introduction

9.1.1 Background

Measurements of phosphorus (P) concentrations in streams around the year 1900 are scarce. We are only aware of one study (Westermann, 1898), which includes a limited number of measurements in a few streams with old methodologies, making its representativeness uncertain. Consequently, the P load to coastal waters around the year 1900 is largely unknown.

Background P concentration is defined as the concentration that can be measured in anthropogenically undisturbed streams. However, such streams do not exist in intensively cultivated Denmark. Thus, here background concentration is defined as the least anthropogenically disturbed streams. Bøgestrand et al. (2008) deduced the regional background P concentration from current P concentrations in streams from minimally disturbed catchments. These concentration estimates were used in the River Basin Management Plans 2015 -2021 to calculate the land-based P loading to the sea around the year 1900. However, the data material in Bøgestrand et al. (2008) is limited to only 19 streams, and no assessment of around year 1900 diffuse and point sources was included in the calculation of P loading.

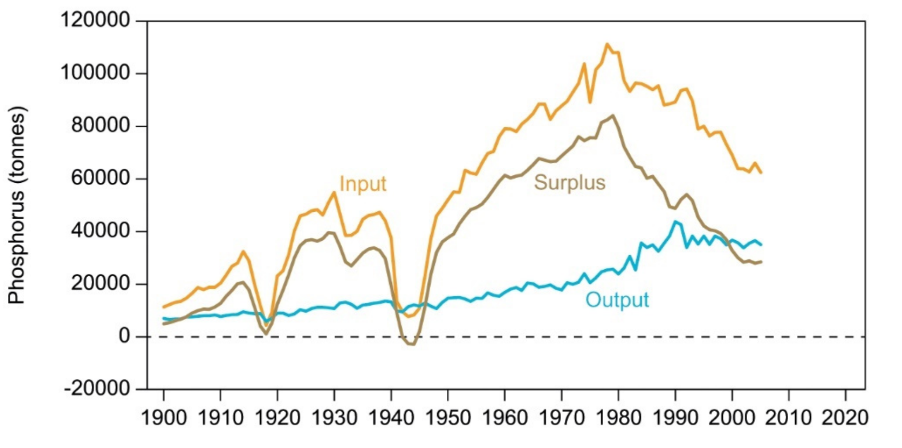
The population in 1900 was lower than today, but a larger proportion lived in rural areas where facilities to collect human waste were poorly developed. Farming was already intensive, covering 76.6% of the land area (Table 5.4, chapter 5) and with a rather high livestock density of 0.89 units / ha (Danmarks Statistik, 1969), a large population of cattle (1.4 million LU, chapter 5) and more widespread grazing. Manure storage facilities were poor (chapter 5) and handling of nutrients in manure much less sophisticated than today, suggesting that P losses from storages, through simple drainage installations around the farms and from manure deposited or applied on the soil surface, were larger in 1900 than today.

Currently, the quantification of P transfer from agricultural land to surface waters along different transport pathways is associated with many difficulties and large uncertainties (Andersen and Heckrath, 2020). These difficulties are even more pronounced when trying to quantify losses around year 1900. We can, however, point towards major differences in factors affecting P losses from agriculture between today and around year 1900 and suggest whether these differences would have caused either larger or smaller contributions of agricultural P to surface waters in 1900 compared with today (Table 9.1).

Table 9.1. Qualitative comparison of factors affecting the P loss around year 1900 with today.

	Increased contribution	**Decreased contribution**
External inputs and thus the net surplus of P in Danish agriculture was low before 1900 (Figure 9.1), and the stock of P in agricultural soils was much lower than today.		+
There were many small and scattered farms in 1900, most of them with livestock, which annually must have cycled considerable amounts of P on-farm through livestock in spite of little use of inorganic fertilisers. o Poor facilities for storage of animal manure resulted in losses by runoff from manure storages and farmyards. o Poor facilities for storage of animal manure, resulting in manure application on the soil surface outside narrow windows for incorporation, manure application also in autumn and winter. o Animal manure was handled less efficiently than today, i.e., often it was not incorporated into the soil soon after application, increasing the risk of surface runoff losses, and it was typically applied to land close to the farm, leading to local P enrichment of soils.	+	
No or poor facilities for collecting and treating waste and wastewater in rural areas.	+	
Negligible use of inorganic fertiliser and feed phosphates.		+
Grazing and thus deposition of manure excreted onto the soil surface was more widespread than today, increasing the risk of surface runoff-induced P loss.	+	
Organic lowland soils were not yet intensively drained.		+
Streams and lakes were typically not fenced in, i.e., cattle had direct access to surface waters, causing poaching and increased sediment and faeces transfer to water.	+	

Figure 9.1. Phosphorus balance for Danish agriculture 1900-2005. After Kyllingsbæk (2008).



9.1.2 Objectives

The overall objective of this chapter is to estimate the P loading from the entire Danish land area to the sea around year 1900. To do this, we estimate stream water background P concentrations using several approaches, assuming that today's background concentration resembles the background concentration in 1900. Subsequently, and to the extent possible, we estimate and add inputs from additional diffuse and point sources to arrive at ranges of likely stream water concentrations of total phosphorus (TP) around year 1900. Stream water transport of P at catchment scale is then calculated using modelled stream water discharge from historical climate data. The P load is routed downstream in a connecting river network including P retention in larger lakes, resulting in a final estimate of P loading to the sea.

9.2 Material and methods

9.2.1 Background phosphorus concentrations in Danish streams

Background concentration inferred from stream measurements (according to Bøgestrand et al., 2008)

Bøgestrand et al. (2008) did a comprehensive study to determine the background concentration of P in Danish streams. They mapped the P concentration in deep reduced groundwater (i.e. both oxygen and nitrate concentrations are below 1 mg/l) and in shallow oxidized groundwater (concentrations of oxygen > 3 mg/l or nitrate > 1 mg/l) based on 4,406 and 2,211 samples, respectively (Figure 9.2 and 9.3).

The P concentration in deep, reduced groundwater (Figure 9.2) is high at Ærø, Als, near Ribe and Esbjerg and towards Ringkøbing, in Vendsyssel and in parts of western and northern Zealand. These areas are characterized by interglacial marine deposits, which may have a natural high content of P. The P concentration in the shallow oxidized groundwater (Figure 9.3) is lower and seemingly without correlation with geological deposits. For the majority of Denmark, the P concentration in the shallow oxidized groundwater is below 0.06 mg/l.

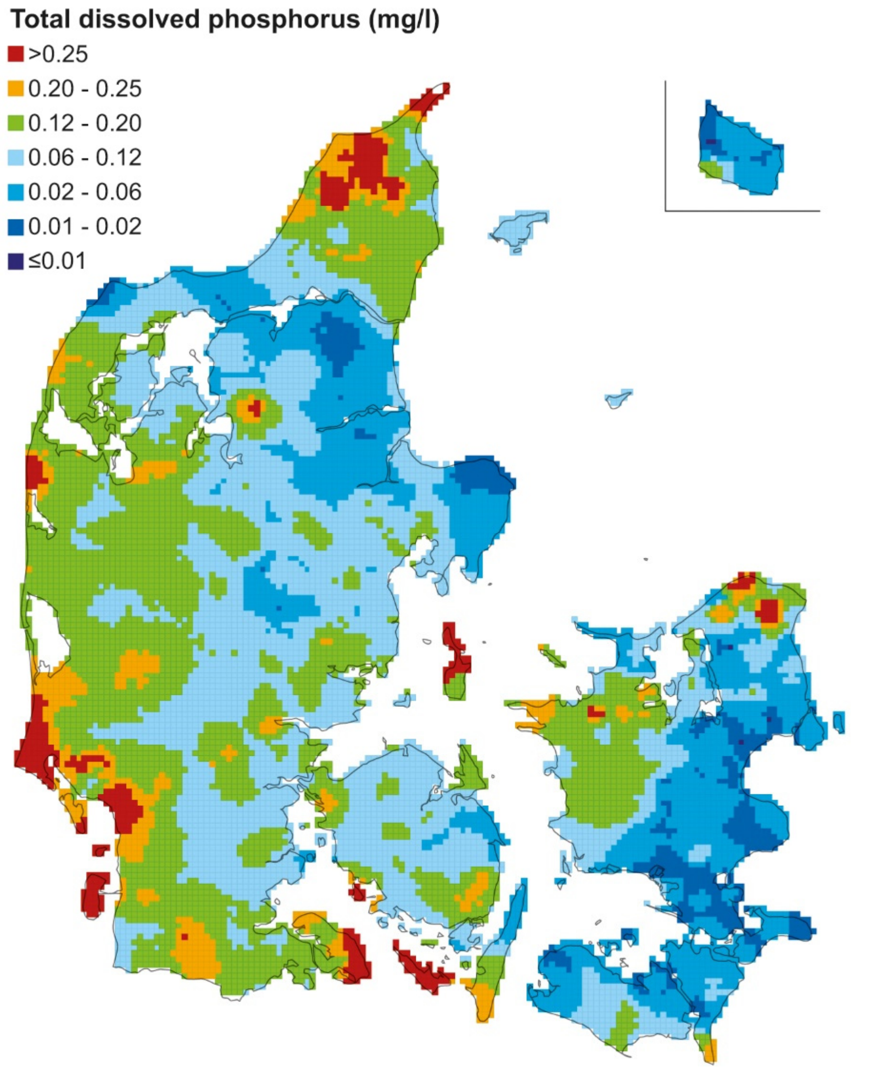


Figure 9.2. The concentration of total dissolved phosphorus in reduced groundwater (Bøgestrand et al., 2008).

The P concentrations observed in "nature streams", i.e., streams draining catchments without point sources and with less than 10% agriculture, were, however, not related to the mapped P concentrations in shallow groundwater as was otherwise initially hypothesized (Bøgestrand et al., 2008). The missing correlation was explained by a coarse mapping of groundwater (2 km grid), possible inputs of reduced groundwater, sorption of P in riparian sediments, declining P concentrations in surface waters and inputs of organic P from wetlands.

As an alternative to model background stream water P concentration as a function of P concentration in groundwater, Bøgestrand et al. (2008) calculated geo-regional estimates of background concentration of TP as discharge-weighted means from measurements in 18 "nature streams" (Figure 9.4). P concentrations ranged from 0.029 mg P/l on Bornholm to 0.089 mg P/l in Himmerland. For geo-regions without "nature streams", the overall median concentration value (0.055 mg P/l) was applied. These concentration estimates were used nationally in the River Basin Management Plans 2015-2021 to calculate the land-based P loading to the sea around the year 1900.

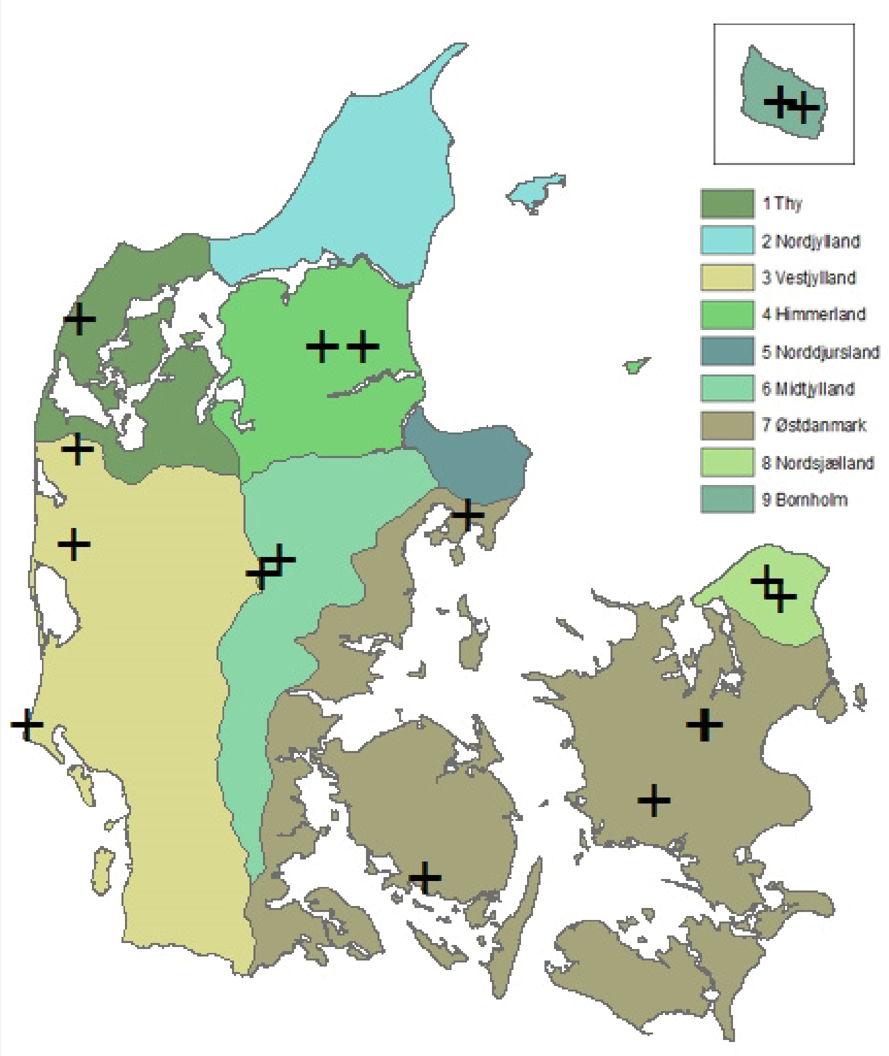


Figure 9.4. Location of the 18 "nature streams" draining catchments without point sources and with agriculture covering less than 10%. Also shown are the nine geo-regions.

Update and expansion of background concentration inferred from stream measurements

For this analysis, we selected 414 streams included in the Danish national environmental monitoring program (NOVANA) where water discharge and TP concentrations were measured during 2010-2017 and calculated the annual mean discharge-weighted concentration of TP by dividing annual TP transport with annual discharge. Since TP transport is based on bi-weekly grab samples, there is a well-known risk of underestimating the true transport and thus the true discharge-weighted TP concentration. Andersen and Heckrath (2020) estimate that the TP transport based on grab samples on average is underestimated with 30% in small streams and 5% in larger streams. We derived the annual mean discharge-weighted concentration of TP associated with diffuse sources for each stream by subtracting the P contributions from point sources and scattered dwellings not connected to a central sewer (both reported by Miljøstyrelsen, 2019) from the measured TP concentration. Thus, in theory, the main remaining stressor causing a P concentration above the background concentration should be agriculture. Erosion of stream banks and the associated P loss are considered parts of the background loading. For each catchment, we collected land use information, including the area occupied by agriculture. Stream networks including a lake with an area above 5% of the total catchment area and streams with a catchment area larger than 100 km^2 were removed from the initial dataset to reduce the influence of in-catchment retention of P. We also excluded catchments with impervious surfaces (e.g.

built-up areas) occupying more than 10% of the total catchment area (one catchment has 13% built-up area), focusing on catchments dominated by nature, forest or agriculture. The reduced dataset comprised 246 streams. Since this dataset is dominated by streams with catchments with a high proportion of agriculture, we supplemented the dataset with data from 21 streams identified by the former counties as the least anthropogenically impacted streams and with agriculture occupying less than 40% of the total area. These 21 streams were, however, only sampled four times during 2004-2005. From this dataset of 267 streams, we selected streams where agriculture occupies less than 20% of the total catchment area. This criterion was met by 26 streams, including 17 of the "nature streams" analysed by Bøgestrand et al. (2008).

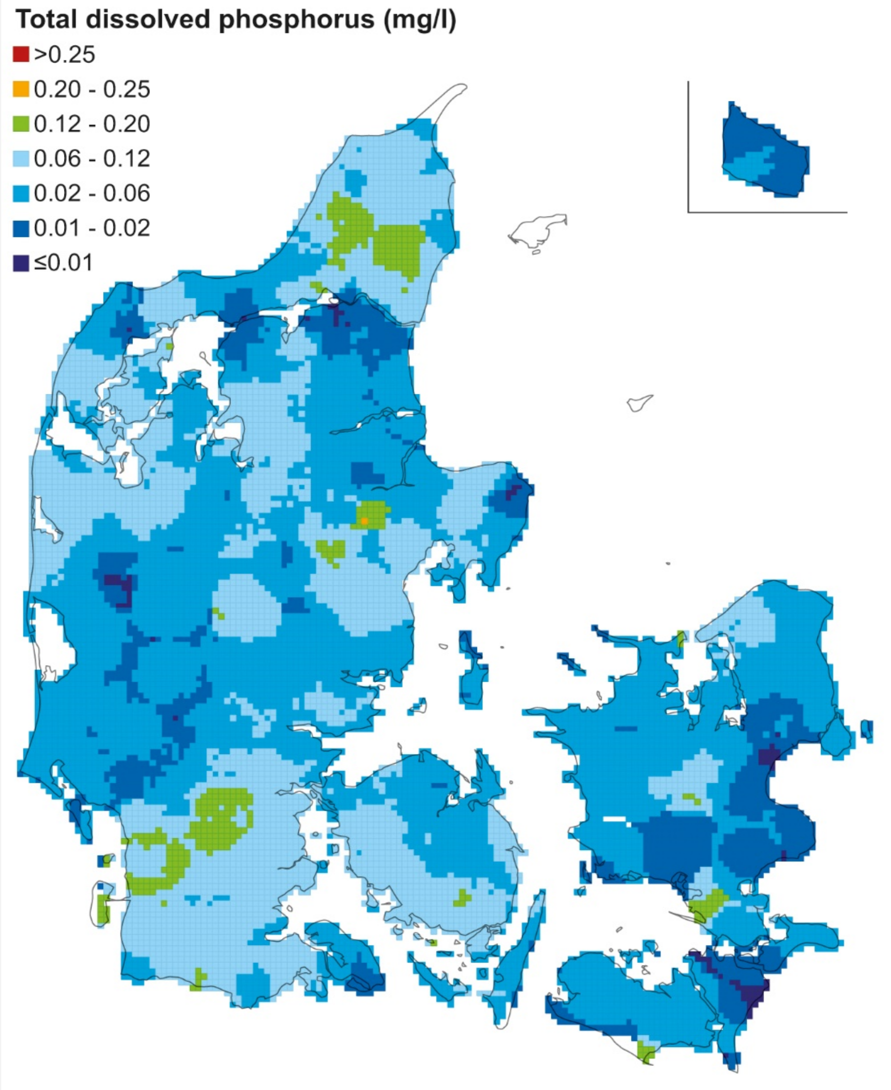


Figure 9.3. The concentration of total dissolved phosphorus in oxidised groundwater (Bøgestrand et al., 2008).

The criterion of 20% agriculture was set based on an initial analysis that showed two distinct groups having, respectively, below and above 20% agriculture, with the lowest TP concentrations in the first group. Allowing the share of agriculture to increase from 10% to 20% only enhanced the overall mean TP concentration in the group of streams with 2%, however the number of streams included increased from 18 to 26. For that reason, it was decided to include also streams with up to 20% agriculture in the catchment. We then calculated overall mean values per station so that each station has an equal weight irrespective of the number of years that the station has been sampled. Finally, we calculated mean values per geo-region as estimates of background

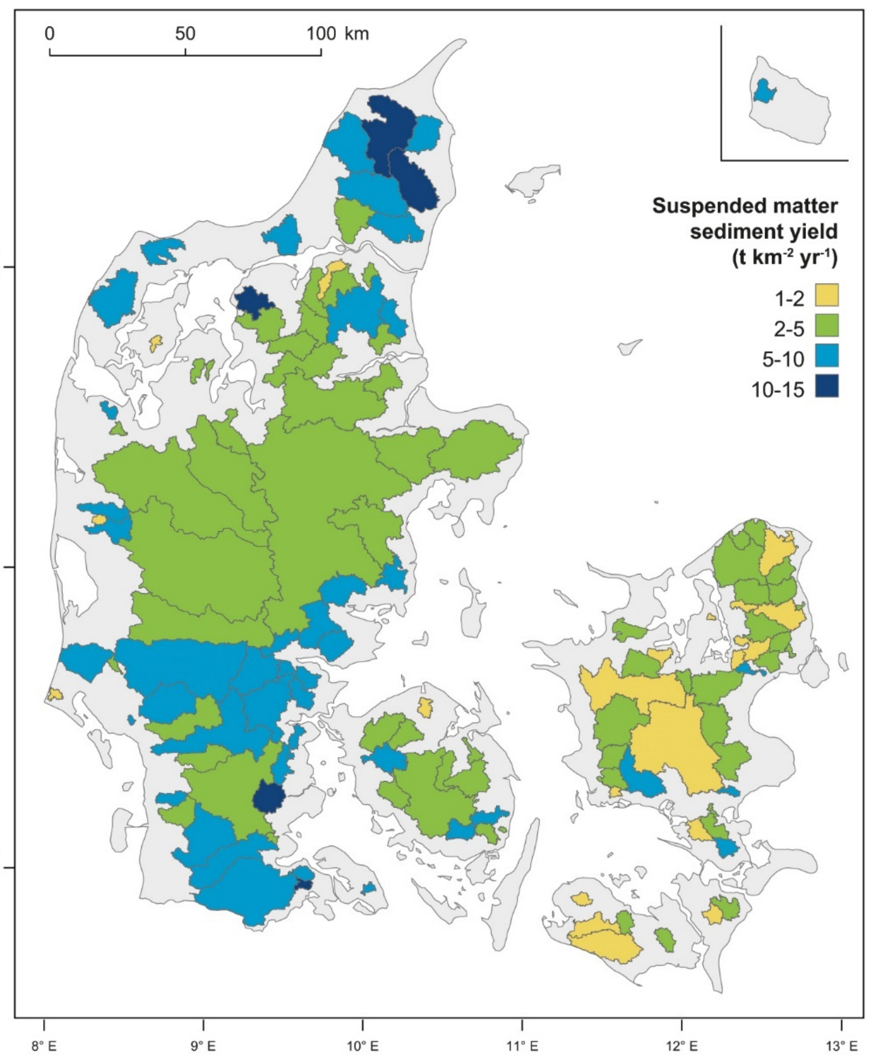
TP concentration. Table 9.2 compares the geo-regional estimates of background TP concentration from Bøgestrand et al. (2008) with estimates from the present analysis. In the beginning, NOVANA also comprised monitoring of water quality of springs. P concentrations in spring water in nature areas may be considered representative for groundwater-fed streams of nature areas and thus conservative (minimum) estimates of background concentration (since contributions from, for instance, bank erosion are not included). TP concentrations in 12 springs located in nature areas (Larsen et al., 1995) are shown as averages for the period 1989-1994 in Table 9.2.

Table 9.2. Geo-regional estimates of annual discharge-weighted background concentration of total phosphorus (mg TP/l) from Bøgestrand et al. (2008) and this study; 95% confidence intervals included for the latter study. Also shown is average total phosphorus concentration (mg TP/l) measured in springs in nature areas during 1989-2004 (Larsen et al., 1995). The number of streams/springs behind each estimate is given in parentheses.

Georegion	Bøgestrand et al. (2008): 18 ”nature streams”	Larsen et al. (1995): 12 springs in nature areas	This study: 26 streams with agriculture < 20% and corrected for P contributions from point sources and scattered dwellings. 95% confidence interval indicated where applicable
1. Thy	0.058 (1)	0.090 (1)	0.085 (1)
2. North Jutland	0.055 (0)	0.070 (1)	0.074 (1)
3. West Jutland	0.043 (3)	0.065 (2)	0.043 +/- 0.020 (4)
4. Himmerland	0.089 (2)	0.010 (1)	0.073 +/- 0.015 (4)
5. North Djursland	0.055 (0)		
6. Central Jutland	0.040 (2)	0.100 (2)	0.019 (2)
7. East Denmark	0.054 (5)	0.043 (4)	0.061 +/- 0.006 (7)
8. North Zealand	0.069 (2)		0.066 +/- 0.050 (3)
9. Bornholm	0.029 (3)	0.010 (1)	0.020 +/- 0.005 (4)

Average and median values in the dataset of Bøgestrand et al. (2008) are 0.052 and 0.055 mg TP/l, respectively. The corresponding values in the dataset from Larsen et al. (1995) are 0.057 mg TP/l and 0.040 mg TP/l. Average and median values in our updated analysis including 26 streams with agriculture < 20% are 0.053 and 0.050 mg TP/l, respectively. Thus, at the national level there is reasonable agreement between the three sets of estimated background P concentrations. However, compared with Bøgestrand et al. (2008), our new analysis yields considerably higher estimates of background P concentrations for geo-region 1 and 2 (Thy and Nordjylland). The relatively high background P estimates in these two geo-regions are supported by findings of Thodsen et al. (2019), who provided a national overview of suspended matter in streams based on measurements at 572 stations during 1976-2016 (> 100,000 water samples). Suspended matter is often perceived as an important carrier of P. Thodsen et al. (2019b) found very high values of sediment yield in geo-region 1 and especially in geo-region 2 (Figure 9.5). Furthermore, Figures 9.2 and 9.3 demonstrate that also the P concentration in both the reduced and the oxidized groundwater is high in these two geo-regions.

Figure 9.5. Sediment yields for 132 catchments (after Thodsen et al., 2019).



International data on background concentration

A few studies from neighboring countries with similar geology report background concentration of P (Table 9.3). The values are generally lower albeit in the same order of magnitude as the Danish estimates (average values) of background concentration. Note that the Swedish estimates of background concentration do not include contributions from stream bank erosion.

Table 9.3. Stream water background concentration of total phosphorus (dissolved inorganic phosphorus concentration in parentheses) measured in neighbouring countries.

Country	Location	mg TP/l (mg PO_4-P/l)	Stream characteristics	Source
NE Germany	Catchment of River Spree	0.030-0.050 (0.010-0.020)	Brooks in small unpolluted catchments, paleolimnological investigations in river valley	Gelbrecht et al. (2005); Schönfelder et al. (2002)
Estonia		0.031-0.095, avg. 0.045 (0.006-0.045, avg. 0.019)	8 streams in nature areas w. agriculture < 20%, 1994-2017, sizes from tens to hundreds of km^2	Arvo Iital, Tallinn University of Technology, pers. comm.
Latvia	Lielupe River Basin District	0.020-0.056, avg. 0.037 (0.008-0.037, avg. 0.020)	3 streams w. agriculture 10 – 29%, 2005 – 2018, sizes 9 – 28 km^2	Ainis Lagdzins, Latvia University of Agriculture, pers. comm.
Sweden	Southern Skåne	Sand: 0.04 Sandy loam: 0.03 Loamy sand: 0.02	Background concentration is calculated with ICECREAMDB (Persson et al., 2007) for extensive grassland.	Karin Blombäck, Swedish Agricultural University, pers. comm.

Which background concentration estimates to use in further calculations?

Based on the review of several attempts to estimate background P concentration in streams, we choose to base our work on the updated stream-based geo-regional analysis. However, for geo-region 5, for which there are no observations, we apply the overall median value of 0.050 mg P/l (Table 9.4). It is important to stress that (i) these estimates are geo-regional averages and that several streams with both lower and higher background concentrations can probably be found within each geo-region, depending on, for instance, connectivity to groundwater systems, and (ii) these estimates come with a very high degree of uncertainty as they are based on a limited number of streams.

Table 9.4. Updated geo-regional estimates of present annual discharge-weighted background concentration of total phosphorus (mg TP/l) including 95% confidence intervals where applicable. The number of streams behind each estimate is given in parentheses.

Georegion	This study: 26 streams with agriculture < 20% and corrected for P contributions from point sources and scattered dwellings. 95% confidence interval indicated where applicable.		
1. Thy	0.085		(1)
2. Nordjylland	0.074		(1)
3. Vestjylland	0.043	+/- 0.020	(4)
4. Himmerland	0.073	+/- 0.015	(4)
5. Norddjursland	0.050		(0)
6. Midtjylland	0.019		(2)
7. Østdanmark	0.061	+/- 0.006	(7)
8. Nordsjælland	0.066	+/- 0.050	(3)
9. Bornholm	0.020	+/- 0.005	(4)

9.2.2 Input related to soil drainage

Around the year 1900, an area of 659,000 ha was artificially drained (Aslyng, 1980). Most of the draining was carried out between 1860 and 1900 (Jensen, 1988; Olesen, 2009). Artificial drainage was primarily established on the loamy soils on the Danish islands and in East Jutland (see Figure 3.4). The tile-drained area is distributed on geo-regions as follows: Thy 40,000 ha; North Jutland 11,000 ha; West Jutland 33,000 ha; Central Jutland 47,000 ha; East Denmark 509,000 ha; Bornholm 19,000 ha. Draining of low-lying organic soils, primarily situated in Jutland, took place after 1900 and most intensively between the two world wars and up to 1960 (Olesen, 2009; Olesen, 2019). Hence, we will not consider P losses from draining of low-lying organic soils further.

Tile drains represent a direct transport pathway from the root zone to surface waters, and installment of tile drains may thus increase the P loading of surface waters. However, even today the P concentration in most tile drains is low (Andersen et al., 2016), and in 1900 the soil P content at the depth of the tile drains would not have been enriched above the natural content. However, structured soils have macropores that may convey water, dissolved and particulate substances directly from the surface and the topsoil to tile drains during the runoff season (autumn and winter). Freshly added manure constitutes a mobile source of P for transport in macropores (Soupir et al., 2006). In 1900, most of the animal manure was applied in the autumn and winter periods (chapter 5). Poulsen and Rubæk (2005) estimate that tile drains on minerogenic "low risk" soils today have loss rates of 20-80 g P/ha and that tile drains on 'high risk' soils with active macropores have loss rates of 100-500 g P/ha. Poulsen and Rubæk (2005) estimate that 85% of tile-drained minerogenic soils are "low risk" and 15% are "high risk". Assuming similar loss rates and a similar ratio between low and high-risk soils in year 1900 as today, total P losses from tile-drained soils would have contributed 21- 94 ton P annually.

9.2.3 Input related to land reclamation

During 1860-1900, about 40,000 ha of land were reclaimed of which 7,500 ha were drained lakes. The remainder was fjords and coastal areas (Hofmeister, 2004). We assume that P losses from cultivation of former fjords and coastal areas were low and on par with losses from "low-risk" minerogenic soils. Lakes, however, have served as sinks in the landscape for particulate P for a long time, and hence draining of lakes may result in increased P losses. We have access to data from one drained lake, the 11 ha artificial Brande Elkraft Sø, which was created in 1910 and drained in November 2013 due to a dam burst (Hoffmann, 2014). Hoffmann (2014) studied the P loss for three months from the lake sediments in augered sediment columns (30 x 30 cm) taken immediately after drainage of the lake. The columns were kept at a temperature corresponding to the average temperature in June, July and August and irrigated with artificial rain at rates corresponding to the average precipitation for these months. Hoffmann (2014) measured an average TP loss of 0.07 kg P/ha from lake sediments under conditions excluding plant growth and with favorable conditions for mineralization. Phosphorus losses from the remaining part of the year were not simulated in this laboratory study. Due to lack of further data from drained lakes, we have additionally included information on P losses from drained organic soils (Table 9.5). At Skovsbjerggård, Volsted and Gøderup, the soils were drained 1-2 years prior to the start of the monitoring, whereas drainage at Fussingø took place several decades before. The P losses from these soils exhibit a large variation with highest losses from the newly drained soils. Based on the data presented here, we estimate the additional annual loading from drained lakes to range from 0.5 to 1 kg P/ha/yr, which translates into 3.75-7.5 ton P annually for all drained lakes in Denmark. Lakes drained during 1860-1900 are located in all geo-regions except Bornholm (no. 9).

Table 9.5. Losses of P monitored from drained organic soils. The soils at Skovsbjerggård, Volsted and Gøderup were drained 1-2 years prior to the start of the monitoring, whereas drainage of the soils at Fussingø took place several decades before (after Andersen et al., 2016).

Location	Soil type	Period	Total-P mg/l	Total-P loss kg/ha	Reference
Skovsbjerggård	Deep peat, pumped	1988/89	0.320	1.2	Hansen et al. (1990)
		1989/90	(avg. 1988-90)	0.9	
Volsted	Deep peat, pumped	1988/89	0.660	7.0	Hansen et al. (1990)
		1989/90	(avg. 1988 – 90)	4.3	
Gøderup	40 cm peat on sand, pumped	1989/90	0.100	1.2	Hansen et al. (1990)
Fussingø, Vest, integrated investigation	Outlet from deep peat area with tile drains and ditches, permanent grass, grazing	1998-2000	-	0.670	Hoffmann & Ovesen (2003)
Fussingø, Øst, integrated investigation	Outlet from deep peat area with tile drains and ditches, permanent grass, grazing	1998-2000	-	0.920	Hoffmann & Ovesen (2003)

9.2.4 Inputs related to grazing animals and surface-applied animal manure

The agricultural sector included 2.6 million livestock units in 1898 (Danmarks Statistik, 1969) with 54% cattle, 16% pigs, 15% horses, 8% poultry and 7% sheep and goats. The livestock density was 0.89 units / ha on land under agricultural use, almost equal to the density of 0.86 units / ha in 2017 (Blicher-Mathiesen et al., 2019). Fresh applications of P on the soil surface excreted by grazing livestock or spread by man from manure storages may cause "incidental" losses of dissolved and particulate P forms in surface runoff when rainfall interacts directly with manure. Rates of P loss are temporarily and spatially very variable depending on the amount of P applied, the P release properties of the manure, the timing of storm events after application and the amounts of runoff generated (Withers et al., 2003). Table 9.6, which compiles results from international studies on incidental P losses, also demonstrates this. The landscape in Denmark, which is characterized by flat terrain or mainly gentle slopes and soils with a relatively high infiltration capacity (especially when covered by grass) and with low intensity rainfall being the most common, suggests that infiltration excess surface runoff would have been rare in 1900. Therefore "incidental" losses of excreted manure from grazing animals and surface-applied manure on arable fields are considered of minor importance around year 1900.

Table 9.6. Examples of total phosphorus (TP) concentration and loss in surface runoff following precipitation on grazed fields.

Location	Precipitation	Surface runoff mm/yr	Stocking rate LU/ha	P concentration mg TP/l	P loss kg TP/ha	Reference
Ohio, USA	+1,000 mm/yr (6- yr avg.)		0.6 LU/ha	< 0.1 mg TP/l	0.1 kg TP/ha/yr	Owens et al. (1989)
UK	12.5 mm/hr for 4 hrs		Lightly grazed		0.08 kg TP/ha per event	Heathwaite et al. (1999)
UK	12.5 mm/hr for 4 hrs		Heavily grazed		2.9 kg TP/ha per event	Heathwaite et al. (1999)
Nebraska, USA	689 mm/yr (3. yr avg.)	39 mm/yr (3 yr.avg.)	Ungrazed ca. 1 LU/ha	1.28 mg TP/l 2.14 mg TP/l		Schepers & Francis (1982)

However, grazing animals were to a lesser extent than today fenced off from streams and lakes. Today, at least 2 m wide riparian buffer zones are mandatory along all natural streams and lakes (> 100 m^2) in Denmark. Where relevant, the buffer zones comprise fences preventing livestock access to surface waters. Mismanagement of fencing of stock can be detrimental to water quality, as demonstrated in many British and New Zealand catchments where cattle activity in and by rivers, particularly trampling (poaching, treading) of river margins with associated defecation, is problematic even today (Wilson and Everard, 2017; McDowell et al., 2003). Line et al. (2000) reported a 76% and 82% decrease in weekly TP and sediment loads, respectively, following livestock exclusion from streams in a North Carolina (USA) catchment. Muenz et al. (2006) compared water quality between three streams without buffer zones and two fenced streams at a farm in Georgia (USA) with a diversified row crop and beef cattle operation. They found lower and more stable concentrations of suspended solids (SS) and dissolved P in the fenced streams; 0.4 mg / l vs. 4.1 mg / l SS and 0.01 mg / l PO_4-P vs. 0.02 mg / l PO_4-P in fenced vs unfenced streams, respectively. Thus, undoubtedly, in 1900 access by livestock to surface waters contributed significantly to total P load in surface waters. Unfortunately, we do not have any means to quantify this contribution.

9.2.5 Input related to soil erosion by water

Water erosion transports dissolved and particulate P from land to water bodies. Today, water erosion on farmland occurs in all regions of Denmark despite the low relief and the typically low to moderate rainfall erosivity in the country. Water erosion varies strongly in space and time depending on complex interactions between factors related to climate, topography, soil and cropping. Erosion modelling involving these factors currently provides the only means of quantifying the risk of soil redistribution by water. The extent of water erosion and sediment delivery to water bodies has recently been estimated by fine-scale spatial modelling for all of Denmark (Onnen et al., 2019). The model is calibrated with data on riverine sediment yields in several catchments in Denmark and characterizes the average erosion risk over a period of about 10 years. With the help of calibration, it is possible to account for landscape- and land use-specific conditions that are not directly represented by the input data. Subsequently, the erosion modelling results have been used to predict erosional P transfer from land to water based on mapped soil P status information and assumptions of sediment P content (Andersen and Heckrath, 2020). However, due to the lack of observational data on such P transfer, the model predictions could not be validated.

In principle, a similar approach could be used for estimating P delivery to waterbodies around the year 1900. However, this would require spatially explicit model input data for all of Denmark being representative of a period of about 10 years around year 1900 of similar quality as in 2019. While topography and soil properties will not have changed very much, most of the other input data are not available in necessary detail. Importantly, data for model calibration are not available either. This makes a sophisticated modelling approach redundant. In the following, it is considered how different conditions around the year 1900 may have influenced the risk of sediment and thus P delivery to surface waters in general.

Climate

Annual rainfall was in general lower around the year 1900 than today (chapter 1), suggesting a lower risk of surface runoff. However, the climate factor of the erosion model is based on hourly rainfall intensity data from several climate stations in Denmark and periods of about 10 years. These data are not available, and it is hence not possible to estimate whether rainfall was locally more or less erosive than today.

Cropping

Different crops and cropping practices affect the erosion risk differently. Erosion risk assessment requires sound information on typical crop rotations. The widespread occurrence of bare fallow and ploughed fields during winter is expected to have increased the risk of water erosion. However, a lower proportion of winter cereals, the absence of maize and especially a larger proportion of grass on farmland compared with today (chapter 5) would have lowered the risk.

Landscape structure and landscape elements

The spatial arrangement of different land uses in landscapes and the landscape structure in general have an essential influence on the soil redistribution by water and sediment delivery to streams. Grassland along streams would act as buffer zones retaining sediment. Likewise, field borders and narrow, vegetated strips between fields act as barriers for runoff and sediment transfer. Smaller fields with greater length of field borders as well as the frequency of riparian grasslands around the year 1900 would have reduced hydrological connectivity in landscapes and hence the risk of sediment transfer.

Soil P content

No historical measurements of soil P are available. However, mass balance calculations for Danish agriculture indicate an average P accumulation in agricultural soils of ca. 1,100 kg P / ha during 1900-1987 (Kyllingsbæk, 2008). The average soil P content measured in 338 Danish agricultural soils in 1987 was, respectively, 526 mg P / kg and 381 mg P / kg in topsoil (0-25 cm) and subsoil (25-50 cm) (Rubæk et al., 2013). A back-calculation suggests an average topsoil concentration of ca. 340 mg P / kg around the year 1900.

Although erosion and sediment delivery to water bodies were possibly lower around the year 1900 than in the early 21st century, it was not possible to quantify by how much. It is therefore our best, albeit rough, estimate to assume the same regional sediment delivery to waters at both times. The potential P load is then calculated assuming a total P (TP) concentration in sediment of 340 mg P / kg (Table 9.7).

Table 9.7. Estimated annual phosphorus input by water erosion to surface waters per geo-region assuming a phosphorus content of 340 mg TP/ kg in the eroded sediment. The regional sediment delivery is based on Onnen et al. (2019).

Georegion	Model-estimated sediment input to surface waters, ton	Model-estimated phosphorus load to surface waters, ton P
1. Thy	8,400	2.8
2. Nordjylland	15,000	5.1
3. Vestjylland	15,000	5.1
4. Himmerland	6,400	2.2
5. Norddjursland	1,500	0.5
6. Midtjylland	14,000	4.7
7. Østdanmark	27,000	9.3
8. Nordsjælland	2,300	0.8
9. Bornholm	2,300	0.8
Total		31.3

Input related to uncovered animal manure storages, farmyards, roads and tracks

Around the year 1900, storage tanks for liquid animal manure and roof-covered manure heaps were uncommon: 28,000 tanks in 1896 and 16,500 roof-covered manure heaps in 1907 (Iversen, 1944), whereas the number of farms and small holdings was 237,000 to which should be added 35,000 holdings without land (Christensen, 1985 and chapter 5). Such unprotected manure storages will serve as local micro point sources of P to surrounding surface waters if connected by a transport pathway. Additionally, farmyards, outdoor areas with high density of traffic (cattle tracks etc.) close to farms where manure will be deposited and where trampling and traffic compact the soil, may serve as local hotspots / point sources. Today, contributions from storage of animal manure are practically eliminated due to improved handling of storage facilities for animal manure. It was also assumed that the contribution from farmyards is lower today compared with around year 1900 due to better handling of manure and collection and treatment of runoff water from impervious surfaces.

Unfortunately, no data allowing proper quantification of the contribution from such micro hotspots in Denmark are available, neither from more recent times nor from around the year 1900. Some examples of P concentrations from such areas monitored recently and reported in studies from UK and USA (summarised in Table 9.8) show that the concentration of P leaving such areas can be very high but also that the variation in concentrations is large. The concentrations leaving similar areas in Denmark would probably be of the same range and variation, but we do not have data on the number and the sizes of such areas and to which extent manure storages, farmyards, roads and tracks were hydrologically connected to surface waters.

Table 9.8. Concentrations of P measured in case studies in the UK and US (Delaware).

Reference	Site description	Country	Total P mg/L	Total dissolved P mg/L	Remarks on measurement
Hively et al. (2005)	Dairy farm, heifer barnyard with heavy manure deposits	Delaware, US	13.2	11.6	Overland flow measurements 1x2 m plots simulated rainfall for 38 mm for 30 minutes, replicated plots 2 time points
Hively et al. (2005)	Cow path leading up from heifer stream crossing	Delaware, US	1.0	0.2	Overland flow measurements 1x2 m plots simulated rainfall for 30 minutes
Edwards and Withers (2008)	Farmyard runoff	Mainly UK	30.8 (0.02-247)	-	33 observations gathered from other sources
Edwards and Withers (2008)	Pig slurry	?	41.1 (39.4-43.6)		Data from Lee et al. (2004), 3 observations
Edwards and Withers (2008)	Road runoff	?	0.3 (0.26-0.34)		2 observations from Mitchell (2001)
Edwards and Withers (2008)	Track runoff	UK	2.7 (0.24-7.3)		13 observations (Withers pers. Com.)
Edwards and Withers (2008)	Dairy cow yards	UK	54 (12-115)	28 (9.82)*	Data from DEFRA WAO523
Edwards and Withers (2008)	Sheep handling areas	UK	13	12*	Data from DEFRA WAO523
Edwards and Withers (2008)	General purpose machine area	UK	3 (0-5)	0.1 (0-0.2)*	Data from DEFRA WAO523
Withers et al. (2009)	Roads	UK	2,030 (61-17,272)	381(4-1,330)*	2 years measurements from 3 micro watersheds, 29 observations
Withers et al.,(2009)	Farmyards	UK	2,710 (72-20,010)	1,108 (61-5,680)*	2 years measurements from 3 micro watersheds, 24 observations

*Dissolved reactive P

9.3 Results and discussion

9.3.1 Stream water concentrations of total phosphorus (TP) around the year 1900

Regional estimates of stream water concentrations of TP are calculated in the following way: first geo-regional TP inputs from diffuse and inland point sources are converted to discharge-weighted average annual TP concentrations by dividing the inputs with annual geo-regional water discharge (average for the period 1890-1910, chapter 3). Secondly, these concentrations are added to the geo-regional background TP concentration estimated in section 9.2.1. Tables 9.9a and 9.9b give an overview of the estimated contributions from diffuse sources and point sources (chapter 4) and the resulting stream water TP concentrations.

Table 9.9a. Estimated P inputs from diffuse sources per geo-region. Minimum and maximum values are calculated, respectively, by assuming no inputs from grazing livestock and manure storages, and by assuming that inputs from these two sources each are at an equivalent size as input from soil erosion.

Geo-region	Soil drainage ton P	Land reclamation ton P	Grazing livestock ton P	Soil erosion ton P	Manure storages etc. ton P
1. Thy	1.3-5.7	0.3-0.5	0-2.8	2.8	0-2.8
2. North Jutland	0.4-1.6	0.3-0.6	0-5.1	5.1	0-5.1
3. West Jutland	1.1-4.7	0.9-1.8	0-5.1	5.1	0-5.1
4. Himmerland	0	0.4-0.7	0-2.2	2.2	0-2.2
5. North Djursland	0	0.1-0.2	0-0.5	0.5	0-0.5
6. Central Jutland	1.5-6.7	0.4-0.8	0-4.7	4.7	0-4.7
7. East Denmark	16.3-72.8	1.4-2.7	0-9.3	9.3	0-9.3
8. North Zealand	0	0.1-0.2	0-0.8	0.8	0-0.8
9. Bornholm	0.6-2.7	0	0-0.8	0.8	0-0.8
Total	21-94	3.75-7.5	0-31.3	31.3	0-31.3

Table 9.9b. Summary of calculations of year 1900 stream water TP concentration. Annual water discharge calculated with the National Water Resources Model (DK-model) forced by historical climate data (chapter 3). Inputs from diffuse sources from Table 9.9a. Inputs from inland point sources from chapter 4 (Table 4.3 includes five major inland towns, data shown here include inputs from additionally 75 inland towns). Increase in TP concentration: The sum of diffuse and inland point sources divided by the annual water discharge. Background TP concentration: Table 9.4.

Geo-region	Area km^2	Annual discharge $1,000\ m^3$	Diffuse sources ton P	Inland point sources ton P	Increase in TP concentration mg P/l	Background TP concentration mg P/l	Resulting TP concentration mg P/l
1. Thy	3,059	838,924	4.4-14.7	0.2	0.005-0.018	0.085	0.090-0.103
2. North Jutland	3,582	1,037,032	5.8-17.5	0.7	0.006-0.018	0.074	0.080-0.092
3. West Jutland	9,972	4,383,591	7.0-21.8	2.9	0.002-0.006	0.043	0.045-0.049
4. Himmerland	4,155	1,236,308	2.6-7.3	0.3	0.002-0.006	0.073	0.075-0.079
5.North Djursland	899	212,630	0.6-1.7	0.0	0.003-0.008	0.050	0.053-0.058
6. Central Jutland	4,412	1,567,855	6.6-21.6	1.6	0.005-0.015	0.019	0.024-0.034
7. East Denmark	15,324	3,282,947	26.9-103.4	4.1	0.009-0.033	0.061	0.070-0.094
8. North Zealand	994	164,726	0.9-2.6	0.5	0.008-0.019	0.066	0.074-0.085
9. Bornholm	589	131,121	1.4-5.1	0.1	0.011-0.040	0.020	0.031-0.060
Total			56.1-195.6	10.5			0.062-0.075[1]

1) Area-weighted average concentration.

The national average stream water TP concentration around the year 1900 was in the range 0.062 – 0.075 mg P/l, which is 60-70% of the present-day stream water TP concentration of 0.1 mg P/l (median of more than 200 stream water stations in NOVANA, Thodsen et al., 2019a).

9.3.2 Comparison of estimated year 1900 stream water concentration values with lake P concentrations estimated in paleolimnological studies and to historical data

Amsinck et al. (2003) analyzed sediment samples representing year 1900 from 17 Danish lakes for diatom subfossils. By applying existing transfer functions, they reached estimates of average annual in-lake TP concentrations at year

1900 (Table 9.10). Average and median TP concentrations for the 17 lakes were 91 µg/l and 78 µg/l, respectively.

Table 9.10. Estimates of average annual in-lake concentrations of TP in Danish lakes around the year 1900 inferred from sediment diatom analysis (Amsinck et al., 2003).

Lake name	Geo-region	Estimated in-lake total phosphorus concentration year 1900 µg/l
Helle Sø	1	175
Møllesø	2	45
Sjørupgårde Sø	4	48
Vallum Sø	5	150
Velling Igelsø	6	15
Vedsted Sø	6	78
Skærsø	6	70
Ormstrup Sø	6	130
Hostrup Sø	7	80
Hvidsø	7	53
Agsø	7	25
Avnsø	7	25
Huno Sø	7	145
Søbo Sø	7	100
Vedsø	7	160
Sønderby sø	7	220
Agersø	8	27

Historical measurements of P concentrations in stream water are extremely scarce. However, Professor T. Westermann collected water samples during November 1889 from several large streams in Denmark. He took care to collect the samples upstream of cities to avoid influence from sewage. The samples were analyzed with an old method whose results we judge to resemble the TP content as measured by today's method fairly well, albeit it has a relatively high detection limit (based on personal communication with Professor Ole Borggaard, Copenhagen University). Due to the elevated detection limit, it was only possible to quantify the P concentration in samples taken during autumn but not from samples taken at other times of the year (Table 9.11).

Seven out of 17 investigated lakes (Table 9.10) have year 1900 TP concentrations lower than today (0.015-0.053 mg TP/l). The remaining lakes have TP concentrations resembling present-day in-lake concentrations (compared withto NOVANA lakes (Johansson et al., 2021). The historical measurements of TP concentrations in streams are, on average, 22% lower than present-day values. The lake sediment studies and the historical stream measurements support our finding that stream water TP concentrations around the year 1900 were lower than today but considerably higher than the background concentration.

Table 9.11. P concentration in water samples collected in November 1889 (Westermann, 1898) compared with water samples collected in November 2013-2017 at the same sampling sites.

	Station id	Geo-region	Westermann (1898) mg TP/l	NOVANA 2013 – 2017 mg TP/l
Gudenå upstream Silkeborg	210087	6	0.090	0.069
Storå	220057	3	0.130	0.122
Kongeå	360009	3	0.090	0.140
Suså	570058	7	0.090	0.119
Outlet Søborg Sø	480010	8	0.070	0.190
Odense Å	450003	7	0.110	0.102

9.3.1 Phosphorus transport to the sea

The around year 1900 discharge is calculated (chapter 3) with the National Water Resources Model (DK-model) forced by historical climate data (chapters 1 and 2) and routed through a network of connected catchments. Average catchment size is 15 km^2, Denmark being subdivided into more than 3,000 catchments. The streams in each catchment are assigned the specific geo-regional year 1900 TP concentration range (Table 9.9b). The monthly stream water TP transport is calculated by multiplying TP concentration by stream water discharge aggregated to monthly values. During transport, P retention in 611 larger lakes is taken into account. Retention is calculated on a per quarter basis as a percentage reduction in input to the lake (Table 9.12). Retention rates are based on a study of 16 shallow lakes (Søndergaard et al., 2001). The overall P retention may, however, be underestimated since small lakes are omitted from the calculation. P retention by sedimentation of particulate P during flooding of riparian areas is not considered due to lack of data.

Table 9.12. Per quarter retention of P in lakes (Søndergaard et al., 2001).

Quarter	Lake P retention, % of input
1	14.3
2	-15.2
3	-13.9
4	14.1

Inputs from direct point sources (coastal cities, chapter 4) are finally added at the outlets to the sea arriving at figures for the total P transport from the Danish land area. Overall, TP transport to the sea around year 1900 was within the range 1,200-1,340 ton P (Table 9.13). Present-day TP loading to the sea is 2,021 ton P (average 2014-2018; Andersen and Heckrath, 2020): thus the around year 1900 TP load constitutes 60-65% of the present-day loading. The total loading to the sea around year 1900 translates into an average TP concentration of 93-104 mg TP / l, which can be compared with a present-day average TP concentration in the total load of 130 mg TP / l (Thodsen et al., 2021). The relatively high around year 1900 TP concentration in the total load compared with today is partly explained by the lower year 1900 freshwater runoff (approx. 12% lower than today, chapter 3). Table 9.13 summarizes the calculations.

Table 9.13. Summary of calculation of total P loading to the sea around the year 1900.

Background concentration	0.050 mg TP/l	Median value, area-weighted average for Denmark (Table 9.4)
Diffuse sources on top of background contribution	56-196 ton P	Table 9.9a
Inland point sources	11 ton P	Chapter 4 and Table 9.9b
Stream water TP concentration	0.062-0.075 mg TP/ l	Average 1890-1910, Table 9.9b
P transport to the sea from inland sources	748-887 ton P	This chapter
P retention in lakes	6-8 ton P	This chapter
Direct point sources (coastal cities)	460 ton P	Chapter 4
Total P loading to the sea AD 1900	1,200 – 1,341 ton P	This chapter
Total freshwater runoff, Denmark	12,855 mio. m^3	Chapter 3
Average TP concentration in total load to the sea	93 – 104 mg TP/l	

9.4 Conclusion

The around year 1900 stream water TP concentration is estimated at to 0.062-0.075 mg P/l, which is equivalent to 60-70% of the present-day stream water TP concentration (0.1 mg P/l). The contribution from inland and direct point sources is estimated to 471 ton P, 65-70% of the present-day value (704 ton P, average 2014-2018). The total around year 1900 P loading to the sea, including background, other diffuse sources, inland and direct point sources and subtracted P retention in lakes, is estimated to 1,200-1,340 ton P, 60-65% of the present-day P loading (2,021 ton, average 2014-2018). The corresponding average TP concentration in the total load to the sea around the year 1900 was 93-104 mg TP/l, 70-80% of the present-day average TP concentration (130 mg TP/l).

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10 Uncertainty and sensitivity

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In this chapter, some considerations on uncertainty and sensitivity are given. For some variables, the considerations have been quantified, but for most variables only qualitative considerations are presented.

Not all aspects concerning the uncertainty and sensibility of the model complex have been sought to be quantified as most of the uncertainty analysis was exempted from the project due to limitation of resources. The uncertainty deals with the degree of certainty / precision to which a parameter, variable or a process can be estimated / determined. Sensitivity is the effect of a parameter, variable or process on the result; in this case, the result is the estimated national nitrogen or phosphorus load to the sea around the year 1900.

The focus on the year 1900 (120 years ago) of course makes most aspects of calculating the national nitrogen load more uncertain than when calculating it for the present. For some variables, present measurements are available, and these can be used either directly for modelling the nitrogen load or as calibration and validation data. For the time around year 1900, much less data on many fewer variables are available. Therefore, parameter and variable value estimates and modelling results are more uncertain for this period. The knowledge of how, for example, the farming systems worked or how point sources were managed around year 1900 is more limited than for the present, and the uncertainty around year 1900 is consequently larger than for the present period (sections 4.3.5 and 5.2). Precipitation data do exist for the period 1890-1910, but as shown in section 1.4 the uncertainty of these data, the associated metadata and other weather / climate data necessary to calculate the corrected precipitation is relatively large, and the data can therefore only be employed as monthly national averages over the entire period. This, of course, introduces a larger regional uncertainty compared with precipitation data with full spatial resolution.

The overall sensitivity is believed to be almost the same for the period around the year 1900 and for the present as the modelling approach for the two periods is almost identical: however, in some model's parameters have proven sensitive to changes in climate (e.g. Melsen and Guse, 2021).

The uncertainty of model outputs increases with both decreasing spatial scale and time scale. Because of the propagation of the error principle, the uncertainty is larger when assessing single / few or small fourth order catchments rather than large or multiple catchments. The same principle is valid when assessing a single month rather than a year or multiple years.

Some uncertainty originates from the model structure of the NNM, which is a complex modelling system with interdependent modules. There is a risk that the ID15-subcatchments (n > 3,000) in a few places are not correctly connected. Also, there is a risk that, in a few places, the routing of the hydrological model (DK-model) and the ID15 map does not match completely. The different modules of the NNM all have an associated uncertainty, and the sequence of calculations influences the model outputs. The NNM and its submodules, will not perform equally well in all fourth order catchments as it does not perform equally well for all catchments upstream monitoring stations (Højberg et al., 2015). The individual modules (sources and sinks) will perform differently across both location and time.

10.1 Quantitative uncertainty and sensitivity - nitrogen

The sensitivity of a few model parameters and input variables was quantified by running the NNM_{1900} with different parameter settings (Table 10.1). These model runs were not originally designed as a sensitivity analysis, however, and therefore only relative changes are presented. Potentially, a sensitivity analysis could have been made for more model parameters, but this was beyond both the scope and the resources of this project.

Table 10.1. Sensitivity of some parameters to the year 1900 modelled (NNM_{1900}) national nitrogen load to the sea.

Baseline	Scenario	Percent change national N load
Natural wetland source area (3 × natural wetland area)	Natural wetland source area (2 × natural wetland area)	6
Natural wetland source area (3 × natural wetland area)	Natural wetland source area (4 × natural wetland area)	-6
Double of present, small lake area	Present, small lake area	2
120% length of present small watercourses	100% length of present small watercourses	1
100% precipitation on Zealand	90% precipitation on Zealand	-4

The natural wetland source area is a relatively sensitive parameter as changing the extent from 3 to 2 or 4 times the natural wetland area changes the N-load by 6% (Table 10.1). The parameter value "*3 times the natural wetland area* "was found through a calibration procedure and is believed to be a good estimate (see section 7.3). The area of small lakes and the length of small watercourses (<2 m width) are shown to represent a relatively low sensitivity. As expected, the precipitation is a relatively sensitive model input variable. The 4% reduction in national nitrogen load originating from a 10% reduction in precipitation on about 17% of the land area is a relatively large uncertainty / sensitivity. However, the nitrogen loss would have been above average from Zealand as both the fraction of agricultural area and the percentage of tile-drained area were larger than the average for the whole country. Therefore, it would be an overestimation to extrapolate this reduction to the whole country. Besides, it is unlikely that precipitation has a large bias for the whole country for the time around year 1900.

The uncertainty of the NNM is tested in Højberg et al. (2015). The nitrogen load error is reported to deviate 2% from the measured load across 169 monitoring stations covering 57% of the Danish land area for the period between 1990 and 2010. The mass balance error is larger for individual years –31% to 15% (measured – simulated) / measured x 100%) – and at smaller geographical scale. The version of the NNM is not the same in this study as in Højberg et al. (2015), but the uncertainty is believed to be comparable, the main difference is the inclusion of the “natural wetlands” module. The uncertainty of a newer version of the NNM_{2020} (Højberg et al., 2021) also including the natural wetlands module is comparable to the Højberg et al. (2015) NNM_{2015} version. It is not possible to make a direct comparison between the $NNM_{present}$ used in this study and the measured loads for the period 1990 with 2010 because the root zone N leaching in this study only represents 2011 and not the continuous period 1990-2010.

10.2 Qualitative uncertainty and sensitivity -nitrogen

Evaluation of qualitative uncertainty and sensitivity is provided in Table 10.2. The uncertainty of variables varies according to the knowledge and assumptions on which both the year 1900 and the present period are based. Climate inputs are based on observations from around the year 1900 period, though for precipitation a “delta change” procedure based on 1990-2010 gridded precipitation is used. Year 1900 temperature observations are thought to be relatively certain as a thermometer is easy to read and quite accurate, while for example wind data are given in a visual, Beaufort-like, scale and have a large uncertainty compared with presently observed wind speed. For the year 1900 precipitation, a delta change approach (see section 1.3.8), with the 1990-2010 precipitation as a baseline, is used, meaning that the relative geographical precipitation pattern is almost identical for the two periods. This is probably not the case in reality. Therefore, it is likely that regional/local biases (both over- and underestimations) are introduced, but the locations and amounts are unknown. These biases are transferred to the rest of the NNM_{1900} and the model results.

N leaching from the root zone is estimated from land use documented in agricultural statistics from 1896 and 1900 at the church parish level combined with measurements from recent experiments with around year 1900-relevant N concentrations in root zone percolates. As the parish boundaries have remained almost unchanged since the time around year 1900, the parish probably represents the most conservative land area unit; the present study relies on 1766 parish units. The estimated N concentrations for root zone percolates for the land use categories autumn- and spring-sown crops, grass-clover and root crops are derived from well-monitored field experiments under organic farming regimes and with an animal stocking density of 0.9 unit/ha. Although organic farming excludes the use of mineral fertilisers and chemical plant protection measures, the present crop varieties are superior compared with those used around year 1900. Further, a large part of the animal manure around year 1900 was applied at times associated with a substantial possibility of N leaching losses. The increased N use efficiency associated with modern crops grown on well-drained soils and spring application of animal manure leads to higher yield levels than around year 1900. The higher N use efficiency recorded in current organic field experiments with year 1900-relevant stocking density may lead to underestimation of N leaching for the agriculture around year 1900. However, an inferior quality of manure associated with the low productivity around year 1900 animal husbandry may counterbalance this discrepancy.

The main uncertainties in relation to point sources for N and P are investigated in section 4.3.5. The most important factors are identified as the initial load of nutrients from human and animal excrements and the minimum population required (>5,000 in habitants) for inclusion of towns in the assessment.

Of these, changes in the initial load of nutrients in animal and human excrements affected the resulting nutrient emissions most significantly; thus, changing the baseline value between +/- 25% resulted in a +/- 30% change in emissions (see chapter 4.)

Even though there is a rather large uncertainty regarding the emissions from individual towns, the values are, as such, a qualified indication of the magnitude of nutrient loads from point sources around year 1900 and a robust national estimate of emissions.

As the point sources constitute a minor contribution to the total nitrogen load in the NMN model (2,500 out of 36,000 ton), it is assumed that the uncertainty regarding the point sources has a small effect (sensitivity) on the estimated total N load (Table 10.2).

The national hydrological model (DK-model) was used for simulation of current and around year 1900 conditions of stream discharge and nitrogen retention in groundwater. For the current conditions, the model was calibrated against observations of head and stream discharge (water and nitrogen) data covering a period of 20-30 years. The hydrogeology properties are not expected to change, except for the near surface geology in the – -since then – urbanised areas. The overall effect of these changes is assumed to be insignificant in this context. The two main sources of uncertainty related to change in groundwater transport are the year 1900 climate input and the year 1900 drainage conditions. Uncertainty related to the year 1900 climate input is partly dealt with using the delta change approach, where the nationwide change in precipitation is assumed to be equally distributed across the entire country.

Today, a large part of the water and nitrogen load to streams flows through the tile drainage system, where no denitrification is assumed to take place once the water has entered the tile drains. For the present-day situation, almost all areas that need drainage are covered by tile drainage, which makes it relatively easy to simulate in a hydrological model, but this was not the situation around year 1900. Both density and the drainage type affect the nitrogen load to the streams, and they are both subject to high uncertainty for the year 1900 period. The water balance errors simulated using the best estimate of drainage density and precipitation for the period just after year 1900 indicate that the drainage density used in the hydrological simulations might have been overestimated for Zealand plus islands and underestimated for the western part of Jutland. (Table 3.10).

This could be the case as changes in drainage density could impact the groundwater table and thus the evapotranspiration (the lower the density, the higher the evapotranspiration) and that this might play an additional factor in the East-West water balance error differences.

The surface water nitrogen retention modules are also associated with uncertainty. Thus, all modules have a model uncertainty (e.g. as to kg/ha retention) and an uncertainty originating from the applied maps (e.g. whether the length of a stream in an ID15 catchment is the same on the map as in reality). On top of these uncertainties, there is uncertainty concerning the assumptions made about the changes between the two periods; for example, it is assumed that the area of the year 1900 small lakes was double that of the present area. The uncertainty of both the model and the applied maps is, by way of example, believed to be smaller for larger lakes than for small lakes (Table 10.2) as the applied model for larger lakes is considered the better model, and the knowledge of which lakes existed in the year 1900 is also more extensive for larger lakes.

Table 10.2. Qualitative uncertainty, sensitivity and known bias of parameters involved in calculating the national nitrogen load around year 1900. Uncertainty = separate parameter uncertainty. Sensitivity = the sensitivity of the national nitrogen load to a bias of the given parameter. Comp. present is the around year 1900 uncertainty compared with the present period uncertainty. x = small uncertainty/sensitivity; xx = medium uncertainty/sensitivity; xxx = large uncertainty/sensitivity. + = little-, ++ = medium-, +++ = much larger uncertainty for the around year 1900 period than for the present period, equal = uncertainty is about the same for the present and the around year 1900 period.

Parameter	Uncertainty	Sensitivity	Comp. present	Comments
Climate				
Corrected precipitation	Xx	xxx	+++	Uncertainty primarily connected with regional precipitation pattern.
Temperature	X	x	+	
Solar radiation	Xx	x	+++	
Wind speed	Xxx	xx	+++	New method for estimating wind speed gives a 2.7% bias on corrected precipitation compared with the used values.
Potential evaporation	Xx	xx	++	
Nitrogen sources				
Root zone N leaching (agriculture)	x	xxx	+	Uncertainty almost as today but with some differences in agricultural management – see text.
Root zone N leaching (other)	xx	xx	Equal	Only a few measurements exist.
Atmospheric deposition	xx	x	+++	The main uncertainty on the atmospheric nitrogen deposition around year 1900 originates from the emission scenarios. The uncertainty on the year 1900 nitrogen deposition is substantial (Thomas Ellermann, Aarhus University, pers. comm.).
Organic nitrogen	xx	xx	++	
Point sources	xx	x	+	The historical loads and urban pathways of nutrients are highly uncertain at local scale, although robust at national scale.
Runoff	xx	xxx	+++	Primarily depending on drainage, the corrected precipitation and potential evaporation. Larger uncertainty regionally than nationally.
Land use				
Agricultural area	x	xxx	Equal	As today.
Nitrogen retention				
Groundwater	xx	xxx	+++	Larger regional uncertainty, originating from regional uncertainty on drainage and precipitation, affecting primarily runoff and secondary possible denitrification in the drainage system.
Small lakes	xxx	x	++	Some uncertainty on the estimates of year 1900 lake area and Nret rates.
Streams	xx	x	+	
Natural wetlands	xx	xx	+	
Rivers	xx	x	+	
Larger lakes	x	xx	++	

Parameters not included in the NNM			
Meadow irrigation	xx	x	Not included in the NNM. There would be a substantial uncertainty about potential modelling results, and the sensitivity would be small as meadow irrigation only occurred on about 10,000 ha in the year 1900 (Rasmussen, 1964). There is, though, a small bias, as N retention is likely to have taken place on meadow-irrigated areas, primarily river valleys in heath areas in central and western Jutland, fed by stream water with relatively low nitrogen concentrations.
Modelling approach	x	x	As the NNM_{1900} and $NNM_{present}$ are near parallel/identical approaches, there is little relative difference in uncertainty or sensitivity between the two. As a "delta change" method, based on a separate estimate of the present nitrogen load is applied for estimating the year 1900 nitrogen load to the sea, there is little sensitivity in the modelling approach.

The surface water nitrogen retention calculations are not expected to have serious geographical biases. However, the development, between 1900 and the present as to, for instance, the area / number of small lakes will differ substantially between, for instance, intensely agricultured areas (expected large change) and a more or less unchanged heathland (expected low change). As the same modelling approach and the same map inputs (except for natural wetlands) are used for both time periods, the uncertainty is believed to be comparable between the two. For natural wetlands, two separate estimates of the wetland area are applied, which in itself introduces some uncertainty, but this uncertainty is believed to be compensated for by avoiding introducing an assumed change in wetland area.

Generally, the sensitivity is dependent on the size of the nitrogen source / sink and with the major components of the water balance. Therefore, the root zone leaching, the ground water nitrogen retention, the precipitation and the runoff are the most sensitive parameters / parts of the modelling complex.

Comparing the uncertainty of the around year 1900 nitrogen load (as presented in section 8.3.2) with the 1990-2019 load (Thodsen et al., 2021), the around year 1900 load has a larger uncertainty. Because of the delta change approach, the larger uncertainty originates from the larger uncertainty on the NNM_{1900}, originating from the larger uncertainty on model input data, than for the $NNM_{present}$ (Table 10.2). The difference between the year 1900 nitrogen load (as presented in section 8.3.2) and the 1990-2019 load (Thodsen et al., 2021) is therefore only attributed to the difference between NNM_{1900} and the $NNM_{present}$ and the differences in point sources. The 1990-2019 national nitrogen load estimate also has an uncertainty originating from laboratory and hydrometric field measurements and data interpolation uncertainties (estimated to 4-7%, Søren E. Larsen, pers. comm). Besides this uncertainty, uncertainties from data management errors, model uncertainty for models used in ungauged areas and some dependency on the chosen load estimation method add to the overall uncertainty. However, as stated earlier, the difference between the NNM_{1900} and the $NNM_{present}$ is independent of these uncertainties as well as the uncertainties existing in equal measures in both the NNM_{1900} and the $NNM_{present}$ model.

10.3 Uncertainties on phosphorus load around year 1900

The phosphorus load calculation around year 1900 (chapter 9) relies on the assumption that the background TP concentration can be inferred from present-day measurements in streams draining catchments with low anthropogenic impact. However, there is a risk that present-day measurements in even relatively undisturbed catchments overestimate the background TP concentration since some level of anthropogenic contamination is unavoidable, at least in densely populated, highly cultivated Denmark. A few studies from neighboring countries with similar geology report background concentration values that are generally lower but in the same order of magnitude as the background estimates presented in this report (Table 9.3). The background TP concentration estimate is considered medium uncertain. Since the background load dominates the total diffuse P load, it is therefore assumed that the uncertainty on the background concentration has a high effect (sensitivity) on the total P load estimate (Table 10.3).

Estimation of contributions from other sources than background is hampered by limited and fragmented knowledge of farming practices around year 1900, including handling of manure and fencing of livestock. The quantification of P transfer from agricultural land to surface waters along different transport pathways (tile drains, erosion) is even today associated with many difficulties and large uncertainties (Andersen and Heckrath, 2020). These difficulties persist in the attempt to quantify P losses around year 1900.

The overall size and the spatial distribution of the artificially drained area around year 1900 are uncertain. No data exist on P leaching from drained soils around year 1900. Alternatively, present-day leaching estimates were used. For P leaching through the soil matrix pore system, this was justified by the fact that even today, the P concentrations at tile drain depth are generally very low and close to the concentration in uncultivated soils. For macropores where P losses are mobilized from the topsoil, this was justified by the year 1900 practice of applying most of the animal manure in the autumn and winter period, i.e. the period for macropore flow.

A major P input around year 1900 was undoubtedly caused by access of livestock to surface waters. Unfortunately, no data are available to quantify this input, which makes our estimate very uncertain. We attempted to estimate the order of magnitude by equating the importance of this source to water erosion of cultivated fields.

For water erosion of agricultural fields, use of a regular modelling approach was not possible due to lack of historical data. Therefore, through a number of considerations, the same sediment input to streams as today is assumed. This was combined with an average year 1900 topsoil P content back-calculated from the present-day soil P content minus the estimated P accumulation in agricultural soils since 1900.

Uncovered manure storages, farmyards and outdoor areas with high density of traffic (cattle tracks etc.) may serve as local hotspots / point sources if connected to surface waters by a hydrological transport pathway. No data are available to allow a proper quantification of the contribution from such micro hotspots, making the estimate very uncertain.

Compared with the N load, point sources contribute a relatively large fraction of the total P load to the sea (471 ton out of 1,200-1,340 ton, see chapter 9);

therefore, it is assumed that the uncertainty on the point sources has a medium effect (sensitivity) on the estimated total P load (table 10.3)

Overall, the estimates of the various diffuse P inputs are considered medium to highly uncertain. Still, the lake sediment studies and the historical stream measurements reported in section 9.3.2 support our finding that the stream water TP concentrations around the year 1900 were lower than today but considerably higher than the background concentration.

Table 10.3. Uncertainty, sensitivity and bias of parameters involved in calculating the national phosphorus load around year 1900. Uncertainty = separate parameter uncertainty. Sensitivity = the sensitivity of the national phosphorous load to a bias of the given parameter. x = small uncertainty/sensitivity; xx = medium uncertainty/sensitivity; xxx = large uncertainty/sensitivity. Known bias positive (+) or negative (-)

Parameter	Uncertainty	Sensitivity	Known bias
Climate			
Precipitation	xx	xxx	
Temperature	x	x	
Solar radiation	xx	x	
Wind speed	xxx	xx	
Potential evaporation	xx	xx	
Point sources	xx	xxx	
Runoff	xx	xxx	
Phosphorus concentration/load			
Background TP concentration	xx	xxx	+
Soil drainage	xx	x	
Land reclamation	xx	x	
Grazing livestock and surface-applied manure	xxx	x	-
Soil erosion	x	x	
Manure storage, farm yards etc.	xxx	x	-
P retention in lakes	xx	x	
Not included retention by flooding of riparian areas	xx	x	

10.4 References

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11 Synthesis of results

Background

The nutrient load from land to the sea around year 1900 has been estimated considering the various factors affecting the nutrient inputs and transport based on data from that time, literature, comparative analysis methods and modelling tools. The main factors to consider include climate, hydrology, land use, agricultural practices and drainage, urban development and landscape (e.g. nutrient retention in groundwater, wetlands, lakes and streams). The ambition was to use as much data and information as possible from around year 1900 considering the quality and representativeness and use modelling and GIS tools to provide a geographically distributed estimate of total nitrogen (TN) and total phosphorus (TP) concentrations and the load from the root zone to the sea.

Climate

The climate was colder and drier around year 1900 compared with the present-day. The estimated average annual precipitation around year 1900 was about 60 mm, or 7% lower than today. Digitized climate data from around year 1900 at observation points across the country, including temperature, wind and rainfall, were used to find monthly values of bias-corrected precipitation. The correction approach was evaluated for the period 1917-1950 using water balance modelling of discharge. At national level, a water balance error of 3 % indicated reasonable correction estimates, but large regional differences in error level was found. To obtain spatially distributed corrected precipitation for the period 1890-1910 a delta change climate factor approach was used. In this approach national monthly correction factors were calculated based on corrected precipitation for 1890-1910 compared with 1989-2010. These national factors were then applied to the present daily corrected precipitation assuming a similar geographical distribution of precipitation around year 1900 as in the present time reference period (1989-2010) to provide a spatially distributed daily time series of precipitation for the period 1890-1910.

To be able to model nitrate leaching, global radiation and potential evapotranspiration must be calculated. By using the measured minimum and maximum air temperatures for 1890-1950, the global radiation and potential evapotranspiration can be calculated and used in the simulation of nitrate leaching in this period. The modelled global radiation and potential evapotranspiration around year 1900 are in good agreement with values measured at Foulum from 1987-2013.

Hydrology

The total discharge based on these precipitation estimates, and drainage density estimated for the historical time was on average 292 mm / yr for the period 1890-1910 compared with 333 mm / yr for the present period (1990-2010) as calculated by the hydrological model (DK-model, chapter 3). After applying a delta change method, the total discharge is recalculated to 335 mm / yr for the present period and 297 mm / yr for the year 1900 period (chapter 8). This means that for the total average, annual discharge was about 11% lower around year

1900 compared with the present time. The change in discharge for the two periods largely reflects the changes in precipitation but is amplified in some areas due to the lower density of drainage in the historical period. The calculated change in discharge comparing the present to the time around year 1900 was found to be 0-20% for most of the country, which agrees with the trend analysis of long discharge time-series presented in Jensen (ed.) 2017. However, for the western part of Zealand observed data indicate an increase in discharge between the two periods of approximately 30%, while the simulation resulted in a decrease in discharge of approx. 5%. The methodology used implies that the total discharge to the sea may resemble the conditions around year 1900, but it cannot be expected to reproduce the local conditions at that time.

Nutrient inputs

The nitrogen reaching the sea from land mainly originated from agricultural activities and dwellings across the country around year 1900. For phosphorus, the main inputs were natural background loading (mainly from groundwater and erosion of stream banks) and direct point sources, i.e. coastal cities.

Agriculture

The area in agricultural use increased dramatically during the last half of the 19th century and accounted for close to 3/4 of the area under Danish administration around year 1900. Crop production differed significantly from current agriculture for virtually all growth factors: inferior crop varieties, higher weed pressure, lack of chemical crop protection and inferior plant nutrient supply, including the absence of mineral fertiliser. The main sources of nutrients were solid farmyard manure, liquid manure and nitrogen fixation by legume crops. The number and categories of livestock as well as the farm structure and management practices around year 1900 also differed from today's practices.

Parish level statistics from around year 1900 for the area under current Danish administration were unified into eight categories (winter and spring crops, grass, root crops, fallow, nature and forest), and for each category a nitrogen concentration was ascribed to the root zone percolate. The nitrogen root zone concentrations were set using data from studies of organic farming as a proxy for the past-time situation. Literature data were found for the remaining categories. These values were applied in the nitrogen modelling. The calculation of the area-weighted average nitrogen concentration for land in agricultural use (78% of the land area) resulted in a value of 12 mg N/l, while the value in root zone percolate (inorganic nitrogen) for the entire land area was 9.6 mg N/l.

The estimation of agricultural sources for phosphorus considered factors such as soil drainage, land reclamation, grazing animals, soil erosion and manure storage. These factors were difficult and uncertain to determine, leading to an estimated range from 56 to 196 ton P annually around year 1900.

Point sources

Sewer systems were increasingly implemented in towns, but still without wastewater treatment in year 1900. Therefore, towns acted as significant point sources around year 1900, with 4,261 ton N/yr and 764 ton P/yr emitted in excrements from humans and animals and industrial wastewater. These figures indicate that most of the nutrients from point sources were discharged directly to receiving waters (55%), but emissions to landfills (20%) and agricultural soil (25%) were significant as well. The total contribution from inland and direct point sources to water was estimated to 471 ton P, about 65-70% of the present-day value (704 ton P, average 2014-2018) and 2,531 ton N, about 47% of the present-day TN point sources (5,400 ton N, 2020).

Other sources including background nutrient concentration

Nitrogen inputs from the atmosphere were estimated by multiplying EMEP simulations for year 2000 by 0.3 (Jensen (ed.), 2017). Organic nitrogen originating from landscape sources and internal surface water sources was included to be able to calculate total nitrogen concentrations. Estimates based on literature studies assume that the organic nitrogen concentration around year 1900 was about 20% below the current levels. Furthermore, it is assumed that the current geographical distribution of organic N is valid for the time around year 1900.

A literature review and measurements from largely undisturbed streams allowed estimation of background TP stream concentration, and an area-weighted TP median value at 0.052 mg/l was estimated.

Nutrient transport to the sea

Nitrogen percolates through the soil and reaches the groundwater where reduction (retention/removal) of nitrogen under oxygen-free conditions takes place before the remaining nitrogen ends up in surface waters (wetlands, lakes, streams). The National Nitrogen Model simulates transport and retention in groundwater based on water discharge and the nitrogen percolate input. The surface water component calculates the nitrogen retention in wetlands, streams and lakes, while also considering point source inputs, atmospheric inputs and the contribution of organic nitrogen. Landscape changes between the time around year 1900 and the present time were handled by modifying the current landscape maps based on various information sources on the past landscape related to rivers and lakes. For wetlands, different maps were used.

The phosphorus load calculation was based on total phosphorus considerations and used an approach of a ”background” or ”nature” concentration level, on top of which the relevant additional agricultural and point sources were added and retention in lakes was subtracted. The transport and routing of phosphorus through the catchments were simulated using the same water discharge as in the nitrogen modelling.

The nitrogen retention in inland surface water was shown to be higher in the present period (28,000 ton N) than in the 1900 period (26,000 ton N) due to a larger present-day nitrogen load. However, the relative nitrogen retention was higher around the year 1900 as 43% of the load was removed compared with 33% for the present period.

The total nitrogen load is modelled to be approximately 36,000 ton N/yr around year 1900, which is approximately 42% less than for the present period (59,000 ton N/yr). The nitrogen concentration is modelled to be around 2.8 mg N/l around year 1900 compared with 4.1 mg N/l in the present period. The national nitrogen model yields regional results, which are utilised for estimating regional year 1900 nitrogen and freshwater loads.

The average stream water phosphorus concentration around year 1900 was estimated to 0.062-0.075 mg P/l, equivalent to 60-70% of the present-day stream water TP concentration (0.1 mg P/l). The TP values were calculated for nine geographical regions across the country. The total TP loading to the sea, including background concentration, other diffuse sources, inland and direct point sources and subtracted phosphorus retention in lakes, was estimated to 1,200-1,340 ton P, 60-65% of (or 35-40% less than) the present-day phosphorus loading (2,021 ton, average 2014-2018).

Uncertainties

Working with a period 120 years ago naturally makes most aspects of calculating the national nitrogen and phosphorus load more uncertain than when calculating it for the present period. An in-depth analysis of uncertainties of data layers, variables, model and model assumptions was not a part of the present study however, some considerations regarding uncertainty and sensitivity (the effect of a given parameter on the result) have been made.

Most of the parameters used to estimate the nitrogen loads around the year 1900 are considered to have “medium” uncertainty (on a three-step scale from low to high). The uncertainty of the nitrogen loads is influenced by a variety of factors, the most important being the uncertainty of the estimates of precipitation, run-off, root zone concentration of nitrogen and retention in surface and groundwater.

Overall, the model concept used to calculate the year 1900 nitrogen load is considered relatively robust and the overall uncertainty at national scale acceptable. However, the uncertainty increases with decreasing geographical- and timescales.

Most of the parameters used to estimate phosphorus loads are considered “medium” to “highly” uncertain. The uncertainty of phosphorous loads is especially influenced by the uncertainties of the estimates of precipitation, run off, P input from point sources and the background TP concentration. Despite the many uncertainties the results of this study are believed to be the best possible estimate of the year 1900 phosphorous loads. Furthermore, the results are supported by historical lake measurements that also find the historical TP-concentrations to be lower than today but considerably higher than the background concentration, though.

12 Perspectives of results

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12.1 Comparisons to other root zone nitrate leaching studies

Mean annual nitrate leaching from agriculture is modelled to about 40 kg N / ha in year 1900, based on measurements in modern organically farmed crop rotations similar to those around 1900, with nitrate concentrations in leachate of 12 mg N / l and the distributed year 1900 percolation as calculated by the hydrological model. For the present period (2007) the comparable value is about 58 kg / ha (Børgesen et al. (eds.), 2009). This is comparable to the concentrations determined in the Agricultural Catchment Monitoring Program (LOOP) during 2004 / 05-2015 / 16 of 14 mg N / l (Blicher-Mathiesen et al., 2019) and lower than the 1990 / 91-93 / 94 mean number of 28 mg / l. As nitrate leaching is closely connected to drainage volume (Blicher-Mathiesen et al., 2019), the same concentrations in year 1900 would lead to lower leaching losses than today. For south and central Sweden, similar results were found by Hoffmann et al. (2000) when comparing nitrate leaching in the late part of the 19th century to the 1980s. They found that specific leaching rates were approximately the same as those today using the SOIL / SOILN model to calculate N leaching.

Opposite to the two studies for Denmark and Sweden, a study for the UK found that modelled annual N loss by leaching, runoff and soil erosion increased from 15 to 52 kg N / ha in arable farming in the periods 1800-1950 to 1970-2010 and from 18 to 36 kg N / ha in grassland for the same periods (Muhammed et al., 2018). Arable and grassland leaching were modelled and calibrated separately on data from the Broadbalk and Park Grass long-term experiments for arable and permanent, semi-natural grassland, respectively, during 1800-1950. This setup was chosen as only after 1950 semi-natural grassland was converted to improved grass and arable land (Muhammed et al., 2018). This situation is very much different from the conditions in Denmark, where in year 1900, 69% of the total grassland area was in rotation with arable crops (Danmarks Statistik, 1968). As grassland cultivation is a main source of N leaching when combined with bare fallow and winter cereals (see chapter 5), these differences in crop rotations between UK and Denmark / southern Sweden probably explain the differences in historical nitrate leaching.

The N surplus as calculated from simple input / output to Danish agriculture was estimated to 28 kg N / ha in year 1900 in a previous study (Kyllingsbæk, 2008). This cannot be directly linked to losses for several reasons (Christensen et al., 2017), one being that it does not include mineralisation of the soil organic N pool, which was estimated to 39-67 kg / ha in the UK study for 1800-1950 (Muhammed et al., 2018). Furthermore, in Kyllingsbæk (2008) biological N_2 fixation by legumes in grasslands was estimated to 50 kg N / ha, which seems to considerably underestimate the N input from this source. As average of two soil types during 1907-1922, the yields of grass-clover leys in animal-manured plots of the Askov long-term field experiments were 4,765 kg DM with 42% clover (Iversen and Dorph-Petersen, 1951). Using an empirical model (Høgh-Jensen et al., 2004) for grass-clover leys, the N2-fixation based on the Askov yields and legume contents can be estimated to 117 and 183 kg N / ha for clay and sandy soil, respectively. This gives an average input of 150 kg N / ha, which is three times higher than the estimate from the balance by Kyllingsbæk (2008).

12.2 Comparisons to other river load studies

This section provides a few comparisons to other studies attempting to estimate the year 1900 riverine nitrogen concentrations or loads.

Danish studies

Jensen (ed.) (2017) conducted a study, to which some of the authors of this report contributed, estimating the Danish riverine concentrations in year 1900 using several approaches. In contrast to the present study, Jensen (ed.) (2017) did not attempt to estimate any loads (national, regional or local) or to calculate monthly N concentrations / loads but estimated a national N concentration range of 1.2 to 2.2 mg N / l (rounded off to 1-2 mg N / l). This range is based on a total retention range of 76-87% for 1900 and an average leaching concentration of 9.25 mg N / l. In this study, the total retention rate was estimated to 78% (Table 7.10) and thus the higher end of the concentration range at 2.0 mg N / l. However, the estimate of Jensen (ed.) (2017) is only based on nitrate leaching through soils and retention in groundwater and surface water and does not consider the organic nitrogen fraction. Including the organic fraction would increase the total nitrogen concentration by approximately 0.5 mg N / l, as calculated for 1900 in this study (chapter 6). This would increase the total N concentration range in Jensen (ed.) (2017) to 1.7-2.7 mg N / l, ending up 2.5 mg N / l using the 78% total retention rate found in this study. In Jensen (ed.) (2017), point sources were considered to be small and therefore not quantified. However, in this study point sources have been quantified to about 2,500 ton N / yr, which corresponds to about 0.20 mg N / l (with no retention on inland point sources). Thus, if including point sources, the Jensen (ed.) (2017) estimate range rises to 1.9-2.9 mg N / l. The total load concentration of 2.8 mg N / l modelled in this study thus falls within the range of the Jensen (ed.) (2017) range corrected for the organic nitrogen fraction and point sources.

Jensen ed. (2017) (see Figure 5.5) uses a relation where the annual nitrogen surplus in Danish agriculture between 1990 and 2014 is used for calculating the normalised diffuse nitrogen concentration for 1900 (note that the equation as presented in Jensen (ed.) (2017) is not correct, a corrected version is presented below). Jensen (ed.) (2017) gets a diffuse nitrogen concentration between 2.0 and 2.2 mg N / L using a nitrogen surplus around year 1900 (agrohydrological year (1 April to 31 March) 1900-01 – 1903-04) ranging between 69,000 ton and 87,000 ton (Kyllingsbæk, 2008). However, the Kyllingsbæk (2008) estimate of the year 1900 nitrogen surplus is underestimated due to the use of too low N fixation rates (see section 12.1). A new nitrogen balance was calculated based on Kyllingsbæk (2008) (graphs read with graphreader.com) and multiplying the fixation amount by three. In the new estimate based on the exact agricultural year 1900-1901, the nitrogen surplus is about 176,000 ton N. Using the range of the period 1900-01 to 1903-04, as in Jensen (ed.) (2017), the nitrogen surplus is about 216,000 ton N. Based on an updated version of Figure 5.5 in Jensen (ed.) (2017), the above-mentioned relation (updated equation, diffuse N concentration = 0.0106 x nitrogen surplus + 1.486; as in Jensen (ed.) (2017) 1995-96 is omitted from the dataset) yields a year 1900-1901 diffuse nitrogen concentration of 3.3 mg N/l. Again, the year 1900 point source concentration of about 0.20 mg N/l needs to be added to obtain the total load concentration of about 3.5 mg N/l (Table 12.1). Note that the national farm nitrogen surplus estimate for the present has changed a little due to a change in method (Blicher-Mathiesen et al., 2015). Also note that this approach is an extrapolation of an empirical relation, which is a method with considerable uncertainty, as mentioned in Jensen (ed.) (2017). The results in Table 12.1 are comparable to the 2.8 mg N/l concentration and 36,000 ton N/yr load to the sea calculated in this study. The results presented here are in the middle range of the estimated loads shown in Table 12.1.

Table 12.1. Agricultural field nitrogen surplus year 1900 and corresponding diffuse and total river nitrogen concentrations and total nitrogen load to the sea. *Total concentration is diffuse + 0.2 mg N/l from point sources. [1]is the low limit, and [2]is the high limit of the agricultural nitrogen surplus range given in Kyllingsbæk (2008) for the period 1900-1901 to 1903-1904. [3] is the low limit, and [4]is the high limit of the recalculated agricultural nitrogen surplus given in Kyllingsbæk (2008) but with a corrected nitrogen fixation component for the period 1900-1901 to 1903-1904. See text above for more information.

Agricultural nitrogen surplus Ton N/yr	Diffuse nitrogen river concentration mg N/l	Total nitrogen river concentration* mg N/l	Year 1900 runoff mm	Total nitrogen load to sea ton N/yr
0	1.5	1.7	297	22,000
69,000[1]	2.2	2.4	297	31,000
87,000[2]	2.4	2.6	297	33,000
176,000[3]	3.3	3.5	297	45,000
216,000[4]	3.8	4.0	297	51,000

European studies

Savchuk et al. (2008) ran the SANBALTS (marine model) to simulate annually averaged coupled nitrogen and phosphorus cycles in the major basins of the Baltic Sea around year 1900 (“a century ago”). As the riverine nutrient forcing the assessment by Schernewski and Neumann (2005) is used, they estimate background inorganic (DIN) concentrations from the 15 largest rivers around the Baltic Sea. They report year 1900 (“about one century ago”) DIN concentrations between 0.06 mg/l in northern Sweden and Finland and 1 mg/l in the Vistula and Oder rivers in Poland/Germany; no TN concentrations are given. However, the TN concentration will be >1 mg/l in Oder and Vistula as the DIN concentration is given as 1 mg N/l, and there is always an organic fraction. None of the 15 rivers are Danish. The German/Polish catchments are probably the ones that are most comparable to the Danish catchments because of the similarities in climate and agricultural use (more comparable than most other parts of the Baltic Sea catchment), even though the Oder and Vistula catchments have mountainous upland areas and more forest than the Danish catchments around year 1900. Gadegast et al. (2012) reports 24% forest in the Oder catchment, for Denmark the corresponding figure is about 7% (section 5.2). Therefore, the concentration in the Oder is expected to be lower than the 2.8 mg N/l for Denmark, the difference is relatively large, though. Savchuk et al. (2008) reports around year 1900 nitrogen loads for the “Danish straits” of 27% and for “the Kattegat” of 31% of contemporary loads (1997-2003). These results are as mentioned above based on Schernewski and Neumann (2005). However, to some degree, the results contrast the recognition of Savchuck et al. (2008) of the Hoffmann et al. (2000) paper that states that the N leaching from agriculture in southern Sweden was about the same around year 1900 (and in the mid-19th century) as in the late 1990s.

From the water discharge data presented in Schernewski and Neumann (2005), a runoff of 177 mm/yr can be calculated for the Oder River (1970-1990). This is about half of the 2008-2019 runoff from Denmark, 335 mm/yr. In itself, the difference in runoff probably yields a difference in nitrogen load as the amount of runoff and the soil water percolation will be closely linked, as will the percolation and the soil nitrogen leaching. The dependence of the annual nitrogen load on the annual runoff is clear in the Danish assessment (Thodsen et al., 2021).

Gustafsson et al. (2012) calculated monthly mean river flows for the period 1850-2009 to the Baltic Sea. The N loads around year 1900 are based on Savchuk et al. (2008) but with reevaluated point source contributions from larger coastal cities, however, how this affects the nitrogen load is not discussed.

Gadegast et al. (2012) modelled the change in nitrogen emissions into the Oder River system (136,528 km^2) between 1875 and 1944 using the MONERIS model (Venohr et al., 2011). During this period, the Oder watershed was part of Germany but is now mostly part of Poland. The climate is comparable to Denmark, though drier and with a more continental temperature regime. The geology, especially in the northern part of the Oder basin, is comparable to that of Denmark, while the southern parts contain some mountainous landscapes, which are not present in Denmark. Gadegast et al. (2012) found that the load about doubles from 25,300 ton N/yr in 1880 to 46,600 ton N/yr in 1940. It is modelled that 57% of the load in 1880 is derived from point sources/urban sources, although only about 10% of the population were connected to sewer systems. This is markedly higher than estimated for Denmark, where the point source load is calculated to be about 2% (not including direct point sources to the sea) (Table 7.10). Between 1880 and 1910, the land use of the Oder catchment is reported to be relatively stable with around 58% arable land, 9% grassland, 26% forest and 2% urban areas. In comparison, the Danish arable land constitutes about 67% and about 10% permanent grass and 7% forest in 1896/1901. Approximately 13% of the arable land in the Oder catchtment would have been tile drained around year 1900, assuming a 1.9% annual increase between the reported values of 9% in 1880 and 28% in 1940. This is lower than the values for tile draining in Denmark (26%) around year 1900 (section 5.2). Gadegast et al. (2012) estimates a nitrogen surplus around -5 kg/ha (agricultural area) for year 1900, calculated using the OECD method, but they do not specify whether the “farm gate balance” or “soil surface balance” is used or which components are included in the calculation (OECD, 1997). It seems likely, though, that the “farm gate balance” approach is used since negative N surplus values are reported for 26 years in a row, between 1893 and 1918. The leaching of nitrogen is around 40 kg N/ha (section 12.1). The high Danish leaching value is largely due to high N fixation rates in clover grass and other N fixation crops utilised in the cropping system of the time. N fixating crops will have increased the fixation rates with low fertilizer application rates compared with a situation with high fertilisation rates. Nitrogen fixation is not mentioned in Gadegast et al. (2012); therefore, a comparison cannot be made for this important parameter. Some TN measurements from between 1877 and 1881 are presented for the Oder River, around the city of Wroclaw in southwest Poland, showing 1.5 mg N/l (at two locations) and a modelled concentration of 2.3 mg-N/l at the same location around 1880. The modelled outflow concentration of the Oder River for year 1900 is modelled to 1.1 mg N/l (Gadegast et al., 2012) (Markus Venohr, pers. comm.). For Denmark, the corresponding value is 2.8 mg N/L.

Many of the European studies report nitrogen concentrations around the year 1900 that are considerably lower than in the present study. The reasons for this are probably differences in landscape, land use, farming practices and runoff between the investigated areas and Denmark. It probably also reflects the degree to which agricultural practices and nutrient dynamics are included in the study. In our study, a year 1900 root zone leaching is calculated, and nitrogen fixation, the main nitrogen source in Danish agriculture in year 1900, is considered, which is not the case in most other studies. In Denmark, the present measurement of "undisturbed" streams (streams draining catchments with <10% agricultural land use (Bøgestrand et al., 2014) display nitrogen concentrations ranging between 0.61 and 1.48 mg N/l. If these concentrations were representative for year 1900 as well, the national nitrogen load could be calculated by multiplying these concentrations by runoff for year 1900 (the 297 mm/yr at the fourth order coastal catchments scale (Table 8.2 and Figure 8.3). This would give a nitrogen load of about 15,000 ton N/yr, with a flow-weighted concentration of 1.1 mg N/l, which is considerably lower than the 36,000 ton N/yr and 2.8 mg N/l found in this study. This emphasises that the nutrient concentrations around year 1900 in Denmark were influenced by human activity. To a certain degree, this study builds on Jensen (ed.) (2017), which gives a concentration interval of 1.2 and 2.2 mg N/l (not including point sources and organic nitrogen) and thus also higher estimated concentrations than background concentrations.

A key strength of the present study compared with most of the studies mentioned above is the wide range of the authors' scientific backgrounds, ranging from climatologists, agronomists specialised in nitrogen leaching, groundwater modellers, surface water specialists, specialists in landscape and river phosphorus dynamics and urban water/point source specialists. Such wide diversity of scientific backgrounds is fundamental for conducting a study like this. Therefore, we perceive our study to be more thorough than the other studies mentioned, thus giving a more accurate picture of the year 1900 conditions.

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Appendix to chapter 4 (4.1 and 4.2).

Appendix 4.1

Further documentation is found here: https://www.mdpi.com/2073-4441/12/3/789 where a spreadsheet appendix is available as Supplementary Material. The spreadsheet contains background calculations and resulting emissions to different environmental compartments from each town and slaughterhouse.

Appendix 4.2

Flow charts illustrating the alternative disposal routes tested in the uncertainty analysis (Figures A2-A4)

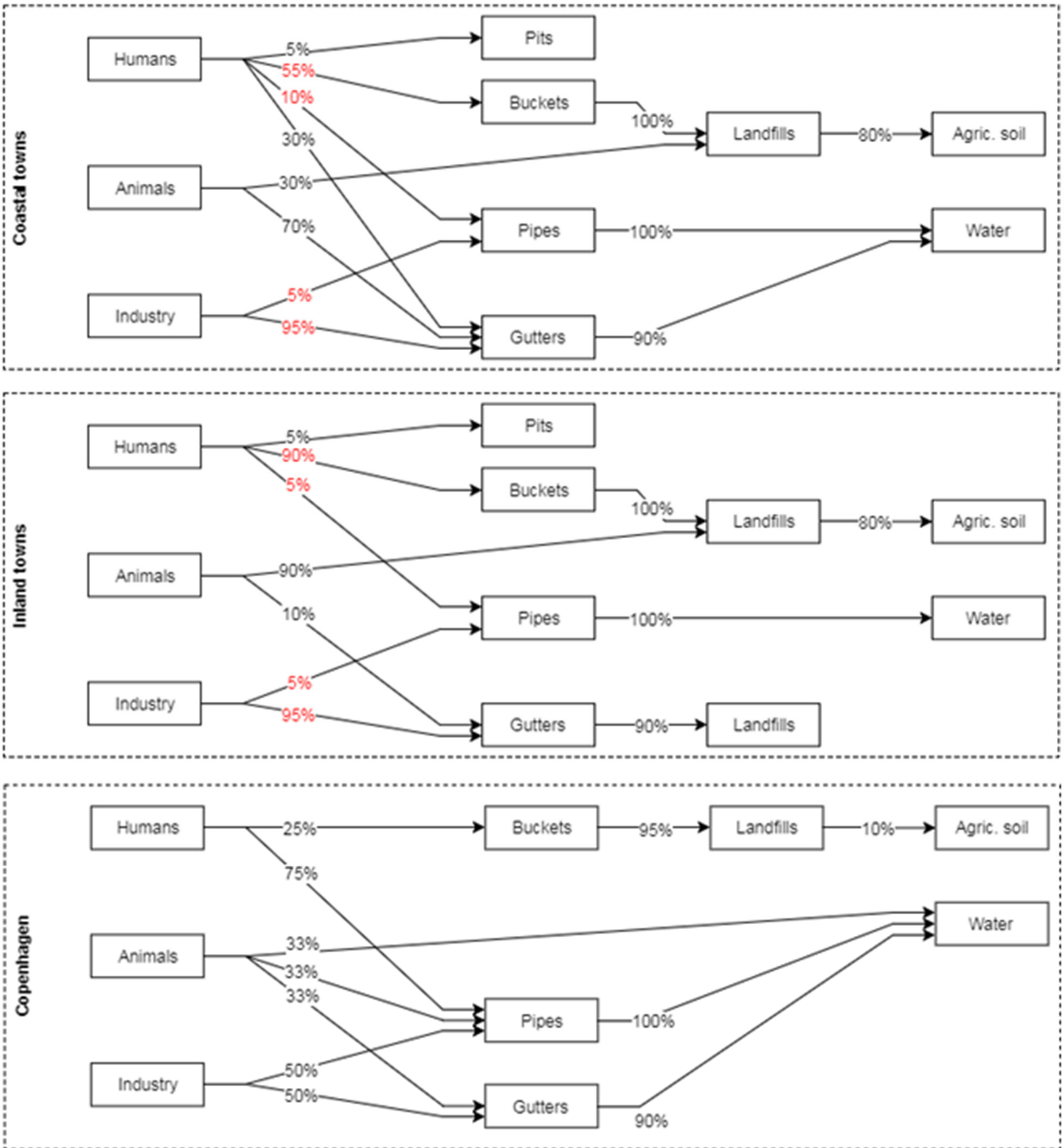

Figure A1. Alternative flow chart assuming 50% less pipes and more buckets in coastal and inland towns (Table 4.1). Changes relative to the assumed baseline scenario (Figure 4.2) are highlighted in red.

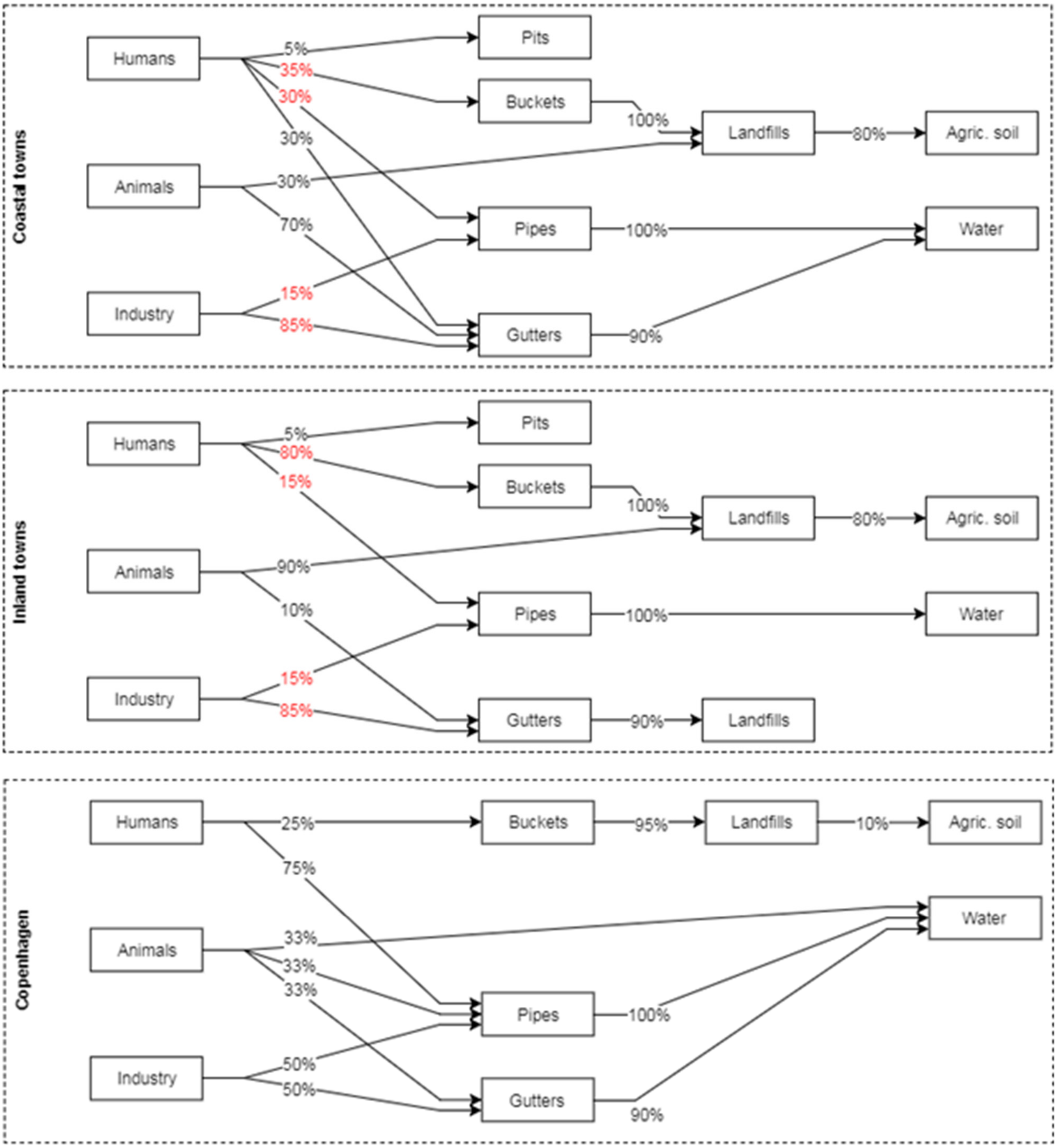

Figure A2. Alternative flow chart assuming 50% more pipes and less buckets in coastal and inland towns (Table 4.1). Changes relative to the assumed baseline scenario (Figure 4.2) are highlighted in red.

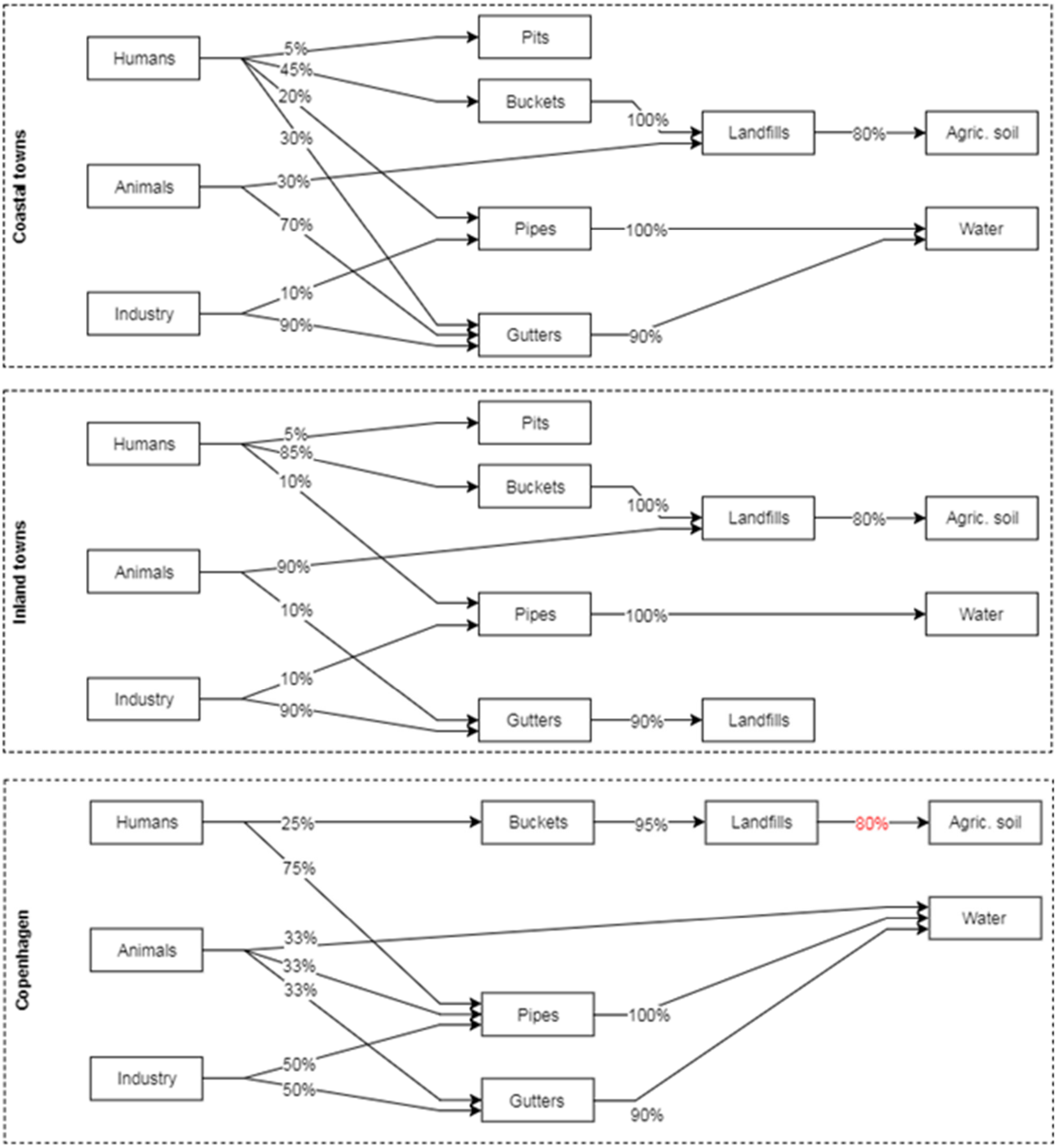

Figure A3. Alternative flow chart assuming more buckets sold to Copenhagen farmers. Changes relative to the assumed base-line scenario (Figure 4.2) are highlighted in red.

Appendix to chapter 5 (5.1)

Establishing land use and agriculture map at parish level in 1900

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From around year 1830 and every 5-10 years onwards, the Danish authorities frequently gathered agricultural, arable land and land use statistics. In the period 1864 to 1920, the southernmost part of Jutland (approx. 1/11 of the Danish territory today) was under German reign. The German authorities conducted similar statistical work on the land use and arable land under their reign.

The most detailed agricultural and land use statistics on the Danish territory from around 1900 are available at parish (sogn/Amtsbezirk/Flecken) level and aggregated at shire (herred) level as well. The data sources closest to year 1900 at parish level come from both the Danish Statistics Agency (year 1896[1]) and the German Statistical Agency (year 1900[2]).

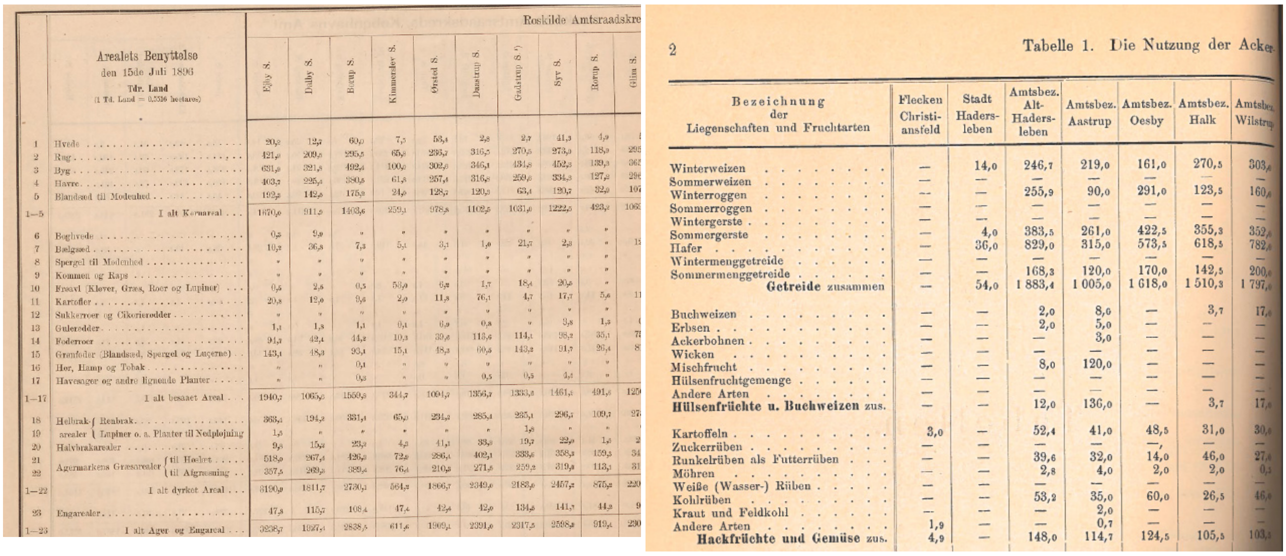


Figure A.1. Extract from the Danish (left) and German (right) statistics.

Both statistical sources use parish level data. Most (around 90%) of the parish data follow the single parish boundaries and contain only one parish, where the areas recorded match the area of the parish. However, the statistical data also contain some merged parishes and data on specific land use on, for instance, contained and drained lakes, bogs between parishes and other areas

[1] Statens Statistiske Bureau & Danmarks Statistik, 1898. Arealets Benyttelse i Danmark den 15. juli 1896 (Statistisk Tabelværk Rk. 5 Litra C Nr. 1). København, Bianco Lunos Hof-Trykkeri (F. Dreyer).

[2] Engelbrecht, Th. H., 1907. Bodenanbau und Viehstand in Schleswig-Holstein nach Ergebnissen der amtlichen Statistik. II, Anhang, Tabelle 1.

(Store Vildmose etc.) belonging to more parishes. For these 10% of the data, we needed to adjust the numbers to keep the details and completeness.

A polygon layer of the parishes was available from the Ministry of Higher Education and Science[3]. The parish boundaries are stored in a database with all applicable parish boundaries from around 1800 and up to the current parish boundary map. For the purpose of the project, we extracted the applicable parish boundaries on 1 July 1896 to fit the statistical dataset.

The land register (cadastral map) forms the basis for the parish map. In some cases, there is a delay in updating the land register and the cadastral map. Furthermore, there may be a delay in updating the parish maps when matriculating drained sea areas and internal lake areas that transition into active agricultural land. The situation is similar along coastlines where land areas either emerge or disappear. Moreover, in the period 1864-1920, the parish map for the German-reigned areas was not updated.

Table A.1 Categories and areas from the Danish and German data.

DK category	DK_category_text	Ha (S26)	Merged_category	Merged_category_text	DK-MODEL	Ha (DK-model)	TY_category	Ty_category_text
DA3	Barley	301.057	S03	Barley	Spring cereals	982.110	TY6	Spring barley
DA4	Oat	479.084	S04	Oats			TY7	Oats
DA5	Mixed cereals (mature)	129.831	S05	Mixed cereals			TY2	Spring wheat
							TY4	Spring rye
							TY8	Mixed cereal (winter)
							TY9	Mixed cereal (summer)
DA6	Buckwheat	14.530	S06	Buckwheat			TY10	Buckwheat
DA7	Pulses	11.600	S07	Pulses			TY11	Peas
							TY12	Fava bean
							TY13	Vetch
							TY14	Mixed cereals
							TY15	Mixed pulses
							TY16	Other types
DA8	Spurrey (mature)	7.641	S08	Spurrey			TY32	Spurrey
DA9	Caraway and oil-seed rape	525	S09	Caraway and rape			TY25	Winter rape and radish
							TY39	Mustard
							TY42	Mustard
DA16	Flax, hemp and tobacco	293	S16	Flax, hemp and tobacco			TY27	Flax
							TY28	Other types
DA17	Garden crops	37.549	S17	Garden crops			TY45	Gardens and fruit plantations
DA27	Gardens and plant nurseries							
DA1	Wheat	41.428	S01	Wheat	Winter cereals	357.426	TY1	Winter wheat
							TY5	Winter barley
DA2	Cereal rye	315.998	S02	Cereal rye			TY3	Winter rye
DA26	Hedgerows and shelters	295.580	S22	Fores	Forest	295.580	TYI	Forests
DA28	Forest areas (planted)							
DA29	Forest areas (unplanted)							
DA11	Potatoes	56.743	S11	Potatoes	Roots	153.771	TY17	Potatoes
DA12	Sugarbeets and Chicory	13.583	S12	Sugar beets			TY18	Sugar beets
DA13	Carrots	6.535	S13	Carrots			TY20	Carrots
DA14	Fodder beets	76.910	S14	Fodder beets			TY19	Fodder beets
							TY21	Fodder radish
							TY22	Swedes
DA25	Moor and Peatland	587.555	S21	Moors, peat- and	Nature	587.555	TYK	Uncultivated land
DA30	Heathland							
DA31	Shifting sands and sand dunes							
DA32	Stone fields, swamps, foreshores etc							
DA10	Seed production (clover, grass, beets and lupines)	25.028	S10	Seed production	Grass	1.537.640	TY29	Clover (for forage)
							TY30	Lucerne
							TY31	Serradel
							TY33	Seed production (Grass-clover,grass)
DA15	Green forage (mixed cereals, spurrey and lucerne)	51.277	S15	Green forage			TY23	Field herbs and caddish
							TY24	Other types
							TY35	Vetch
							TY36	Lupines (for forage)
							TY37	Mixed legumes
							TY38	Mixed vegetables (for forage)
							TY40	Lupines
DA21	Cultivated grass for hay	1.053.714	S19	Cultivated grass			TY44	Cultivated grass
DA22	Cultivated grass for grazing							
DA23	Meadows	407.621	S20	Meadows, fens and commons			TYG	Meadows
DA24	Fens and commons						TYH	Pastures
DA18	Black fallow land (vegetation free)	267.843	S18	Fallow	Fallow	267.843	TY43	Fallow
DA19	Black fallow land (green manure before ploughing)							
DA20	Semi-black fallow land (early summer-crop)							
DA33	Roads, building sites and storage areas	88.336	S23	Roads and building sites	Other	121830	no code	no code
DA34	Lakes, ponds, streams (outside sea territory)	13.086	S24	Lakes, ponds and stremas			no code	no code
no code	no code	2.967	S25	Buildings and yards			TYJ	Buildings and yards
no code	no code	17.441	S26	Roads and water areas			TYL	Roads and lakes, ponds, streams
	Total area on the ID15 map from 2015	4.303.755				4.303.755		

[3] Available at the website: http://digdag.dk. Funded and created by the Ministry of Higher Education and Science, Denmark. https://ufm.dk/en

Compared to the current parish map of Denmark and the current water catchment map (ID15)[4], there are some minor differences in the parish boundaries along the coastlines and the inland lakes; these are included in the water catchment map but are not part of the parish maps and statistics.

The statistical data from the Danish Statistics Agency include 34 different crop types / land use types (DK categories in Table A.1), while the German statistical data include 51 categories (TY categories in Table A.1). Some of the 34 / 51 categories are merged, resulting in 26 (new) common groups (merged categories in Table A.1) that accommodate the differences in the provided data. Furthermore, the number of categories was minimised for further calculations, implying that the 26 categories were divided into eight major groups (DK-model), and the data analyses conducted based on the DK-model use these eight groups. Table A.1 also shows the total area of the 26 common categories and the sum of the eight major categories.

Accordingly, the use of parish maps gives many details on the farming and the actual land use in 1900, but a certain tweaking was needed to show the details on a map that could be applied for comparisons with current maps and statistics. Part of this tweaking process was to match and align the statistical data with the parish maps and areas. Some of the data and polygons were merged to give a more correct picture of the land use. The final map contains 1,702 parishes from the Danish data and 64 from the German data, 1,766 in total.

Further details on how the statistical data and parish maps were made are given in the next chapter.

Ad 1 Adapting the statistical data – description of methodology

Statistical data on agricultural and other land use from different data sources created the basis for the survey. To sum up the data for the 316 coastal land areas, the data needed alignment at the most detailed level.

The methodology used for establishing the background map for land use in 1900 is roughly described in Figure A.2., including also the distribution of land use on the ID15 and the water catchment map. The available data are also described in more detail. The data material included:

1. Digital map of parishes in 1900 - download from digdag.dk.
2. Statistics on agriculture and land use for the Danish part of Denmark as of 1 July 1896.
3. Statistics on agriculture and land use for the German part of Denmark as of 1 July 1900.
4. Digital ID15 water catchment map.

[4] https://www.geus.dk/media/13243/national-kvaelstofmodel-oplandsmodel-til-belastning-og-virkemidler-sep2015.pdf

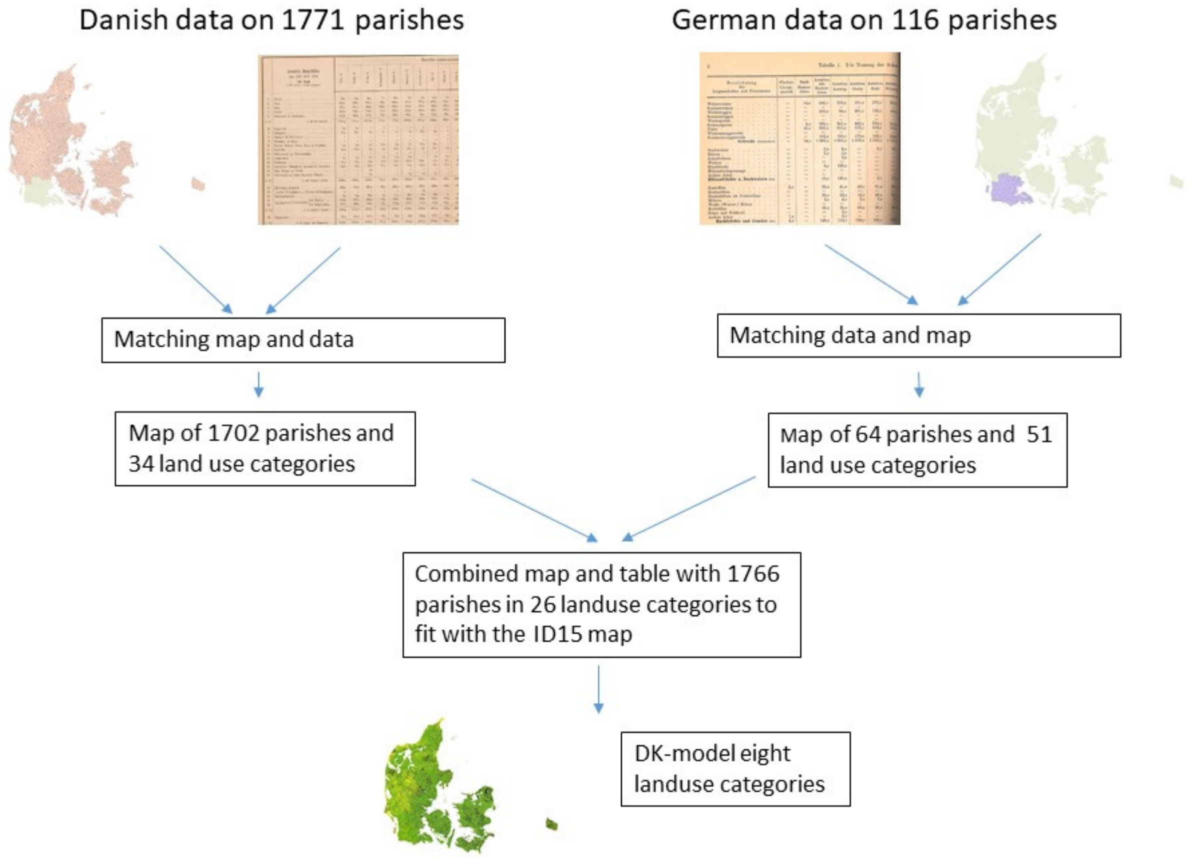
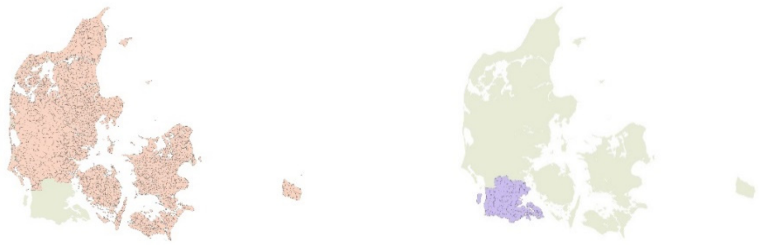


Figure A.2. Methodology.

Re 1) - Digital map of parishes in 1900 - download from digdag.dk

From the digital parish map, the actual parish boundaries were extracted as of 1 July 1896 for optimum match with the agricultural statistics for the Danish part (2). In addition, a map for the German part calculated per unit was extracted as of 1 July 1900 (3). As it turned out that the German part had not changed since the German takeover of the areas in 1864, the parish maps as of 1 July 1896 were used for the entire current Danish territory. There are a total of 1,860 parish polygons in this cohesive parish map, of which 1,744 of the parishes are located north of the Kongeåen, the border between Denmark and Germany.

Figure A.3. Danish (left) and German (right) parishes in 1900.



Re 2) - Statistics on agriculture and land use for the Danish part of Denmark as of 1 July 1896

All data at Danish parish level were entered into and a table including 1,771 unique parishes with available area data. For most of the towns, the total area covered both a “district” and a “land part”. To be comparable to the parish map – usually containing only one parish polygon – the urban and rural parish figures had to be merged.

Furthermore, the division into parishes is not fully identical with the parish map and the table data, which is why both polygons and table data had to be merged and added to create a map with coherent data. There was coincidence between approx. 90% of the parishes and the table data, while the remaining table data and corresponding polygons for the parishes had to be ”tweaked”.

Areas are also found that, for some reason, are included in or excluded from the parish table data. For example, land use for a part of Store Vildmose was calculated collectively instead of using the 3 + 2 parishes where Store Vildmose is located.

The overall process was further complicated because of name coincidences and mistyping during the entry of around 100,000 single figures. In addition, a number of input errors and deficiencies were identified and subsequently rectified in connection with the quality check.

In connection with the quality check, it was also found that almost no parish areas in the polygon areas in the parish maps and total area in the table data for the same parishes were identical. Thus, there are a number of major differences, particularly along the coasts, where ongoing erosion, containment and drying created major changes in the landscape around the turn of the century – for example, at Vejlerne in Hanherred and in southern Lolland. However, most area deviations are within 5%.

For the Danish part, the total land use statistics yield the percentages shown in Table A.2.

In order to create a uniform map, the table area was adjusted to ensure that it was 100% aligned with the polygon area of the parish map, although this produced a change in the statistically recorded data. For the largest of these area deviations, for example along the coast, an individual assessment was made of whether or not the “water bodies” category should be increased to match the areas. Furthermore, for some parishes recovered land was included in table data but not in the parish polygons. For these areas, the table area was reduced proportionally. See also Figure A.4.

The areas were calculated on 34 crops and other land uses and several summaries. See also Table A.2.

The final map contained 1,702 parishes. A complete overview of the modifications made was prepared to facilitate other inventories, for example concerning livestock statistics. This is not included in this annex, however.

Table A.2 Land use categories and distribution of the area under Danish administration in 1900: Parish data collected in 1896.

Code	Land use category	% of total area
DA1	Wheat	0.9
DA2	Cereal rye	7.6
DA3	Barley	7.4
DA4	Oats	11.6
DA5	Mixed cereals (mature)	3.1
DA6	Buckwheat	0.3
DA7	Pulses	0.2
DA8	Spurrey (mature)	0.2
DA9	Caraway and oil-seed rape	0.0
DA10	Seed production (clover, grass, beets, lupines)	0.1
DA11	Potatoes	1.4
DA12	Sugarbeets and chicory	0.3
DA13	Carrots	0.2
DA14	Fodder beets	1.8
DA15	Green forage (mixed cereals, spurrey, lucerne)	1.3
DA16	Flax, hemp and tobacco	0.0
DA17	Garden crops	0.0
DA18	Black fallow (vegetation-free)	5.1
DA19	Black fallow (green manure before ploughing)	0.1
DA20	Semi-black fallow (early summer-crop)	1.4
DA21	Cultivated grass for hay	6.9
DA22	Cultivated grass for grazing	17.9
DA23	Meadows	6.0
DA24	Fens and commons	2.5
DA25	Moors and peatland	2.0
DA26	Hedgerows and shelters	0.2
DA27	Gardens and plant nurseries	0.9
DA28	Forest area (planted)	6.3
DA29	Forest area (unplanted)	0.7
DA30	Heathland	9.2
DA31	Sand dunes and shifting sands	1.1
DA32	Swamp, foreshores, stone fields etc.	0.4
DA33	Roads, building sites and storage areas	2.3
DA34	Lakes, ponds, streams (outside sea territory)	0.3
Total		100.0

Re 3) Statistics on agriculture and land use for the German part of Denmark as of July 1 1900

The German agricultural data were calculated as of 1 July 1900 in “Amtsbezirk” and “Flecken”, which are approximately parishes and towns. The parish maps contains 116 polygons, while the agricultural data contains 88 parishes and towns. Of the 88 parishes in the table data, two small areas (less than 25 ha) cannot be accurately located and are not included in the total area.

As for the Danish part of the German data, polygons and table data had to be combined to create a coherent map. The combination process was complicated as the old parish boundaries along the current state border did not fully coincide with the current state border. For the areas containing data from both sides of the current border, a proportionate part of the total land use was used.

In addition, there were large area deviations along the entire Wadden Sea coast and in the Vidå area, partly due to a lack of or delayed updating of the parish map in relation to the course of the coastline, including continuous improvement of coastal protection and containment and drying of former land areas in the latter half of the 1800s. There may also be errors in data or at least a difference in the cadastral area of the parishes and the aggregated area specified in table data.

The parental map cannot be customised to ensure 100% correspondence between data and polygons. Therefore, the polygon areas were maintained, and the land use was distributed proportionally within the polygons. For a number of parishes along the Wadden Sea coast, an individual assessment of whether the excess table area had to be adapted by reducing the category of "water bodies" was made.

A complete overview of the adjustments was prepared. The final parish map contained 64 parish polygons so that similar inventories on, for example, livestock statistics, were provided. The table of modifications is not included in this annex.

The German data contained more crop categories than the Danish data. To maintain the original data and to allow comparison, three code tables were used, of which the original crop categories were used on the sub-maps (the German and the Danish part), while a collective code table was then applied to the resulting background map for the Danish Environmental Protection Agency. The total code table contains 26 land uses. The German categories are shown in Table A.3, which also shows the distribution among the categories.

Table A.3 Land use categories and distribution of the area under German administration in 1900.

Category Code	Land use category	% of total area
TY1	Winter wheat	1.6
TY2	Spring wheat	0.0
TY3	Winter rye	5.6
TY4	Spring rye	0.0
TY5	Winter barley	0.0
TY6	Spring barley	4.4
TY7	Oats	8.9
TY8	Mixed cereals (winter)	0.0
TY9	Mixed cereals (summer)	2.1
TY10	Buckwheat	0.7
TY11	Peas	0.1
TY12	Fava bean	0.0
TY13	Vetch	0.0
TY14	Mixed cereals	0.4
TY15	Mixed pulses	0.0
TY16	Other types	0.0
TY17	Potatoes	1.0
TY18	Sugar beets	0.0
TY19	Fodder beets	0.6
TY20	Carrots	0.1
TY21	Fodder radish	0.1
TY22	Swedes	1.3
TY23	Field herbs and caddish	0.0
TY24	Other types	0.0
TY25	Winter rape and radish	0.0
TY26	Leindotter (Camelina sativa)	0.0
TY27	Flax	0.0
TY28	Other types	0.0
TY29	Clover (for forage)	1.0
TY30	Lucerne	0.0
TY31	Seradel	0.0
TY32	Spurrey	0.0
TY33	Seed production (clover, grass-clover)	4.2
TY34	Maize	0.0
TY35	Vetch	0.0
TY36	Lupines (for forage)	0.0
TY37	Mixed legumes	0.2
TY38	Mixed vegetables (for forage)	0.0
TY39	Mustard	0.0
TY40	Lupines	0.0
TY41	Mixed vegetables	0.0
TY42	Mustard	0.0
TY43	Fallow	3.3
TY44	Cultivated grass	25.0
TY45	Gardens and fruit plantations	0.7
TYG	Meadows	10.7
TYH	Pastures	11.1
TYI	Forests	3.6
TYJ	Buildings and yards	0.7
TYK	Uncultivated land	5.8
TYL	Roads and lakes, ponds, streams	6.7
TOTAL		100.0

After establishing both the totals from the Danish and the German statistics, a total of the statistics on the Danish territory for 1900 could be made by merging some of the 34/51 categories into 26 groups using the code table in Table A.4.

Table A.4 Combinations of the merged land use categories.

Code	Land-use category	Area (ha)	% of total area	DA code	TY code
S01	Wheat	41,428	1.0	1	1, 5
S02	Cereal rye	315,998	7.3	2	3
S03	Barley	301,057	7.0	3	6
S04	Oats	479,084	11.1	4	7
S05	Mixed cereals	129,831	3.0	5	2, 4, 8, 9
S06	Buckwheat	14,530	0.3	6	10
S07	Pulses	11,600	0.3	7	11, 12, 13, 14, 15, 16
S08	Spurrey	7,641	0.2	8	32
S09	Caraway and rape	525	0.0	9	25, 39, 42
S10	Seed production	25,028	0.6	10	29, 30, 31, 33
S11	Potatoes	56,743	1.3	11	17
S12	Sugar beets	13,583	0.3	12	18
S13	Carrots	6,535	0.2	13	20
S14	Fodder beets	76,910	1.8	14	19, 21,22
S15	Green forage	51,277	1.2	15	23,24, 35, 36,37, 38, 40
S16	Flax, hemp and tobacco	293	0.0	16	27, 28
S17	Garden crops	37,549	0.9	17, 27	45
S18	Fallow	267,843	6.2	18, 19, 20	43
S19	Cultivated grass	1,053,714	24.5	21, 22	44
S20	Meadows, fens and commons	407,621	9.5	23, 24	G, H
S21	Moors, peat- and heathland	587,555	13.7	25, 30, 31, 32	K
S22	Forest	295,580	6.9	26, 28, 29	I
S23	Roads and building sites	88,336	2.1	33	No code
S24	Lakes, ponds and streams	13,086	0.3	34	No code
S25	Buildings and yards	2,967	0.1	No code	J
S26	Roads and water areas	17,441	0.4	No code	L
Total		4,303,762	100.0		

The map in Figure A.4 shows where polygon areas fitted with table data within 5% (yellow), where the table data were lower by at least 5% compared to the parish polygon (green) and where the table data were larger by at least 5% compared to the parish polygon (red).

After the creation of the common categories, a single map could be drawn for the whole of Denmark for the year 1900, and area distribution was calculated for the 1,766 parishes. For the areas in Hvidding and Skærbæk parishes south of Ribe along the Wadden Sea coast, a specific ”sea area“ was withdrawn from the table area to align it with the parish polygon area. For the rest of the parishes, the areas were adjusted proportionally.

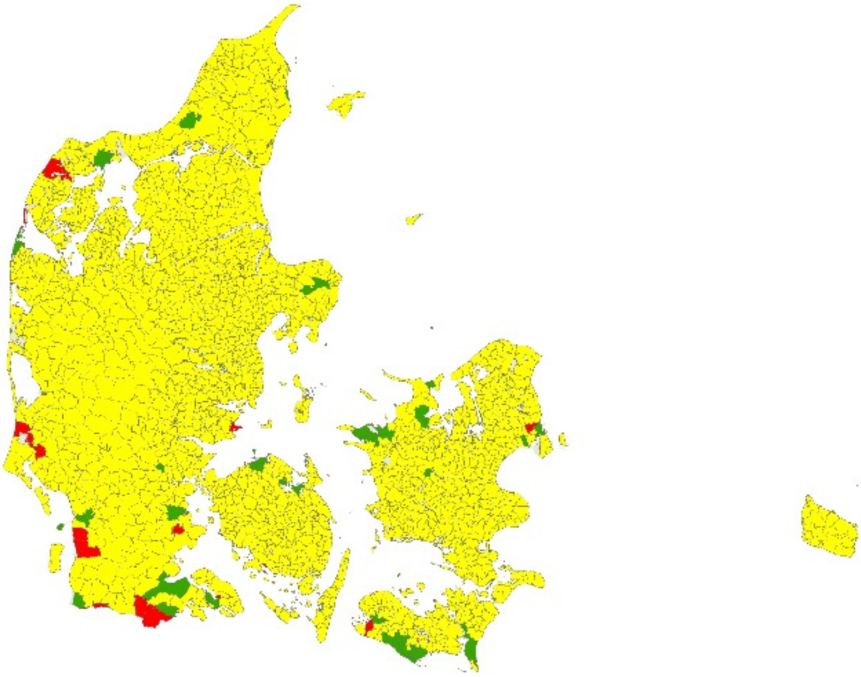


Figure A.4 Map showing the alignment of table and polygon data in the parishes map.

Re 4) - Digital ID15 water catchment map

After creating a parish map for the total Danish territory in 1900, it was dis-/aggregated to the 3,134 ID15 areas and 316 coastal water areas. A comparison of the parish map with the ID15 map showed that the area of the ID15 map was 795 km^2 larger than the area of the parish map, while 139 km^2 in the parish map were not included in the 3,037 km^2 large ID15 map. See the maps in Figure A.5 – A.7.

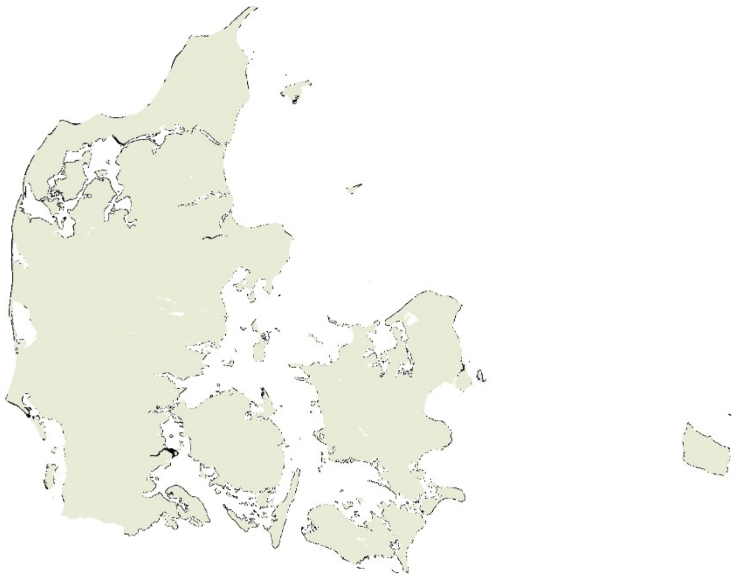


Figure A.5 Map of areas in the parish map not found in the ID15 map.

Figure A.6 Map of areas in the ID15map not found in the parish map.

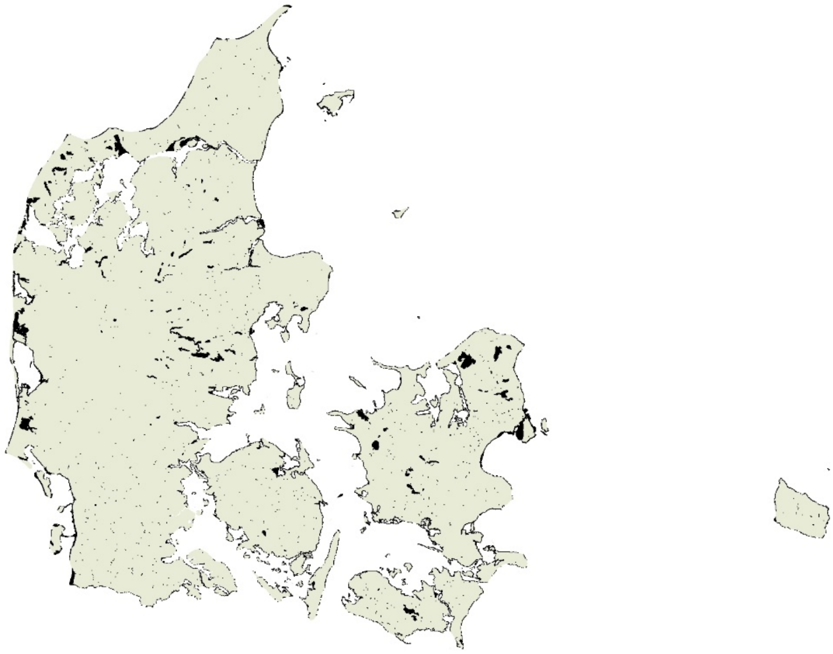


Figure A.7 Map of Denmark whole country (top) and zoomed in at “Limfjorden” (bottom) showing the difference between the ID15 map and the parish map. The differences are marked in green and yellow. Green is mainly flooded land and yellow mainly lake area and former sea territories (see text below).

Overall, it is the lake areas (yellow areas in Figure A.7) that are not included in the parish map. Some of these areas have been reclaimed and dried out, others are emerged sea areas along the coasts that have not yet been included in the parish map. Finally, it is primarily flooded land that is not part of contemporary ID15 maps (green areas in Figure A.7.). In the aggregation to ID15, a “water area” was therefore added to the area calculation to compensate for any missing ID15 area. This is not entirely correct, but it difficult to get more specific considering the uncertain statistics.

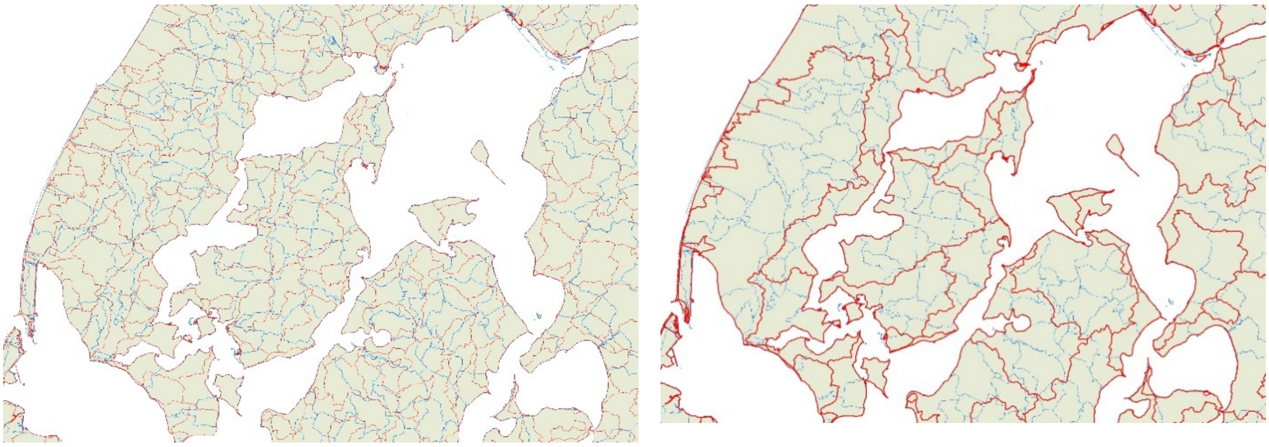


Figure A.8 Parish map versus ID 15 map (left) and coastal land map (right).

Table A.5 Categories and areas from the Danish and German data.

Combination categories	Land use	Area DK (ha)	Pct	DK-MODEL
S01	Wheat	41,428	1.0%	Winter crops
S02	Cereal rye	315,998	7.3%	Winter crops
S03	Barley	301,057	7.0%	Spring crops
S04	Oats	479,084	11.1%	Spring crops
S05	Mixed cereals	129,831	3.0%	Spring crops
S06	Buckwheat	14,530	0.3%	Spring crops
S07	Pulses	11,600	0.3%	Spring crops
S08	Spurrey	7,641	0.2%	Spring crops
S09	Caraway and rape	525	0.0%	Spring crops
S10	Seed production	25,028	0.6%	Grass
S11	Potatoes	56,743	1.3%	Root crops
S12	Sugar beets	13,583	0.3%	Root crops
S13	Carrots	6,535	0.2%	Root crops
S14	Fodder beets	76,910	1.8%	Root crops
S15	Green forage	51,277	1.2%	Grass
S16	Flax, hemp and tobacco	293	0.0%	Spring crops
S17	Garden crops	37,549	0.9%	Spring crops
S18	Fallow	267,843	6.2%	Fallow
S19	Cultivated grass	1,053,714	24.5%	Grass
S20	Meadows, fens and commons	407,621	9.5%	Grass
S21	Moors, peat- and heathland	587,555	13.7%	Nature
S22	Forest	295,580	6.9%	Forest
S23	Roads and building sites	88,336	2.1%	Other land use
S24	Lakes, ponds and streams	13,086	0.3%	Other land use
S25	Buildings and yards	2,967	0.1%	Other land use
S26	Roads and water areas	17,441	0.4%	Other land use
Total		4,303,762	100.0%	

There were 1,766 parish polygons, where the areas had to be transferred to 3,134 ID polygons. As seen in Figure A.8 to the left, the red ID15 polygons were joined by portions of the area distribution from the blue parish polygons. In the Figure to the right, the ID15 polygons were replaced with the 316 coastal catchments.

In the ID15 map, data were aggregated to the 316 coastal catchments. The total statistics used in the calculations for the Danish EPA thus included the area for 26 crop categories for each of the 316 coastal catchments. In order to run the NNM-model calculations for the 500 m grid and 10 km DMI grid, were needed. Land use data at these levels was calculated in the same way as from parish to ID15, as described above.

The data processing allows calculation of the total land use in 1900 for the various aggregate area categories related to the 316 coastal water catchment area. Table A.5 shows that approx. 67% of the area was used for agriculture or cultivation purposes (S1-S19).

For the use of GEUS' work in the DK-model, a map based on 500 m grid (250 m grid on Bornholm) was used, see further in section A.2. The DK-model uses only eight categories, and the 26 categories therefore had to be aggregated into fewer groups. This was done following the model in Table A.5.

The following Figures (A.9-A.16) show the distribution of all eight DK-model categories in 1900 for the whole country at parish level (upper) and at ID15 level in 2015 (lower).

Figure A.9. Winter crops.

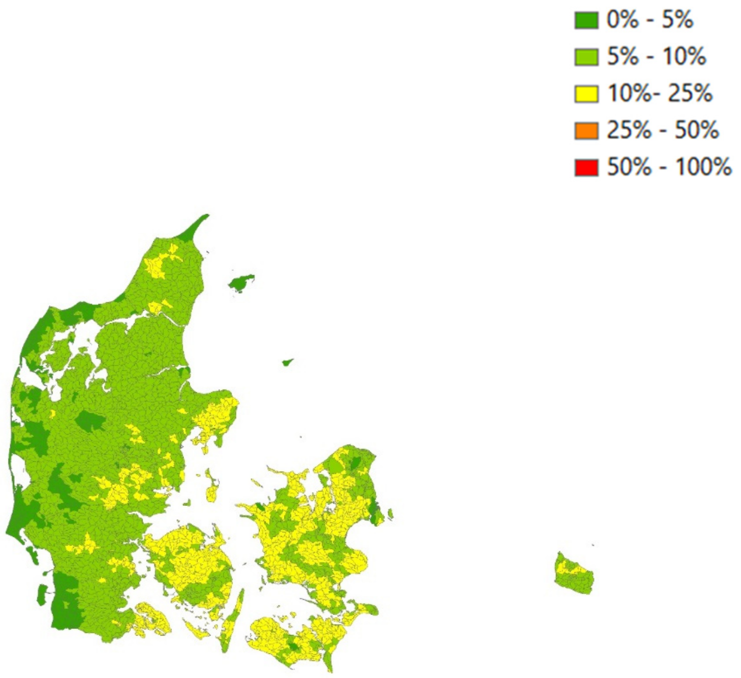


Figure A.10 Spring crops

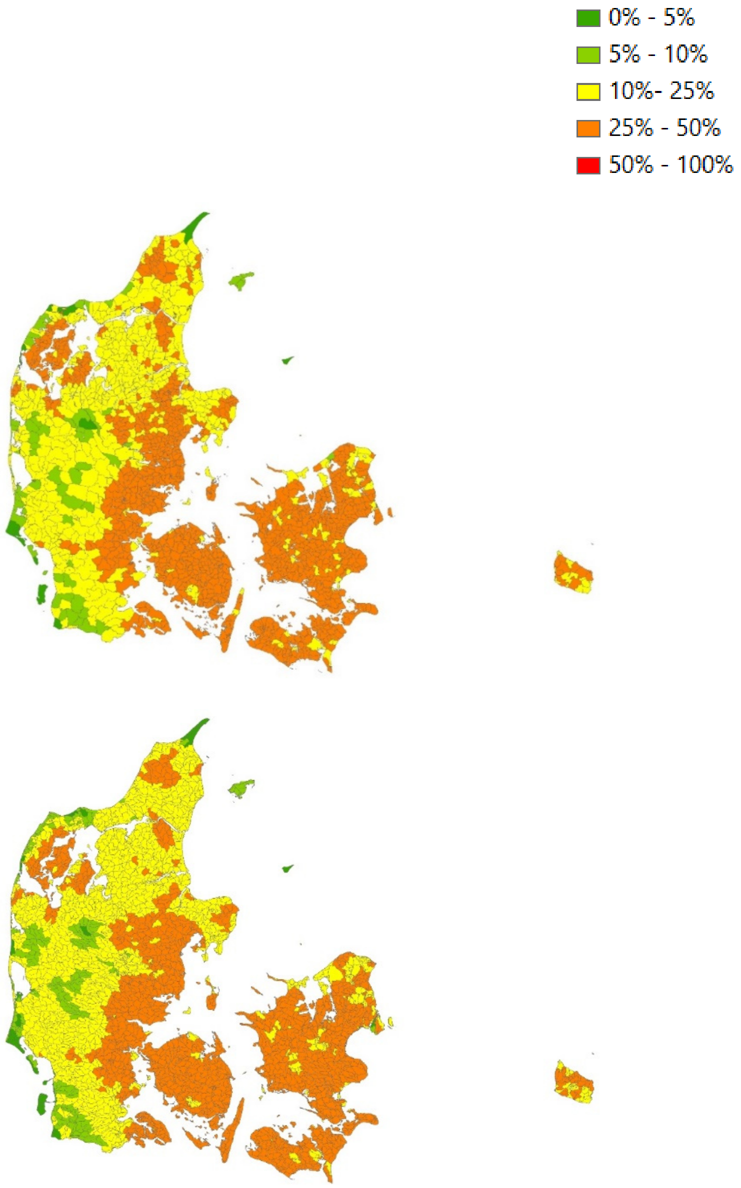


Figure. A.11 Grass.

Figure. A.12 Root crops.

Figure A.13 Fallow.

Figure A.14 Nature.

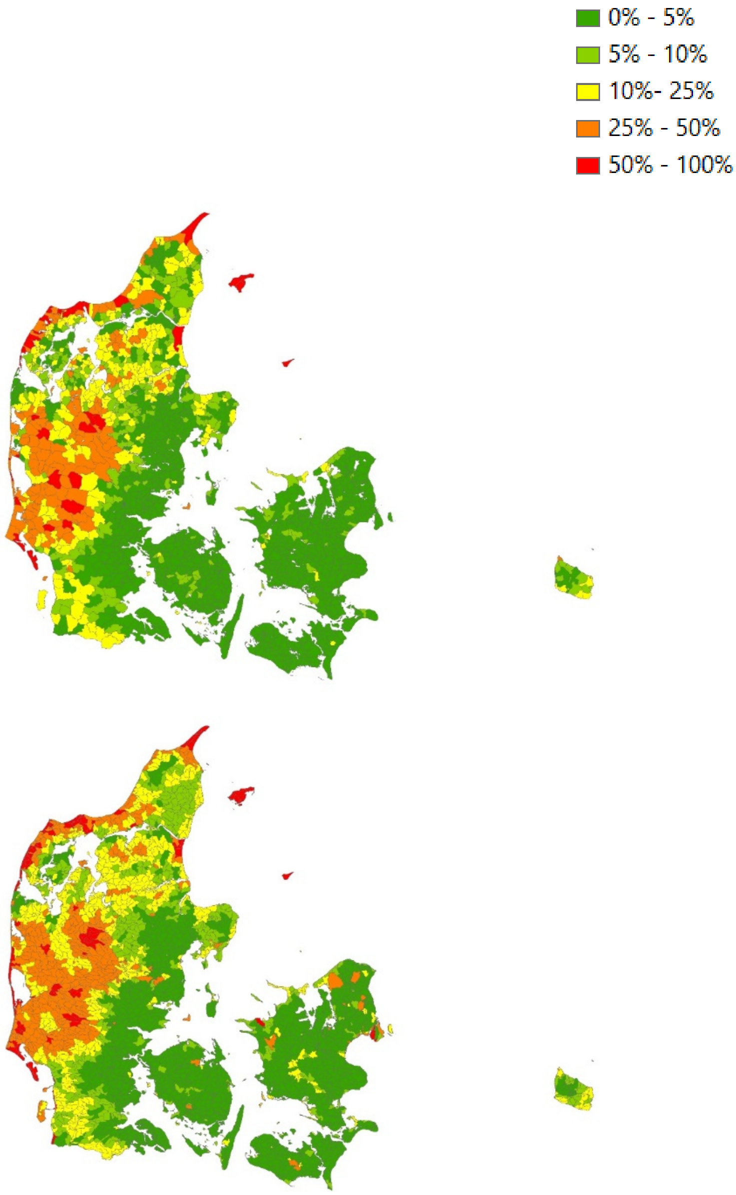


Figure A.15 Forest.

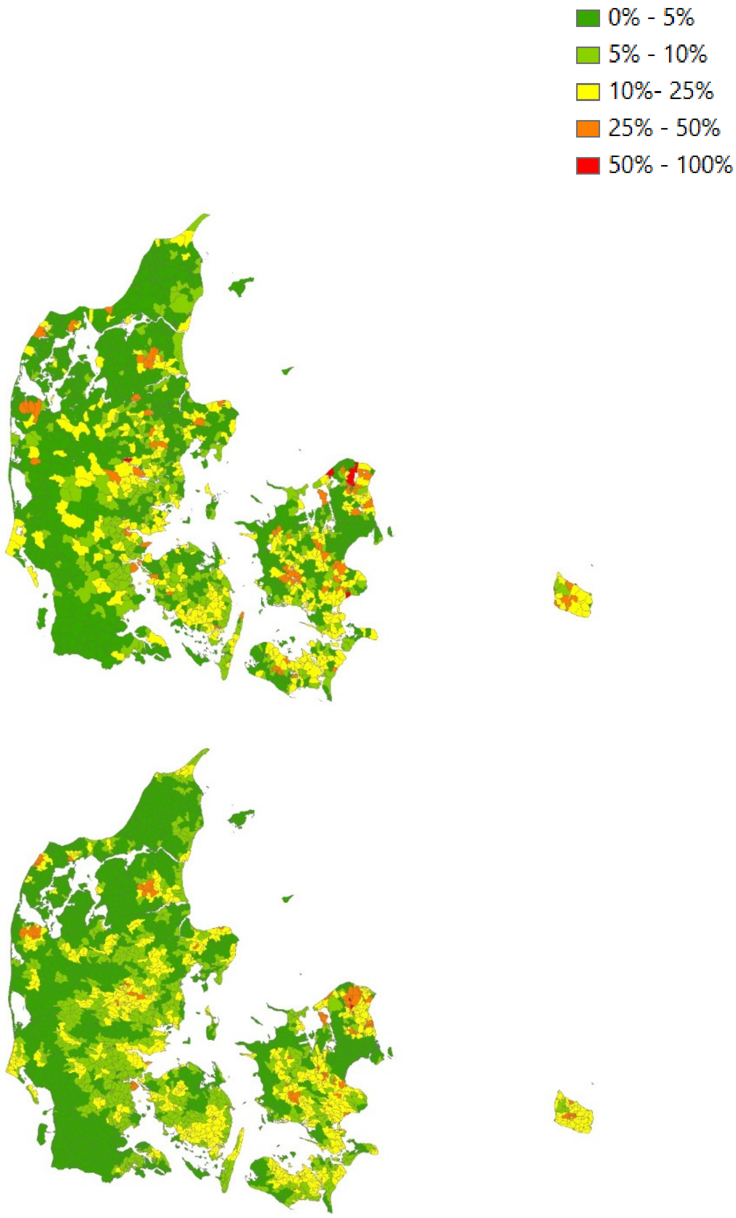


Figure A.16. Other land use.

A.2 DK-model

The DK-model is a National Water Resources Model for Denmark developed by the Geological Survey of Denmark and Greenland in 1996[5]. The DK model is grid based. For Bornholm (blue in Figure A.16.), a 250 m grid was used or 0.0625 ha per point/grid, and for the rest of Denmark (green in Figure A.16.) a 500 m grid or 0.25 ha per grid/point was applied. The DK-model does not cover the whole country as seen in Figure A.16, excluding, for instance, some remote islands like Samsø and Læsø. This means that only 1,747 of the 1,766 parish polygons hold one or more grid points. The parish boundaries of 1896 are shown with red hatch and black outline in Figure A.17.

[5] http://dk.vandmodel.dk/in-english/

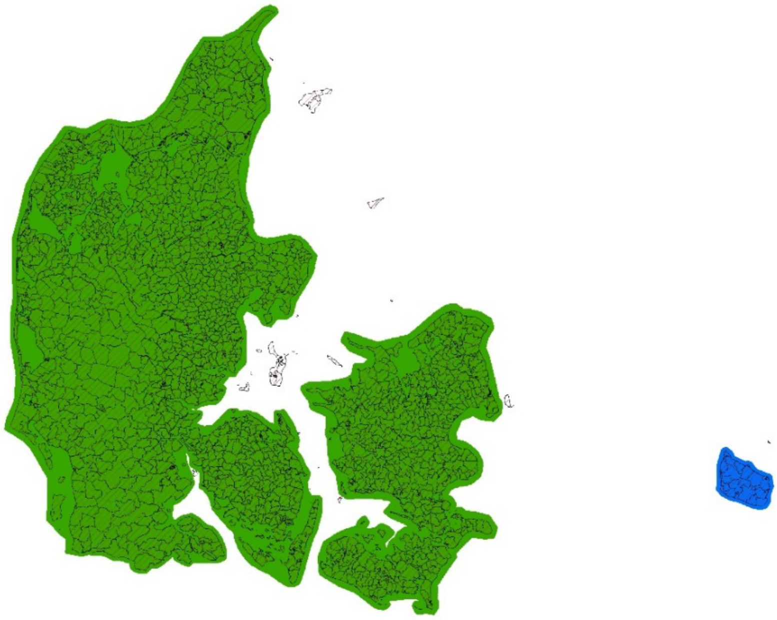


Figure A.17. DK-model coverage and parish boundaries in 1896.

The model consists of 220,935 points / grids. A comparison between the grid map and the parish polygons was made, and the number of points / grids per parish was calculated.

A total of 175,251 points are found within the parish polygons. There are between 2 and 1,115 of these grid points per parish. Bornholm, covered by a 250 m grid, has the parishes with the most points, see Figure A.18.

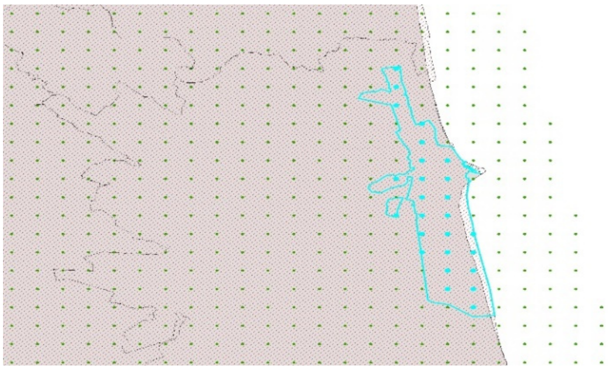


Figure A.18 Example of the distribution of points within the parish boundaries (Sæby Parish).

Vestermarie Parish thus has 1,115 points, corresponding to 279 points in a 500 m grid. The largest parish polygon in the rest of the country is Gram Parish with 917 points. For all parishes, the number of points for each of the eight categories were calculated (example in Table A.6, where the top line shows hectares for each category the bottom line the number of points for the categories.

Table A.6. Example of distribution of points/grids per parish.

Parish_ID	Parish_Name	Winter crop	Spring crop	Grass	Roots	Fallow	Nature	Forest	Other	Ha	Number
30921	Sæby Sogn	74	151	278	23	34	37	10	39	646	26
30921	Sæby Sogn	3	6	11	1	1	2	0	2		26

For a number of parishes, minor differences (+/- 2) occurred between the calculated number of points (total area per parish in ha divided by 0.25 ha outside Bornholm and by 0.0625 on Bornholm). Therefore, the final number of grid point per parish was adjusted to the DK-model point numbers.

The distribution of points for the eight categories of the 1,747 parish polygons was calculated and a long list of two variables, category and parish, was calculated for the 175,251 points within the parishes.

Table A.7 Example of randomizing the order of the categories.

Category_distribution

ID	OBJ_id	Parish_name	Category	Order
128387	30921	Sæby Sogn	Winter crops	0.983833727693675
128388	30921	Sæby Sogn	Winter crops	0.135477146238217
128389	30921	Sæby Sogn	Winter crops	0.848905959640247
128390	30921	Sæby Sogn	Spring crops	0.722893372527041
128391	30921	Sæby Sogn	Spring crops	0.748253493622873
128392	30921	Sæby Sogn	Spring crops	0.410818219434944
128393	30921	Sæby Sogn	Spring crops	0.147878651785771
128394	30921	Sæby Sogn	Spring crops	0.275325349568977
128395	30921	Sæby Sogn	Spring crops	0.930087926500275
128396	30921	Sæby Sogn	Grass	0.513536983510489
128397	30921	Sæby Sogn	Grass	0.853150756147839
128398	30921	Sæby Sogn	Grass	0.155372852730436
128399	30921	Sæby Sogn	Grass	0.273081025060814
128400	30921	Sæby Sogn	Grass	0.867565884409888
128401	30921	Sæby Sogn	Grass	0.894961922037269
128402	30921	Sæby Sogn	Grass	0.570764009625787
128403	30921	Sæby Sogn	Grass	0.961505090513572
128404	30921	Sæby Sogn	Grass	0.743253093446627
128405	30921	Sæby Sogn	Grass	0.172367963090125
128406	30921	Sæby Sogn	Grass	0.899721533760677
128407	30921	Sæby Sogn	Roots	6.04009572611242E-02
128408	30921	Sæby Sogn	Fallow	0.769277974608645
128409	30921	Sæby Sogn	Nature	0.854412472136659
128410	30921	Sæby Sogn	Nature	0.679376938655891
128411	30921	Sæby Sogn	Other land use	0.986322715960438
128412	30921	Sæby Sogn	Other land use	4.08918354819406E-02

Via the Excel function RAND (), the categories in the list were distributed ”randomly” within the parishes and according to the category attached to the points lying within the individual parish via sorting of the “Order” column – see Table A.7. This list of randomised categories was used in the further DK-model analyses.

The total areas for parish and grid maps were then calculated without the areas (islands) that are not covered by the DK-model. As can be seen in Table A.8, the percentages were very well met.

Table A.8. Total areas after creating the randomised map for the DK-model

	Category	Legend	Area (km^2)			Percentage		
			Parish map	Grid	difference	Parish map	Grid	difference
DK1	Winter crops		3,560	3,553	7	8.5%	8.5%	0.0%
DK2	Spring crops		9,793	9,788	5	23.3%	23.3%	0.0%
DK3	Grass		15,358	15,374	-16	36.5%	36.6%	-0.1%
DK4	Roots		1,530	1,525	5	3.6%	3.6%	0.0%
DK5	Fallow		2,668	2,663	5	6.3%	6.3%	0.0%
DK6	Nature		5,000	4,988	12	11.9%	11.9%	0.0%
DK7	Forest		2,950	2,936	14	7.0%	7.0%	0.0%
DK8	Other land		1,221	1,224	-3	2.9%	2.9%	0.0%
	Total		42,081	42,052	30	100.0%	100.0%	0.0%

Finally, a map was prepared (see Figure A.19) based on the random distribution of crops/land use within the individual parishes from the 1900 parish map.

Figure A.19 Map of the DK-model with land use categories in 1896 from Table A.8.

TRANSPORT OF NITROGEN AND PHOSPHORUS FROM LAND TO SEA AROUND YEAR 1900

The nutrient loads from land to sea around year 1900 in Denmark are estimated using a delta change modelling approach considering the numerous factors affecting the nutrient inputs and transport. The estimates are based on available data from that time, literature, comparative analysis methods and modelling tools. The main factors investigated are climate, hydrology, land use, agricultural practices and drainage, urban developments and landscape (e.g. nutrient retention in groundwater, wetland, lakes and streams). Nutrient loads around the year 1900 were affected by human activity, with total nitrogen and phosphorous loads being approx. 40% and 25-40% less than presentday loadings, respectively.

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