SECOND OPINION READERS GUIDE TO RBMP 3 MODELS AND SCENARIOS IN DENMARK

Technical Report from DCE – Danish Centre for Environment and Energy no. 268 2023

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DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

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Contents

Preface

This memorandum or readers guide was commissioned and funded by the Danish Ministry of Environment as a part of a larger project called Second opinion. One of the topics in the Terms of Reference (ToR) for this Second opinion project is an international evaluation of the Danish implementation of the WFD i.e. the Danish River Basin Management plans (RBMP). This memorandum acts as readers guide to the relevant reports regarding the Danish RBMP and MAI estimates for the coastal water bodies and the models, methods and choices behind the MAI estimates. The memorandum is prepared by AU, DTU and DHI – hence, it is a guide prepared by the institutions behind the development of models and methods being evaluated.

1 Introduction

The purpose of this, "readers-guide" to the Danish River Basin Management Plans 2021-2027 (RBMP3) models and scenarios, is to help the international experts in the second opinion process of the Danish implementation of the Water Frame Directive (WFD), to get an overview of the tools, methods and processes of calculating maximum allowable input (MAI) from data and models to the final MAIs.

The guide will be structured according to four of the six main subjects in the second opinion Terms of Reference (ToR)

The main topics in second opinion (translated from Danish)

1. Reference condition and setting target for good ecological status (GES): Importance of reference condition in relation to the need for reductions, including (almost) undisturbed areas and relation to nutrient input in 1900. Determination of environmental targets based on the reference state.

2. Time series for nutrient input data: The importance of including different years in the calculation, including 2019-2022

3. Burden sharing: Handling of burden sharing between countries covered by the Water Framework Directive.

4. Seasonal variation: Consequences of accounting for seasonal variation in nitrogen input.

5. Exception provisions: The possibility of the use of exception provisions.

6. Pressures: Other environmental pressures than nitrogen and possible actions/countermeasures.

With this document we will guide the reader to the relevant reports that can be used to review the scientific development and research behind the advisory of the Danish authorities with regard to point one, three, four and six.

Furthermore, the scientific development for the RBMP3 was guided by the recommendations from the international evaluation from 2017 (IE-report 2017). In the present report changes in tools, methods and processes behind the MAIs based on the international review process from RBMP2 are presented.

2 Readers Guide to Model and Methods behind the Danish River Basin Management Plans 2021-2027

2.1 Introduction to WFD

According to the WFD all inland waters, transitional and coastal surface waters should reach GES (or good ecological potential) before 2027. The WFD defines GES as a situation where the Biological Quality Elements (BQEs) only deviate slightly from an undisturbed condition. For coastal waters the BQEs encompass "Phytoplankton", "angiosperms and macroalgae" and "benthic macro invertebrates".

Each member state is obliged to develop indicators for each of the biological quality elements as well as participate in an intercalibration process with other EU member states to determine the deviation from an undisturbed condition characterizing GES as well as the other ecological status classes. Member states are also obliged to produce and adopt a "River Basin Management Plan" (RBMP) that include the actions and measures needed to ensure good ecological status in the relevant river basin by 2027. In compliance with this, the Danish Environmental Authorities published a 3rd RBMP in 2021 and this readers guide provide an overview of the scientific reports and methods behind the Danish implementation of the WFD.

2.2 WFD implementation in a Danish context

After the Water Framework Directive (WFD) entered into force in EU in 2000 (Directive 2000/60/EC), it was adopted by the Danish parliament in 2003. The essence of the directive is that all surface waters (e.g. lakes, rivers, coastal waters) should achieve at least good ecological status (GES) and good chemical status (GCS).

For the Danish RBMP 2021-2027, ecological status is classified according to three indicators:

- Chlorophyll-a concentration is an indicator for phytoplankton biomass and is assessed as the average (May-September) chlorophyll-a concentration within the inner Danish waters and 90-percentile of the March to September chlorophyll-a concentrations for water bodies located in the North Sea and the Skagerrak.

- Eelgrass depth limit is an indicator for the quality element angiosperms and defined as the maximum depth with at least 10% cover. Notice, that for the development of individual MAIs, we use light availability as a proxy/condition for eelgrass potential depth limit (see later in this document).

- Danish Quality Index (in Danish: Dansk Kvalitets Index - DKI) is an indicator for the composition and abundance of benthic fauna and a multi-metric index including both biodiversity and sensitivity/tolerance towards disturbance (not used for estimating MAI).

Based on those three indicators the Danish EPA has assessed the ecological status of the marine coastal waters as in Figure 2.1. The Figure shows the overall ecological status, whereas the status of the different indicators are all shown here: Miljøgis (mim.dk).

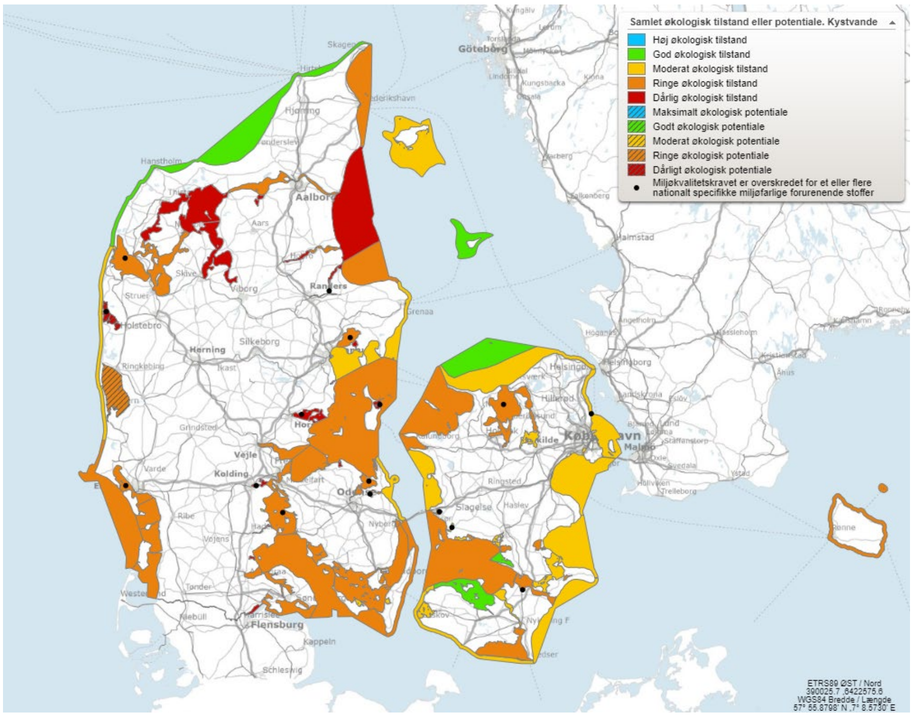


Figure 2.1. Assessment of ecological status of Danish marine water bodies (Reference: Miljøgis (mim.dk))

As shown in figure 2.1, most water bodies do not meet at least Good Ecological Status (GES). Several pressures are present in Danish coastal waters. Later in this document a summary on different pressures is included. However, the most governing pressure is still excess loadings with nutrients – and the governing nutrient being nitrogen in most of the water bodies - and eutrophication that affects the indicators at water body level. Therefore, nutrient reductions are still the main tool to improve the ecological status of the Danish marine water bodies.

- The scientific developments of models and methods behind the RBMP 2021-2027 is founded on improvements related to especially four overall topics: A new typology (Typology -report in Danish, but highlights described further down in this document).

- New bayesien models for modelling light and chlorophyll-a conditions (Modelling light conditions and Modelling Chlorophyll-a concentrations) A set of 11 new mechanistic models (11 hydrodynamic models, 11 biogeochemical models), covering two regional models, three local models and six estuary specific models (Figure 2.2) (The hydrodynamic and biogeochemical models are all described in individual reports – see section 3.5 here: RBMP-reports). The calibration/validation is summarised in the individual reports whereas all-time series are available here: RBMP (dhigroup.com).

- Management scenarios addressing the importance of Phosphorus for the indicators and maximum allowable Nitrogen inputs to Danish water bodies Scenario summary.

- Management scenarios addressing the importance of nutrient loadings from neighbouring countries Scenario2c and atmosphere Scenario3a for Danish MAIs.

With the model development 107 out of the 109 Danish marine water bodies is now covered by a mechanistic model or a mechanistic and a statistic model.

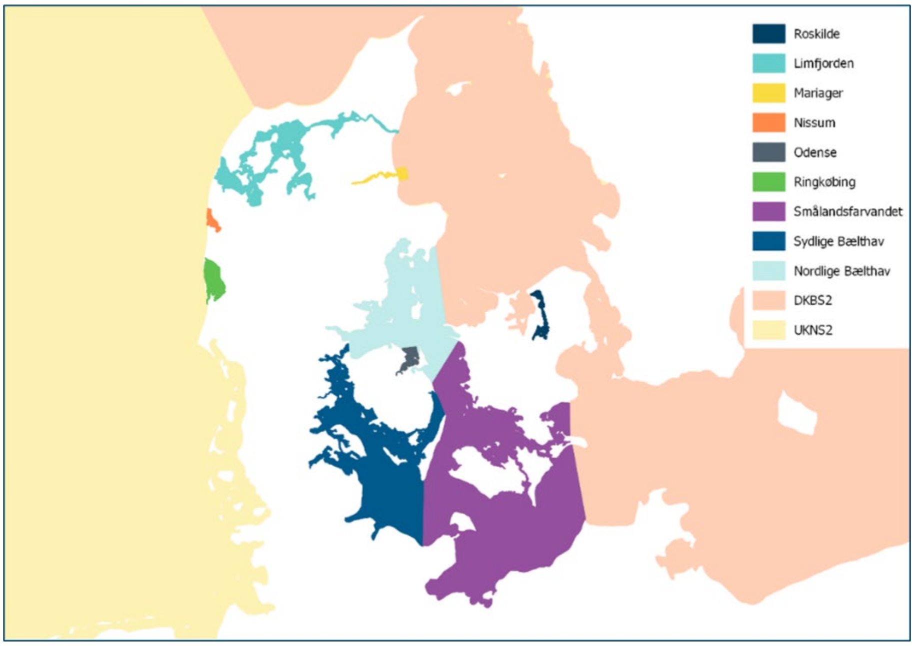


Figure 2.2. Mechanistic models developed as part of the RBMP 2021-2027.

In addition to the model developments and the MAI calculations (as described below), one additional project was carried out assessing the shallow water effects from nutrient reductions. Shallow water effects were also briefly addressed in Herman et al (2017). In the present project the mechanistic models were used to assess additional ecological improvements in shallow areas for four specific estuaries: Horsens Fjord, Vejle Fjord, Odense Fjord and Roskilde Fjord. Based on 30% reduction scenarios in Danish land-based loadings (N or P), the effects were evaluated as new areas suitable for eelgrass growth, see Shallow Water Effects for more details.

The results from this project were not directly used to assess the final MAIs but used to underline additional benefits of especially N-reductions in shallow waters, and the report concludes that the MAI estimations for the four estuaries has an impact. However, the results also indicate that a 30% reduction might not be sufficient (and hence somehow similar to MAIs) in all water bodies, but we cannot conclude that the MAIs are sufficient in all water bodies to allow eelgrass to expand into new shallow water areas. The results, of course, only represents four estuaries (and 8 water bodies) but we expect the findings to be similar in many of the other enclosed and semi-enclosed estuaries.

3 Reference conditions

The aim of the water framework directive is to achieve "Good ecological Status" (GES). For coastal waters GES is defined as a minor deviation from an "undisturbed" condition designated "reference condition". Estimation of reference condition is a central element in WFD implementation as it has implications for e.g. target setting (GES), boundaries between status classes and estimation of maximum allowable nutrient input and the nutrient reduction requirement to achieve GES.

According to CIS, reference conditions should be determined either from i) observations from existing undisturbed sites, ii) historical data, iii) modelling or iv) expert judgement in prioritised order. In a Danish context the reference condition has been established for the indicators:

- "Summer chlorophyll-a", representing the BQE "phytoplankton"
- "Eelgrass depth limit", representing the BQE "angiosperms and Macroalgae" and
- "Danish Quality Index" representing benthic invertebrate fauna

While these indicators are used for determining GES and for assessing the ecological status in Danish coastal waters, only the chlorophyll-a and eelgrass is used for calculating MAI and determining the need for nutrient reductions to achieve GES. Because chlorophyll-a and light conditions can be directly linked to nutrient input on a short time scale – whereas the DKI-index has a more complex relationship with the nutrient state.

3.1 Reference condition for eelgrass depth limit

The establishment of reference conditions for eelgrass depth limits in each Danish coastal water body is estimated from historical observations as described in Referenceværdier for ålegræsdybdegrænser (au.dk) (Danish report with English summary).

Briefly, reference conditions for eelgrass are based on a large historical dataset of eelgrass observations collected from 1880-1930. Eelgrass observations from this time period is assumed to reflect a reference condition, which according to the Water Framework Directive is defined as a condition with no, or only very minor anthropogenic alterations from undisturbed conditions. However, as agriculture and cities existed in Denmark at that time period, eelgrass may have been affected by nutrients from streams and point sources at that time, especially in inner estuaries and close to "larger" cities.

Historical eelgrass observations exist for 48 out of 109 coastal water bodies, and in these water bodies, the 90th percentile of the observed depths is used as the water body specific reference condition for the eelgrass depth limit. For water bodies with no historical observations, eelgrass depth limit is determined using a statistical regression model, describing eelgrass depth distribution in a water body as a function of the physical parameters: "water exchange", average water depth" and "stratification" (figure 3.1). For three water bodies a type specific approach was used to establish eelgrass reference conditions.

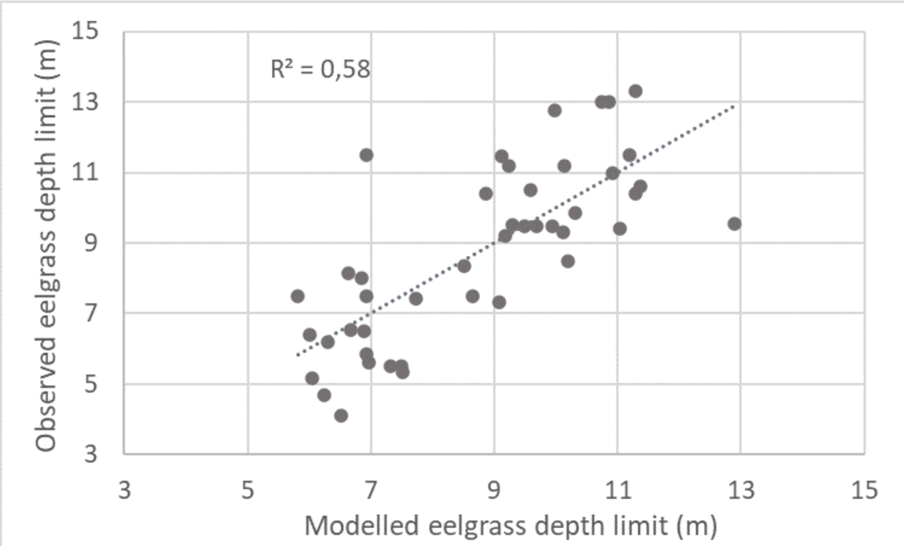


Figure 3.1 Scatter plot of observed and modelled historical eelgrass depth limits from water bodies with at least one historical observation of eelgrass depth limit. Modelled eelgrass depth limits are estimated from MLR regression using water depth, stratification and water exchange as explanatory variables.

Danish coastal waters may have been affected by increased nutrient inputs at the time of the historical eelgrass observations so the historical eelgrass might have been affected by human activity implying that the "true" reference depth limit for eelgrass is deeper than estimated based on the historical observations. On the other hand is healthy eelgrass beds able to withstand a certain pressure from eutrophication, so the observations from 1880 to 1930 might reflect a situation where an increase in nutrient loadings not yet have had a negative impact on the eelgrass populations. Hence eelgrass observations from this time period are in general assumed to reflect a reference condition, which according to the Water Framework Directive is defined as a condition with no, or only very minor anthropogenic alterations from undisturbed conditions.

3.2 Reference condition for chlorophyll-a

Reference conditions for the chlorophyll-a indicator is based on quantitative modelling which is considered the most feasible option as there are no undisturbed marine sites in Denmark and no historical quantitative chlorophyll-a observations. The methodology, model framework and input data used to represent an (almost) undisturbed situation is described in Cholorophyll-a reference conditions.

Briefly, two independent model approaches (Bayesian and mechanistic models) are used to conduct reference scenarios where nutrient inputs from Danish catchments, atmospheric nitrogen deposition and nutrient load from the Baltic Sea catchment are set to "background" levels and by adjusting sediment nutrient pools and eelgrass covers to reflect a reference situation, but with present days water flow and meteorology (i.e. not accounting for human induced climate change or changes in freshwater run off). As the Bayesian models only accounts for effects of nutrients from Danish catchment, results from mechanistic models are used to adjust the statistically derived reference chlorophyll-a concentrations accounting for the impact of other countries and atmospheric deposition. The reference scenario results from the statistical and mechanistic models are used as inputs in a "combined" regression model using MLR, where physical and hydro-morphological parameters characterizing the individual water bodies are used as explanatory variables. The process of deriving chlorophyll-a reference values for each water body is illustrated below.

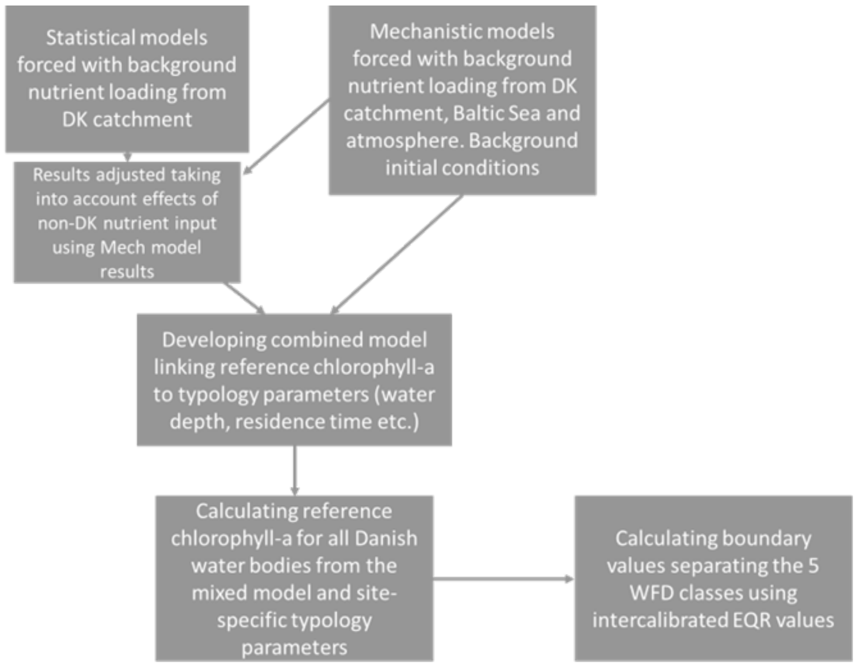


Figure 3.2. Schematic overview of the method applied to establish water body specific chlorophyll-a reference conditions and boundary values in Danish WFD water bodies

The background levels for TN and TP loadings from Danish catchments are estimated from concentrations of TN and TP in streams draining catchments with a low (< 10% for TN and < 20% for TP) proportion of agricultural land and no or very few point sources, however with present day atmospheric deposition. Atmospheric nitrogen deposition in a reference situation is calculated using an atmospheric model with year 1900 European emissions and data representing reference loadings for the North Sea and Baltic Sea catchments are computed using data from OSPAR and HELCOM, respectively. Detailed description of input data used for constructing the reference scenarios, including reference nutrient inputs from Danish, Baltic Sea and North Sea catchments, atmospheric nitrogen deposition as well as adjustments in the N and P sediment pools and areas covered by eelgrass in a reference situation etc. can be found here: Chlorophyll-a_reference_and_target_values.pdf.

The model results from the reference scenarios are used as dependent variables in a multiple linear regression model where physical and hydro-morphological parameters characterizing the individual water bodies are used as explanatory variables. The selected variables describing reference chlorophyll-a concentrations are "water depth" and "freshwater influence". Using these physical and hydro-morphological parameters and the combined model, water body specific chlorophyll-a reference values are calculated for all Danish water bodies.

Target values are calculated from reference values using intercalibrated EQR-values. For eelgrass the intercalibrated value for the good-moderate boundary is 0.74. Water body specific EQR-values for chlorophyll-a are described in Carstensen et al (2016).

4 Burden sharing (impact of other countries on MAI)

The overall aim of developing models (STAT and MECH models) is to run model scenarios to be applied for setting Maximum Allowable N and P Inputs (MAIs). However, a large number of the Danish water bodies depends on actions taken in neighbouring countries, like reductions in nutrient inputs from Germany directly impacts Danish water bodies in the Wadden Sea and southern Baltic Sea.

Hence, we have developed a method for calculating MAIs that take into account various assumptions from land-based nutrient reductions in neighbouring countries, assumptions on reductions from atmospheric depositions and some more WFD related assumptions.

The overall method is described in [MAI methods, RBMP 2021-2027 (au.dk).](#) We assume that the total pool of nutrients in any water body is the sum of various sources: Background loadings, anthropogenic land-based nutrients from neighbouring countries, anthropogenic atmospheric depositions, and anthropogenic land-based nutrients from DK catchments, see Figure 4.1. On top of this internal loading and recycling processes impacts the nutrient pool, but these eventually also originate from one of the four overall inputs.

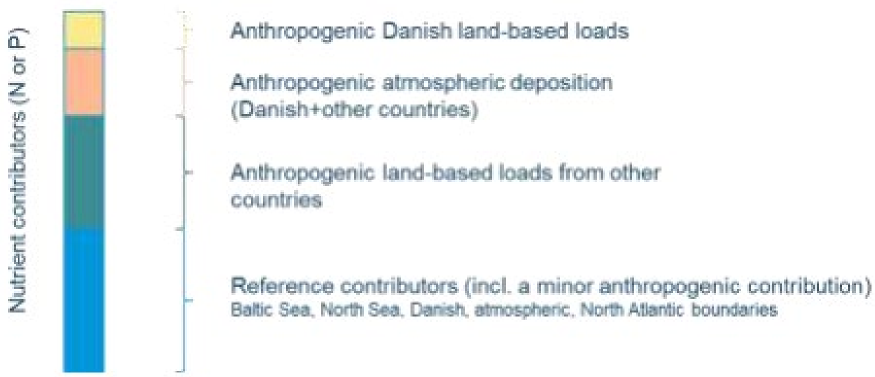


Figure 4.1. Schematic figure showing the contributors to the concentration of nutrients in a specific water body. The relative parts of the different contributors will vary between the different water bodies.

To assess the impacts of the various input sources we have run a number of scenarios with the mechanistic models to separate the dose-response between nutrient reductions and reductions in the indicator values (summer chlorophyll-a and light). Hence, the purpose of the different scenarios is to separate the individual dose-response (slopes) within each individual water body with the aim of being able to estimate the effects on the two indicators used (summer chlorophyll-a and Kd) from reductions in the five scenario parameters:

- Dose-response Scenario 1 (S1): 30% reduction in all Danish land-based N-loads
- Dose-response Scenario 2 (S2): 30% reduction in all Danish land-based P-loads
- Dose-response Scenario 3 (S3): 30% reduction in all land-based N-loads from other countries

- Dose-response Scenario 4 (S4): 30% reduction in all land-based P-loads from other countries

- Dose-response Scenario 5 (S5): 30% reduction in atmospheric N-deposition

When applying the STAT model in the MAI calculations the S1 and/or S2 dose-responses are replaced by the STAT models dose-responses, where we keep the S3, S4 and S5 from the MECH models. Hence, MAIs estimated by STAT models includes effects from neighboring countries and the atmosphere from the MECH models.

To account for time delays in N-fixations, sediment pools, ecosystem services etc we introduce a system-contribution which we distribute between the different slopes, assuming that over time good ecological status can be reached if nutrient reductions are achieved, see MAI methods, RBMP 2021-2027 (au.dk) for details – section 2.3.5.

Furthermore, the basic method calculates the individual N-MAIs, but various P-scenarios are included for most of the scenarios, introducing a 10%, 20%, 30% and 50% P-reduction.

As mentioned in the beginning of this section, the individual Danish MAIs rely on whatever happens in neighbouring countries (land-based nutrient inputs and atmospheric depositions), why we have calculated a number of scenarios related to this:

1. Regional Treaties and RBMP 2015-2021: This is kind of the basic scenario, and most comparable to the MAIs developed for the RBMP 2015-2021, including Baltic Sea action plan, implementation of the NEC-directive, and with additional reductions from Germany according to reported reductions in German RBMP 2015-2021.

2. Various scenarios related to land-based nutrient loadings– in these scenarios the atmospheric deposition is kept as described in management scenario 1, i.e. full implementation of the NEC-directive:

   a. Neighbouring countries are assumed to have had the same percentage of nutrient reduction as Denmark when Danish land-based N-MAIs are reached. The reduction percentage is relative to the basis period 1997-2001.

   b. Neighbouring countries are assumed to have the same area-specific anthropogenic loadings (kg/ha) as Denmark when Danish N-MAIs are reached.

   c. Loadings from neighbouring countries are unchanged compared to the present-day loadings (2014-2018).

   d. Danish land-based N-MAIs assuming updated BSAP targets. A new set of targets is being developed in HELCOM and will be adopted by the end of 2021.

e. Like management scenario 1 but with additional Wadden Sea P-reductions according to German suggestions for additional P reductions.

3. Various scenarios related to atmospheric depositions– in these scenarios the land-based loadings are kept as described in management scenario 1, i.e., BSAP and German WFD plans:

    a. Danish land-based N-MAIs assuming 2027 NEC-prognosis.

    b. Danish land-based N-MAIs assuming synergy impacts from climate actions. As Denmark and other countries work to minimise climate changes, some synergies are expected to impact N-depositions as well. This scenario consists of three alternatives (20% (3b1), 30% (3b2) and 50% (3b3) reductions).

4. Various scenarios related to the definitions in WFD:

    a. Averaging the indicators and model results

    b. Aiming at a higher degree of certainty (80%) for all water bodies achieving GES.

    c. One-out-all-out principles. This approach will use average model results per indicator but include the lowest MAI between the two indicators.

The precise assumptions and model implementations are described in a number of reports: [RBMP-reports](#) - see section 3.6, and is summarised in this report: [ManagementScenario_summary_v4 (au.dk)](#). The overall results of various scenarios are included in Figure 4.2, including the national MAI with zero reductions in P as well as a 50% P-reduction.

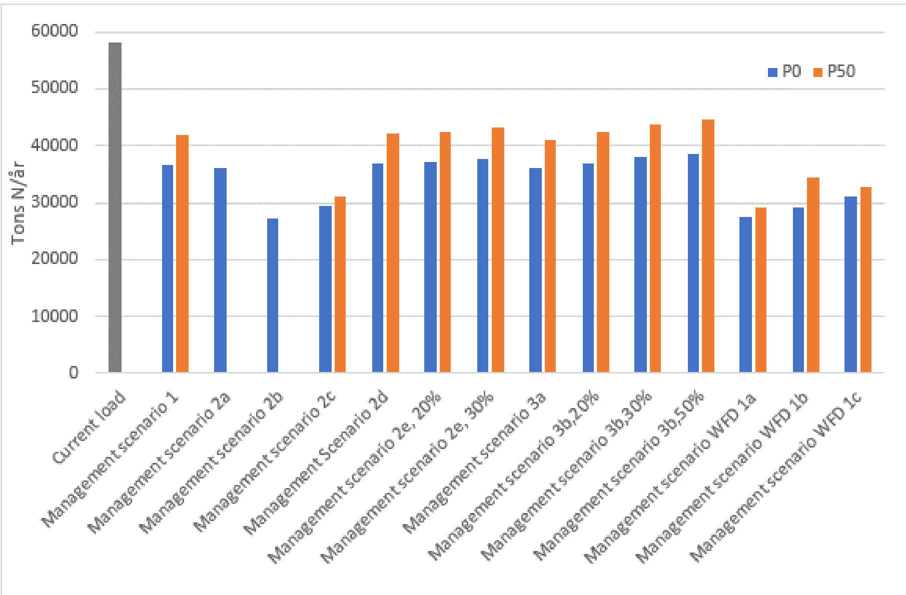


Figure 4.2. Present-day N loading (column to the left), and the estimated national MAIs based on the assumptions behind the various scenarios described above. Blue columns include no P-reductions where orange columns include a 50% P-reduction. The management scenarios are named according to the nomination in the bullets above (1-3) but where the WFD relates to bullet 4 above.

The final MAI results are an average of MAI estimates from each of the two model-types (STAT and MECH) in water bodies were there are estimates from both model types. The individual model MAI estimates from each model are also an average of the MAI results based on chlorophyll-a concentration and light limitation depth, respectively. All individual MAI estimates are truncated at either background load or status load before averaging.

As part of the assessment of the individual Danish RBMPs a report on uncertainties was also published: Estimating Confidence Intervals MAIs - in this report we have assessed sensitivity of MAI based on slope uncertainties and the associated uncertainties of MAI estimates in water bodies with untruncated MAI estimates from both model-types, by applying the error propagation method for calculating confidence intervals. The error propagation method is considered an appropriate approach, especially in situations where the complexity of the calculations prohibits analytical confidence estimates.

The error propagation method was used to estimate the sensitivity of model-slope uncertainty for the estimation of maximum allowable nutrient input (MAI) to individual water bodies, applying the Danish land-based N-slopes.

The results revealed that the confidence intervals (Q10-Q90) for the MAIs were < ± 10% of the median MAI for 93 out of 98 water bodies estimated with MECH models and 22 out of 28 water bodies estimated with 11 STAT models. For five and six water bodies, the uncertainty exceeded 10% of MAI for the MECH and STAT models, respectively, and the maximum uncertainty for a single water body was 40% (waterbody in Nissum Fjord).

This is an expression of how the uncertainty of one crucial parameter (the slopes of the nutrient input-quality element relationship) propagates through the calculation of MAI and does not cover uncertainty of state (based on monitoring data), model bias, uncertainties in forcing data (e.g. meteorological data, loadings etc.). Uncertainties related to the fulfilment of the assumption regarding nutrient reductions by neighbouring countries are also not considered.

The best estimate of the confidence interval for a "national-scale" MAI was calculated summarizing water body MAIs calculated with both MECH and STAT models where MAI distributions were unaffected by truncation (see MAI methods, RBMP 2021-2027 (au.dk) for details). The results revealed that the 80% confidence interval (Q10-Q90) was <2%. This is an attempt to include some model bias in the uncertainty measure but is restricted to only a subset of water bodies, and hence it should be considered as a minimum estimate. These results indicate that the MAIs and the nutrient reduction requirements are estimated with a high degree of certainty given the conditions mentioned above.

Seasonal variation

As described by some stakeholders and evaluated by the international expert panel in 2017, some water bodies might be more sensitive to the nutrient loadings discharged to the water body during the growth season (growth season loading) compared to yearly loadings. This was indicated by a report by DHI finansed by SEGES (Dannisøe[1] J (2017) and recognised as a potential method for optimising measures to obtain GES, why the international expert panel concluded: *If river basin models are able to provide nutrient load data on a monthly basis, this would allow the development of scenarios that take into account the seasonality of emissions. Assessing how seasonally differentiated emissions affect the status of coastal water bodies could lead to optimised, cost-effective management.*

As part of the overall model development a project expanding the findings from the one water body modelled in 2017 to more water bodies was therefore initiated: Seasonal variation (in Danish).

The aim of the project was to identify if more water bodies were sensitive to loadings especially during growth season (May-September) and to try to evaluate if and how measures could focus on growth season loadings more than yearly loadings.

The project was split into three part which were run in parallel: i) A part looking at specific catchments with the aim of analysing if any agriculture measures could target loadings during growth season, ii) a part analysing if measures reducing draining contributions could be applied, and iii) a part trying to identify water bodies on a nationwide scale which could be sensitive to the growth season loadings.

As they were all run in parallel, first task was a screening to identify a few catchments (5 catchments) that could be part of the analysis in i) and ii) whereas iii) applied two of the mechanistic models to assess the potential in more details.

Ad i): Based on a screening five catchments were identified, not based on the variations within the catchments, but based on the receiving water bodies identified with a high potential for sensitivity to growth season loadings. The catchments turned out to be quite similar, and the overall conclusion was that no known measures was expected to have a significant and systematic impact on growth season loadings.

Ad ii): In contrast to field measures, targeted use of measures aimed at drains (e.g. mini-wetlands) can reduce growth season loadings. However, some drains are often dry during summer why this might not constitute an effective measure. The five catchments analysed, however, did show some drainage contribution of TN during the entire year, around 20-40% of the TN load during May to September, and even more when including March and April.

In the section on drainage measures, the N turnover is estimated on the basis of N turnover percentages calculated for respectively open mini-wetlands and closed matrix systems (established in the catchment area of Norsminde Fjord). For filter matrix measures, a very large N turnover for the spring of 93% has been calculated. When this is combined with a large share of drainage water in the first spring months, a large reduction between 17 and 37% can be estimated for the catchments analysed. For N turnovers based on open mini-wetlands, the total reduction in the catchments is somewhat more modest and lies

[1] Dannisøe J (2017). Optimisation of the Nitrogen Loadings to Karrebæk Fjord Seasonal Effects from Nitrogen Reductions. DHI report (project no. 11824516)

between 5 and 11%. In the summer months, the total N turnover for the two drainage measures are more similar, and is between 13 and 24%.

Ad iii): To identify potential water bodies sensitive to reduction in growth season loadings, two of the mechanitic models were applied, the model covering the Northern Belt Sea and the Smaalands farvand. These two models covers 36 closed, semi-closed and open water bodies.

As the overall method for estimating MAIs, as described in MAI methods, RBMP 2021-2027 (au.dk) to a great deal rely on does-response (slopes) estimated based on model scenarios (MECH and STAT models) we have applied the same approach in this project. By reducing Danish land-based N- respectively P-loadings by 30% during the period May-September, new slopes were developed. These slopes were then compared to full-year reductions and if the relation between growth season slopes and full year slopes were between 1.0 and 0.42 (0.42 is corresponding to 5 months out of 12) we conclude there is a growth season impact. See Figure 4.3 and Figure 4.3 in Development og Mechanistic Models, RBMP 2021-2027 (au.dk) (in Danish).

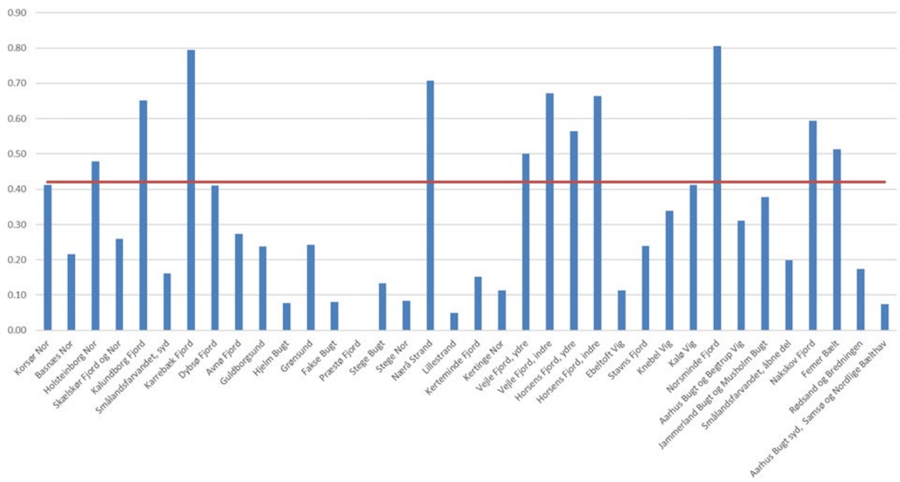


Figure 4.3. Relative difference in dose-response (based on Danish land-based N-loadings and summer chlorophyll-a). If the value is 1.0, there is no difference between the two dose-responses meaning that only the growth season loadings have an effect, while a value of 0.0 indicates a zero effect of growth season reductions.

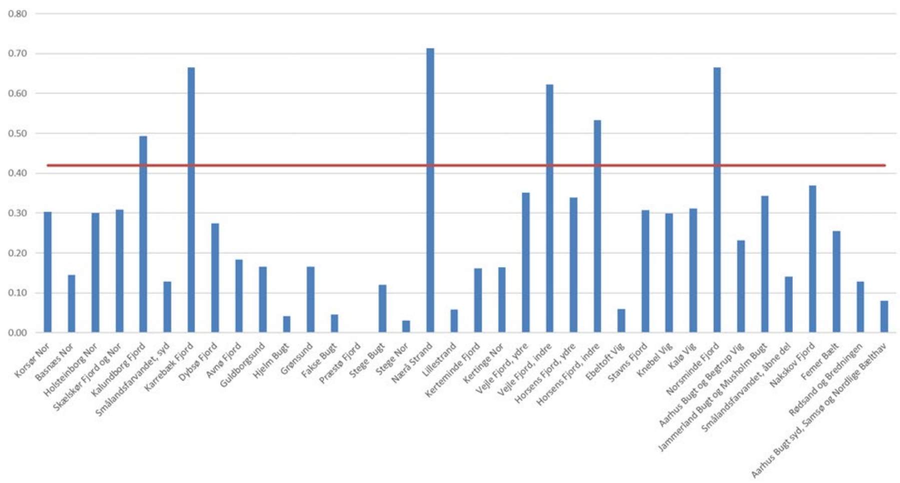


Figure 4.4. Relative difference in dose-response (based on Danish land-based N-loadings and light). If the value is 1.0, there is no difference between the two dose-responses, while a value of 0.0 indicates a zero effect of growth season reductions.

Again, we use typology parameters to extrapolate to all Danish water bodies. Here we use a GAM-model and the parameters surface salinity, water exchange, freshwater input, water depth and tides. This modelling exercise resulted in 18 water bodies scattered around Denmark with a potential for being sensitive to growth season N-loadings. We did not find any significant correlation to extrapolate model findings to similar growth season P-loadings. The latter most likely, because only few of the investigated water bodies were sensitive to P-reductions all together.

Finally, the report includes data on the split between diffuse loadings and most common point sources (industry, WWTP, combined sewage outlets and rainwater outlets, freshwater and marine aquaculture) estimated for a full year and growth season, respectively.

The project described was carried out based on a somehow idealized situation to clarify if there is a potential for growth season sensitivities in marine water bodies across Denmark, and the analysis confirms a sensitivity potential for growth season loadings in specific water bodies, and indicates ways of optimising measures to obtain GES, but without providing the full answer to which measures that could be implemented and how this impacts the overall need for reductions.

During 2022-2023, and in parallel with the international expert evaluation in phase II of the second opinion, the effects of growth season reductions, including both N and P, is being further qualified. This qualification involves:

1. Monthly distribution of point source loadings (N and P) according to data in the downstream marine water bodies, including impacts from larger lakes.

2. An analysis of potential for improved treatment of the individual point sources (with in specified catchments, identified as either P or growth season sensitive, see Figure 4.5 and Figure 4.6).

3. Detailed analysis of drainage measures and potential impact on monthly diffuse N-loadings.

4. Detailed dose-response analysis using all relevant models (9 out of 11 models) to analyse specific reductions in point sources (like 30% reductions in WWTP loadings etc), and diffuse loadings.

5. Economic optimisation, assessing impacts and costs to achieve the reductions needed to obtain GES.

The results of this project (growth season reductions, including both N and P) are expected to be ready within the first half of 2023, with some deliverables in early autumn.

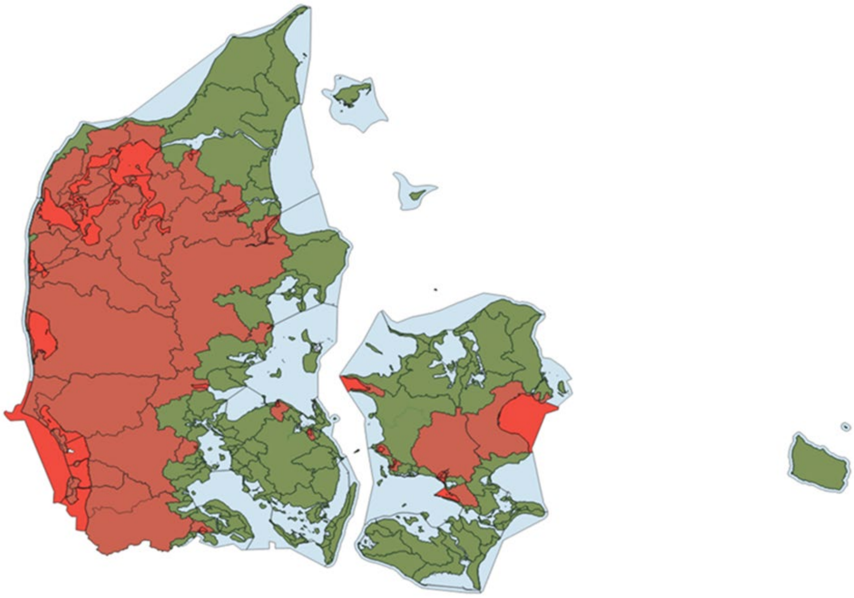


Figure 4.5. Water bodies (and corresponding catchments) that are relatively sensitive to P. Red areas are relatively sensitive to P-reductions and green areas have little or no sensitivity to P-reductions.

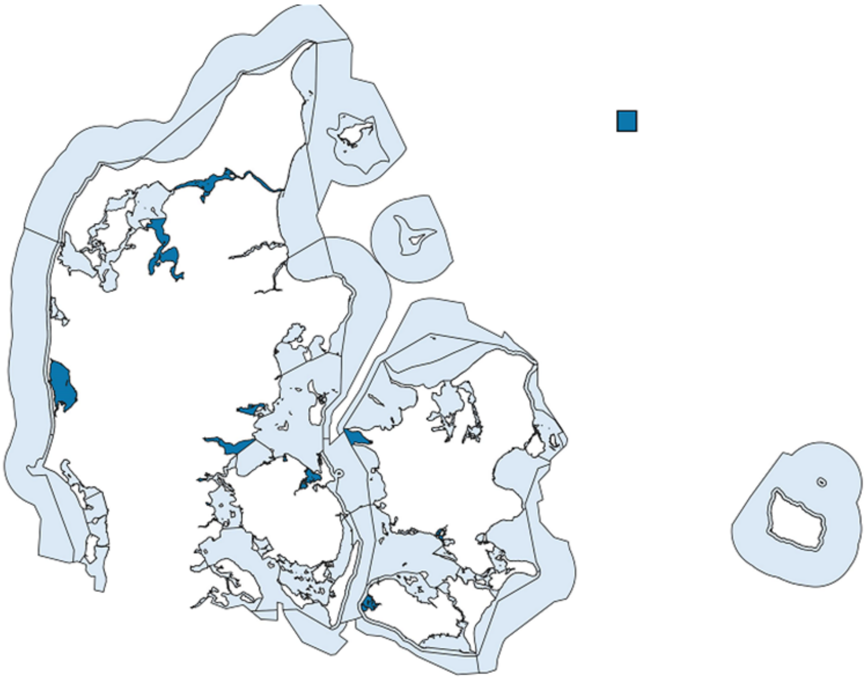


Figure 4.6. Water bodies identified as sensitive to growth season N-loadings in [Development of Mechanistic Models, RBMP 2021-2027 (au.dk)](au.dk) (in Danish)

5 Impact of pressures other than nutrients relevant for achieving good ecological status.

Although eutrophication is well-known for affecting coastal waters worldwide and particularly in Danish waters due to our high nutrient output pr. area, other anthropogenic pressures may also impact water quality and thus hamper achievement of good ecological status.

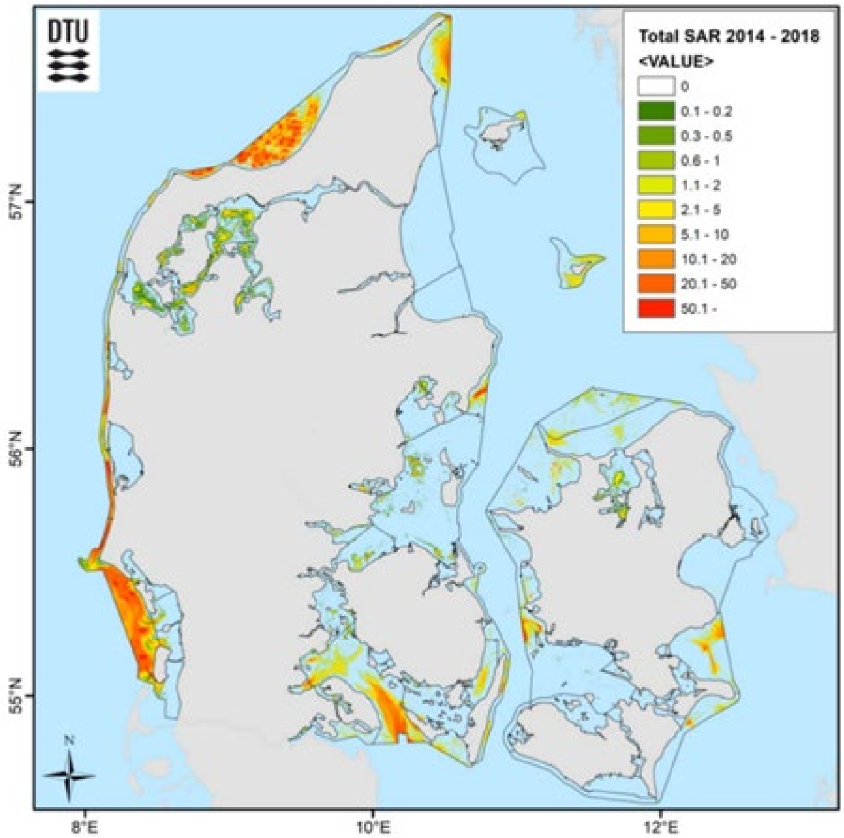
In a literature review of potential effects of a number of pre-defined pressure factors - sand and gravel extraction, dredging of shipping lanes and harbours and clipping of the dredged material, physical constructions, fishery, shipping, plastic waste incl. micro plastics, hazardous sub-stances and invasive species – was carried out with the aim to identify activities with documented impacts on the marine biological quality elements (seagrasses and macroalgae, benthos and phytoplankton) and selected supporting indicators (light and oxygen) Other anthropogenic pressures (in Danish).

Based on the results of the review, quantitative analyses for Danish coastal waters were carried out for effects of fishery and other localized pressure, sediment chemistry, selected invasive species and exploitation of boulder reefs. Overall, the performed data analyses show that primarily fishing and secondary - and to a much lesser extent - invasive species are currently the most significant pressures for the WFD quality elements in the WFD water bodies besides nutrient loading and climate change. See section 3.3 https://mst.dk/natur-vand/vandmiljoe/vandomraadeplaner/vandomraadeplanerne-2021-2027/supplerende-oplysninger/. The impacts identified here is not directly affecting water transparency and chlorophyll-a concentration, which the MAI estimates are based on. Hence these results have not been included in the MAI-calculation.

5.1 Fishery

Fishery with trawl, dredge or other mobile bottom-contacting gear (MBCG) occurs in almost half of the 109 Danish water bodies (fig. 5.1), and in 27 out of 109 water bodies the sea bed area affected by fishery overlap with areas where eelgrass could grow in good ecological conditions. The impacts of fishery and other site-specific pressures for eelgrass is addressed in https://mst.dk/media/201146/361-2020-effekter-af-stedspecifikke-presfaktorer-paa-aalegraes.pdf (in Danish).

Figure 5.1. Total swept area ratio (SAR, the number of times where the sea floor was impacted by bottom-contacting gear) in the period 2014-2018. Only SAR from WFD water bodies is shown.



It was not possible to detect significant impacts of dredging on the Danish quality index (benthic fauna), likely due to i) the location of the monitoring stations, ii) that Danish quality index (benthic fauna indicator) is designed specifically to detect effects of eutrophication, not fishery, and thus gives high weight to species number; and iii) that the effects of fishery may be masked (and comparatively small) in areas already heavily disturbed by eutrophication.

Furthermore, results from model scenarios and literature review suggests that the impact of fishery on phytoplankton (chlorophyll-a concentration) is insignificant.

The impact of fishery on benthic fauna (DKI) and phytoplankton (chlorophyll-a) is addressed in the report https://mst.dk/media/189078/358-2020-effekter-af-fiskeri-paa-bundfauna-og-fytoplankton.pdf (in Danish).

5.2 Invasive species

The potential impact of the invasive species *Mnemiopsis leidyi* and *Neogobius melanostomus* on the biological quality elements are addressed in https://mst.dk/media/205229/vurdering-af-de-invasive-arter-amerikansk-ribbegople-og-sortmundet-kutling-rapport-fra-dtu-nr-365-2020.pdf (in Danish). Briefly, the analysis did not detect significant impacts of the invasive species on the quality elements partly because there is an insufficient data basis for the analysis.

In contrast, impacts of the invasive species *Sargassum muticum* (Japanese wireweed) on the macroalgae assemblages causing reduction in distinct species from especially the larger brown algal species, affecting species richness and in particular evenness of the macroalgal assemblages with increased predominance of Japanese wireweed. The analysis further showed that eelgrass and Japanese wireweed can coexist in mixed hard and soft bottom habitats without significant inter species competition. The impacts of Japanese wireweed on eelgrass and macroalgae is addressed in the report https://mst.dk/media/186864/353-2019-effekter-af-sargassotang.pdf (in Danish).

5.3 Sluices, dams etc.

Physical constructions such as sluices, dams and other construction affecting the hydrodynamic properties can have a major impact on individual water bodies. Although these constructions are present in several water bodies (figure xx), it is assumed that a potential impact on the biological quality elements require that the constructions are closed a significant part of the year or if they are used to control the salinity in the water body.

Figure 5.2a. Water bodies with sluices or dams (grey). In most water bodies, lock operation practice and/or the location of the construction do not affect the overall hydrodynamic properties. There are 15 areas potentially affected by sluices or dams (MiljøGis).

Figure 5.2b. Heavily modified water bodies (grey hatching) where the target is "good ecological potential". There are 4 water bodies that are heavily modified (MiljøGis).

Four water bodies (one in Ringkøbing fjord and three in Nissum fjord) have been identified as being changed to such an extend due to lock operation, that they have been named "heavily modified water body", meaning that they are subject to altered ecological targets relative to an equivalent water body with no sluice. The ecological targets in these water bodies are "good ecological potential". Identification of heavily modified water bodies is described in chapter 4.2 in the report https://mst.dk/media/187927/afgraensning-karakterisering-typologi.pdf (in Danish).

5.4 Excavation, dumping and extraction of materials at sea

Activities such as excavation of harbours and sailing routes, dumping of materials and extraction of raw materials at sea occur in a major part of Danish water bodies. The (local) impact of these activities for the indicators chlorophyll-a, DKI and eelgrass was assessed by comparing the location and size of the affected area relative to the area of the water body. The analysis revealed that the impacted areas were small (< 5%) compared to the water body area and it was concluded that although these activities have a local impact on benthos and benthic vegetation the impacted areas were too small relative to the water body area to have an impact at water body scale. The analysis is described in chapter 2 and 3 in https://mst.dk/media/186771/11-menneskeskabte-paavirkninger-af-havet-andre-presfaktorer-end-naeringsstoffer-og-klimaforandringer-rapport-fra-dtu-og-dce-for-miljoestyrelsen.pdf (in Danish). A specific analysis only showed significant effect of these activities on eelgrass as overlap between affected areas and the depth where eelgrass can grow in good ecological conditions in one water body in https://mst.dk/media/201146/361-2020-effekter-af-stedspecifikke-presfaktorer-paa-aalegraes.pdf (in Danish).

5.5 Climate change

Above, other pressures than nutrients and climate has been assessed. The nutrients are basically been assessed in setting the various individual MAIs, why only climate has not been assessed. To make up for this a project analysing climate changes was initiated.

The projects aim was not to analyse expected climate change in 2100, but more to analyse the climatic imprint on the two indicators summer-chlorophyll-a and light, Klimaændringernes betydning for indsatsbehov for kystvande (au.dk) (in Danish).

First the 11 mechanistic hydrodynamic models were forced with present day meteorological data adjusted for changes in air temperature, wind speed and precipitation between present day and 1900. The results from the hydrodynamic models (based on both present day and presumable historic meteorological data) were then applied in a spatial habitat GIS model for predicting eelgrass depth limits (Frontiers | Habitat Model of Eelgrass in Danish Coastal Waters: Development, Validation and Management Perspectives (frontiersin.org)) and the difference between the models assessed.

Similarly, the present day and presumable historic hydrodynamic models were superimposed with the biogeochemical model to evaluate changes in summer chlorophyll-a concentrations.

With respect to eelgrass, the model results show that the depth limit of the eelgrass in most water bodies would have been lower in a historic (year 1900) climate compared to present day climate. As the reference values for eelgrass depth limit are historically based, the status values would likewise have been lower than compared to the status values we compare to in a present-day climate. However, comparing to the present-day climate the eelgrass depth limits target values would equally have been pushed towards deeper waters, why the climate has worked to improve the ecological status.

For the chlorophyll indicator, the model results show that the chlorophyll-a concentrations in most water bodies are higher in a historical climate compared to the present-day climate. This basically indicate that the reference values applied based on present day climate data would have been higher than the reference data applied for setting reference values and targets.

Hence, climate changes have an impact on the need for reductions to obtain GES; We estimate that the need for reductions would increase by approx. 600 tonnes N/year, if the status value for eelgrass was measured in a year 1900 climate compared to the present-day climate, whereas the need for reductions would be approx. 1500 tonnes of N less, if the chlorophyll-a target was based on a historical climate compared to a present-day climate. Thus, the two indicators react opposite with the climate changes assessed in the present project.

The project has not assessed future climate changes. As we are looking at deadlines towards 2027, we do not anticipate any significant climate changes, why this was not included.

6 Improvements from RBMP 2015-2021 to RMBP 2021-2027 based on the recommendations from the international expert panel (International evaluation)

The international evaluation of the Danish RBMP2 2015-2021 criticized the coarse typology used to estimate chlorophyll-a reference level and nutrient input and chlorophyll-a relationship in estuaries and fjords outside the modeled areas. The old typology before RBMP2 described 21 types of waterbodies and was based on Dahl et al. (2005). To reduce the uncertainty of the reference level in the waterbody types the number of types was reduced to 9 in RBMP", before aggregating the model results during the RBMP-work.

During the current RBMP3 2021-2027, the typology has been completely revised. The revision is described in Typology (in Danish). Here we provide a comprehensive summary.

The revision of the typology of the Danish RMBP water bodies consists of three steps. The first one is the overall characterization of the waterbody types answering the overall question: Is it a coastal water type in contrast to; lakes, transitional waters and heavily modified waters? This is done in accordance with the CIS guide no. 5. and some additional criteria:

1. The water body must be saline (does not make it a coastal water body, alone).

2. There must be a free (or nearly free) exchange between the water body and nearby coastal waters. This could e.g., be reflected in co-oscillating water level variations.

3. In cases of doubt, flora and fauna can be included in the assessment of whether the water body is dominated by marine flora and fauna, or whether it is dominated by freshwater species.

Secondly delimitation of the outer boundaries of the waterbodies were revised. This was done following these guidelines from WFD CIS Guidance Document No. 5 section 2:

1. Waterbodies must not overlap with each other.

2. A waterbody must be continuous - the waterbody must therefore not consist of bodies of water that are, for example, physically separated.

3. The waterbody must belong to one type – not several – which ensures that the water area has the same reference state and state thresholds.

4. Waterbodies must be subdivided if the environmental condition is very different within the waterbody.

Basically, the final delimitation of a water area must ensure that the individual water body is uniform both with regard to the hydro-morphological, physical-chemical and biological characteristics and their respective pressures and associated ecological state (i.e. same type, environmental thresholds and reference condition within the waterbody). However, it must also be ensured that the water bodies do not become so small that they cannot practically be managed - i.e. the balance between coastal water bodies that are, to the greatest extent possible, uniform units, but at the same time considering not to divide water bodies into such small areas that the subsequent administrative burden grows inappropriately (see CIS guide no. 2). In the final delimitation, it applies to ensure that a water body can be managed in such a way that the water body is generally in good ecological state (GES). This is an iterative process where the final delimitation (and type division) can show that a water body must be divided further to ensure that the individual area comes in a suitable type and can thus be administered uniformly.

The review of the demarcation of the individual water bodies has been an assessment of whether:

i. Limits must remain as they are: This is the case if criteria 1-4 are assessed to be fulfilled.

ii. Boundaries must be removed (i.e. water bodies merged): This is the case if neighboring water bodies belong to the same type and have the same environmental condition.

iii. Boundaries must be established (i.e. water bodies are subdivided): This is the case if a current water body is assessed to consist of several types, and/or if the environmental condition changes class in a subarea of the water body.

iv. Border must be moved. This is the case if the current limit is not appropriate, e.g. due to Natura 2000 boundaries or physical conditions.

v. It is also assessed whether there are water bodies that are so small that those of administrative reasons not to be handled as independent water bodies (administrative amalgamation with adjacent water area).

The assessment of whether the current demarcation must be adjusted is based on the following criteria (from CIS guide no. 2):

i. Physical characteristics: To the extent that there are physical conditions which "naturally" delimit one water body, these can be used to delimit the water body ("physical" demarcation). These physical characteristics may be geographical and/or hydromorphological – especially if the hydro-morphological characteristics of a sub-area are assessed to be different due to changed physical design.

ii. Typology: To the extent that a body of water is assessed to consist of areas of different type, the typology is used for delimitation ("type" delimitation).

iii. Physical Modifications: Man-made physical modifications which have significant impact on a body of water, can be used for delimitation ("SMV4" boundary).

iv. Difference in status. If within a body of water there are large differences in status, status is used for demarcation, so that a water area actually ends with a unique one condition classification ("Status" delimitation).

v. Protected areas under EU legislation (e.g. Natura2000 etc.).

vi. Administrative cancellation of watershed boundaries if catchment area < 1,500 ha., which is the size of the smallest manageable catchment unit in Denmark.

Finally, after the revision of the delamination of the water bodies, the revision of typology can be applied. This typology is important for determining the reference levels of chlorophyll-a and to some extend for eelgrass depth limit, for the individual water bodies. The typology is based on hydro-morphological and physio-chemical (meta) variables that are characteristic for the water bodies. There are a set of variables that are mandatory and some that are optional, in the type classification, according to the WFD. The so-called mandatory variables are latitude and longitude, tidal amplitude and the salinity of the water bodies, while the optional variables include depth, current speed, wave exposure, average and variation in water temperature, mixing (residence time), as well as the nature of the bottom substrate. Based on the mandatory and optional variables we have systematically extracted physical and hydrodynamic data, which characterize the individual coastal water bodies. The water bodies have been categorized using multi-dimensional scaling analysis (MDS) combined with a cluster analysis to group the different types.

Table 6.1. The variables that are included in the typology are:

Variable	Comment
Longitude and latitude	Mandatory
Tidal variation	Mandatory
Water column stability/ mixing characteristics	Optional
Retention time	Optional
Freshwater impact (combination of retention time and current)	Optional
Substrate combination	Optional
Average water depth	Optional
Catchment area/water body area ratio	Optional

According to CIS guide no. 5, there are three additional optional variables: current velocity (included indirectly, see below), wave exposure and turbidity, which are not included in the Danish typology. These variables have biological relevance to some degree, but we have no data, or the variable are dependent on the degree of eutrophication and therefore are not suitable for inclusion in a typology (which is used for defining reference condition).

6.1 Results of the typology revision

During this revision, five coastal waters were re-characterized as lakes due to their limited water exchange with the coastal zone. None of the waterbodies was characterized as transitional waters and finally, one of the six highly modified waterbodies was re-characterized into coastal waters while it was assessed that the modification did not hinder the attainment of GES in that waterbody. In addition, one highly modified waterbody was re-characterized as coastal waters because it was merged with a much larger area and the modification, therefore, was negligible on the waterbody scale. The last four waterbodies were unchanged.

Based on the aforementioned criteria, the previous 119 coastal water bodies (including 6 heavily modified water bodies) have been reviewed, consolidating the existing demarcation and/or updating the demarcation. Based on the review of the individual existing coastal water bodies, changes have been proposed to the delimitation of 21 of the 119 existing RBMP 2 water bodies:

• For 7 of the existing RBMP 2 water bodies, the precise demarcation is proposed to be updated primarily due to geographical conditions (narrowing) and/or due to existing boundaries for protected areas

• 6 RBMP 2 water bodies are proposed merged with neighboring water bodies

• 4 RBMP 2 water bodies are proposed to be subdivided

• 1 restored coastal water body is proposed to be included as part of the adjacent coastal water body.

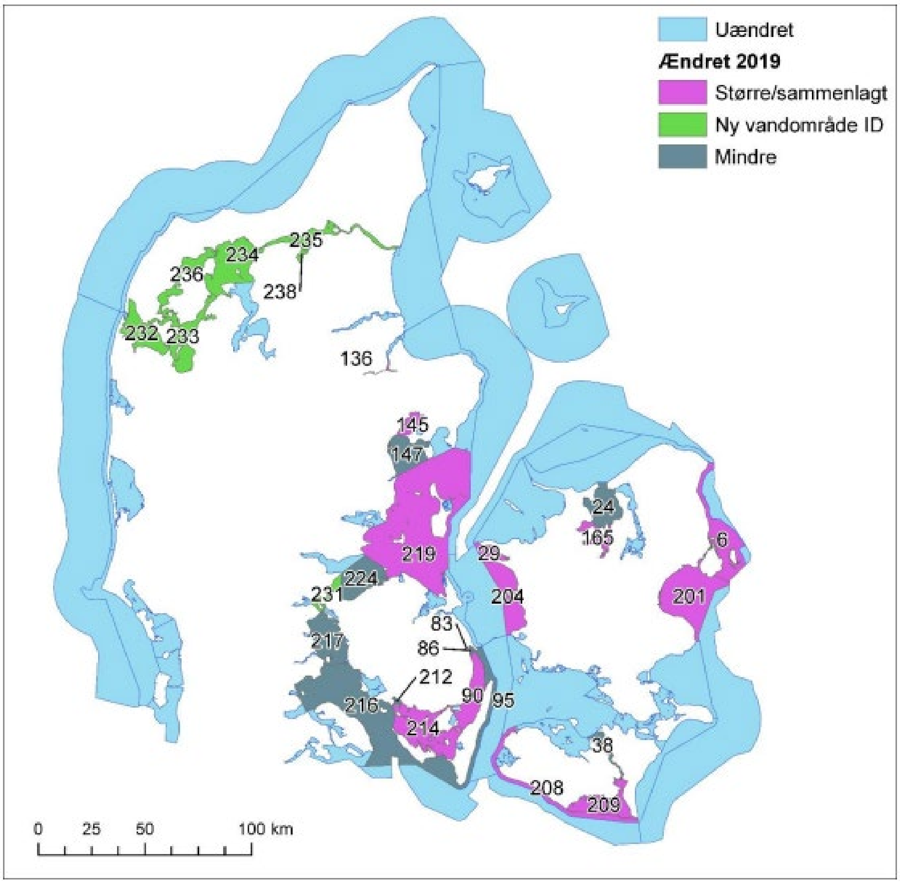


Figure 6.1. Water bodies that have been changed during the revision of the typology. Pink are areas that have been merged with other areas or are increased in size (from changed delimitation), green are new water bodies arising from subdivision of larger areas. Grey are water bodies that have decreased in size.

The final number of waterbodies after revision are 114 but five of these have catchment areas smaller than the "administrative" minimum size and are proposed merged with larger areas.

The MDS and cluster analysis resulted in 39 water area types, which can ensure reasonably uniform water areas within each type and at the same time ensure that the typology is a useful tool for e.g. determination of reference states. The typology variables are also used directly in meta-models, for the estimation of reference levels of chlorophyll-a and for eelgrass depth limit from areas lacking historical observations.

6.2 Other improvements

The RBMP 2 evaluation also highlighted six other points that the panel believed could be improved.

1. Indicators: The evaluation report criticizes the use of light attenuation (Kd-coefficient) as indicator of eelgrass depth limit, whereas the chlorophyll-a indicator in general is considered a more robust indicator. Furthermore, the additional indicators are criticized.

The criticism of Kd as an indicator is based on two points. One is that the exponential relationship between Kd and the light intensity at a certain depth means that the average Kd is an imprecise measure of the average light intensity - especially if the variation in Kd is large. The other point is that kd has some properties that make it a less suitable eutrophication indicator and that the relationship between load and indicator is not as strong as for chlorophyll.

Response: In the RBMP 3 modelling development, average Kd was replaced with average light penetration depth (16% of surface irradiance). The light climate still is a very important eutrophication indicator in Danish waters – though it does react on nutrient input on another time scale than phytoplankton (chlorophyll-a indicator) and to other additional pressures than the chlorophyll-a indicator (e.g. re-suspended particles and increased CDOM input). (Reports DHI Report DK (mst.dk) (Danish), Modelling light conditions in Danish coastal waters).

2. Favoring N over P: The panel accepts that N is typically the most important of the two nutrients, but the panel does not consider it to be adequately proven that this is the case everywhere and thus, cannot ignore that additional gains may be achieved by also reducing P in some water bodies.

Response: Both N and P has been integrated in the statistical models, so they "co-exist" in contrast to the statistical models in RBMP 2 that only were forced by either N or P. There has been made N and P reduction scenarios in both the mechanistic and statistical models based on annual loads and calculated as N-MAI for each water body at the national P-reduction of 0%, 10%, 20%, 30% and 50%. (Reports Reports (mst.dk) scenarios in 3.6).

3. Model development: The panel supports the approach with two different model types but believes that the mechanistic models should be expanded to cover more water bodies and that statistical models, to a greater extent,

should include cross-system analysis as well as rely on Bayesian statistics. Furthermore, the panel is of the opinion that the model approach should be more harmonized, thus the same indicators and methods are used for estimating the effort needs.

Response: The coverage of both models has been expanded and the mechanistic models now cover most of the Danish water bodies. The statistical models were design to work "cross systems" and based on Bayesian statistics, but were finally only applied as single station models. For the reference levels of chlorophyll-a and eelgrass depth limit, cross system analysis was applied. Indicators in both model approaches was harmonized as well as the calculation of MAI (Reports Reports (mst.dk) under 3.5 and Modelling chlorophyll-a concentrations. (au.dk) and Modelling light conditions. (au.dk))

4. Meta models: The panel estimates that regression based meta modelling could be better than the type-based approach used, and that meta models for the North Sea are uncertain and should be improved.

Response: The type-based models for estimating reference levels have now been replaced by regression-based meta-models based on the typology metavariables. (Report Establishing Chlorophyll-a reference conditions (au.dk) and Referenceværdier og grænseværdier for ålegræsdybdegrænser (au.dk) (in Danish, but the meta-modelling is analogues to the one used to establish chlorophyll-a reference conditions))

5. Effort requirement calculations: An important part of the evaluation panel's criticism addresses the estimation of the effort needed, and corresponding maximum allowable input (MAI), where they, among others, believe that there is an inconsistency between methods used in the statistical models and in the mechanistic models, including differences in the indicators used as well as in handling the response to local nitrogen inputs. Furthermore, the panel believes that the measurement process is averaged too early, which makes it difficult to examine each individual MAI.

Response: The MAI is now estimated for each type of model and averaged as the final step after the two independent MAIs have been estimated. MAI methods, RBMP 2021-2027 (au.dk), ManagementScenario_summary_v4 (au.dk), MAI uncertainty, RBMP 2021-2027 (au.dk) and scenario reports under 3.6

6. Other pressures than N: One point of criticism highlighted by some stakeholders is the lack of other pressures than nutrients. The expert panel understands that other pressures may cause an ecosystem to fail in achieving good ecological status but estimates that no other pressures are as significant as N (and P).

Response: See chapter five and Other anthropogenic pressures (in Danish).

SECOND OPINION READERS GUIDE TO RBMP 3 MODELS AND SCENARIOS IN DENMARK

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