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Application of the Danish EPA's Marine Model Complex and Development of a Method Applicable for the River Basin Management Plans 2021-2027

Conceptual Method for Estimating Maximum Allowable Inputs

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Application of the Danish EPA's Marine Model Complex and Development of a Method Applicable for the River Basin Management Plans 2021-2027

Conceptual Method for Estimating Maximum Allowable Inputs

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Eelgrass in Kertinge Nor
Photo: Peter Bondo Christensen

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Preface

This report is commissioned and funded by the Danish Environmental Protection Agency (EPA). The data, methods and results included in the report are intended to be an integrated part of the material behind the Danish River Basin Management Plans (RBMP) 2021-2027.

The work reported was managed and performed by DHI and AU/DCE. During the project, a steering committee followed the development and was involved through dialogue and follow-up on progress, etc. This steering committee consisted of members from the Danish Ministry of Environment and Food (MFVM), Danish EPA (MST), DHI and AU.

In addition, a follow-up group consisting of members from The Danish Agriculture & Food Council, SEGES, Sustainable Agriculture (BL), the Danish Society for Nature Conservation, the Danish Sports Fishing Association, Danish Fishermen PO (DFPO), the Danish Ports and KL/municipalities were affiliated with the project. The follow-up group has been continuously informed about the progress of the project at meetings convened by the MFVM.

Choice of methods, data processing, description and presentation of results have been solely AU's and DHI's decision and responsibility. A draft version of this report has been reviewed by MST and the follow-up group.

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1 Introduction

When preparing the Danish River Basin Management Plans 2015-2021 (RMBP 2015-2021), DHI and Aarhus University (AU) developed a number of mechanistic (DHI) and statistical (AU) models that were used for calculating chlorophyll-a target values defining the threshold (GM) between 'Good Ecological Status' (GES) and 'Moderate Ecological Status'. The models were also used for calculating Maximum Allowable Inputs (MAIs) of total nitrogen (N) from Danish catchments based on chlorophyll-a threshold values and a proxy for eelgrass depth limit. Hence, the development aimed at both the model development and the development of a method for calculating the MAIs.

As part of the political, regulatory package 'The Food and Agriculture Package from 2015', an international evaluation of the methods and scientific background used in the RBMP 2015-2021 was conducted. The evaluation was finalised autumn 2017 with a report (Herman *et al.* 2017) including a number of recommendations for improving the scientific background behind the RBMP 2021-2027.

To follow up on the international evaluation, the Danish EPA facilitated a range of R&D projects with the overall aim to develop methods to calculate robust, transparent and differentiated chlorophyll-a reference values (and corresponding target values) and MAIs in as many water bodies as possible for incorporation into the RBMP 2021-2027.

Two central R&D projects relate to the continued model development in the assessment of reference chlorophyll-a values (and corresponding target values) and final MAI calculations. Other projects also support different aspects of the final MAI calculations, but here we focus on those two central R&D projects:

- 'Recommendations for the continued development of models and methods for use in the River Basin Management Plan 2021-2027. Follow-up on the international evaluation of marine models behind the River Basin Management Plan 2015-2021' (Erichsen & Timmermann 2018).
- 'Application of the Danish EPA's Marine Model Complex and Development of a Method Applicable for the River Basin Management Plans 2021-2027'.

To be able to carry out the MAI calculations, the following is required:

- A robust conceptual method that combines model results from both mechanistic and statistical models
- Target values for the two Water Framework Directive (WFD) indicators; summer chlorophyll-a concentration and depth limit of eelgrass
- Model results quantifying effects of changes in nutrient input from the atmosphere and other countries generated through a range of supporting model scenarios (dose-response scenarios)
- Assumptions about future development in nutrient input from the atmosphere and other countries as these nutrient sources may influence Danish water bodies and MAI

International experts evaluated the method developed and used for the RBMP 2015-2021, and recommendations for improvements were listed. Based on those suggestions – and an overall update by DHI and AU – the conceptual method for calculating MAIs has been modified and improved to fit the needs of the RBMP 2021-2027.

This technical note describes the developed conceptual method for estimation of individual MAIs as well as a description of the supporting model scenarios (dose-response scenarios) required in support of the method as well a description of the different scenarios (management scenarios) reflecting the development in nutrients from the atmosphere and non-DK nutrient sources.

2 Method

2.1 Background

During the projects ‘Application of the Danish EPA’s Marine Model Complex’ and ‘Development of a Method Applicable for the River Basin Management Plans 2021-2027’[1] a number of statistical models and mechanistic models (DHI 2019a – DHI 2019k; DHI 2020a – DHI 2020k) were developed to describe the indicators used in the MAI calculations towards RBMP 2021-2027.

Both model types are developed based on existing hindcast data. The statistical models use existing measured data from individual water bodies between 1990 and 2018 as a basis for the model development, whereas the mechanistic models are developed to describe the years 2002-2016 and are validated against existing measured data covering those years.

The two types of models are developed with the primary purpose to ensure a robust basis for MAI calculations, and the method developed and presented in the present technical note builds on model results retrieved from those two model types.

To be able to calculate any MAI, several steps need to be accounted for:

1. *Indicators need to be identified:* According to the Water Framework Directive (WFD) several quality elements shall be assessed by representative indicators. In the MAI calculations for RBMP 2015-2021, one intercalibrated indicator ‘summer chlorophyll-a’ (representing phytoplankton abundance) and one proxy-indicator ‘light attenuation K_d’ (representing the intercalibrated indicator ‘eelgrass depth limit’/angiosperm abundance) were used. During the model development for RBMP 2021-2027, the scientific foundation for these indicators was revisited and updated. Summer-chlorophyll-a continues to be an essential indicator, whereas the indicator representing the eelgrass depth limit was transformed into depth with sufficient light to support[2] eelgrass growth.

2. *Status values for the indicators need to be established:* Based on measurements, or a combination of measurements and model results, the actual status of the individual indicators is established. The status is based on relevant data from the National Monitoring Programme (NOVANA 2016) and estimations presented in Larsen *et al*. (2020) based on data from 2014-2018. Here we apply status data between 2014-2018 to ensure a strict correlation between status data and status loads.

3. *Definition of an indicator target value:* The target (GES) is generally defined as a ‘slight’ deviation from reference conditions, and according to *BEK nr 1001 af 29/06/2016* the deviation is determined by an Ecological Quality Ratio (EQR). The EQR values are also defined in *BEK nr 1001 af 29/06/2016* and in (Carstensen 2016). Before the EQR is applicable, the reference values of the individual indicators need to be established. For eelgrass depth limit, reference values are based on historical measurements (Krause-Jensen & Rasmussen, 2009) and distributed according to (Timmermann *et al.* 2020a), whereas the referenced chlorophyll-a values are estimated using the developed models forced with nutrient loadings that define nutrient concentrations from streams with limited anthropogenic impact and present-day’s freshwater discharge. The modelled referenced chlorophyll-a data are presented in (Timmermann *et al.* 2020b).

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[1] Videreudvikling af Miljøstyrelsens marine statistiske hhv. mekanistiske modeller til brug for vandforvaltningen

[2] Allow for existing eelgrass to continue to be present, but not increase biomass nor extend spatially.

4. *Establishment of indicator response to a change in e.g. the land-based nutrient loadings (N and/or P) from Danish catchments:* The indicator response is solely determined by the different models covering the individual water bodies.

5. *Establishment of indicator response to changes in nutrient loadings originating from non-Danish catchments*, i.e. the North Sea, the Baltic Sea and atmospheric deposition allowing for addressing future changes in non-Danish and atmospheric nutrient input to Danish water bodies.

6. *Construction of scenarios reflecting the potential development in nutrient input from non-DK catchments and atmospheric deposition* allowing for a suite of DK-MAIs depending on future non-DK nutrient inputs.

2.2 Objective

The present study is part of the project 'Application of the Danish EPA's Marine Model Complex', and the objective is to develop a robust and transparent method that will ensure differentiated MAIs in as many water bodies as possible taking nutrient contributions from other countries and the atmosphere into account.

The method is based on the indicator response due to changes in loadings from Danish catchments considering the current and future contributions of nutrients originating from non-Danish catchments.

2.3 Conceptual Method

2.3.1 Assumption

The concentration of nutrients in a given water body, at any given time, originates from various sources. As the bioavailability depends (among other things) on origin, the impact of a specific nutrient source does not always scale with the total amount of nutrients. In e.g. Kattegat, the Baltic Sea is a significant contributor to TN, but the bioavailability of TN from the Baltic Sea is low. Atmospheric deposition contributes with a small amount to the TN pool in Kattegat, but as the atmospheric N is highly bioavailable, the impact on chlorophyll-a from atmospheric deposited N will be larger (per tonnes N) than N from e.g. the Baltic Sea in some water bodies.

Hence, when quantifying the effects of nutrient loadings from various sources in a specific water body, we need to consider both the amount of nutrients, the origin and the relative impact on the individual indicators.

In the following, the different elements of the method applied in the estimation of MAIs are described in more detail.

2.3.2 Nutrient Origin

As mentioned above, the nutrients present in any water body at any given point in time originate from different sources. Here we group the nutrients into reference/background loadings and an anthropogenic contribution separated into 3 sub-groups based on sources of origin:

Reference/background loading: In every water body, a part of the total nutrient input is a reference/background loading originating from different sources. The reference loading to each water body can be calculated based on reference atmospheric depositions and reference loadings from Danish and non-Danish catchments (see Timmermann et al. 2020b) for details).

The reference data are assumed to represent a situation where the anthropogenic contribution[3] from the individual data sources is minimal.

The different nutrient contributors in the reference situation are boundaries (North Atlantic boundaries), atmospheric deposition and land-based loadings including diffuse and point sources. For the reference load, we do not distinguish between the locations of the individual sources and the corresponding chlorophyll-a levels.

- **Anthropogenic contributors:** On top of the reference contributors we need to add the anthropogenic part of the different contributors. These parts refer to:
    - An anthropogenic contribution from the land-based Danish sources.
    - An anthropogenic contribution from the land-based sources from other countries within the North Sea and the Baltic Sea[4].
    - An anthropogenic contribution from the atmospheric deposition (some Danish and some from other countries).

Hence, we assume that nutrients within the North Sea and the Baltic Sea originate either from the part which is regarded as the reference situation (background) or from one of the three anthropogenic contributors mentioned above.

The sediments (internal loads of N and P) and N-fixation, from cyano-bacteria, also contribute to the nutrient concentrations in the water bodies. However, the contribution from the sediments is a result of past land-based and atmospheric depositions which over time has increased the sediment pools of nutrients, whereas the N-fixation is linked to the load of especially TP to the Baltic Sea and hence, indirectly linked to the changes in the three anthropogenic contributors. Here we assume that the sediments and the N-fixation will settle into a new steady-state when changing the loads, although we do not know when (how long it takes) the new steady-state will be reached.

As a result of the above assumptions, the nutrient in one specific water body consists of four different nutrient contributors, as illustrated in Figure 2-1.

Figure 2-1 Schematic figure showing the contributors to the concentrations of nutrients in a specific water body.
The relative parts of the different contributors will vary significantly between the different water bodies.

[3] The anthropogenic contribution is not zero, but the contribution from anthropogenic activities is minimal.

[4] We assume a zero anthropogenic contribution in the north-western boundaries of the North Sea model (northern part of the Atlantic Ocean)

2.3.3 Dose-Response

The next step is to evaluate the response of the indicators to changes in nutrient (dose) loadings from different nutrient contributors to the various water bodies. The dose-response is assessed by a number of scenarios performed with both mechanistic and statistical models.

In the following, the response to nutrients is described in more detail.

To be able to describe the relative (short-term) response to changes in nutrient inputs in a specific water body, three parameters need to be estimated:

Reference indicator value: The reference values for the indicator' eelgrass depth limit' are based on historical observations (Timmermann *et al.,* 2020a), whereas the reference values for 'summer chlorophyll-a' are calculated with the models forced with reference levels of nutrient inputs from all sources (reference scenario) (Timmermann et al. 2020b).

Status indicator value: The status indicator value corresponds to the present-day situation and is based on observations of the indicators (or potential proxy-indicators). The nutrient concentration in the specific water body is the results of present-day land-based loadings, atmospheric depositions and nutrient transport across boundaries[5] to adjacent water bodies.

Dose-response of indicators to changes in nutrient loadings: The final step is to extract the dose-response[6] of the modelled effect (α) on the indicators when changing the nutrient loadings from the different anthropogenic contributors.

Note: For both the reference situation and the status situation all nutrient contributors correspond to either the reference contributors or the present-day contributors, whereas the (short-term) dose-response is determined by changing one anthropogenic contributor at a time. This is illustrated in Figure 2-2.

In Figure 2-2, the reference situation (nutrient contributors and indicator values), target indicator value and present-day situation (nutrient contributors and indicator values) are shown for an arbitrary indicator and water body. The dose-response for Danish land-based N-load is also shown in the figure. The Danish N-load is only one out of several contributors, and other contributors could be illustrated similarly.

In Figure 2-2, we assume a linear relationship between the Danish land-based N-load and changes in the indicator, which will also be the case for the other contributors. According to work carried out as part of the RBMP 2015-2021 and reported in Erichsen & Timmermann (2017), this is a good approximation in most water bodies. However, for some water bodies where the primary production is not (or only partly) limited by nutrients, this approximation will be less certain. For further details, see the mechanistic model discussion in Erichsen & Timmermann (2017) on the water body 'Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord and Lovns Bredning' (water body no. 157).

In Figure 2-2, the x-axis depicts the land-based N-load. Similar figures and sensitivities can be produced by changing the Danish land-based P-load, the land-based N-load from neighbouring countries, the land-based P-load from neighbouring countries and the atmospheric N deposition. Hence, a number of sensitivities can be estimated (α_{DK-P}, $\alpha_{Others-N}$, $\alpha_{Others-P}$, $\alpha_{Atmos-N}$) and these sensitivities (or slopes) will be essential input parameters in the final calculation of MAIs.

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[5] The boundaries to the entire mechanistic model complex are located west of the UK and are North Atlantic Ocean boundaries, and here we assume no changes between present-day and reference situation.

[6] The sensitivity is also referred to as the 'slope' according to the slope α in Figure 2-2.

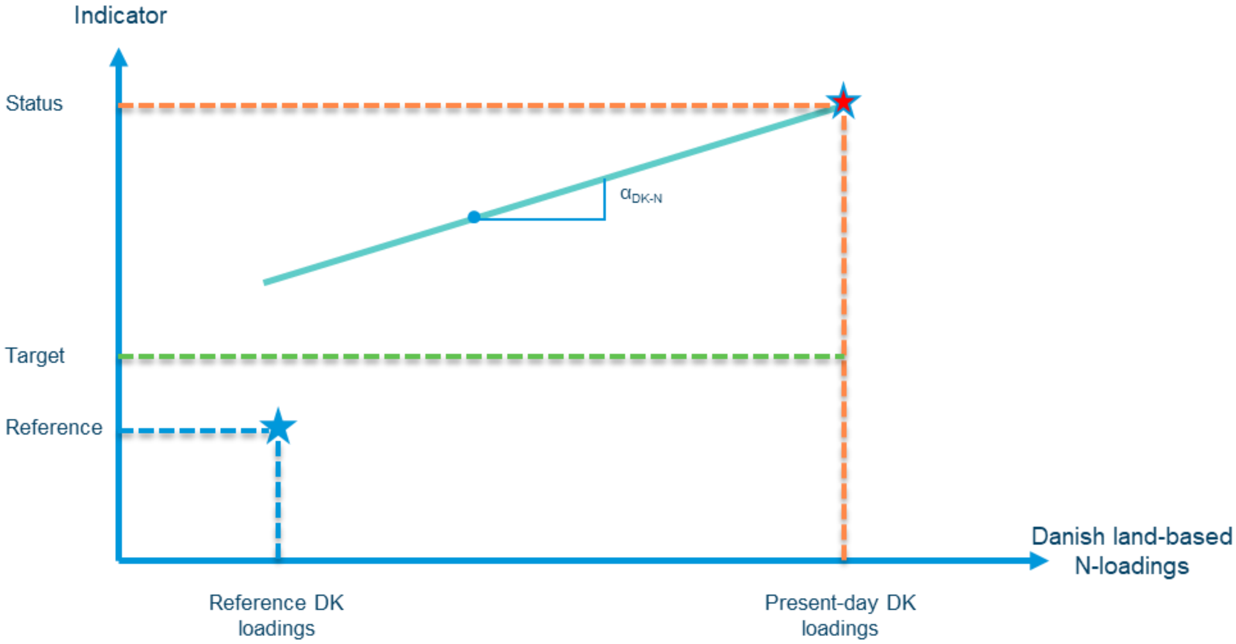


Figure 2-2 Schematic description of the dose-response of an indicator (y-axis) to Danish land-based N-loadings.
The reference contribution represents the land-based reference N-load from Denmark, and the corresponding reference indicator value (blue star). The reference value is transformed into an indicator target value (green line) according to *BEK nr 1001 of 29/06/2016*, but with an unknown corresponding target N-load (MAI). The present-day contribution represents the present-day land-based N-load from Denmark and the corresponding status value estimated based on measurements in the specific water body (red star). The slope (α_{DK-N}) represents the effects on the indicator value when changing the Danish land-based N-loading.

To establish the different slopes a number of scenarios have been executed. These scenarios are an outcome of the project 'Application of the Danish EPA's Marine Model Complex and Development of a Method Applicable for the River Basin Management Plans 2021-2027' and includes:

- 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

All five scenarios have been executed applying the mechanistic models whereas scenarios 1 and 2 have been executed applying the statistical models. In the final MAI estimations, however, slopes from the mechanistic model scenarios 3-5 are combined with the statistical models to ensure effects from neighbouring countries and atmospheric depositions.

From scenarios 1-5, we extract an indicator response to estimate the slope, and these specific slopes are used in the final MAI calculations (here illustrated by the chlorophyll-a indicator):

$$\alpha S1 = \frac{\left(1 - {ModelS1}/{ModelBaseline}\right)}{0.3}$$

where αS1 is the estimated slope resulting from Scenario 1 (see list above), ModelBaseline corresponds to the modelled chlorophyll-a status in a specific water body, and ModelS1 corresponds to the modelled chlorophyll-a concentration after a 30% reduction in Danish land-based N-load. Similar slopes are estimated for scenarios 2-5 (αS2, αS3, αS4 and αS5).

2.3.4 Cumulative Dose-Response

We assume that the different contributors can be separated into individual sensitivities (or slopes). This is probably a suitable approximation when analysing the sensitivities of Danish N-loadings, N-loadings from other countries and the atmospheric input of N. However, when separating the N- and P-loadings in, e.g. the Danish sources, the suitability of the approximation is unknown: A potential effect of reducing one nutrient could perhaps be overruled when reducing the other nutrient, and potentially the effects can be cumulated.

2.3.5 System Contribution

When analysing the different sensitivities (i.e. slopes), the nutrient loadings are reduced while the effects of essential ecosystem processes such as sediment nutrient release and N-fixation rates do not respond immediately. A new steady-state for these processes will develop over time, and this needs to be accounted for in the method developed to estimate MAIs.

From Figure 2-1 the different contributors to the concentration of nutrients, and hence the indicator values, are shown: Danish anthropogenic land-based N- and P-loads, anthropogenic land-based N- and P-loads from other countries, anthropogenic atmospheric N-depositions and the reference contributors. When changing the different anthropogenic contributors, we can assess the maximum impact on each indicator in each water body (see section 2.3.3). By moving from the present-day load to the reference load (removing the present anthropogenic contribution) and applying the corresponding dose-response (slope) the maximum effect of the individual anthropogenic contributors can be evaluated (when assuming a linear correlation - see section 2.3.3 for considerations about this assumption):

$$RefS1 = \left(1 - \alpha S1 \cdot (1 - LRefS1)\right)$$

Where RefS1 equals the reference indicator value when applying the slope (αS1) and reference load (see Figure 2-3), αS1 is the slope estimated from Scenario 1, and LRefS1 equals the relative Danish land-based reference N-load (from S1) compared to the status load (present-day). Similar estimations are conducted for scenarios 2-5.

When doing this for all five contributors the results show the maximum (short term) effect we can expect, based on slopes alone:

$$Ref\alpha = RefS1 \cdot RefS2 \cdot RefS3 \cdot RefS4 \cdot RefS5$$

where Refα represents the minimum value obtained from the five different scenarios when assuming reference loads.

For some water bodies Refα will equal the water body reference indicator value, but for many water bodies, this will not be sufficient to explain the difference between the status and the reference indicator value completely. This remaining difference is named the system-contribution, see Figure 2-3:

$$Ref = Ref\alpha - Sys$$

where Ref is the water body reference value (Timmermann et al. 2020b), Refα is the minimum indicator value based on slopes (α's), and Sys represents the system-contribution.

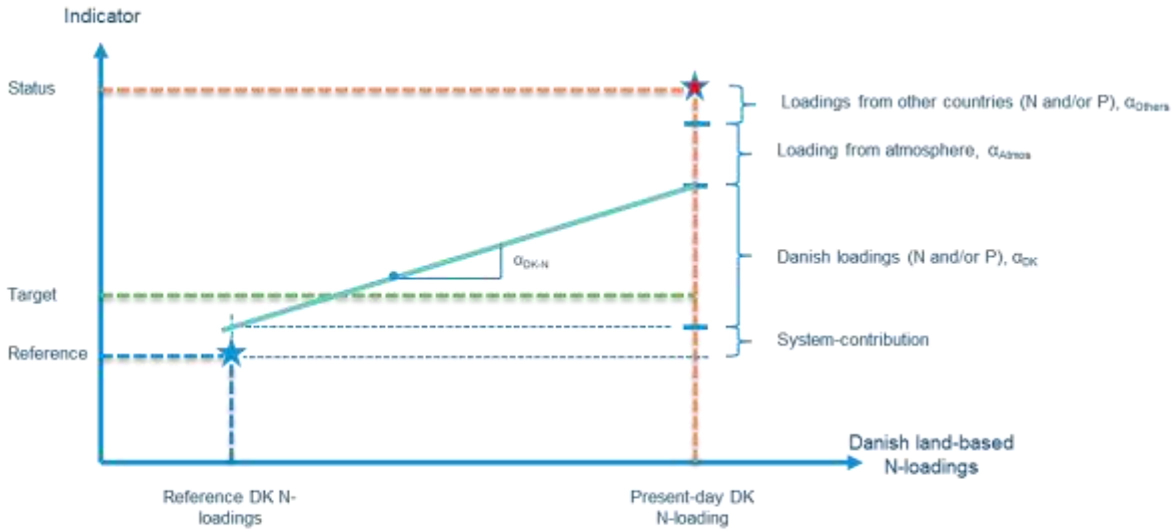


Figure 2-3 Schematic description of the cumulative sensitivities when changing from present-day loadings to reference loadings in Denmark, other countries and the atmosphere, respectively.
The sensitivities are determined one-by-one and can be due to both changes in N- and/or P-loads (which is not visible in the figure). In the figure, the x-axis and the corresponding slope show the effect of changes in Danish land-based N-loads. When taking all sensitivities into account a part of the reference indicator value might not be accounted for, and this is named the system contribution (see text for explanation).

A number of different factors can explain the system contribution. The system contribution will vary between the various water bodies, and the governing factors behind the system contribution in the individual water bodies will also vary. The system contribution encompasses e.g.:

- **Delays or lag-time**: When changing the loadings to the different water bodies, the ecosystem will respond to the changes but not necessarily straight away. Pools of nutrients in the sediments from previous years need to go into a new steady-state and this takes time. Especially the Baltic Sea reacts slowly to changes (over decades), whereas water bodies with low retention time will respond faster (within few years) (see Høgslund *et al.* 2019).
- **Feedback mechanisms**: Historically, large areas were covered by eelgrass, whereas today, the coverage is reduced significantly. Eelgrass meadows take up nutrients, recycle nutrient slowly, prevent re-suspension, etc., and these mechanisms help maintain an ecosystem with lower chlorophyll-a value and increased light penetration.
- **Changes in climate**: Over the last 100 years, meteorological conditions have changed. This can potentially impact e.g. the eelgrass depth limit. The project 'The importance of climate change on MAIs in marine waters' will evaluate the climate change footprint on the indicators, but in the method described in this technical note, the climate change footprint is included in the system contribution.
- **Uncertainties**: Uncertainties might also explain a part of the system contribution. These uncertainties relate to both uncertainties in observations and model results in the present-day situation and in the reference situation.

2.3.6 System Allocation

As described above the system contribution can be explained by different factors. However, we assume that the most important factors (delays and feedback mechanisms) will be affected by the nutrient reduction over time. From the mechanistic model results it is possible to estimate a reference situation (see (Timmermann et al. 2020b) for details) that results in e.g. lower chlorophyll-a concentrations compared to the chlorophyll-a concentrations obtained by the slope-approach (Refα). Hence, we know that the nutrient reductions over time will allow for the reference chlorophyll-a concentrations, but the short-term response from slopes alone does not allow for it. In the 'true' reference situation (Ref) both initial fields and sediment pools have been reduced, and oxygen depletion is minimised, and eelgrass covers large areas.

To account for this, the system-contribution can be distributed according to the impact from the different nutrient sources:

$$Sys = SysS1 + SysS2 + SysS3 + SysS4 + SysS5$$

where Sys accounts for the entire system contribution and the Sys1-5 account for system contributions allocated according to the relative importance of the different scenarios. Hence, we allocated the system contribution between the different nutrient scenarios:

$$SysS1 = Sys \cdot \left(\frac{1 - RefS1}{5 - RefS1 - RefS2 - RefS3 - RefS4 - RefS5}\right)$$

Where Sys1 is the fraction of the total system contribution (Sys) based on Danish land-based reference N-loads (RefS1). Similarly fractions of Sys2-5 are estimated.

Based on these assumptions we can now calculate the reference based on the different slope- and system-contributions:

$$Ref = RefS1 \cdot RefS2 \cdot RefS3 \cdot RefS4 \cdot RefS5 - (SysS1 + SysS2 + SysS3 + SysS4 + SysS5)$$

For the final MAI calculations, we assume that the system contributions will be realised when approaching reference conditions. How close to reference loads we need to be to realise the system contribution we do, however, not know. Hence, we realise the system contributions linearly as we reduce nutrient loads from the different contributors. This corresponds to a system-slope calculated as:

$$\alpha sysS1 = \frac{SysS1}{1 - LRefS1}$$

where αsysS1 equals the slope estimated based on the system contribution explained by Danish land-based N-loads (SysS1) and the relative Danish land-based reference N-load. Similar system slope estimates are estimated for scenarios 2-5.

2.3.7 MAI Calculations

By gathering the above equations it is possible to estimate the exact MAI for each individual water body where slopes, loads and status/targets exist:

$$Ref = RefS1 \cdot RefS2 \cdot RefS3 \cdot RefS4 \cdot RefS5 - (SysS1 + SysS2 + SysS3 + SysS4 + SysS5)$$

To allow for a simpler notation we transform this equation to:

$$Ref = RefS1 \cdot Ref_{S2-5} - (SysS1 + Sys_{S2-5})$$

where

$$Ref_{S2-5} = \prod_{N=2}^{5} \left(1 - \alpha SN \cdot (1 - LRefSN)\right)$$

and

$$Sys_{S2-5} = \sum_{N=2}^{5} \alpha sysSN \cdot (1 - LRefSN)$$

where SN denotes one of the scenarios 2-5.

Re-writing Eq.1 allows for the estimation of the ‘true’ reference as:

$$Ref = \big(1 - \alpha S1 \cdot (1 - LRefS1)\big) \cdot Ref_{S2-5} - \alpha sysS1 \cdot (1 - LRefS1) - Sys_{S2-5}$$

or estimation of the Danish land-based reference N-load:

$$LRefS1 = \frac{Ref + Sys_{S2-5} - Ref_{S2-5} + \alpha sysS1 + Ref_{S2-5} \cdot \alpha S1}{Ref_{S2-5} \cdot \alpha S1 + \alpha sysS1}$$

Reference loads are, however, not the target, why we substitute reference loads with MAIs:

$$LMaiS1 = \frac{Target + SysTarget_{S2-5} - RefTarget_{S2-5} + \alpha sysS1 + RefTarget_{S2-5} \cdot \alpha S1}{RefTarget_{S2-5} \cdot \alpha S1 + \alpha sysS1}$$

where Target equals the GES-threshold for the individual indicators and individual water bodies and

$$RefTarget_{S2-5} = \prod_{N=2}^{5} \big(1 - \alpha SN \cdot (1 - LMaiSN)\big)$$

and

$$SysTarget_{S2-5} = \sum_{N=2}^{5} \alpha sysSN \cdot (1 - LMaiSN)$$

where SN denotes one of the scenarios 2-5 and LMai denotes the specific loadings from, e.g. the Baltic Sea Action Plan (BSAP) or the NEC-directive concerning atmospheric depositions.

In cases where one or both of the indicators cannot reach their GES value by reducing N-loading from Danish catchments, N-MAI for that indicator is cut off/truncated at the reference loading.

Since all Danish water bodies are more or less connected to neighbouring water bodies, the reduction needed for a single water body cannot be assessed in isolation. In addition, it is necessary to consider the load reduction requirement estimated for nearby water bodies. In order to account for connected water bodies, the following scheme was applied:

1) Catchments are assigned to each water body. Local catchments are assigned to the inner part of estuaries (up-stream water bodies) whereas two or more local catchments are aggregated for the outer part of estuaries and more open water bodies (downstream water bodies).

2) Load reductions (in %) for each individual water body are calculated as described above and transformed to a reduction requirement in tons using the assigned catchment.

3) For up-stream water bodies (with local catchments) the calculated reduction is a minimum requirement.

4) Reduction requirements for downstream water bodies are re-calculated taking into account any minimum reduction handled by up-stream water bodies.

As neither a mechanistic or statistical model for Randers Fjord exists, model derived slopes representing the dose-response of the indicators to changes in loadings were derived using model estimated slopes for water bodies with similar physical characteristics (mainly freshwater input) as Randers Fjord.

3 Results

As a result of the various dose-response scenarios, and the conceptual method described above, several results have been extracted from the models. These results will form the foundation for the MAI calculations behind the RBMP 2021-2027.

In the following, the governing results are presented.

3.1 Slopes Based on Danish Loadings

Based on the 30% reductions of Danish land-based N- and P-loadings, a set of dose-response relations (slopes) was developed. The slopes have the unit %/% and represent the change (in %) of the indicator value per 1% change in loadings. The slopes are calculated based on scenarios using both mechanistic models as well as statistical models. The value of the slopes, distributed on water bodies, based on Danish land-based N-loading, are presented in Figure 3-1, and the similar slope distribution for Danish land-based P-loading are presented in Figure 3-2.

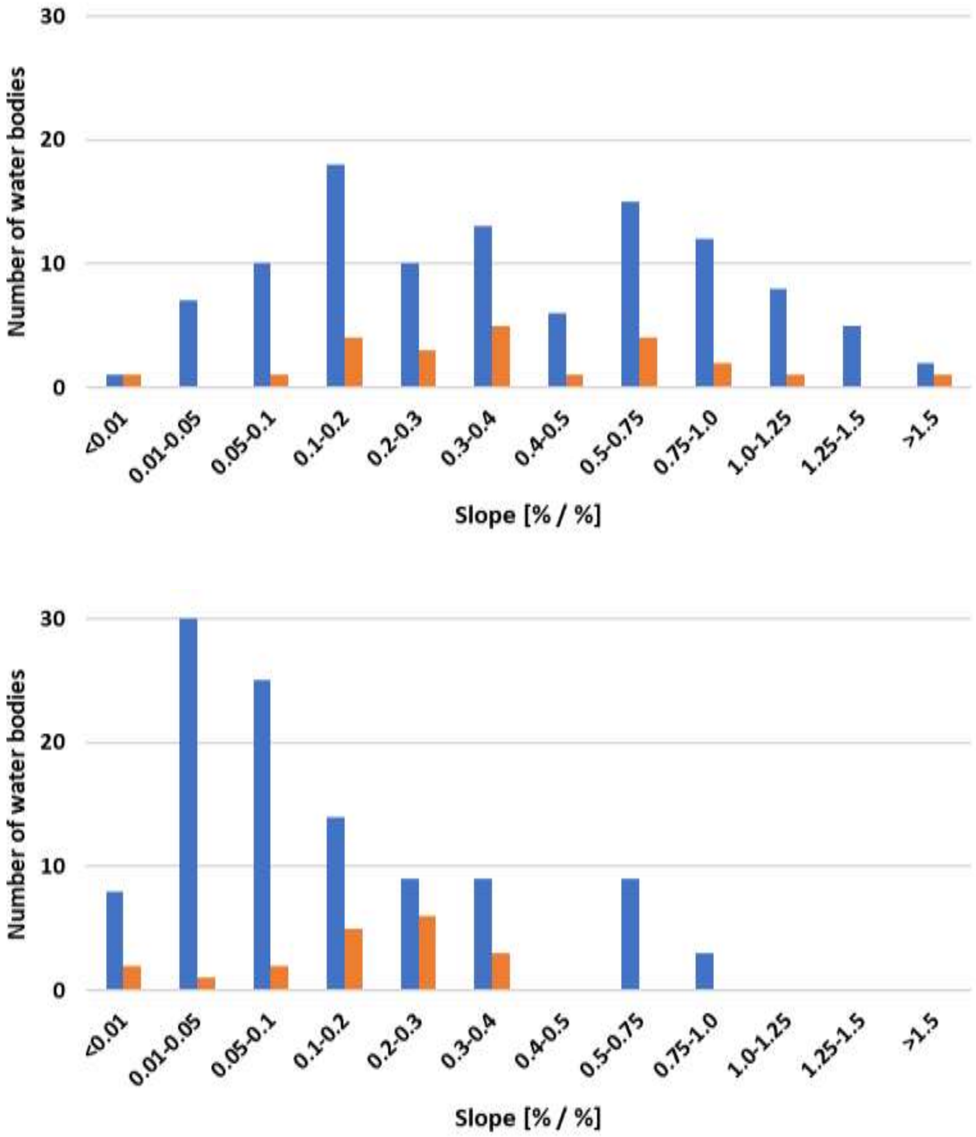


Figure 3-1 Slopes (dose-response) in % change in chlorophyll-a values (top panel) and light penetration depth values (bottom panel) when reducing Danish land-based N-loadings by 1%. Blue bars represent results from the mechanistic model, and orange bars represent data from statistical models. Note that light penetration depth values (bottom panel) are negative slopes.

The majority (89 out of 105[7] water bodies concerning mechanistic modelling and 21 out of 23 water bodies relating to statistical modelling) of the Danish water bodies are sensitive to Danish land-based N-loadings above a slope of 0.1 %/% (Figure 3-1).

With respect to the water depth with sufficient light available to sustain an existing eelgrass depth limit, dose-responses are, as expected, lower than compared to chlorophyll-a (see Figure 3-1 bottom panel). Here we find 69 out of 105 water bodies sensitive above 0.05% /% with respect to mechanistic modelling and 16 out of 19 water bodies with respect to statistical modelling.

[7] Christians Ø, Randers Fjord, indre, Randers Fjord, ydre og Kattegat, Nordsjælland >20m not included.

Similar results are presented in Figure 3-2 for sensitivities when changing Danish land-based P-loadings. The majority of the water bodies (64 out of 105 water bodies with respect to mechanistic modelling and 7 out of 22 water bodies concerning statistical modelling) are sensitive below 0.05 %/% for chlorophyll-a (top panel) and 61 out of 105 water bodies with respect to mechanistic modelling and 5 out of 19 water bodies with respect to statistical modelling) are sensitive below 0.01 %/% for chlorophyll-a (bottom panel).

In the mechanistic modelling 35 water bodies show no response to changes in P loadings (a dose-response relation of 0) for summer chlorophyll-a. However, as seen from Figure 3-2, a number of water bodies are impacted by Danish land-based P-loadings.

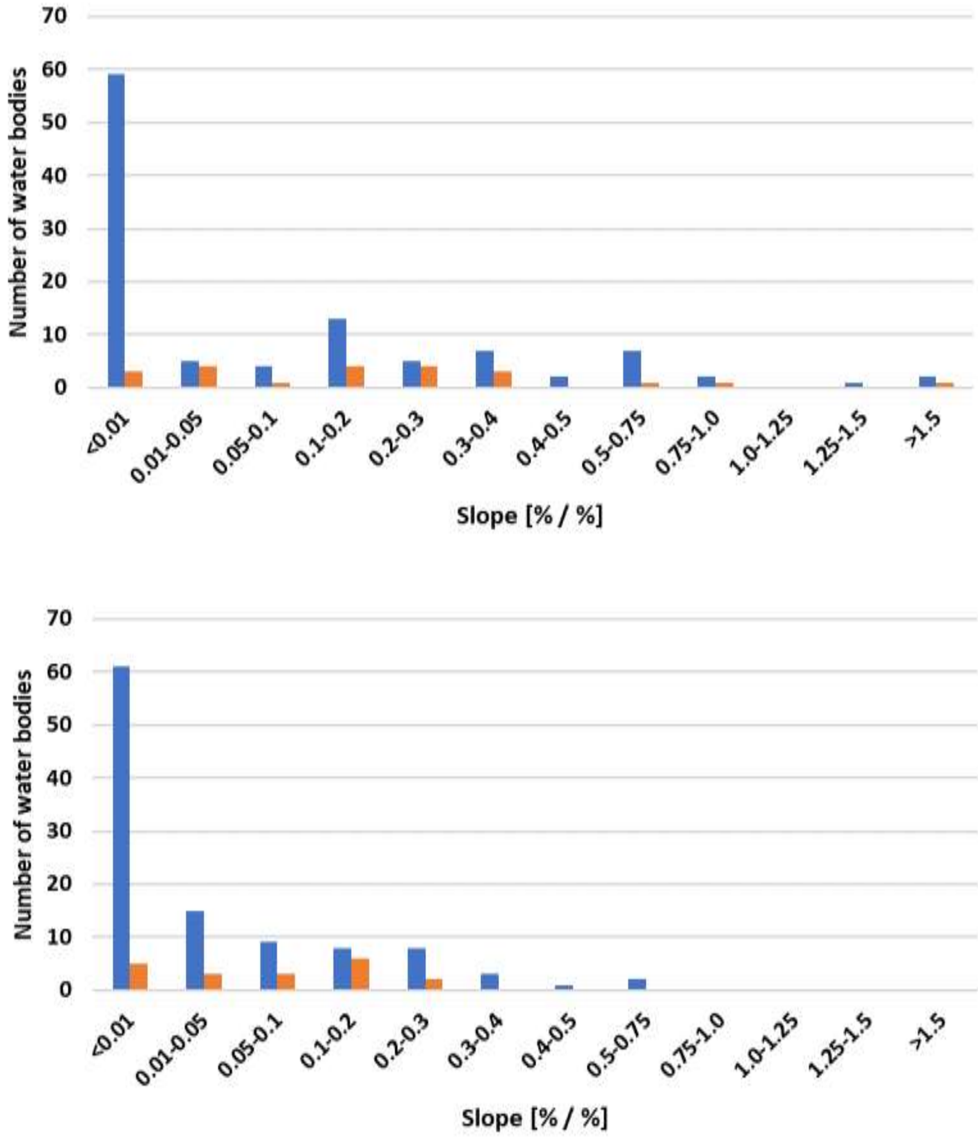


Figure 3-2 Slopes (dose-response) in % change in chlorophyll-a values (top panel) and light penetration depth values (bottom panel) when reducing Danish land-based P-loadings by 1%.
Blue bars represent results from the mechanistic model, and orange bars represent data from statistical models. Note that light penetration depth values (bottom panel) are negative slopes.

3.2 Slopes Based on Loadings from Neighbouring Countries

Similar to the dose-responses based on Danish land-based loadings (N and P), we have assessed sensitivities to land-based N- and P-loadings from neighbouring countries. The assessment of sensitivities from neighbouring countries – and the atmospheric depositions – is estimated based on mechanistic modelling results and then applied in the overall calculation of MAIs from both mechanistic modelling and statistical modelling.

The results of the slope-estimates are included in Figure 3-3 and Figure 3-4. As for land-based N-loadings, a large amount of the Danish water bodies is also sensitive to land-based N-loadings from neighbouring countries. According to Figure 3-3, 81 out of 105 water bodies are sensitive above 0.1 %/% with respect to chlorophyll-a, and 82 out of 105 water bodies are sensitive above 0.05 %/% with respect to depth values.

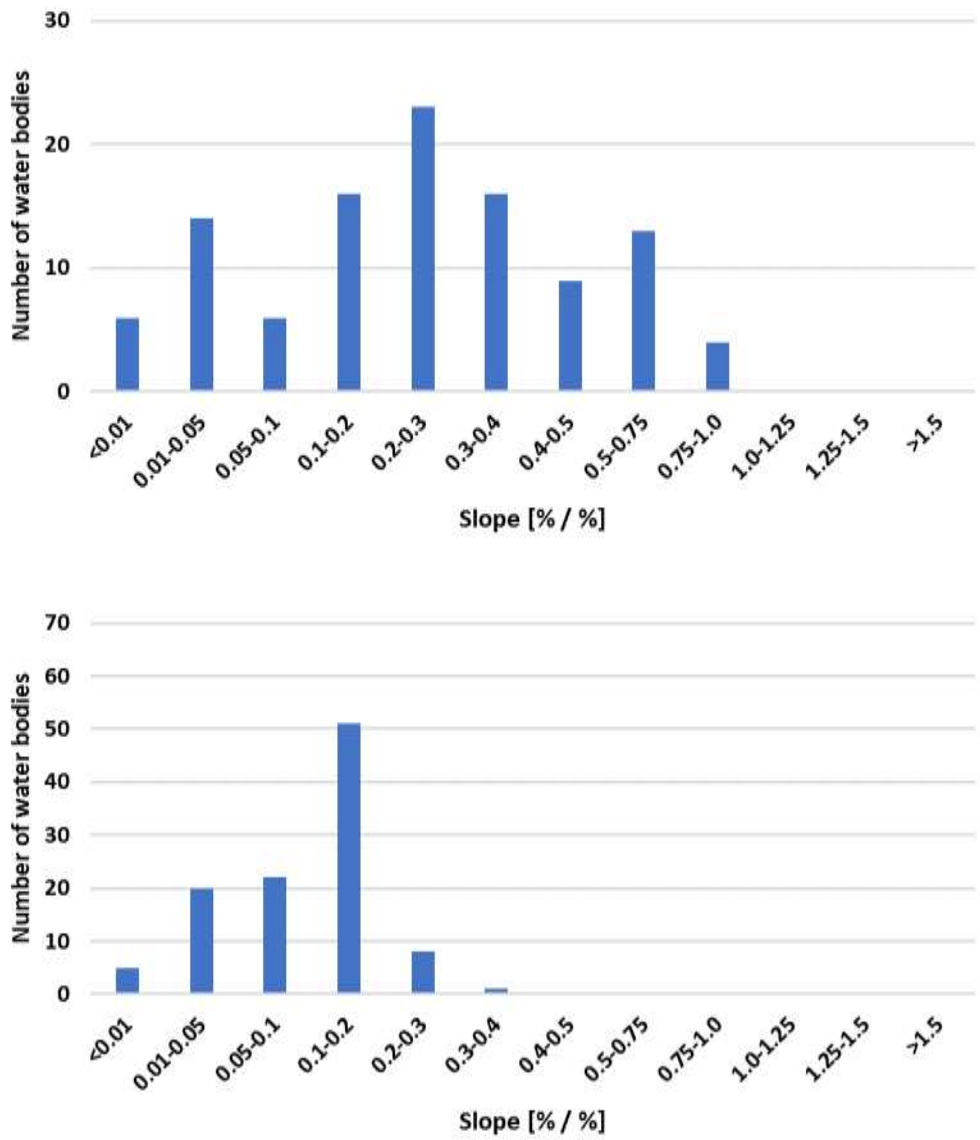


Figure 3-3 Slopes (dose-response) in % change in chlorophyll-a values (top panel) and depth values (bottom panel) when reducing land-based N-loadings from neighbouring countries by 1%. Note that light penetration depth values (bottom panel) are negative slopes

On the other hand, only a few water bodies show dose-response to land-based P-loadings from neighbouring countries (see Figure 3-4).

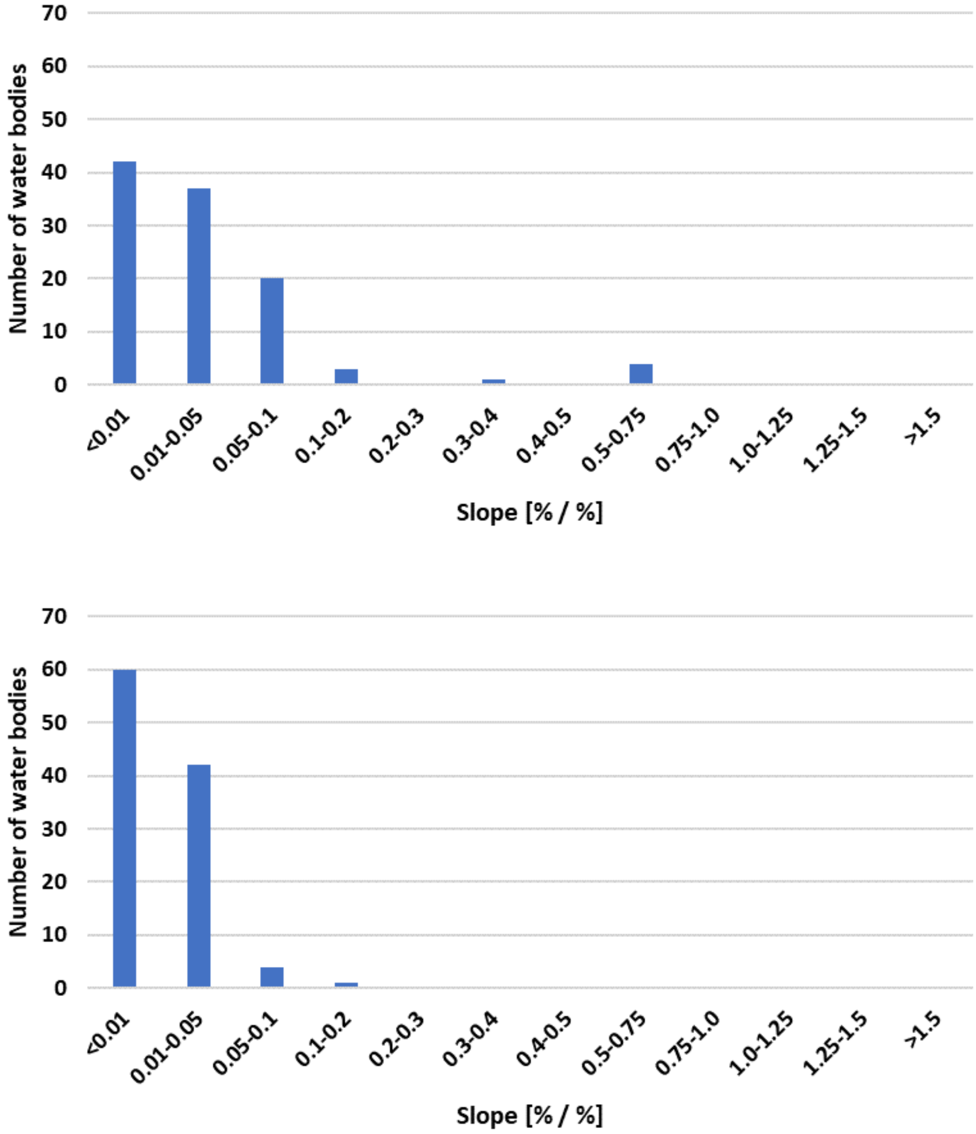


Figure 3-4: Slopes (dose-response) in % change in chlorophyll-a values (top panel) and light penetration depth values (bottom panel) when reducing land-based P-loadings from neighbouring countries by 1%.
Note that light penetration depth values (bottom panel) are negative slopes

3.3 Slopes Based on Atmospheric Deposition

Finally, we have assessed the dose-response of atmospheric N-depositions (see Figure 3-5). Likewise, the other N-distributions, water body chlorophyll-a and depth-values are sensitive to atmospheric N-depositions.

79 out of 105 water bodies are sensitive above 0.1 %/% with respect to summer chlorophyll-a (top panel), and 53 out of 105 are sensitive above 0.05 %/% with respect to depth values (bottom panel).

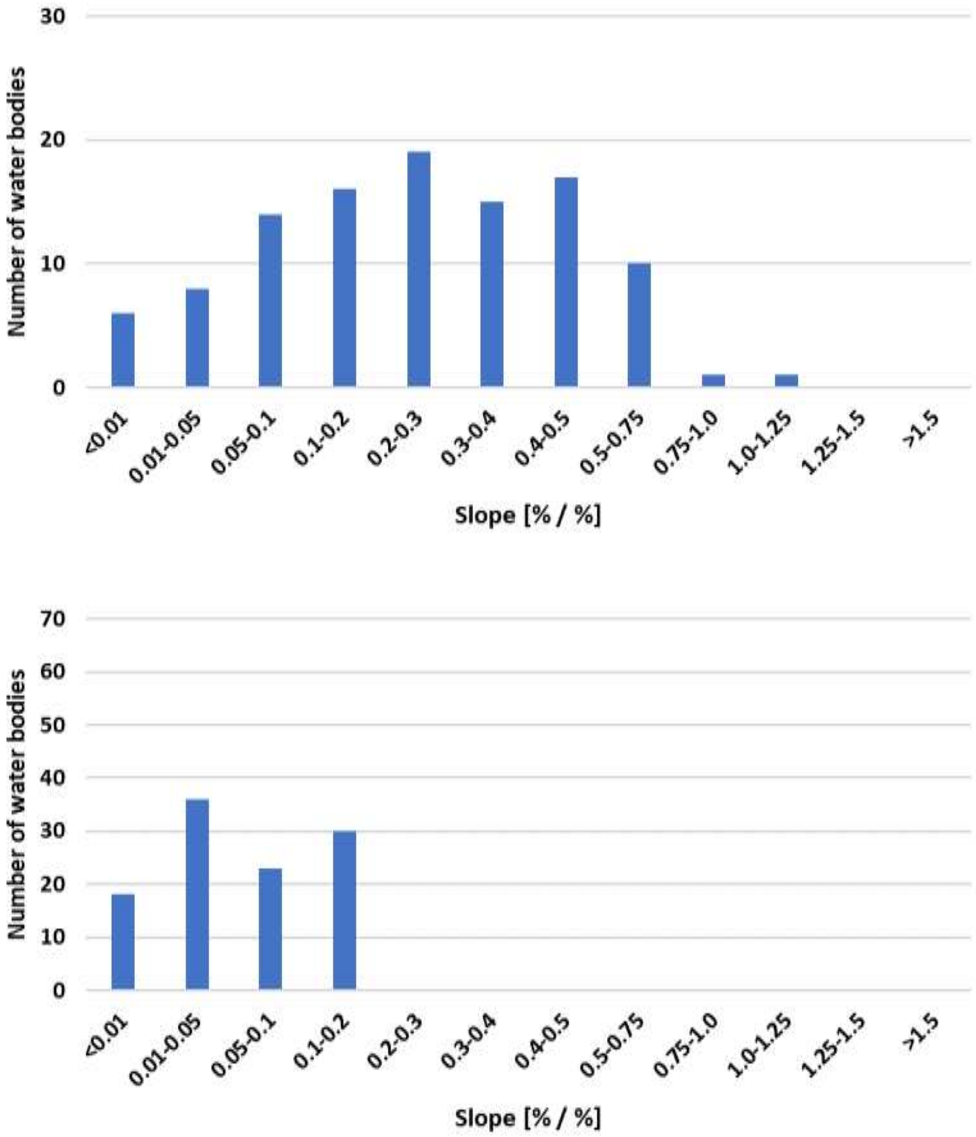


Figure 3-5 Slopes (dose-response) in % change in chlorophyll-a values (top panel) and light penetration depth values (bottom panel) when reducing atmospheric N-depositions by 1%. Note that light penetration depth values (bottom panel) are negative slopes

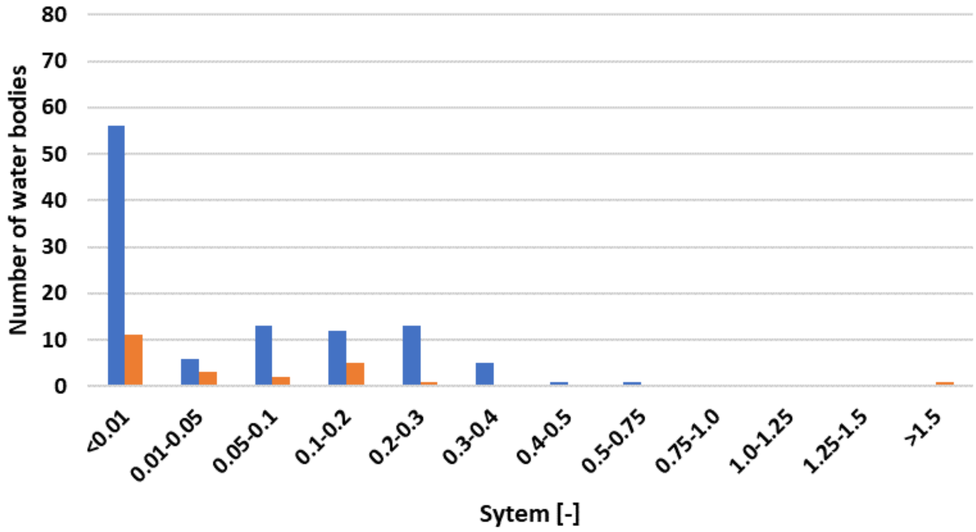
3.4 System Contribution

According to the method description in section 2.3.5, we also assessed the system contribution. The system contribution represents the difference between the ‘true’ reference (Ref) value of the indicator and the estimated reference values based on slopes alone (Refα) (see section 2.3.5 for details).

Applying mechanistic modelling to estimate the reference values of either depth values or chlorophyll-a and compare it to Refα clearly indicate the difference between an ecosystem with sufficient eelgrass and no (or minor) oxygen depletion, and the slope-method taking only present-day ecosystem services into account. This is especially evident for depth-values sustaining eelgrass presence.

The estimated system contributions within the individual water bodies are illustrated in Figure 3-6. As can be seen from the top panel, the system contribution is less than 0.1 for 75 out of 105 water bodies for summer chlorophyll-a status value, i.e. less than 10%, for the mechanistic modelling and for 16 out of 23 with respect to the statistical modelling.

This means that the model-sensitivities, to a large extent, explain the changes in summer-chlorophyll-a but also that some water bodies have lag-times and feedback mechanisms that are not included in the present-day (model) slopes.



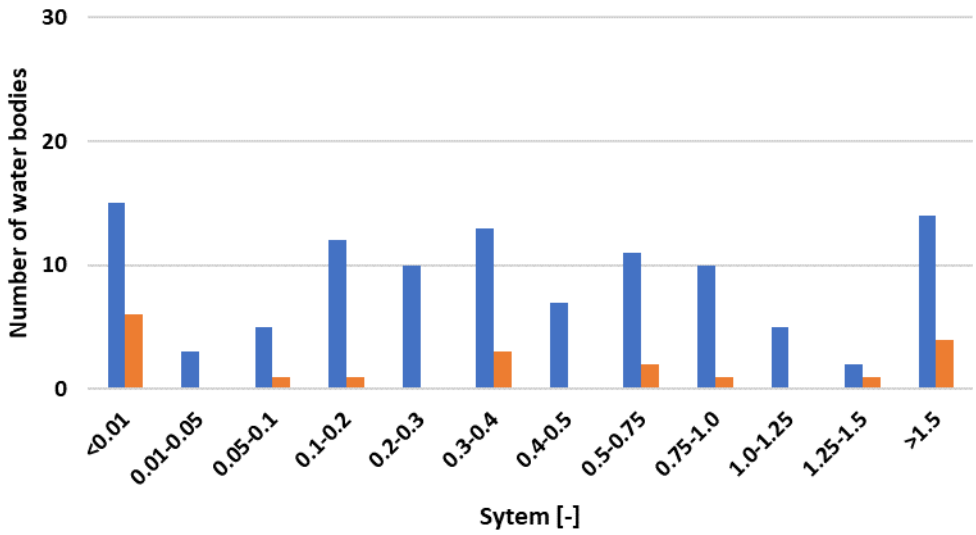


Figure 3-6 System contribution (relative numbers) within the individual water bodies based on summer chlorophyll-a (top panel) and depth-values (bottom panel).
Blue bars represent results from the mechanistic modelling, and orange bares represent combined results from mechanistic and statistical modelling. Note that light penetration depth values are increasing while reducing nutrient loadings why values can be above 1.0.

As expected, the system contribution is generally larger for light penetration depth values. Here we find 65 out of 105 water bodies with a system contribution which is less than 0.5 (i.e. 50%) of the difference between status and reference depth-values for the mechanistic modelling and 11 out of 19 water bodies for the statistical models.

4 Management Scenarios/Preconditions for MAI Calculations/Scenario Preconditions

The Danish MAIs will, among other things, depend on future loadings from neighbouring countries and atmospheric N-depositions, as illustrated in Figure 2-3. In addition, some water bodies may respond to Danish land-based P-loadings. Therefore, one set of Danish land-based N-MAIs corresponds to a set of Danish land-based P-MAIs.

Hence, to be able to calculate a set of Danish land-based N-MAIs we need to make assumptions on future loadings and management strategies from neighbouring countries (management-scenarios) as well as assess potential reductions in future Danish land-based P-loadings.

For future loadings from neighbouring countries, the Danish EPA has defined a set of prerequisites to be used for constructing management scenarios defining potential developments in future non-Danish land-based loadings and atmospheric deposition. For each scenario, Danish land-based N-MAIs are calculated based on either 0%, 10%, 20%, 30% or 50% Danish land-based P-reductions.

During the modelling work, we have not analysed whether or not the scenarios defined by the Danish EPA are realistic or even possible but solely provide N-MAIs that will ensure target reaching given that the corresponding conditions related to nutrient loading from other countries, atmospheric deposition and P loading from Danish catchments are fulfilled.

4.1 Management-Scenario Definitions

As mentioned above, the Danish EPA has defined a set of assumptions regarding nutrient inputs from other countries and the atmosphere, to be used as a precondition for the Danish land-based N-MAI calculations. These preconditions are grouped in three management-scenarios. On top of the three management scenarios, a set of assumptions related to the interpretation of the WFD is included (WFD scenarios). The three groups of management scenarios are briefly described in the following section, whereas the WFD scenarios are described in section 4.1.4. Specific input parameters (loadings) and the results of the different management scenarios and WFD-scenarios will be presented in separate technical notes.

4.1.1 Management Scenario 1 – Regional Treaties and RBMP 2015-2021

The first scenario assumes that all national and international adopted treaties related to nutrient management, including RBMP 2015-2021, have been implemented. This corresponds to:

- Full implementation of BSAP (HELCOM) and similar reduction targets in the North Sea (OSPAR)
- Implementation of RBMP 2015-2021 in all EU countries
- Full implementation of the NEC-directive with respect to atmospheric N-deposition

This scenario is comparable to the preconditions used to establish MAIs for RBMP2015-2021.

4.1.2 Management Scenario 2 - Land-based Nutrient Scenarios

The second scenario encompasses assumptions for the land-based loadings from neighbouring countries that are not based on adopted treaties: The assumptions include:

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) Additional Wadden Sea P-reductions.

For the above four sub-scenarios, the atmospheric deposition will be kept as described in management scenario 1, i.e. full implementation of the NEC-directive with respect to atmospheric N-deposition.

4.1.3 Management Scenario 3 - Atmospheric N Scenarios

The third scenario relates to assumptions regarding the future development of the atmospheric N-depositions:

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.

For the above two sub-scenarios, the land-based nutrient loadings will be kept as described in management scenario 1, i.e. adopted treaties (BSAP and RBMP2015-2021) have been implemented.

4.1.4 WFD-Scenarios

As described in Erichsen & Timmermann 2017, the final MAI-calculations within the Danish RBMP 2015-2021 assumed an average between indicators and model-results (statistical and mechanistic model results, respectively).

Towards the final Danish RBMP 2021-2027 we will assume similar averaging in the calculation of the individual MAIs. Averaging ensure a more robust estimate of the individual MAIs as it dampens the effect of extreme values. However, this approach does not ensure GES in all water bodies. In theory, only 50% (assuming normal distribution) will achieve GES when averaging indicators and model results.

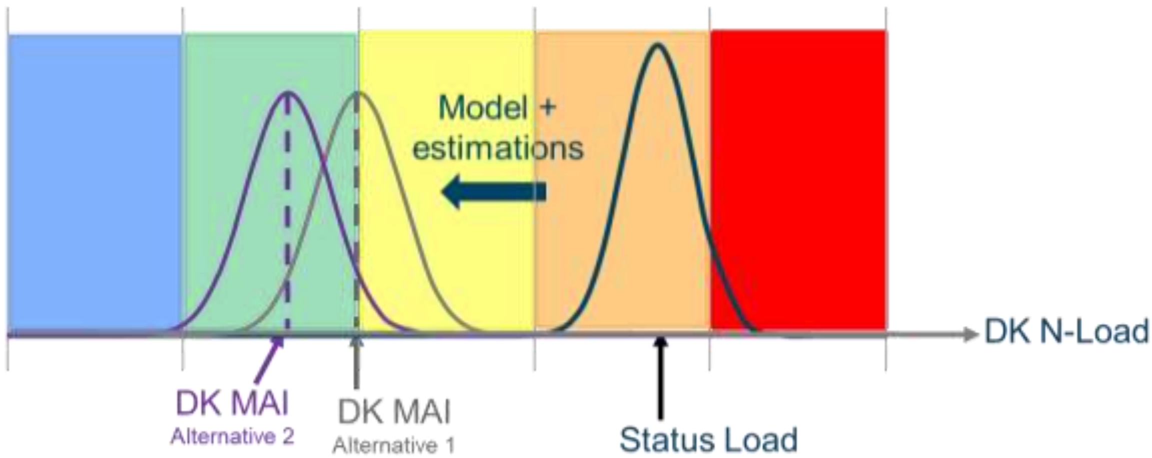


Figure 4-1 Calculation of MAI based on averaging or increased certainty.

The present-day loading results in an indicator status value (curve placed in the orange field). The status value is determined with a certainty determined by the observations.

In the WFD-scenarios the Danish land-based N-MAIs are based on:

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.

For the above three sub-scenarios, the land-based nutrient loadings and atmospheric N-depositions will be kept as described in management scenario 1.

4.2 Scenario Results

Based on the above scenarios/preconditions for MAI calculations, a set of MAIs is calculated. The results of the calculations are reported in a number of separate technical notes.

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