ESTABLISHING CHLOROPHYLL-A REFERENCE CONDITIONS AND BOUNDARY VALUES APPLICABLE FOR THE RIVER BASIN MANAGEMENT PLANS 2021-2027

Scientific Report from DCE – Danish Centre for Environment and Energy No. 461 2021

AARHUS UNIVERSITY
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Abstract: To comply with the EU water framework directive, Denmark needs to establish chlorophyll-a reference levels for all its water bodies. Here we combine model results from two independent water quality models, estimating chlorophyll-a levels at reference conditions (no, or only very minor, anthropogenic alterations). The results are combined in a new model, predicting reference concentration of chlorophyll-a based on waterbody-specific physical and hydromorphological data.

Keywords: Chlorophyll-a, reference conditions, WFD.

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Contents

Preface

This report was commissioned and funded by the Danish Environmental Protection Agency (EPA) as part of the project "Application of the Danish EPA's Marine Model Complex and Development of a Method Applicable for the River Basin Management Plans (RBMP) 2021-2027".

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

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

Choice of methods, data processing, description and presentation of results have been solely AU / DCE's, DTU's and DHI's decision and responsibility.

Summary

Summer Chlorophyll-a concentrations are used as environmental indicator to assess ecological status of Danish coastal waters regulated by the Water Framework Directive (WFD). According to WFD, ecological status has to be classified relative to a reference level corresponding to an undisturbed condition. In this report, we use established Bayesian and mechanistic models to establish water body specific Chlorophyll-a reference conditions for Danish WFD water bodies. Since no Danish coastal areas or similar coastal ecosystems in proximity can be regarded as undisturbed by human activities and no historical chlorophyll-a data from pristine conditions exists, we use water quality models to estimate the reference level of chlorophyll-a. Here we demonstrate how to combine reference scenarios from two independent water quality models, in a combined model using water body specific physical and hydromorphological data as forcing data for the model. This model allows us to obtain site-specific reference values for all Danish water bodies within the calibration range.

Sammenfatning

Sommer klorofyl-a koncentrationer anvendes til vurdering af miljøtilstanden for danske kystvande som reguleres af vandrammedirektivet (VRD). Ifølge VRD skal miljøtilstanden klassificeres relativt til en reference tilstand, som repræsenterer en tilstand uden påvirkning fra menneskelig aktivitet. I denne rapport anvender vi Bayesianske og mekanistiske modeller til at fastlægge vandområde-specifikke referenceniveauer for klorofyl-a indikatoren i danske VRD vandområder. Da ingen danske kystområder eller lignende kystøkosystemer i nærheden kan betragtes som uforstyrrede af menneskelige aktiviteter, og der heller ikke findes historiske klorofyl-a data fra upåvirkede forhold, bruger vi vandkvalitetsmodeller til at estimere referenceniveauet for klorofyl-a. Her demonstrerer vi, hvordan man kombinerer referencescenarier fra to uafhængige vandkvalitetsmodeller, i en kombineret model ved hjælp af vandområdespecifikke fysiske- og hydromorfologiske data som input-data. Denne model giver os mulighed for at etablere stedsspecifikke referenceværdier for alle danske vandområder inden for kalibreringsområdet.

1 Introduction

The EU Water Framework Directive (WFD) aims to achieve at least Good Ecological Status (GES) in all surface water bodies no later than 2027. GES is defined as a condition where the values of the biological quality elements for the surface water body type show low or no levels of impact resulting from human activity but deviate only slightly from those normally associated with the surface water body type under undisturbed conditions (DIRECTIVE 2000/60/EC. annex V). Chlorophyll-a concentration is an indicator of the biological quality element “phytoplankton abundance” used to assess Danish coastal waters' ecological status. In the Danish part of the Baltic Sea region (from Skagen to Bornholm) the chlorophyll-a indicator is defined as the average chlorophyll-a concentration from May to September, whereas the 90th percentile from March to October is used in the North Sea region as the indicator for ‘Phytoplankton abundance.’

The WFD defines GES values, as well as the boundary values separating the five ecological status classes (high, good, moderate, poor and bad), as a deviation from the reference condition. Based on WFD guidelines, the reference condition should be determined for each type of water body; either from i) observations from existing undisturbed sites. ii) historical data. iii) modelling or iv) expert judgement in prioritised order (Guidance Document No. 5). All these approaches have been used to develop reference values for several biological elements in different marine waters throughout Europe (Basset et al. 2013; Borja et al. 2012; Muxika et al. 2007; Krause-Jensen et al. 2005; Schernewski et al. 2015).

Chlorophyll-a data from undisturbed sites are preferable for establishing reference values for the chlorophyll-a indicator. There are, however, no undisturbed marine areas in Denmark and to our knowledge, no European marine areas have been identified as undisturbed at present. Hence, it is impossible to base the method for establishing reference conditions on chlorophyll-a data from undisturbed marine sites.

Use of historical chlorophyll-a data is the second choice for establishing reference values. However, the first quantitative chlorophyll-a measurements from Danish coastal waters are from the 1970s (Henriksen 2009), when eutrophication was already high. Hence, relevant historical chlorophyll-a data are not available for establishing reference values for Danish coastal waters.

Since options 1 and 2 are not applicable due to lack of suitable chlorophyll-a data, quantitative modelling (option 3) is the most feasible way to establish reference conditions. Different modelling approaches have been applied to both Danish waters (Carstensen & Henriksen 2009. Erichsen & Timmermann 2017) and other regions of the Baltic Sea area (Schernewski et al. 2015; Gustafsson et al. 2012; Schernewski & Neumann 2005) to establish chlorophyll-a reference conditions.

New and improved statistical and mechanistic models have been developed for Danish coastal waters (Shetty et al., in prep. Erichsen et al., in prep), and these models will be used to establish reference conditions for the chlorophyll-a indicator.

The five ecological status classes are defined as a specific deviation from the reference condition. E.g. the normative definition of *high* status is that the ecological quality elements show no or only minor alterations from undisturbed conditions. Similarly, the normative definition of *good* status is that the biological quality elements deviate only slightly from undisturbed conditions (DIRECTIVE 2000/60/EC. annex V). The quantification of the boundaries separating the status classes is part of the intercalibration exercise. Here, the ecological quality ratios (EQR) defining the boundaries between status classes are established. The EC member states perform this exercise to ensure consistency and comparability of boundary values between the classes of high and good status and between good and moderate status (Guidance Document No. 14). The chlorophyll-a indicator has been intercalibrated with neighbouring countries and will be used to establish boundary values for all Danish water bodies.

1.1 Objective

This report aims to establish reference conditions and corresponding boundary values for the chlorophyll-a indicator that comply with the Water Framework Directive and applies to the Danish River Basin Management Plans 2021-2027.

We aim for establishment of water body specific reference and boundary values that reflect the heterogeneity of the water bodies while minimising the uncertainty of the estimates.

2 Data and Method

2.1 Method overview

The establishment of reference chlorophyll-a concentrations is based on model scenarios reflecting an undisturbed. or only slightly disturbed condition. Statistical and mechanistic models developed for RBMP2021-2027 are forced with model-specific forcing data representing an undisturbed / a less disturbed condition. For the statistical models, the required forcing data are restricted to Danish land-based reference loadings, whereas the mechanistic models also require reference nutrient loadings originating from the atmosphere, Baltic Sea, North Sea as well as adjustments in the sediments etc.

As the statistical models can only perform nutrient scenarios with nutrient loadings from the DK catchment and not, e.g. the atmosphere or the Baltic Sea catchment, the scenario results are adjusted using results from the mechanistic models to account for the effects of reference loadings from the Baltic Sea and atmosphere on the reference conditions in Danish water bodies.

The reference scenario results are used to establish a combined model that links reference chlorophyll-a concentrations estimated with statistical and mechanistical models to physical and hydro-morphological parameters characterising each water body (water depth, residence time, stratification, etc.). The combined model is then used to calculate reference conditions for all Danish water bodies, and the intercalibrated EQR values are used to estimate boundary values separating the five WFD ecological classes from reference conditions.

Figure 2.1 provides a schematic representation of the method.

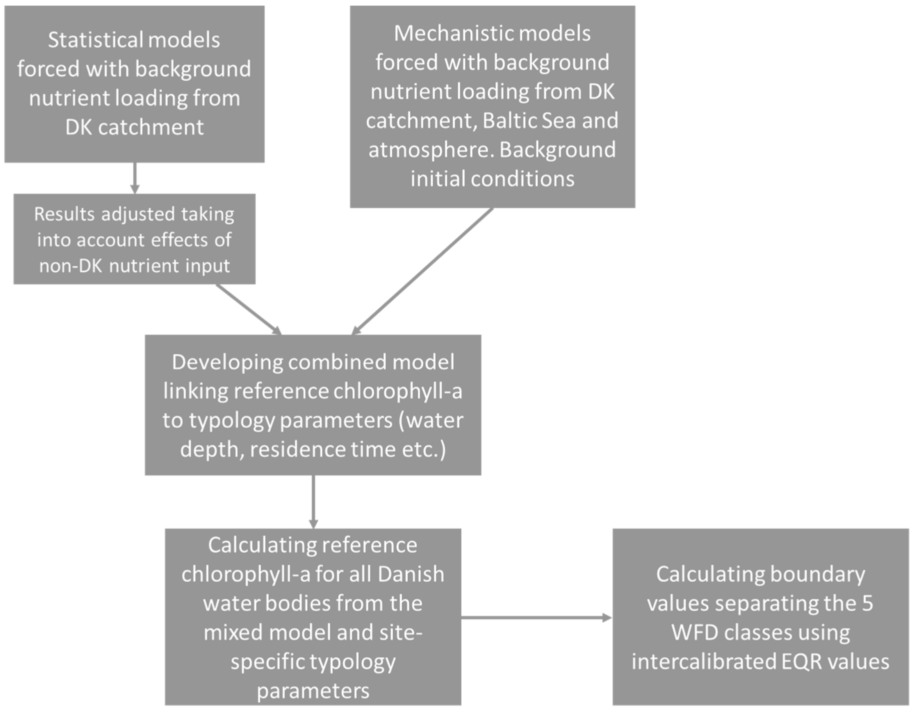

Figure 2.1: Schematic overview of the method applied to establish water body specific chlorophyll-a reference conditions and boundary values in Danish WFD coastal waters.

2.2 Data for reference scenarios

The establishment of reference chlorophyll-a concentrations is based on model scenarios reflecting an undisturbed, or only slightly disturbed, condition. In order to perform such a reference scenario, model-specific forcing data representing an undisturbed/slightly disturbed condition are required. For the statistical models, the required forcing data are restricted to Danish land-based reference loadings, whereas the mechanistic models also require reference nutrient inputs originating from the atmosphere. Baltic Sea. North Sea as well as adjustments in the sediments etc.

The data sets used to construct the model scenarios reflecting reference conditions are described in detail in Erichsen and Timmermann (in prep).

Briefly, reference 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 from scattered households and multiplied with the corresponding catchment specific water flow. Estimation of reference stream TN concentrations is described in Bøgestrand et al. (2014b) and Kronvang et al. (2015) whereas reference stream TP concentrations distributed on geo-regions are presented in Andersen & Heckrath (ed.) 2020.

The mechanistic models are forced with reference loadings to the North Sea and Baltic Sea. North Sea reference loadings are based on historical nutrient concentrations in seven different German and Dutch rivers as described in Gadegast & Venohr (2015). The applied Baltic Sea reference loadings are based on the Baltic Nest Institute (BNI) reconstructed nutrient loadings covering the period 1850-2006 (Gustafsson et al. 2012; Savchuk et al. 2012), when the average loading from 1890 to 1910 was used to establish a Baltic Sea reference loading in the present study. For further detail, see Erichsen and Timmermann (in prep).

Atmospheric nitrogen deposition used in the reference scenario is based on model simulations with an atmospheric model describing transport, chemical reactions and deposition of various chemical species including NO_X and NH_4 (Geels et al., 2012). The atmospheric model was forced with historical emissions provided by IIASA, 'Representative Concentration Pathways' (RCPs; from http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page =welcome), while the meteorological forcing corresponds to present days (2002-2016). Hence, the latter is coherent with the mechanistic modelling meteorological forcings (see Erichsen & Birkeland (2020b)).

As the retention time in the Baltic Sea is long (decades), initial values for Baltic Sea pelagic variables are adjusted to match a reference situation by applying the relative differences between modelled historical site-specific concentrations and modelled present-day concentrations (C, N and P parameters) from Gustafsson et al. (2012).

Also, initial sediment pools are adjusted to resemble reference conditions as it may take years for the sediment nutrient pools to reach steady state (Høgslund et al. 2019¸ Erichsen & Timmermann 2017) and decades for the structural sediment composition (Valdemarsen et al. 2014). The adjustment is carried out by applying relative differences between modelled historical sediment pools and modelled present-day pools carried out by Baltic Nest Institute (Gustafsson et al. 2012, 2017). This is done for each of the different Baltic Sea basins reported in Gustafsson et al. (2012).

Under reference conditions, eelgrass will likely occupy larger seafloor areas compared to present-day situations. To allow the eelgrass to develop in a reference scenario, eelgrass model variables were initialised based on historical observations and estimates of historical eelgrass depth limits (Timmermann et al. 2019).

2.3 Data for the combined model

A new typology has been developed for RBMP2021-2027 (Erichsen et al., 2019). This typology is based on nine physical and hydromorphological descriptors encompassing longitude and latitude, tide, salinity, water depth, the impact of freshwater, water exchange, stratification and sediment composition. Data for these typology descriptors characterising each water body are used as potential explanatory variables in developing a standard reference chlorophyll-a model and typology data are used to calculate standard reference chlorophyll-a concentration for all water bodies including those that are not covered by a statistical and / or mechanistic model. Detailed descriptions of each typology parameter as well as the applied estimation methods are described in Erichsen et al., 2019.

2.4 Mechanistic model scenario

The mechanistic models used to calculate chlorophyll-a concentration in a reference situation have been developed for RBMP2021-2027 and documented in detail in DHI (2019a-k) and DHI (2020a-k). Briefly, coupled hydrodynamic and ecological models describing physical transport and biogeochemical processes have been set up for nine local areas and two regional areas covering 107 water bodies out of a total of 109. The models have been run for 2002-2016, with 2012-2016 used to represent the current status or “present-day” scenario.

The chlorophyll-a reference scenario was constructed using data reflecting reference conditions, as described in section 2.2. Briefly, the models were forced with reference N and P loadings from Danish catchments relevant for each model domain, reference boundaries and reference atmospheric N depositions. In addition, the N and P sediment pools were adjusted and eelgrass allowed to grow to the historical depth limit. Meteorological and physical forcing was kept as in the status (present-day) model simulation, meaning that wind, solar radiation and temperature as well as freshwater discharge were identical to the present day (status) modelling. The reference chlorophyll-a concentration was calculated based on the relative difference between modelled present-day summer chlorophyll-a concentrations (average 2012-2016) and reference summer chlorophyll-a multiplied by the measured status summer chlorophyll-a concentrations.

2.5 Statistical model scenario

Bayesian statistical models used for scenarios estimating reference chlorophyll-a concentrations were developed as described and documented in Shetty et al.. 2021. Briefly, the response variable was yearly mean chlorophyll-a concentration from May to September estimated from monitoring data (1990-2018). The bulk suite of explanatory variables consisted of site-specific estimations of nutrient (N and P) loading, freshwater discharge, solar radiation, Temperature, salinity, Brunt-Väisälä buoyancy frequency and wind. Bayesian statistics combined with widely applicable information criterion (WAIC) analysis (Watanabe 2013) was used to select explanatory variables for each water body and estimate the relevant model parameters.

The reference scenario was conducted by forcing the models with background nutrient concentrations from Danish catchments multiplied with the corresponding catchment specific freshwater discharge as well as meteorological forcing from 1990-2018. The reference chlorophyll-a concentration was calculated as the average of the summer means (May-September) over the entire study period (1990-2018); thus, this estimate reflects the chlorophyll concentration under present-day year-to-year variation in weather condition and freshwater discharge but with background nutrient concentrations from Danish catchments.

As the statistical models cannot account for reference conditions in other nutrient sources than Danish riverine nutrient inputs, the calculated reference chlorophyll-a concentrations were adjusted using results from mechanistic models. The method for accounting for neighbouring countries is described in Erichsen et al. 2020. Briefly, mechanistic model predictions of responses in chlorophyll-a for each water body due to changes in nutrient input from the Baltic Sea and atmosphere were used to calculate the chlorophyll-a concentrations when, not only Danish catchments, but also other nutrient sources are in a reference situation.

2.6 Combined chlorophyll-a reference model

Modelling a reference situation is subject to uncertainties related to both model quality and the extensive, but necessary, model extrapolation for simulating a nutrient regime very different from the current nutrient regime used for model calibration. We applied a combined model linking waterbody-specific physical and hydromorphological metadata to reference chlorophyll-a concentrations estimated from the two independent model types described in the previous section to reduce the uncertainties.

2.6.1 Development of the combined model

We chose to use a combined model approach to combine the two model estimates of reference chlorophyll-a concentration. The combined model allowed us to have random effects (intercept and slope) due to the model type.

The first step in the process was to identify the best explanatory variables explaining the variation in reference estimates from both model-types; this was done using multiple linear regression (MLR) and forward selection for each model type. The initial analysis showed that for both model-types, the freshwater influence, log(average water depth), and the sediment ratio were chosen as the three variables that, for each variable, improved the model the most, when selected sequentially. All three variables were significantly ($p<0.05$) explaining estimates from the mechanistic model, while only freshwater influence was a significant predictor for the estimates from the statistical model, The predictors were chosen among a range of potential type-specific (Erichsen et al., 2019) explanatory variables which included: tidal influence, salinity, average water depth, water exchange rate, freshwater influence, sediment ratio of clay, mud, and sand, water column stratification, log(freshwater influence), and log(average water depth).

After the initial variable selection, we combined the three to four best predictors in a combined model to select the best combination of explanatory variables to explain the estimates of reference chlorophyll-a concentration from both models. The best combination of explanatory variables was evaluated using the adjusted R-squared and the Akaike Information Criteria (AIC) and the combined model with the explanatory variables freshwater influence and water depth was selected as the final combined model. As the slopes for the two independent models were not significantly different, the final model was a model with a random intercept and the two predictors, freshwater influence and log(average water depth).

$$Chla_{reference_{ij}} = (\mu_\alpha + \alpha_j) + X_{1.ij}\beta_1 + X_{2.ij}\beta_2$$

where

μ_α is the mean intercept parameter.

α_j is the model-specific deviation from the mean intercept.

$X_{1.ij}$. $X_{2.ij}$ are predictors freshwater discharge and log(average water depth) for the 24 and 75 water body areas (i) from the two models (j=1 or 2) respectively.

β_1. β_2 are the parameters for freshwater discharge and log(average water depth)

For the final estimates of chlorophyll-a reference we used the mean intercept parameter leaving out the model-specific effect (α_j).

2.7 Intercalibrated EQR values

The EQR values applied for all Danish water bodies from Skagen and southwards are based on intercalibrated EQRs between Denmark, Sweden and Norway. Reference values and EQR values for the remaining water bodies (west coast of Jutland) are intercalibrated with Germany. The results from the intercalibration for the types shared with Sweden and Norway are described in Carstensen (2016) and the translation into all Danish water pbodies was carried out by the Danish EPA (see table 2.2 for details).

Table 2.2: EQR values applied for summer chlorophyll-a in all Danish water bodies.

Water body Id	Water body	High-Good	Good-Moderate
1	Roskilde Fjord. ydre	0.83	0.64
2	Roskilde Fjord. indre	0.83	0.64
6	Nordlige Øresund	0.79	0.59
16	Korsør Nor	0.83	0.64
17	Basnæs Nor	0.80	0.60
18	Holsteinborg Nor	0.80	0.60
24	Isefjord. ydre	0.83	0.64
25	Skælskør Fjord og Nor	0.83	0.64
28	Sejerø Bugt	0.83	0.64

29	Kalundborg Fjord	0.83	0.64
34	Smålandsfarvandet. syd	0.80	0.60
35	Karrebæk Fjord	0.80	0.60
36	Dybsø Fjord	0.80	0.60
37	Avnø Fjord	0.80	0.60
38	Guldborgsund	0.80	0.60
44	Hjelm Bugt	0.78	0.62
45	Grønsund	0.78	0.62
46	Fakse Bugt	0.78	0.62
47	Præstø Fjord	0.78	0.62
48	Stege Bugt	0.78	0.62
49	Stege Nor	0.78	0.62
56	Østersøen. Bornholm	0.78	0.62
57	Østersøen. Christiansø	0.78	0.62
59	Nærå Strand	0.83	0.64
62	Lillestrand	0.83	0.64
68	Lindelse Nor	0.80	0.60
72	Kløven	0.80	0.60
74	Bredningen	0.80	0.60
80	Gamborg Fjord	0.80	0.60
82	Aborg Minde Nor	0.80	0.60
83	Holckenhavn Fjord	0.83	0.64
84	Kerteminde Fjord	0.83	0.64
85	Kertinge Nor	0.83	0.64
86	Nyborg Fjord	0.83	0.64
87	Helnæs Bugt	0.80	0.60
89	Lunkebugten	0.80	0.60
90	Langelandssund	0.80	0.60
92	Odense Fjord. ydre	0.83	0.64
93	Odense Fjord. Seden Strand	0.83	0.64
95	Storebælt. SV	0.83	0.64
96	Storebælt. NV	0.83	0.64
101	Genner Bugt	0.80	0.60
102	Åbenrå Fjord	0.80	0.60
103	Als Fjord	0.80	0.60
104	Als Sund	0.80	0.60
105	Augustenborg Fjord	0.80	0.60
106	Haderslev Fjord	0.80	0.60
107	Juvre Dyb	0.67	0.44
108	Avnø Vig	0.80	0.60
109	Hejlsminde Nor	0.80	0.60
110	Nybøl Nor	0.80	0.60
111	Lister Dyb	0.67	0.44
113	Flensborg Fjord. indre	0.80	0.60
114	Flensborg Fjord. ydre	0.80	0.60
119	Vesterhavet. syd	0.67	0.44
120	Knudedyb	0.67	0.44
121	Grådyb	0.67	0.44
122	Vejle Fjord. ydre	0.83	0.64

123	Vejle Fjord. indre	0.83	0.64
124	Kolding Fjord. indre	0.83	0.64
125	Kolding Fjord. ydre	0.83	0.64
127	Horsens Fjord. ydre	0.83	0.64
128	Horsens Fjord. indre	0.83	0.64
129	Nissum Fjord. ydre	0.83	0.64
130	Nissum Fjord. mellem	0.83	0.64
131	Nissum Fjord. Felsted Kog	0.83	0.64
132	Ringkøbing Fjord	0.83	0.64
133	Vesterhavet. nord	0.67	0.44
136	Randers Fjord. indre	0.83	0.64
137	Randers Fjord. ydre	0.83	0.64
138	Hevring Bugt	0.83	0.64
139	Anholt	0.83	0.64
140	Djursland Øst	0.83	0.64
141	Ebeltoft Vig	0.83	0.64
142	Stavns Fjord	0.83	0.64
144	Knebel Vig	0.83	0.64
145	Kalø Vig	0.83	0.64
146	Norsminde Fjord	0.83	0.64
147	Århus Bugt og Begtrup Vig	0.83	0.64
154	Kattegat. Læsø	0.83	0.64
157	Bjørnholms Bugt. Riisgårde Bredning. Skive Fjord og Lovns Bredning	0.83	0.64
158	Hjarbæk Fjord	0.83	0.64
159	Mariager Fjord. indre	0.83	0.64
160	Mariager Fjord. ydre	0.83	0.64
165	Isefjord. indre	0.83	0.64
200	Kattegat. Nordsjælland	0.83	0.64
201	Køge Bugt	0.78	0.62
204	Jammerland Bugt og Musholm Bugt	0.83	0.64
205	Kattegat. Nordsjælland >20 m	0.83	0.64
206	Smålandsfarvandet. åbne del	0.80	0.60
207	Nakskov Fjord	0.80	0.60
208	Femerbælt	0.80	0.60
209	Rødsand og Bredningen	0.80	0.60
212	Faaborg Fjord	0.80	0.60
214	Det sydfynske Øhav	0.80	0.60
216	Lillebælt. syd	0.80	0.60
217	Lillebælt. Bredningen	0.80	0.60
219	Århus Bugt syd. Samsø og Nordlige Bælthav	0.83	0.64
221	Skagerrak	0.67	0.5
222	Kattegat. Aalborg Bugt	0.83	0.64
224	Nordlige Lillebælt	0.83	0.64
225	Nordlige Kattegat. Ålbæk Bugt	0.83	0.64
231	Lillebælt. Snævringen	0.83	0.64
232	Nissum Bredning	0.83	0.64
233	Kås Bredning og Venø Bugt	0.83	0.64
234	Løgstør Bredning	0.83	0.64
235	Nibe Bredning og Langerak	0.83	0.64

236	Thisted Bredning	0.83	0.64
238	Halkær Bredning	0.83	0.64

3 Results

3.1 Combined model

The estimated reference values from the two models were relatively similar. The estimates from the mechanistic models were generally a bit lower than the estimates from the Bayesian model. On average, the Bayesian estimates were 0.3 mg m^{-3} higher than from the mechanistic model on paired differences, but the difference wasn´t significant on the 5% level (paired t-test p=0.09).

Chlorophyll-a reference values calculated with the combined model were compared with the corresponding results from statistical and mechanistic models as shown in figure 3.1.

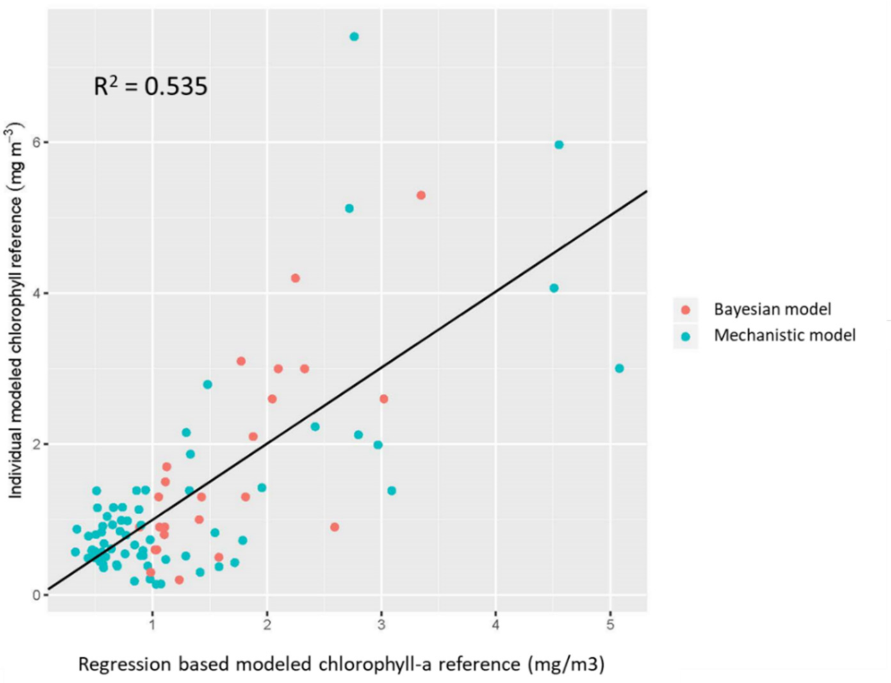

Figure 3.1: Scatterplot of chlorophyll-a reference conditions modelled with the combined model approach and reference conditions modelled with either mechanistic models (blue) or Bayesian models (red). The presented combined model includes the typology parameters “water depth” and “freshwater influence” as well as model-type effects. The solid line is the regression line (slope 1.01. intercept -0.01)

3.2 Chlorophyll-a reference condition

Reference condition for the chlorophyll-a indicator in each of the Danish marine WFD water bodies was calculated using the combined model and water body specific estimates of freshwater input and log (average water depth) and the results are shown in Table 3.1.

Table 3.1 Chlorophyll-a reference conditions (µg/L) in Danish marine water bodies estimated using the combined model that predicts chlorophyll-a reference conditions from freshwater discharge and average water depth. For comparison, estimated chlorophyll-a reference levels from the statistical model (Stat. model) and mechanistic model (Mech. model) are also shown. No significant difference between the Stat. model and Mech. model results were detected (p = 0.09. paired t-test).

Water body Id	Water body	Stat. model (µg/L)	Mech. model (µg/L)	Combined model (Reference chl-a condition) (µg/L)
1	Roskilde Fjord, ydre			1.8
2	Roskilde Fjord. indre	2.6		2.7
6	Nordlige Øresund		0.6	0.9
16	Korsør Nor			1.6
17	Basnæs Nor		0.3	1.7
18	Holsteinborg Nor		0.4	1.9
24	Isefjord. ydre	1.3	1.1	1.2
25	Skælskør Fjord og Nor	3.0		1.8
28	Sejerø Bugt		0.6	0.8
29	Kalundborg Fjord	0.9	0.6	0.8
34	Smålandsfarvandet, syd		0.2	1.1
35	Karrebæk Fjord		1.4	3.4
36	Dybsø Fjord		0.4	2.0
37	Avnø Fjord		0.1	1.3
38	Guldborgsund		0.7	1.3
44	Hjelm Bugt		0.7	0.8
45	Grønsund		0.8	1.0
46	Fakse Bugt		0.5	0.8
47	Præstø Fjord	2.6		1.8
48	Stege Bugt		0.2	1.3
49	Stege Nor			1.6
56	Østersøen, Bornholm		1.3	0.6
57	Østersøen, Christiansø			0.6
59	Nærå Strand		2.0	3.2
62	Lillestrand		0.5	1.6
65	Thuroe Bund			1.2
68	Lindelse Nor	0.5	0.1	1.3
72	Kløven		0.4	1.2
74	Bredningen		6.0	4.8
75	Emtekaer Nor			4.4
80	Gamborg Fjord		0.5	1.2
81	Baagoe Nor			3.1
82	Aborg Minde Nor		3.8	6.5
83	Holckenhavn Fjord		5.1	3.0
84	Kerteminde Fjord		0.8	1.8
85	Kertinge Nor			2.4
86	Nyborg Fjord		1.0	1.1
87	Helnæs Bugt		0.8	1.0
89	Lunkebugten		0.7	1.1
90	Langelandssund		0.5	0.9
92	Odense Fjord. ydre	3.0		2.1
93	Odense Fjord, Seden Strand			4.5
95	Storebælt. SV		1.4	0.8

96	Storebælt. NV		1.0	0.9
101	Genner Bugt	1.3	0.8	0.8
102	Åbenrå Fjord	0.9	0.9	0.6
103	Als Fjord	0.6	0.6	0.7
104	Als Sund		0.9	1.2
105	Augustenborg Fjord	1.3		1.5
106	Haderslev Fjord			4.9
108	Avnø Vig		1.4	2.2
109	Hejlsminde Nor			4.0
110	Nybøl Nor			1.6
113	Flensborg Fjord, indre	1.5	0.9	0.8
114	Flensborg Fjord. ydre	0.3	0.5	0.7
122	Vejle Fjord. ydre		1.2	0.9
123	Vejle Fjord. indre	0.9		2.3
124	Kolding Fjord, indre	5.3	2.1	3.1
125	Kolding Fjord, ydre			1.5
127	Horsens Fjord, ydre		1.4	1.2
128	Horsens Fjord, indre	3.1		1.5
129	Nissum Fjord, ydre		1.4	1.6
130	Nissum Fjord, mellem		2.2	1.6
131	Nissum Fjord, Felsted Kog		7.4	3.0
132	Ringkøbing Fjord		3.0	5.4
136	Randers Fjord, indre			6.8
137	Randers Fjord, ydre			6.0
138	Hevring Bugt		1.0	1.0
139	Anholt		0.5	0.9
140	Djursland Øst		0.8	0.7
141	Ebeltoft Vig		0.4	0.8
142	Stavns Fjord		0.6	1.5
144	Knebel Vig		0.4	1.0
145	Kalø Vig	0.2	0.4	1.0
146	Norsminde Fjord		2.2	2.7
147	Århus Bugt og Begtrup Vig	0.6	0.5	0.8
154	Kattegat, Læsø		0.6	1.2
157	Bjørnholms Bugt, Riisgårde Bredning, Skive Fjord og Lovns Bredning		2.8	1.8
158	Hjarbæk Fjord		4.1	4.8
159	Mariager Fjord, indre	4.2		2.0
160	Mariager Fjord, ydre			2.5
165	Isefjord, indre	2.1	1.9	1.6
200	Kattegat, Nordsjælland		0.5	0.7
201	Køge Bugt	0.8	0.8	0.8
204	Jammerland Bugt og Musholm Bugt		0.4	0.8
205	Kattegat, Nordsjælland >20 m			
206	Smålandsfarvandet, åbne del		0.4	0.8
207	Nakskov Fjord		0.5	1.4
208	Femerbælt		1.2	1.0
209	Rødsand og Bredningen		0.6	1.2
212	Faaborg Fjord		0.5	1.0
213	Torø Vig og Torø Nor			1.2

214	Det sydfynske Øhav	1.7	0.7	0.8
216	Lillebælt, syd		0.6	0.6
217	Lillebælt, Bredningen	0.9	0.6	0.8
219	Århus Bugt syd, Samsø og Nordlige Bælthav		0.6	0.7
222	Kattegat, Aalborg Bugt		0.5	1.2
224	Nordlige Lillebælt		1.2	0.8
225	Nordlige Kattegat, Ålbæk Bugt		0.9	0.9
231	Lillebælt, Snævringen			0.8
232	Nissum Bredning	1.0	1.4	1.1
233	Kås Bredning og Venø Bugt			1.3
234	Løgstør Bredning			1.4
235	Nibe Bredning og Langerak		0.7	2.1
236	Thisted Bredning			1.4
238	Halkær Bredning			4.7

The reference values calculated using the combined model were between 0.6 µg/L (Lillebælt syd. Østersøen) and 6.8 µg/L (Randers Fjord. indre). 34 of the 109 water bodies had reference values < 1 µg/L. whereas the reference value was > 2 µg/L for 25 water bodies. Not surprisingly, reference values in the inner part of estuaries were generally higher than reference values for the more open waters.

Direct comparison between the results obtained with statistical and mechanistic models respectively did not detect any significant difference (p=0.09. paired t-test) between model types, although the average of reference values calculated with statistical models was higher (1.2 µg/L) than the average of reference values calculated with mechanistic models (0.9 µg/L).

3.3 Boundary values

From the reference conditions (table 3.1) and the intercalibrated EQR-values (Carstensen 2016). it is possible to calculate the values for the chlorophyll-a indicator that represents the boundary between the ecological status classes ”high” and ”good” as well as the boundary between the status classes ”good” and ”moderate”. The class boundaries and reference conditions for the chlorophyll-a indicator are shown for each water body in table 3.2.

Table 3.2. Reference conditions (µg/L) and class boundaries for the chlorophyll-a indicator in Danish marine water bodies.

Water body Id	Water body	Reference condition (µg/L)	High-Good boundary (µg/L)	Good-Moderate boundary (µg/L)
1	Roskilde Fjord. ydre	1.8	2.2	2.9
2	Roskilde Fjord. indre	2.7	3.3	4.3
6	Nordlige Øresund	0.9	1.2	1.5
16	Korsør Nor	1.6	1.9	2.5
17	Basnæs Nor	1.7	2.1	2.8
18	Holsteinborg Nor	1.9	2.3	3.1
24	Isefjord. ydre	1.2	1.4	1.8
25	Skælskør Fjord og Nor	1.8	2.2	2.8
28	Sejerø Bugt	0.8	0.9	1.2
29	Kalundborg Fjord	0.8	0.9	1.2
34	Smålandsfarvandet. syd	1.1	1.4	1.9
35	Karrebæk Fjord	3.4	4.2	5.6
36	Dybsø Fjord	2.0	2.5	3.3
37	Avnø Fjord	1.3	1.7	2.2
38	Guldborgsund	1.3	1.6	2.1
44	Hjelm Bugt	0.8	1.0	1.3
45	Grønsund	1.0	1.3	1.6
46	Fakse Bugt	0.8	1.0	1.3
47	Præstø Fjord	1.8	2.3	2.9
48	Stege Bugt	1.3	1.6	2.0
49	Stege Nor	1.6	2.0	2.5
56	Østersøen. Bornholm	0.6	0.8	1.0
57	Østersøen. Christiansø	0.6	0.8	1.0
59	Nærå Strand	3.2	3.9	5.1
62	Lillestrand	1.6	1.9	2.4
68	Lindelse Nor	1.3	1.6	2.2
72	Kløven	1.2	1.5	2.1
74	Bredningen	4.8	6.0	8.0
80	Gamborg Fjord	1.2	1.5	2.0
82	Aborg Minde Nor	6.5	8.1	10.8
83	Holckenhavn Fjord	3.0	3.6	4.7
84	Kerteminde Fjord	1.8	2.2	2.8
85	Kertinge Nor	2.4	2.8	3.7
86	Nyborg Fjord	1.1	1.3	1.6
87	Helnæs Bugt	1.0	1.3	1.7
89	Lunkebugten	1.1	1.4	1.9
90	Langelandssund	0.9	1.1	1.4
92	Odense Fjord. ydre	2.1	2.5	3.2
93	Odense Fjord. Seden Strand	4.5	5.4	7.0
95	Storebælt. SV	0.8	0.9	1.2
96	Storebælt. NV	0.9	1.1	1.4
101	Genner Bugt	0.8	1.0	1.3
102	Åbenrå Fjord	0.6	0.8	1.0
103	Als Fjord	0.7	0.9	1.2
104	Als Sund	1.2	1.5	2.0
105	Augustenborg Fjord	1.5	1.9	2.6

106	Haderslev Fjord	4.9	6.1	8.2
107	Juvre Dyb	3.3	4.9	7.5
108	Avnø Vig	2.2	2.8	3.7
109	Hejlsminde Nor	4.0	5.0	6.6
110	Nybøl Nor	1.6	2.0	2.6
111	Lister Dyb	3.3	4.9	7.5
113	Flensborg Fjord. indre	0.8	1.0	1.4
114	Flensborg Fjord. ydre	0.7	0.9	1.2
119	Vesterhavet. syd	3.0	4.5	6.8
120	Knudedyb	3.3	4.9	7.5
121	Grådyb	3.3	4.9	7.5
122	Vejle Fjord. ydre	0.9	1.1	1.5
123	Vejle Fjord. indre	2.3	2.8	3.6
124	Kolding Fjord. indre	3.1	3.7	4.8
125	Kolding Fjord. ydre	1.5	1.8	2.3
127	Horsens Fjord. ydre	1.2	1.5	1.9
128	Horsens Fjord. indre	1.5	1.8	2.3
129	Nissum Fjord. ydre	1.6	1.9	2.5
130	Nissum Fjord. mellem	1.6	1.9	2.4
131	Nissum Fjord. Felsted Kog	3.0	3.7	4.7
132	Ringkøbing Fjord	5.4	6.5	8.4
133	Vesterhavet. nord	3.0	4.5	6.8
136	Randers Fjord. indre	6.8	8.2	10.6
137	Randers Fjord. ydre	6.0	7.2	9.4
138	Hevring Bugt	1.0	1.2	1.6
139	Anholt	0.9	1.1	1.4
140	Djursland Øst	0.7	0.9	1.1
141	Ebeltoft Vig	0.8	1.0	1.3
142	Stavns Fjord	1.5	1.8	2.4
144	Knebel Vig	1.0	1.2	1.5
145	Kalø Vig	1.0	1.2	1.5
146	Norsminde Fjord	2.7	3.2	4.2
147	Århus Bugt og Begtrup Vig	0.8	0.9	1.2
154	Kattegat. Læsø	1.2	1.4	1.8
157	Bjørnholms Bugt. Riisgårde Bredning. Skive Fjord og Lovns Bredning	1.8	2.1	2.7
158	Hjarbæk Fjord	4.8	5.8	7.5
159	Mariager Fjord. indre	2.0	2.4	3.1
160	Mariager Fjord. ydre	2.5	3.0	3.9
165	Isefjord. indre	1.6	1.9	2.5
200	Kattegat. Nordsjælland	0.7	0.9	1.2
201	Køge Bugt	0.8	1.1	1.3
204	Jammerland Bugt og Musholm Bugt	0.8	1.0	1.3
205	Kattegat. Nordsjælland >20 m	0.6	0.7	0.9
206	Smålandsfarvandet. åbne del	0.8	1.0	1.4
207	Nakskov Fjord	1.4	1.7	2.3
208	Femerbælt	1.0	1.3	1.7
209	Rødsand og Bredningen	1.2	1.5	2.0
212	Faaborg Fjord	1.0	1.3	1.7
214	Det sydfynske Øhav	0.8	1.1	1.4

216	Lillebælt. syd	0.6	0.7	1.0
217	Lillebælt. Bredningen	0.8	1.0	1.4
219	Århus Bugt syd. Samsø og Nordlige Bælthav	0.7	0.9	1.2
221	Skagerrak	2.0	3.0	4.0
222	Kattegat. Aalborg Bugt	1.2	1.4	1.9
224	Nordlige Lillebælt	0.8	1.0	1.2
225	Nordlige Kattegat. Ålbæk Bugt	0.9	1.1	1.4
231	Lillebælt. Snævringen			
232	Nissum Bredning	1.1	1.4	1.8
233	Kås Bredning og Venø Bugt	1.3	1.5	2.0
234	Løgstør Bredning	1.4	1.7	2.2
235	Nibe Bredning og Langerak	2.1	2.5	3.3
236	Thisted Bredning	1.4	1.7	2.2
238	Halkær Bredning	4.7	5.7	7.4

4 Discussion

The ambitious objective of the WFD is that European waters hold at least good ecological status (GES), meaning that ecosystems are deviating only slightly from undisturbed conditions. Since the WFD enactment by the EU in 2000, managers and scientists around Europe have been struggling to transform the political intentions and normative definitions to quantitative goals and operational, managerial frameworks. One of the main scientific challenges is establishing solid reference conditions reflecting an "undisturbed / slightly undisturbed condition".

The present methodology developed to establish reference and GM target values for chlorophyll-a in the Inner Danish waters relies on statistical and mechanistic models. As data from undisturbed coastal water bodies do not exist. quantitative modelling is the most feasible way to establish the reference and boundary values (Guidance Document No. 5). Different modelling approaches were applied to both Danish waters (Carstensen & Henriksen 2009; Henriksen 2009, Erichsen and Timmermann, 2017) and other regions of the Baltic Sea area (Schernewski et al. 2015; Gustafsson et al. 2012; Schernewski & Neumann 2005). The present study is the first attempt to define water body specific chlorophyll-a targets for all inner Danish waters – estuaries as well as open waters. Although the WFD only requires type-specific reference and class boundaries, site-specific reference values may, however, be preferable since each estuary, bay, lagoon etc. has its own characteristics in terms of, e.g. hydrodynamic conditions and morphological characteristics influencing not only present-day chlorophyll-*a* concentrations but most likely also results in chlorophyll-*a* reference conditions differing between sites.

Model prediction of reference conditions is inherently uncertain for several reasons. The two major (but related) reasons are that extrapolation of models beyond the calibration data set inevitable induces higher uncertainties and that disregarding other ecosystem aspects characterising the reference conditions, e.g. more wide spread eelgrass beds providing important ecosystem services, may introduce a bias in the model predictions (Erichsen and Timmermann, 2017). The use of statistical models outside the calibration range area is problematic due to the lag of explicit description of mechanisms and feedback processes. The statistical models applied in the present study are developed using data from eutrophic conditions. However, due to the substantial variation in year-to-year N loadings including "dry years" where N loadings approach the reference load, the models were evaluated under a wide range of load conditions. However, transient low load situations in an otherwise eutrophic situation are not directly comparable to a more stable low load situation primarily due to nutrient pools in the sediments (Erichsen and Timmermann, 2017). The statistical models link chlorophyll-a concentration and loadings from (local / regional) Danish catchments. This means that other variables strongly correlated to Danish loadings might be partly included in the parameterisation. This could apply for e.g. loadings from neighbouring countries (e.g. Germany) located close to a specific water body (e.g. Flensborg Fjord). In most cases, however, effects of nutrients originating from neighbouring countries are not strongly correlated to Danish loadings due to meteorological variations as well as time lag coursed by the transportation time from outlet to the Danish water body. Hence, to account for the effects of nutrients originating from neighbouring countries, results from the mechanistic models were used.

The mechanistic models are less sensitive to the extrapolation outside the calibration range as they include mechanistic process descriptions and feedback mechanisms and operate with, e.g. reduced sediment pools. However, the mechanistic modelling of a reference situation is also associated with considerable uncertainties. These are mainly related to the model parameterisations and uncertainties in historical input data necessary for mimicking conditions prevailing under more pristine conditions, e.g. the database behind the implemented reference sediment flux and pore water pools is largely absent (Erichsen and Timmermann, 2017).

A direct comparison between the reference values predicted by the statistical models and mechanistic models, respectively, showed no significant difference (p=0.09. parried t-test) between the model types indicating that any potential bias in either of the model types is insignificant or the same potential bias applies for both model types. However, there was a tendency for an "offset" between the model types, with statistical model results being higher than results from the mechanistic models, but this "offset" was not significant in the present dataset.

To reduce the uncertainty while maintaining a high degree of differentiation due to hydromorphological differences we applied a combined model approach, combining the statistical and mechanistic model results to provide robust site-specific reference values for all Danish water bodies. As this approach relies on two independent and different model types, the results are less sensitive to e.g., bias in one model type, and in addition the combined model can provide results in areas not covered by either statistical or mechanistic models by predictions based on freshwater discharge and average water depth.

Although traditional validation of the combined model estimates by comparison with observations is not possible, the resulting reference conditions appear reasonable with, e.g., highest reference values in freshwater dominated inner part of estuaries and lowest reference values in more open waters. In addition, the estimated reference and GM boundary values for chlorophyll-*a* (May-Sept) correspond well with results from similar studies (Carstensen and Henriksen, 2009, Bundesministerium 2014, Schernewski et al. 2015).

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ESTABLISHING CHLOROPHYLL-A REFERENCE CONDITIONS AND BOUNDARY VALUES APPLICABLE FOR THE RIVER BASIN MANAGEMENT PLANS 2021-2027

To comply with the EU water framework directive, Denmark needs to establish chlorophyll-a reference levels for all its water bodies. Here we combine model results chlorophyll-a levels at reference conditions (no, or only very minor, anthropogenic alterations). The results are combined in a new model, predicting reference concentration of chlorophyll-a based on waterbody-specific physical and hydromorphological data.

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