Applicability of the WFD indicator "Angiosperm depth limit" in shallow water bodies

Scientific note from DCE – Danish Centre for Environment and Energy

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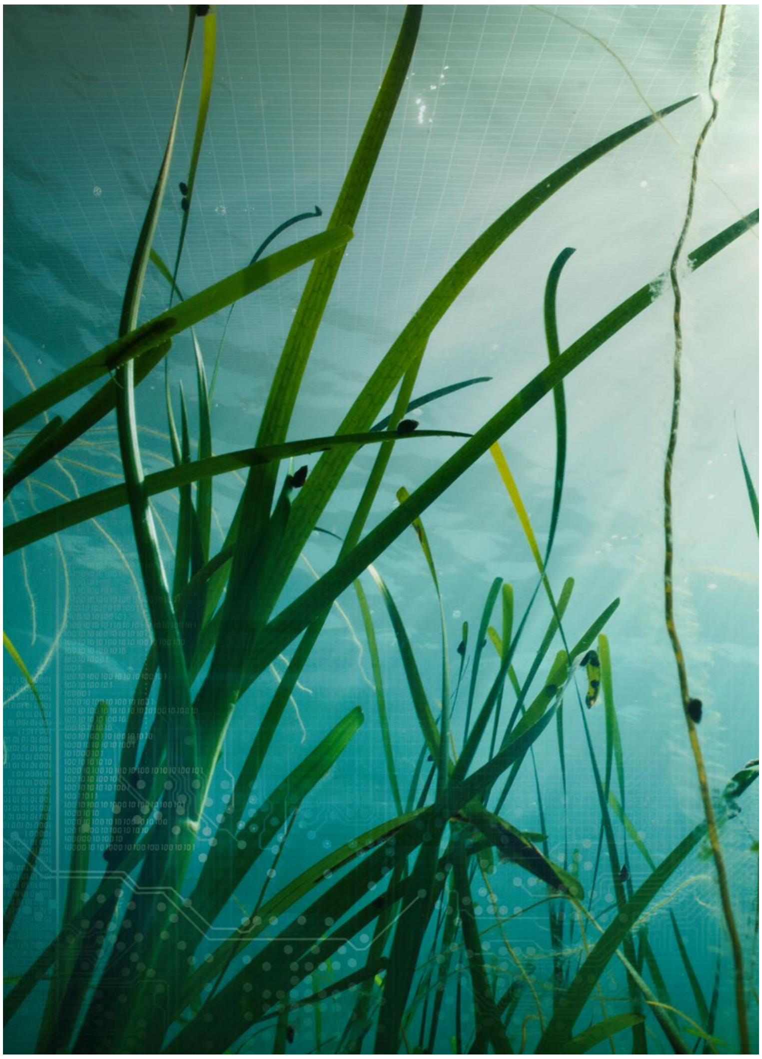

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Data sheet

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Preface

This report is a follow-up to the International Evaluation of the Scientific and Legal Basis for Nitrogen Reduction in the 3rd Danish River Basin Management Plan, which was developed in October 2023. One of the issues identified by the international evaluation panel was that the targets for eelgrass and other angiosperms are set based on their light-limited depth distribution. However, these targets cannot always be identified/classified in shallow areas, where the angiosperm depth limit is not limited by light but by maximum depth. The report is a part of the Second Opinion Project financed by Miljøstyrelsen (The Danish Environmental Protection Agency – EPA). The Danish EPA and the Ministry of Finance have commented on a draft version of this report, but the final decision of methods and conclusions is solely the responsibility of the project group (DHI, DTU and AU).

Sammenfatning

En international evaluering af den danske implementering af vandrammedirektivet har påpeget et problem med et af de biologiske kvalitetselementer i lavvandede vandområder. Problemet er, at ålegræs og andre angiospermer, der er vitale økosystemkomponenter og prioritererede kvalitetselementer i vandrammedirektivet, for nuværende vurderes på den lysbegrænsede dybdeudbredelse. Denne indikator kan ikke klassificeres, når den lysbegrænsede dybdeudbredelse overstiger den maksimale vanddybde. Det kan forhindre tilstandsklassificering i de højeste klasser for det biologiske kvalitetselement i lavvandede vandområder. Denne rapport anbefaler at bibeholde de eksisterende dybdegrænser i tilstandsvurderingen, også i lavvandede områder, da den anvendte referencetilstand er et udtryk for vandets klarhed, som herefter er omsat til et biologiske kvalitetsmål, og som kan udvides til flere biologiske kvalitetsmål, der er mindre dybdeafhængige. Vi foreslår en formalisering af måden at foretage den økologiske tilstandsvurdering på, som kan anvendes indtil videre, samt udvikling af en angiosperm-indikator, som egner sig til lavvandede områder. En løsning. der kan anvendes indtil videre, er at bruge angiosperm-dybdegrænsen med tilstandskategorier til det niveau, som den maksimale vanddybde tillader. Herefter bruges vandets klarhed som et understøttende kvalitetselement til at tilstandsklassificere. Rapporten foreslår også at udvikle nye indikatorer, der bedre beskriver tilstanden i lavvandede økosystemer, herunder en dækningsgrad-modelløsning baseret på ålegræssets dækningsgrad og biomasse eller en indikator baseret på nettotilvækst af ålegræs og øvrige angiospermer.

Summary

An international evaluation of the Danish implementation of the Water Framework Directive has pointed out a problem with one of the biological quality elements in shallow water bodies. The problem is that eelgrass and other angiosperms, which are vital ecosystem components and prioritized quality elements in the Water Framework Directive, are currently assessed on the basis of the light-limited depth distribution. This indicator cannot be classified when the light-limited depth distribution exceeds the maximum water depth. It may prevent status classification in the highest classes for the biological quality element in shallow water bodies. This report recommends maintaining the existing depth limits in the status assessment, including shallow areas, while the reference condition used to set boundary thresholds is an expression of the water clarity, which is then converted into a biological quality target, which can be extended to several biological quality elements that are less depth dependent. We propose a formalization of the way to carry out the ecological status assessment to be used for the time being as well as development of an angiosperm indicator suitable for shallow areas. One solution that can be used for now is to use the angiosperm depth limit with status classes to the level that the maximum water depth allows. Water clarity is then used, as a supporting quality element to classify statuses higher than water depth allows. The report also suggests developing new indicators that better describe the status of shallow-watered ecosystems, including a plant coverage model solution based on the degree of coverage and biomass of eelgrass, or an indicator based on the net growth of eelgrass and other angiosperms.

1 Introduction

In preparation for 3rd Danish River Basin Management Plan (RBMP3), Aarhus University (AU), the Technical University of Denmark (DTU), and DHI A/S developed models and methodologies designed to calculate the maximum allowable nitrogen inputs allowing Danish coastal waters to reach "good ecological status", as required by the Water Framework Directive (WFD). These models and methods are a crucial part of the scientific foundation for the RBMP3 covering 2021-2027, which was implemented in June 2023.

In 2021, as part of the "Agriculture Package" agreement, it was decided to carry out an international evaluation of the models and methods that form the basis of the RBMP3. This evaluation involved foreign research institutions and legal experts and aimed to examine any assumptions, prerequisites, or choices that could influence the calculation of the remaining nitrogen effort within the legal and scientific framework of the Water Framework Directive.

The international evaluation panel completed their evaluation report in October 2023. They identified two key issues. One of the issues raised regarded the use of the indicator 'depth limit for angiosperms' for environmental status assessments in shallow water bodies This specific issue is addressed in this report, while the other issue regarding discrepancy between G/M boundary values for chlorophyll a (Chl-a) calculated in RBMP3 and the intercalibrated Chl-a G/M boundary values is handled in a separate report.

1.1 Implementation of the WFD

The implementation of the WFD in Denmark comprises two parts, a status assessment every 6th year and a development of plans for the protection and restoration of aquatic ecosystems to reach at least good ecological status and prevent deterioration of the ecosystems. These plans are called the River Basin Management Plan (RBMP).

The WFD describes which quality element groups should be included in the classification of the water bodies. The three groups of quality elements are: 1) biological quality elements, 2) hydro-morphological quality elements that support the biological quality elements, and 3) chemical and physico-chemical quality elements.

The WFD uses both Biological Quality Elements (BQEs) and supporting quality elements to assess the ecological status of coastal waters.

The BQEs for coastal waters include:

- BQE1-1 Phytoplankton
- BQE1-2 Other aquatic vegetation – including BQE1-2-1 Macroalgae and BQE1-2-2 Angiosperms
- BQE1-3 Benthic invertebrate fauna

These elements are used to express the overall ecosystem health. If high or good status is achieved, assessments are further supported by assessments of hydromorphological and the physico-chemical supporting elements as described in CIS-guidance 13 Water Framework Directive - European Commission (europa.eu).

Supporting Quality Elements include physico-chemical and hydromorphological parameters. Physico-chemical parameters include, among others, nutrients, oxygen condition, temperature, transparency, salinity, and river basin-specific pollutants. Hydromorphological quality considers, e.g., residence time, sediment composition, and the structure of the physical habitat. The WFD specifies which elements are to be assessed for each water category and requires that biological and supporting quality elements achieve at least good status. The 'one-out-all-out' (OOAO) rule is applied when integrating multiple BQEs into an overall biological status of a water body, i.e., classification is determined by the BQE with lowest status.

In the Danish coastal waters, the average chlorophyll concentration from May to September is used as a measure for phytoplankton. This measure has been intercalibrated with Sweden and Germany (Timmerman et al., 2024; Carstensen, 2016).

For macroalgae, no indicator has yet been put into operation, while for angiosperms, maximum depth distribution with at least a 10% coverage for eelgrass (*Zostera marina*) or other angiosperms such as seagrass (*Ruppia maritima*) has been used. The Danish Quality Index (DKI) is used as an indicator for benthic fauna.

1.2 Setting reference and target for eelgrass depth distribution

The reference depth distribution for eelgrass in the Danish River Basin Management Plan 3 (RBMP3) was estimated using a combination of historical data and regression-based modeling (Timmermann et al., 2020).

The establishment of reference values was based on a large historical dataset on eelgrass collected from 1880-1930. This period is assumed to reflect a reference condition, which according to the WFD is defined as a condition with no or only very minor deviations from undisturbed conditions due to anthropogenic activities.

A regression-based model was constructed, describing the eelgrass depth distribution in each water body as a function of the physical parameters "water exchange", "average water depth", and "stratification".

Historical eelgrass observations exist for 48 out of 109 coastal water bodies. For these water bodies, water body-specific reference values were established based on the observations. For the remaining water bodies, the regression model forced with the physical characteristics for each water body was used to estimate water body-specific reference conditions for the eelgrass light-limited depth limit.

The results showed that the reference condition for depth distribution of eelgrass in Danish coastal areas is between 4 meters and 13.3 meters, with the lowest values occurring in enclosed water bodies (estuaries) impacted by high freshwater and nutrient runoff from land and the highest values in the more open waters (Timmermann et al., 2020).

The historical eelgrass observations used for the development and calibration of the regression model were based on observations chosen with the aim of finding the light-limited depth limit for eelgrass; hence observations in shallow waters where the depth limit was limited by other factors were not included (Krause-Jensen & Rasmussen, 2009).

Therefore, the model reflects the approximate light limitation depth (compensation depth) for eelgrass and other angiosperms (Carstensen and Krause-Jensen 2018) in reference condition and using currently measured light-limited depth limits of eelgrass and water clarity, the empirical relation between water clarity and eelgrass compensation-depth can be estimated. Thus, the model result should be interpreted as the most likely reference light conditions or water clarity in Danish water bodies measured as the theoretical angiosperm light-limited depth limit (compensation point).

In water bodies where the eelgrass depth distribution is regulated by light, the actual depth limit is observable and can be compared with the reference condition and class boundaries, but in areas shallower than the light compensation depth for eelgrass we can only expect eelgrass to grow to the deepest depths, even though it has the potential to grow deeper. This is a challenge when assessing BQE1-2 in a shallow water body already covered by eelgrass or other angiosperms if the depth limit is the only indicator for BQE1-2 in the Danish RBMP3.

For the supporting quality element "transparency", the indicator is based on light attenuation; this is usually measured with light sensors on a profiler, which works fine in most shallow areas. The transparency can also be measured with a Secchi disc, which can be restricted by depth similarly to the eelgrass depth limit.

1.3 Angiosperm indicator, water transparency, and estimation of N-MAI

The depth of the main distribution of eelgrass and other angiosperms is determined as the deepest occurrence of the species with at least 10% cover. This can roughly be assumed to be the average compensation depth for the eelgrass communities in situations where the depth distribution is light limited.

The "compensation depth" for eelgrass (or any photosynthetic organism) refers to the depth in the water column at which the amount of light is just sufficient for the plant to produce enough energy through photosynthesis to support its own metabolic processes and loss processes like grazing and mechanical stress.

At this depth, the rate of photosynthesis equals the rate of respiration and loss, meaning that the plant overall neither gains nor loses biomass (net growth close to zero). If the eelgrass is above this depth, it can grow and reproduce because it produces more energy than it uses (positive net growth). However, below the compensation depth, the eelgrass will eventually die because it uses more energy than it produces (negative net growth).

The amount of light required at compensation depth can be influenced by a lot of factors, including temperature, redox conditions in the sediment, sediment conditions, self-shading, and shading by epiphytes. In general, more light at the compensation depth is required with high nutrient load, organic-rich sediment, and physical exposure in shallow waters (Krause-Jensen et al., 2011; Krause-Jensen & Carstensen, 2018; Flindt et al., 2016).

During the preparatory work for RBMP, we showed that eelgrass has a higher minimum light requirement in shallow water than in deeper water (figure 1.1). From 4 meters and deeper, the light requirement seems to stabilize around 16% of the surface PAR light (Christensen et al., 2021). For the estimated depth limit targets in Danish coastal waters, it is rarely relevant with depths lower than 4 meters, so for the cause of simplicity 16% surface light was used as the goal for the "light penetration depth" for the supporting physico-chemical element and for the calculation of the maximum allowable input of nitrogen (N-MAI). If the goal is "just" to have 10% coverage of eelgrass or other angiosperms to the deepest part of a shallow system, the light goal should be adjusted in accordance with this (e.g. ~30% surface irradiance in a two-meter-deep area).

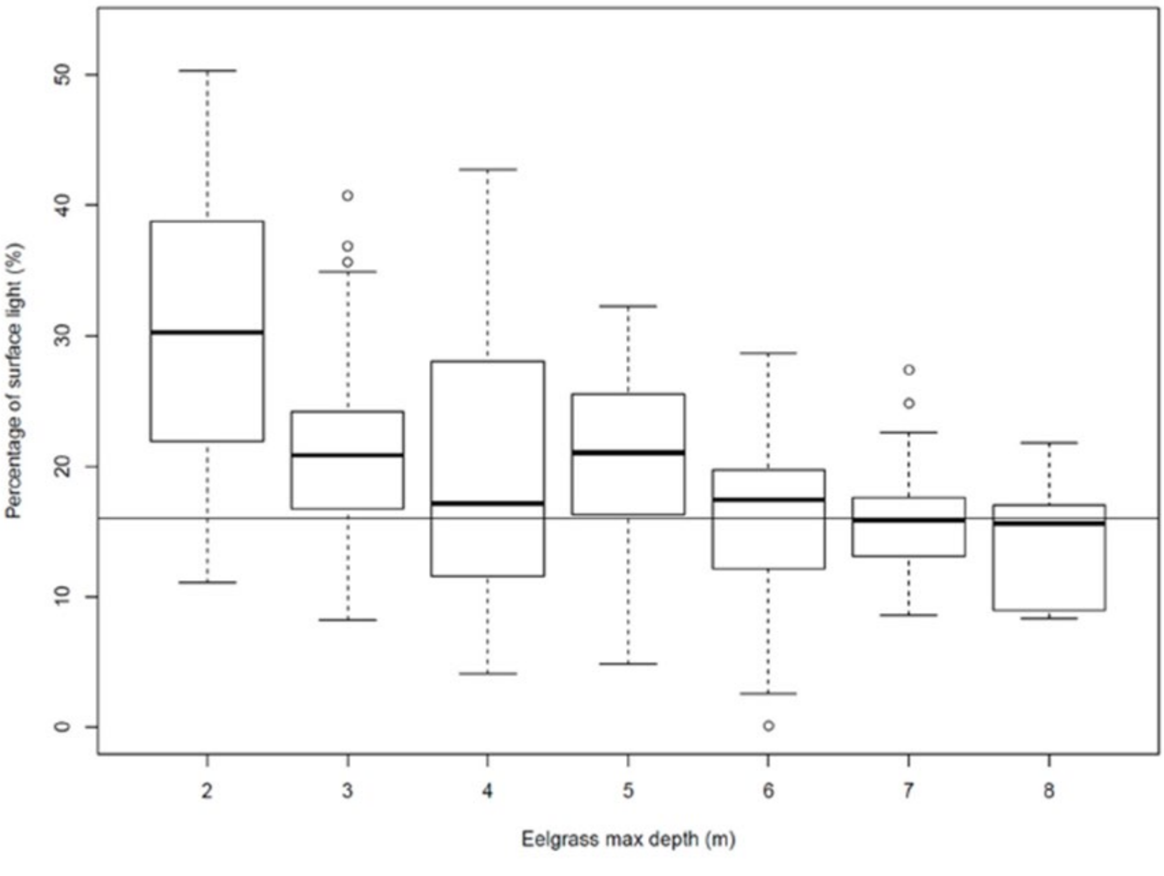

Figure 1.1. Boxplot showing the light requirement of eelgrass as a percentage of surface irradiance as a function of the maximum depth of the main distribution based on the data from the Danish monitoring and assessment program. The horizontal line shows 16% of surface light. This is also the minimum light requirement for eelgrass and angiosperms used to set the water clarity criteria in RBMP3. The light attenuation (water clarity) is typically measured at a central station in each water body (figure from Christensen et al., 2021).

1.4 Affected water bodies

In the Danish RBMP, there are 11 water bodies where the good-moderate boundary for the light-limited depth distribution for eelgrass is below (or equal to) the maximum water depth (table 1.1).

Table 1.2. Water bodies restricted in their status assessment based on the angiosperm maximum depth distribution. Not examined = NE, Not Detected = ND. Data from https://vandplandata.dk. Colors indicate ecological status. Green=Good, Yellow=Moderate, Orange=Poor and Red=Bad.

No.	Name	Maximum water depth (m)	Reference light "compensation point" (CP) for angiosperms (m)	Maximum possible EQR (max. depth/ reference CP-depth)	Maximum possible status assessed based on angiosperms light limited depth distribution	Status and depth limit of angiosperms (m) in RBMP3	Status and light penetration depth limit (m)
17	Basnæs Nor	2.2	5.6	0.39	Poor	NE	2.8
18	Holsteinborg Nor	3.8	5.6	0.58	Moderate	2.3	
49	Stege Nor	3.9	5.3	0.74	Good	2.5	
59	Nærå Strand	3.4	5.2	0.65	Moderate	ND	
74	Bredningen	0.7	6.2	0.11	Bad	NE	1.2
83	Holckenhavn Fjord	4.2	5.8	0.72	Moderate	1.2	
108	Avnø Vig	2.1	6.3	0.33	Poor	ND	
109	Hejlsminde Nor	2.0	6.6	0.30	Poor	NE	2.8
129	Nissum Fjord, ydre	3.4	5.4	0.63	Moderate	1	
146	Norsminde Fjord	1.7	5.6	0.30	Poor	0.6	
238	Halkær Bredning	1.5	5.3	0.28	Poor	1	

As shown in table 1.3, the ecological status of angiosperms does not reflect a slight deviation from an undisturbed condition when the angiosperm depth limit is restricted by water depth but assessed on the light-limited depth distribution. As an example, the ecological status in Basnæs Nor would all equal maximum water depth from reference condition to poor condition. From table 1.4, it can also be seen that in none of the 11 shallow water bodies there is a problem with assessing the status for maximum depth distribution of angiosperms with minimum 10% coverage in RBMP3. And as shown in the last column, the status of the light penetration depth (compensation point) is not restricted by maximum depth either.

1.5 The importance of water transparency

The available light at the bottom of a shallow coastal ecosystem (and other aquatic ecosystems) is important for the structure and function of the ecosystem. The balance between the benthic and pelagic primary productions is proportional to the ratio between light irradiance at the water surface and the light irradiance at the bottom of the water body (but is also affected many other factors) (Krause-Jensen et al., 2012; Striebel et al., 2023). Therefore, we can expect two shallow coastal water bodies to differ in (ecological) structure, dominant species, angiosperm density and coverage, etc. if they differ in water transparency – even if they should both theoretically be able to support angiosperms at maximum depth. The problem using the maximum depth of the main distribution of angiosperms arises in the case where the depth limit reaches the maximum water depth of the water body. If another indicator was used such as maximum coverage or the depth of the light saturation point instead of compensation depth, the ability to classify the highest classes of ecological status would be less prone to water depth limitations.

1.5.1 Transparency and macroalgae

The biological quality element BQE1-2-1, macroalgae, is also dependent on water transparency, and for macroalgae the structuring and layering of the plant cover are probably even more sensitive to light availability than for angiosperms. Light availability is a key factor influencing the cover of macroalgae. In areas with high light availability, macroalgae can grow more densely and cover a larger area. Areas with high light availability can support several layers of algae and hence a larger cumulative macroalgae cover and more species. The depth-dependent structuring of the macroalgae can be described both as cumulative cover and the number of perennial species. Both measures typically exhibit three distinct phases over the depth gradient from regulation by physical exposure near the surface, maximum levels of these macroalgae indices at intermediate depths, and attenuation at deeper depths due to light limitation. This course can be modelled using a non-linear model that describes the three processes and the cover or number of species as a function of depth (Carstensen et al., 2016; Carstensen, 2020).

1.5.2 Transparency and phytoplankton (and phytobenthos)

Phytoplankton concentration, productivity depth distribution (including phytobenthos), and species composition are also related to water transparency (Nielsen et al., 2002; Krause-Jensen et al., 2012), and transparency shall or can therefore also be considered a supporting quality element for phytoplankton.

1.6 Other effects

The structure and resilience of a shallow water ecosystem that has a water clarity exactly supporting an eelgrass cover of 10% (or close to the compensation depth) at the deepest place are not comparable to the structure and resilience of an ecosystem where the compensation depth for eelgrass is at a depth deeper than the maximum depth in relation to resilience, benthic primary production, and the biomass density of angiosperms and macroalgae. For instance, there is a higher risk that the angiosperm population may not recover after a sudden die-off event or intensive grazing.

1.6.1 Downstream effect

The reference values and hence targets for the depth limit of light/water clarity is determined by a model based on the meta-variables water depth, water exchange rate, and stratification. The model estimates the light-limited depth limit for angiosperms in the reference state, which is spatially consistent and changes according to the meta-variables describing the water body. If the water clarity target in an upstream area changes, the clarity target in the downstream or adjacent area will be harder to reach and hence concentrate the measures for achieving GES to the catchment of the downstream water body.

2 Recommendation from the International evaluation panel

In the international evaluation report (Herman et al., 2023), it is stated that the G/M boundary for eelgrass depth limit in certain water bodies is deeper than the maximum water depth of the specific water body. Altogether, 11 water bodies are shallower than the eelgrass depth limit at the G/M boundary, and 17 are shallower than the reference depth limit.

In the cases where the light-limited depth distribution for angiosperms, the G/M boundary, is deeper than the maximum water depth and where the main distribution of angiosperms is spread to the maximum depth in all investigated transects in a water body, the Danish EPA suggests determining the state for angiosperms as unknown and then use the supporting quality element water clarity (kd) to classify the water body. However, the classification based on supporting quality elements can never downgrade the classification based on angiosperm main distribution to the maximum bottom depth in the water body (Miljøstyrelsen). The latter is consistent with the estimation of maximum allowable N input (N-MAI) where summer chlorophyll-a as well as Kd are used in the calculations.

2.1.1 The panel concludes that (Herman et al., 2023, p. 23):

"However, the panel notices this relationship, where the required Kd at G/M boundary in a water body is not truncated by the actual water body depth but used to ensure a sufficient light at the bottom, even at shallow depth."

The panel writes: "The justification for this approach is that in order to have a thriving well-developed eelgrass meadow at the deepest depth of a shallow water body, it is not sufficient to have water clarity just sufficient for 10 per cent cover. In addition, when two water bodies are very similar, but one happens to have a single deep pit and the other not, different water clarity requirements would be needed for these two water bodies. The Panel sees the scientific logic of this argument but notes a lack of rigor in its application. It is not formally defined what a 'thriving meadow' is, or how much more light it needs than a 10 per cent cover meadow."

2.1.2 And recommends that (Herman et al., 2023, p. 23-24 and p.66):

Hence, the Panel believes that this choice creates unnecessary complications and in practice changes N-MAI in only a few very shallow water bodies, why they suggest using the G/M boundary depth limits for rooted angiosperms that are truncated at the maximum water depth, both in the environmental status assessment and in the model calculations of N-MAI. The Panel acknowledges the scientific arguments for the current practice, where Kd replaces the depth limit in shallow systems, but prefers to advise to provide precedence to the biological quality indicator over its supporting physico-chemical variable. "The Panel advises to truncate values for the depth limit of rooted angiosperm vegetation to the maximum depth of the water bodies. Although valid arguments can be brought forward for the current practice, where Kd replaces the depth limit in shallow systems, precedence should be given to the biological quality indicator over its supporting physico-chemical variable", and the Panel is also concerned that it is difficult to communicate and explain “The Panel advises to truncate assessments and model calculations of depth limit of rooted angiosperms to the maximum depth of the water bodies concerned. In practice it will make a difference only for a few water bodies, while it is easier to explain and gives due precedence to observed plant depth limit over its proxy (Kd)”.

3 Response from the model group

3.1 Response to panel recommendation

We appreciate the input from the international expert panel regarding the challenges of using eelgrass depth limit as an indicator in shallow water bodies. The recommendation from the panel is, however, not aligned with our understanding of the normative definition of good ecological status and will introduce inconsistencies in the ecological assessment and thus a need for action in ecosystems that are similar or connected and inconsistencies between the quality elements.

The panel suggests truncating the G/M boundary for the eelgrass depth limit at maximum water depth in shallow water bodies. While this suggestion might be easy to communicate and explain, it is not aligned with the normative definition of status classes defined in the WFD as a slight deviation from undisturbed conditions. Furthermore, as the definition of G/M boundaries would be linked to water depth and not the reference condition and the EQR-scale, the reference condition and the moderate, poor, and bad status classes would be undefined, challenging the ecological status classification system.

The use of the indicator "angiosperm depth limit" can, however, induce challenges in shallow water bodies as the (light-limited) angiosperm depth limit, defined as maximum depth with 10% cover of the main distribution, cannot be identified/measured if the maximum depth distribution is restricted by water depth and not by light. Hence, in shallow water bodies, where water depth and not light limitation truncates the depth distribution of eelgrass, the indicator "eelgrass depth limit" cannot be quantified, and, consequently, the indicator cannot be used to assess the ecological status of the BQE "angiosperms and macroalgae". In shallow water bodies where the depth distribution of angiosperms is light limited at maximum water depth, the depth limit of eelgrass can be quantified, and the indicator "eelgrass depth limit" can be used to assess the ecological status.

3.1.1 Link between light availability and eelgrass in shallow water bodies

Even though the depth distribution of eelgrass can be truncated at maximum water depth, thereby challenging the use of the eelgrass depth limit indicator, there are strong links between light availability and eelgrass performance as documented in, e.g., Thorn et al. (2008) and Flindt et al. (2024). Here we propose an additional eelgrass-based measure, linking the quality of light to the growth performance of eelgrass, which can be used in all, even shallow, water bodies.

The growth of eelgrass measured as, e.g., primary production or the growth rate of shoots is a sensitive measure of how well eelgrass performs in a specific location. Further, a suite of ecosystem services, such as nutrient and carbon dynamics, are directly linked to the eelgrass growth rate, making it essential for ecosystem functioning on larger spatial scales.

The relation between light availability and the growth rate of wild eelgrass and eelgrass leaves has been documented (Thorn et al., 2008; Zimmerman et al., 1997; Flindt et al., 2024) and shows a classical "Photosynthetic and Irradiance" curve (P/I curve) between light availability and the growth rate of eelgrass.

The parameters of the P/I curve can describe the "compensation point" (CP) for the eelgrass bed (growth rate = 0), where the light availability above CP is sufficient to sustain a positive growth rate. The CP for net growth of eelgrass shoots is closely related to the light-limited depth distribution of eelgrass (also referred to as the compensation depth in this report), and ideally CP should be at almost the same depth (and light intensity) as the light-limited depth distribution. The P/I curve levels out at the maximum growth rate of eelgrass when it reaches the light range where the eelgrass community becomes light saturated (or close to), and where a further improvement of light does not result in an increased growth rate. A P/I-curve for eelgrass is illustrated in figure 3.1.

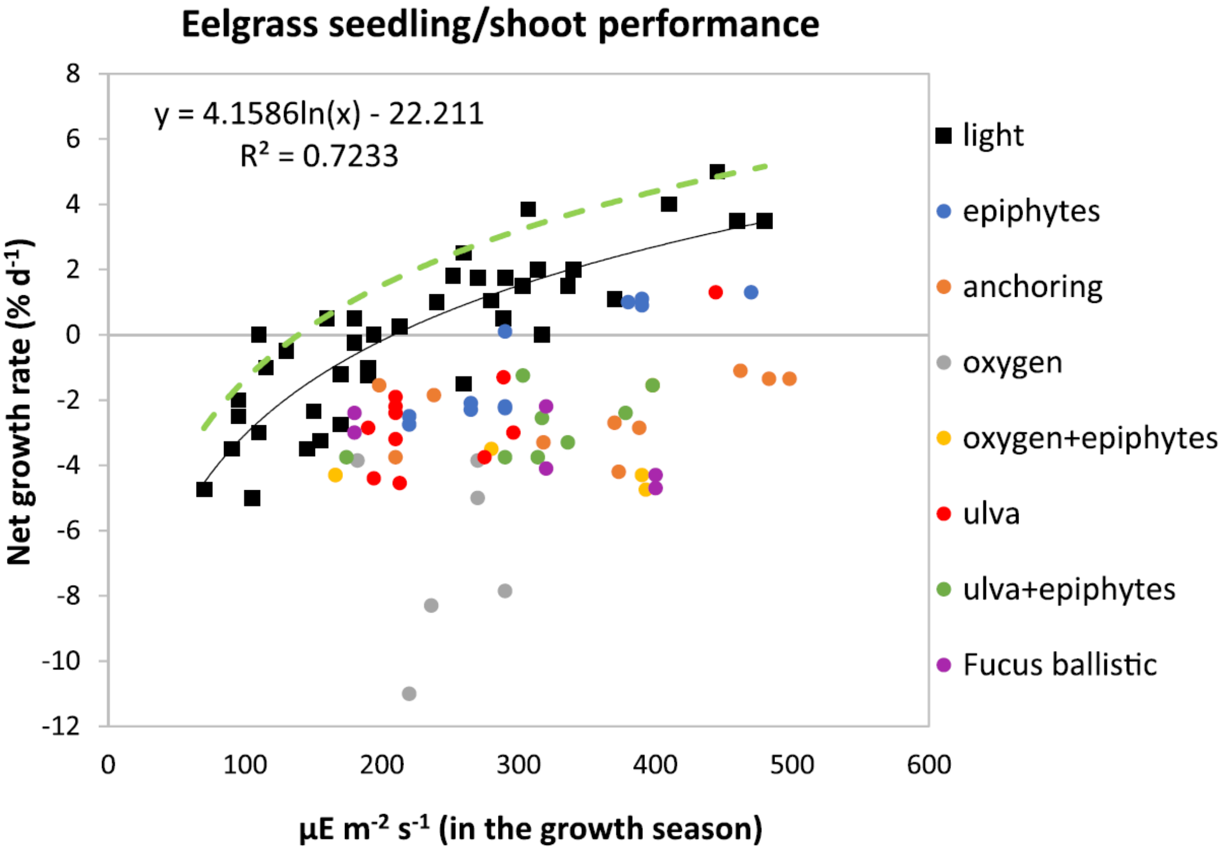

Figure 3.1. Illustration of a typical relationship for eelgrass showing the relation between light availability and eelgrass growth. The relation is based on Flindt et al. (2024), and the black line is a logarithmic regression of the shoot growth rate at a site that was only impacted by light limitation. The threshold for positive net growth is around 200 uE/m2/sec following the black line. If only the highest values are used, the relationship can be described by the green line and gives a threshold of 130 uE/m2/sec. This relationship can be used to establish a temporary eelgrass growth indicator.

The relationship between light and growth rate depends on a variety of environmental parameters such as temperature, organic carbon content in the sediment, hypoxia, season, depth, age of the plants/bed, etc., all affecting the light-eelgrass growth relationship. However, based on field experiments with net growth of eelgrass beds (figure 3.1), a tentative relationship between eelgrass growth and light availability for eelgrass in coastal waters can be formulated as:

GR=a*ln(I)+b,

where GR is the growth rate (% per day), I is the light availability (uE/m2/sec), a is the light efficiency coefficient, and b is the intercept. The compensation point is found by setting GR to 0.

Based on the light-growth curve, it is possible to link the depth limit of eelgrass to the growth rate of eelgrass as both parameters depend on light availability. Likewise, it is possible to calculate the growth of eelgrass at a specific water depth in a reference situation and at the good-moderate boundary based on the corresponding eelgrass depth limit values.

The eelgrass growth indicator is not limited to a specific water depth, but it will be most sensitive at depths where the growth is light limited and less sensitive when light saturation starts to occur. At water depths deeper than the depth limit of eelgrass, net growth rates will be close to zero or negative.

Using the light requirement for the eelgrass depth limit and the relation between light and eelgrass growth, it is possible to calculate the corresponding eelgrass growth rate at a specific water depth (e.g. 3 meters). Another possibility is to calculate the maximum depth where eelgrass is light saturated based on the saturation threshold reported in Flindt et al. (2024). The results for the 11 shallow water bodies are shown in table 3.1.

Table 3.1. An example of indicator and threshold values for G-M boundaries of the eelgrass growth rate at specific depths or at the saturation depth where the eelgrass bed is light saturated based on the relationship described in Flindt et al. (2024), unpublished data from Banke et al. (2024) and Thom et al. (2007).

Water body no.	Max. water depth	Eelgrass depth limit (m)		Kd (m^{-1})		Expected growth rate at 3 m (% per day)		Expected growth rate at max. water depth (% per day)	
		Reference condition	G-M boundary	Reference condition	G-M boundary	Reference condition	G-M boundary	Reference condition	G-M boundary
17	2.2	5.6	4.1	0.33	0.44	3.60	2.17	4.69	3.64
18	3.8	5.6	4.1	0.33	0.44	3.60	2.17	2.52	0.71
49	3.9	5.3	3.9	0.35	0.47	3.37	1.86	2.08	0.12
59	3.4	5.2	3.8	0.35	0.48	3.29	1.75	2.71	0.96
74	0.7	6.2	4.6	0.30	0.40	4.00	2.71	6.82	6.52
83	4.2	5.8	4.3	0.32	0.43	3.75	2.36	2.17	0.24
108	2.1	6.3	4.7	0.29	0.39	4.06	2.79	5.14	4.25
109	2	6.6	4.9	0.28	0.38	4.22	3.01	5.37	4.56
129	3.4	5.4	4.0	0.34	0.46	3.45	1.97	2.89	1.21
146	1.7	5.6	4.1	0.33	0.44	3.60	2.17	5.37	4.56
238	1.5	5.4	4.0	0.34	0.46	3.45	1.97	5.57	4.82

Three things should be noted regarding the suggested indicator. Firstly, the light-growth relationship for an eelgrass bed or other marine angiosperms is very different from a P/I relationship based on a single plant or a single leaf, which is often used for estimating the compensation point and light saturation. Due to self-shading, respiration from the roots, epiphytes, etc., both the compensation point and the light saturation point are at much higher light intensities for an angiosperm community than for a single plant or leaf, and the saturation point is often at light intensities found at water depths lower than 1 meter. Therefore, the community light saturation depth occurs at very shallow depth, and we can thus assume that the net growth of the angiosperm community is, to some extent, light limited at the deepest point, even in shallow water bodies.

Secondly, the loss rates in shallow water are often high due to physical exposure and grazing, and high net growth is therefore an important factor for the robustness of the angiosperm population in shallow water bodies.

Thirdly, the compensation depths for the two independently parameterized BQE indicators are very close (as expected) in the examples given in table 3.1. This shows that the two indicators are, to some extent, complementary and can be linked to similar light requirements. This also strengthens the justification for using light attenuation for ecological status assessment in situations where the biological indicator has not been monitored (or if measurements have been constrained in any other way).

3.2 Recommendations

3.2.1 Estimation of N-MAI

The indicator "eelgrass depth limit" is not used for N-MAI calculations, and hence the potential challenge with truncation of the eelgrass depth distribution in shallow water bodies does not pose a problem. For N-MAI calculations, light/Kd is used as a proxy indicator for the eelgrass light-limited maximum depth distribution. As this indicator is assessed using light sensors (and not a Secchi disc), and as Kd is "a pelagic" parameter, the indicator can be quantified in all water bodies and is not influenced or restricted by water depth. As demonstrated above, there are other possible indicators that could be used to assess the status of the biological quality element angiosperms, and these are strongly coupled to light/water clarity.

For the estimation of N-MAI, we suggest keeping the current approach using light attenuation as an indicator for environmental status as this indicator is not restricted by shallow water depth. This will ensure consistency between the main pressure (nutrient input), the BQEs, and the supporting quality elements so we do not introduce targets for two indicators aiming at different "regimes". Note in this context that the recommended N-MAI estimate is based on the average N-MAI for the indicators and not on the OOAO principle. Therefore, more indicators will strengthen the confidence of a correct N-MAI.

3.2.2 Status assessment based on angiosperms

Eelgrass and other angiosperms are important ecosystem components and a prioritized quality element. While the eelgrass depth limit is an ecologically relevant and well-documented indicator, one of its disadvantages is that the depth limit cannot be quantified in shallow, non-light-limited water bodies, where water depth restricts the depth distribution of eelgrass. We recommend that the depth limit remains part of the status assessment also in shallow waters. However, we have suggestions for modifications that will improve the ecological status assessment of shallow water bodies. Our suggestions for modifying the ecological status assessment for angiosperms include:

Solution 1

Use the angiosperm depth limit with the status categories from bad to the highest possible category that the maximum depth allows (see table 3.2). When the eelgrass depth distribution is not restricted by water depth, the depth limit is well defined and quantifiable and can be used for status assessment in the same way as the use of the depth limit indicator in deeper water bodies.

If maximum depth is reached, use the supporting quality element "light limitation depth" to classify the ecological status of the BQE. Although a supporting indicator will replace the BQE indicator when the depth distribution of angiosperms at maximum water depth is not light limited, the tight coupling between the eelgrass depth limit and the light limitation depth and the elevated light requirement that eelgrass has in shallow waters (< 4 meters) justifies the replacement of a BQE indicator with a supporting indicator. It is important that both criteria (angiosperms at > 10% cover at maximum water depth and light conditions at > G-M threshold) are fulfilled for the water body to be classified as having good (or higher) status.

This solution ensures that there is consistency between the status assessment and N-MAI calculations, and we do not compromise with our ecosystem understanding and the relationship between the supporting QEs and the other biological quality elements. Also, as described in this report, additional less depth-dependent indicators/measures of quality for angiosperms show that the state of the BQE is light dependent, even in very shallow waters.

It should be emphasized that we recommend keeping the transparency G/M boundary at the current levels in the above-mentioned solution. It should also be noted that the water depth currently does not restrict the status assessment for angiosperms in any of the shallow water bodies.

We emphasize that the proposed solution can be used with the current knowledge, data, and indicators, but in the long term we recommend development of new indicators to describe the shallow water ecosystems.

Solution 2 (Net growth indicator)

To ensure a better description of the state of the BQEs in coastal water bodies including shallow water areas, new indicators based not only on the maximum main distribution of angiosperms should eventually be developed.

As demonstrated (in table 3.1), it is possible to use the light-growth rate relationship for angiosperm communities to estimate how much the net growth of angiosperms should be in a healthy shallow ecosystem with only slight deviation from undisturbed conditions and hence to determine threshold values for the G-M boundaries of a measurable indicator. The limitation of using this indicator is that it is not fully developed yet; thus, extra data collection and analysis are required to develop a robust relationship for use in all water bodies. It is also a time-consuming and expensive indicator to monitor and cannot be assessed with the existing monitoring program.

Solution 3 (Coverage-model indicator)

Another solution is to develop an indicator for angiosperms based on cover as an additional indicator to the eelgrass depth limit. As illustrated in Carstensen et al. (2016), eelgrass cover and biomass can be linked to light availability (water transparency) in a coverage model describing eelgrass cover or biomass as a function of exposure and light at the bottom. An indicator based on cover/biomass can be quantified even when the light-limited depth limit is not reached. However, the strength of the result depends greatly on how much of the light-limited part of the population is included in the model calibration. Thus, in the shallowest areas this approach is most likely not applicable. On the other hand, it should be possible to apply this indicator within the framework of the existing monitoring program or with data from remote sensing. This indicator is not fully elaborated and would also take time and effort to develop to a state where it can be used in the status assessment.

It should be noted that it is not trivial to develop biological indicators that are operational and applicable in all shallow water bodies. Thus, water transparency is still an effective measure with great importance for evaluating the general state of the ecosystem regardless of water depth.

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