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Background

The assessment of eutrophication within HELCOM is made with the HELCOM eutrophication core indicators which reflect concentrations of nutrients in the water, water clarity and algae blooms as well as oxygen concentration. However, there are some assessment areas where not all indicators are applicable due to for example lacking threshold values or methodological aspects. One of the primary criteria for Descriptor 5 in the Commission Decision (EU 2017/848) is D5C5 Dissolved oxygen in the bottom of the water column. For this criteria, HELCOM uses the core indicator Oxygen debt but this indicator is only applicable in the deep basins in the Baltic Sea. There are thus shallower assessment areas where the oxygen situation cannot be assessed and there is need of an oxygen indicator for those areas. The Oxygen debt indicator is also currently not functional in the Bay of Bothnia. There are ongoing work around the Baltic Sea and within HELCOM in order to further develop an oxygen indicator and this literature study reviews which oxygen indicators are currently developed with the aim to assist the process.

Action requested

The meeting is invited to:
Take note of the information.

Oxygen indicator for assessing eutrophication in marine waters – a literature review

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SMHI, December 2019

BACKGROUND

The assessment of eutrophication within HELCOM is made with the HELCOM eutrophication core indicators which reflect concentrations of nutrients in the water, water clarity and algae blooms as well as oxygen concentration. However, there are some assessment areas where not all indicators are applicable due to for example lacking threshold values or methodological aspects. One of the primary criteria for Descriptor 5 in the Commission Decision (EU 2017/848) is D5C5 Dissolved oxygen in the bottom of the water column. For this criteria, HELCOM uses the core indicator Oxygen debt but this indicator is only applicable in the deep basins in the Baltic Sea. There are thus shallower assessment areas where the oxygen situation cannot be assessed and there is need of an oxygen indicator for those areas. The Oxygen debt indicator is also currently not functional in the Bay of Bothnia. There are ongoing work around the Baltic Sea and within HELCOM in order to further develop the oxygen indicator and this literature study reviews which oxygen indicators are currently developed with the aim to assist the process.

METHOD

The literature search was made using "Web of Science Core collection" on 2019-10-14 through the SMHI library service. The search phrase resulting in n=5624 papers were:

> *ALL FIELDS: ((marine OR ocean* OR sea) AND (oxyg* OR "O2") AND (eutroph* OR indicator OR status))*

Several different search phrases were tested prior before selecting the current. A quality control of the search phrase accuracy revealed that it successfully picked up the previously known paper by Stoicescu et al. (2019).

An initial filtration step removed all papers >10 years old and duplicate references, leaving n=2206 papers. The second filtration removed all titles and journals off-topic. The remaining number of papers was n=1220. These papers were first scrutinized by title and ranked 0-5 where 5 are most relevant and 0 is off-topic. For example, titles containing either "status" or "oxygen" receive a rank ranging 1-2. Titles containing both, "status" and "oxygen" receive a rank ranging 3-5. If a paper does not contain any relevant words in the title it receives the rank 0. The title scrutiny resulted in n=284 papers ranked 1-5 that was on-topic. Abstract scrutiny was performed on all papers with a rank of >= 3 consisting of n=51 papers. After the abstract scrutiny the rank could be changed to a higher or lower rank. Finally, papers were selected based on relevant contents in both title and abstract corresponding to n=27 papers with a rank ranging 4-5. A full-text copy of each paper was retrieved online or through personal communication with specific authors. All work for scrutinizing and ranking the literature was performed using EndNote X9 (Clarivate Analytics, USA).

Table 1. *Listing and ranking of selected literature with general comments/summary*

Author	**Year**	**Paper**	**Rank**	**Summary**
Bejaoui, B., et al.	2016	"Random Forest model and TRIX used in combination to assess and diagnose the trophic status of Bizerte Lagoon, southern Mediterranean." Ecological Indicators 71: 293-301.	4	A combined multimetric trophic index (TRIX; TRIX = [log10(DIN∗DIP∗|D%O2|∗Chla)+a] /b) and the Random Forest (RF; machine learning method) model were used on data from samples collected in *surface waters* of the Bizerte Lagoon to characterize trophic status. Dissolved oxygen together with nutrients can explain eutrophication status but DO was not solely used in any of the analysed models to predict eutrophication status.
Bonometto, A., et al.	2019	"Assessing eutrophication in transitional waters: A performance analysis of the Transitional Water Quality Index (TWQI) under seasonal fluctuations." Estuarine Coastal and Shelf Science 216: 218-228.	5	Transitional Water Quality Index (TWQI) was used to assess the trophic status in shallow transitional water ecosystems of the Venice Lagoon in *surface waters*. TWQI is less affected by temporal variations than the average of measured single parameters. DO is heavily affected by seasonality and does not explain eutrophication status efficiently.
Brockmann, U., et al.	2018	"Eutrophication assessment in the transit area German Bight (North Sea) 2006-2014-Stagnation and limitations." Marine Pollution Bulletin 136: 68-78.	4	Descriptional paper of what leads to oxygen depletion.

Brown, C. A. and W. G. Nelson	2015	"A method to identify estuarine water quality exceedances associated with ocean conditions." Environmental Monitoring and Assessment 187(3).	5	Water quality was assessed using DO data from the Yaquina estuary influenced by upwellings in *surface waters*. Logistic regression methods were applied to discern the true effect of changes in water quality from that influenced by upwelling and similar oceanographic events. The study is useful to keep in mind due to variation in DO concentrations caused by natural dynamics.
Coffin, M. R. S., et al.	2018	"An empirical model using dissolved oxygen as an indicator for eutrophication at a regional scale." Marine Pollution Bulletin 133: 261-270.	5	Dissolved oxygen was examined as an indicator of eutrophication status for *shallow estuaries, 1-5 m*, in the Arctic. Multivariate statistics showed that variation in DO was explained by nutrient loadings and water residency time, and was a good descriptor of eutrophication. This study is an example of the application of a very simple model that can be directly used in marine management.
Cosme, N., et al.	2015	"Exposure factors for marine eutrophication impacts assessment based on a mechanistic biological model." Ecological Modelling 317: 50-63.	5	DO was not used in the model.
Ferreira, J. G., et al.	2011	"Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive."	5	Overview of eutrophication indicators.

		Estuarine Coastal and Shelf Science 93(2): 117-131.		
Fitzpatrick, J. J.	2009	"Assessing skill of estuarine and coastal eutrophication models for water quality managers." Journal of Marine Systems 76(1-2): 195-211.	5	Review paper that mapped the use of DO as indicator of eutrophication. Of particular interest to this literature study may be the reviewed Chesapeake Bay Water Quality Model (CBWQM) that successfully describes water quality based on DO. Time series analyses of several studies have been addressed and the author highlights that the CBWQM performs better than linear regressions.
Fleming-Lehtinen, V., et al.	2015	"Recent developments in assessment methodology reveal that the Baltic Sea eutrophication problem is expanding." Ecological Indicators 48: 380-388.	4	Review of assessment of eutrophication in the **Baltic Sea** based on new eutrophication targets, the improved eutrophication assessment tool (HEAT 3.0). Indirect effects of eutrophication were represented by an oxygen debt indicator (annual oxygen debt *below halocline*). Poor status in oxygen debt might bias the overall eutrophication assessment but this was not the case in any of the investigated sub-basins. Oxygen debt showed better confidence than Chl *a* and secchi depth in eutrophication status assessment.
Foden, J., et al.	2011	"Searching for undesirable disturbance: an application of the OSPAR eutrophication assessment method to marine waters of	5	Applied use of the OSPAR eutrophication assessment tool. DO was not used solely in the harmonised model of several parameters. The method

		England and Wales." Biogeochemistry 106(2): 157-175.		
Garcia, P., et al.	2010	"Nutrient and oxygenation conditions in transitional and coastal waters: Proposing metrics for status assessment." Ecological Indicators 10(6): 1184-1192.	5	Physico-chemical parameters were used to assess eutrophication status in *surface waters* of the Cantabrian Sea using reference conditions, bootstrap statistical techniques and quality ratios for each parameter. The physicochemical status of each water body was defined according to the "one out all out" principle; requires that all biological and physico-chemical elements must be categorized with at least "good status" in order to achieve the environmental objectives for surface waters (see WFD).
Gholizadeh, M. H., et al.	2016	"A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques." Sensors 16(8).	4	Review paper discussing the use of remote sensors to infer *surface water* quality based on typical parameters applied for status assessment. In terms of DO, the review paper highlights that no single identified and/or recommended sensors can be used with high confidence to perform an appropriate model to measure the reflectance of water resulting from DO. However, statistical methods have shown relationship between the satellites estimated reflectance and DO (and other physico-chemical "water quality" parameters).The review paper lists a table (Table 12) of papers that have investigated remote sensors coupled with e.g. DO of interest to this study. Remote

				sensing of such water quality parameters e.g. DO is promising but have some caveats and more studies are needed.
Giordani, G., et al.	2009	"Simple tools for assessing water quality and trophic status in transitional water ecosystems." Ecological Indicators 9(5): 982-991.	5	The study describes the development of an index, Transitional Water Quality Index (TWQI; see also Bonometto 2019 et al. above), for assessing trophic status and water quality in transitional aquatic ecosystems of Southern Europe and compared this with other methods, e.g. TRIX. DO was not solely used to assess eutrophication but included in the model. The author argues that cross measurements of DO and benthic data or chl *a* will highlight the likelihood of the system to become anoxic where transitional waters with macroalgae are more sensitive to oxygen consumption.
Greenwood, N., et al.	2019	"Utilizing Eutrophication Assessment Directives From Transitional to Marine Systems in the Thames Estuary and Liverpool Bay, UK." Frontiers in Marine Science 6.	4	Using nutrients, chlorophyll *a* and dissolved oxygen in the Thames estuary and Liverpool bay for *surface waters* is a good baseline for the assessment of eutrophication and, with appropriate thresholds, can provide a useful tool to assess the extent and impact of nutrient enrichment. The outcomes for the dissolved oxygen metrics are in line with the WFD and OSPAR criteria and are also similar across all the different assessment areas.
Greenwood, N., et al.	2010	"Detection of low bottom water	5	*Bottom water* oxygen was used as criteria for

		oxygen concentrations in the North Sea implications for monitoring and assessment of ecosystem health." Biogeosciences 7(4): 1357-1373.		eutrophication status for instrumented moorings deployed in the central North Sea, at the Oyster Grounds and on the northern slope of Dogger Bank (North Dogger). DO explained a high degree of the nutrient loadings but management measures must be organised on a regional basis and must be able to monitor changes over a range of time scales. Further measurements over multi-annual timescales and at additional locations of distinct environmental characteristics will be required to provide a fuller understanding of the controls on DO concentration in shelf seas.
Hatzikos, E., et al.	2009	"Applying adaptive prediction to sea-water quality measurements." Expert Systems with Applications 36(3): 6773-6779.	4	Model for one-day ahead predictions of water quality measures.
Iqbal, M. M., et al.	2018	"Assessment of Water Quality Profile Using Numerical Modeling Approach in Major Climate Classes of Asia." International Journal of Environmental Research and Public Health 15(10).	4	Spatial scale variation of the Water Quality Index (WQI) was investigated using QUAL2Kw, a one-dimensional water quality analysis model in *surface waters* of river-coastal systems in Asia. The authors show that longitudinal variation in climate does not influence WQI. However, DO changes decrease in longitudinal gradients of river flow where each climate zone has a different DO dynamic and complicates conclusions on DO for eutrophication status

				assessment.
Kamyab-Talesh, F., et al.	2019	"Prediction of Water Quality Index by Support Vector Machine: a Case Study in the Sefidrud Basin, Northern Iran." Water Resources 46(1): 112-116.	4	River data only.
Khalit, S. I., et al.	2017	"A preliminary study of marine water quality status using principal component analysis at three selected mangrove estuaries in East Coast Peninsular Malaysia." Malaysian Journal of Fundamental and Applied Sciences 13(4): 764-768.	5	Water quality status was investigated using principal component analysis of physico-chemical parameters at three selected mangrove estuaries for *surface waters* in East Coast Peninsular Malaysia. The PCA analyses and hence assessment of marine water quality status were affected by both saltwater intrusion and anthropogenic activities. Variation in DO together with other "water quality" parameters is explained by nutrient loading, in particular NH4.
Kong, X. Y., et al.	2018	"A new technique for rapid assessment of eutrophication status of coastal waters using a support vector machine." Journal of Oceanology and Limnology 36(2): 249-262.	5	Eutrophication status of coastal waters in *surface waters* down to 30 m in the Yellow and East China Sea was determined with three easily measured parameters (turbidity, chlorophyll *a* and dissolved oxygen) using grid search (GS) optimized support vector machine (SVM). The results were compared with trophic index TRIX classification. The application of only three easy-to-measure variables, DO, Chl *a* , and turbidity yielded good

				correlation with TRIX classification. Among the three input variables, DO had the most significant effect on the evaluated eutrophication levels (see Table 6 in the paper).
McQuatters-Gollop, A., et al.	2009	"How well do ecosystem indicators communicate the effects of anthropogenic eutrophication?" Estuarine Coastal and Shelf Science 82(4): 583-596.	5	Review paper on responses to nutrient loading in European seas including the **Baltic Sea**, comparing existing time-series of selected pelagic (phytoplankton biomass and community composition, turbidity, N:P ratio) and benthic (macro flora and faunal communities, bottom oxygen condition) indicators based on their effectiveness in assessing eutrophication effects. DO as indicator in the review paper is only considering *bottom waters* but this parameter works relatively well in the North Adriatic Sea for eutrophication status assessment.
Stoicescu, S. T., et al.	2019	"Assessment of Eutrophication Status Based on Sub-Surface Oxygen Conditions in the Gulf of Finland (Baltic Sea)." Frontiers in Marine Science 6.	5	The authors tested the applicability of high-frequency data from a fixed automated station in the **Gulf of Finland** for *sub halocline waters* and three adapted oxygen indicators for the eutrophication-related status assessments. “Oxygen debt” was found to be the simplest and most accurate indicator, and the assessment results were less influenced natural hydrographic conditions. The “oxygen debt” indicator should be based on data from the stratified season only because the halocline most likely disappears in winter. Caveats include the differentiation between natural

				changes and eutrophication-related impacts. high-frequency profiling should be implemented in the monitoring programs and more accurate estimates of changes due to physical processes are required.
Tallar, R. Y. and J. P. Suen	2016	"Aquaculture Water Quality Index: a low-cost index to accelerate aquaculture development in Indonesia." Aquaculture International 24(1): 295-312.	5	A low-cost simple Aquaculture Water Quality Index (AWQI) was investigated by the authors to determine water quality in lakes and reservoirs in Indonesia. The results were compared with three different WQI methods (NSF, RPI, and MDE) were used to evaluate the spatial and temporal changes in water quality in the study area. DO had an important role in the AWQI, as it had the highest weight factor in Analytical hierarchy process (AHP) method. DO is used together with other "water quality" parameters but had the highest weight/influence for determining eutrophication status.
Tugrul, S., et al.	2019	"Assessment of trophic status of the northeastern Mediterranean coastal waters: eutrophication classification tools revisited." Environmental Science and Pollution Research 26(15): 14742-14754.	5	Different eutrophication assessment tools were examined for the *entire water column* but focused on *surface waters* in stations around NE Mediterranean shelf waters and bays of Turkey. The performance of the following models/parameters was investigated: Trophic Index (TRIX), Eutrophication Index (E.I.), Chl *a*, and HELCOM Eutrophication Assessment Tool (HEAT). The classification results obtained by the classical TRIX are not in line with

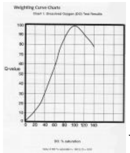
				the result calculated from the revised TRIXs, HEAT, and E.I. scaling tools. The revised TRIX and E.I. tools are not capable of differentiating the actual eutrophication development if the coastal ecosystem has notable fresh water inflows spreading over large areas. DO is only used in the TRIX model together with other parameters.
Wan, Y. S., et al.	2012	"Three dimensional water quality modeling of a shallow subtropical estuary." Marine Environmental Research 82: 76-86.	5	The authors show the development, calibration, and verification of a three dimensional (3D) water quality model for the St. Lucie Estuary. The model is capable of reproducing key water quality characteristics of the estuary relatively well. DO was used in the model but additional field data are needed to determine the relationship between DO variation with the length and spatial extent of algal blooms and hydrographic dynamics such as inflows.
Wang, X., et al.	2016	"Improving real-time forecasting of water quality indicators with combination of process-based models and data assimilation technique." Ecological Indicators 66: 428-439.	5	The authors present a real-time framework which combines the process-based models and data assimilation technique for determining forecasting of water quality indicators. Data was collected from Singapore Regional Water and observation stations. Models were tested on predicting two representative water quality indicators of salinity and DO. The modified local model (MLM) approach in the proposed data assimilation scheme is able to capture

				the dynamic variation of the measurements and improve the model accuracy. the proposed framework is able to correct not only the physical indicators (e.g., salinity, water level and currency), but also chemical indicators such as oxygen in this case study.
Wu, Z. X., et al.	2013	"Application of an integrated methodology for eutrophication assessment: a case study in the Bohai Sea." Chinese Journal of Oceanology and Limnology 31(5): 1064-1078.	5	Eutrophication assessment including both water quality indicators (causative factors) and ecological response indicators (effect factors) was investigated in *surface waters* (<10 m)of the Bohai Sea. DO was used together with other "water quality" parameters. The data processing method, such as the percentile-based approach and multi season use of monitoring data, all increase the likelihood that trophic status will be evaluated in the most useful way.

Table 2. *Review of oxygen indicator method used in the selected papers*

Author	Year	Method
Bejaoui, B., et al.	2016	Discrete sampling. |D%O2| represents the absolute value percentage deviation of the oxygen concentration from saturation conditions (in%)
Bonometto, A., et al.	2019	Discrete sampling. DO was converted to saturation percentage. DO was rated with a weighing factors of 0.15, assuming that its values depend primarily on benthic vegetation and phytoplankton production.
Brockmann, U., et al.	2018	ICES data. The assessment was performed according to the OSPAR guidance for the COMP.
Brown, C. A. & W. G. Nelson	2015	Continuous and discrete data. DO data used to generate logistic regression models LRM, which predict the probability of dissolved oxygen levels <6.5 mg l−1. Test explanatory variables: (1) water temperature, (2) water temperature and salinity, (3) density, and (4) water temperature, salinity, and in situ fluorescence. LRM are simple, provide the probability of an observation exceeding a water quality threshold due to ocean conditions based on water temperature and salinity at time of sampling.
Coffin, M. R. S., et al.	2018	Optical dissolved oxygen loggers. The frequency of measurements<4 mg/L plus those>10 mg/L was created to capture both low and high oxygen and termed 'eutrophic time'. 79 oxygen metrics were examined by PCA. Dissolved oxygen metrics separated into two orthogonal groups along PC1 and PC2 with metrics for low dissolved oxygen (e.g., time under 2 mg/L) loading to PC1, and metrics for high dissolved oxygen (e.g., time over 10 mg/L) loading most strongly to PC2.
Cosme, N., et al.	2015	No specific oxygen indicator.
Ferreira, J. G., et al.	2011	Dissolved oxygen. Monthly, or more frequent as appropriate and as possible especially for dynamic areas. 10th percentile concentration, spatial area of low concentrations
Fitzpatrick, J. J.	2009	A review of possible statistical measures used to assess model skill. No oxygen indicator. Prediction of hypoxia (e.g., dissolved oxygen concentrations less than 3 mg/L).

Fleming-Lehtinen, V., et al.	2015	ICES and BED data. Oxygen debt indicator (the cumulative lack of oxygen (annual oxygen debt) below halocline).
Foden, J., et al.	2011	Dissolved oxygen concentrations. Ospar assessment. % frequency of samples <4 mg l-1.
Garcia, P., et al.	2010	Discrete sampling. Dissolved oxygen. DO was converted to saturation percentage. Oxygen quality ratio (OxQR). OxQR =Oxp5/RC. Oxp5 is the %O2sat value of the percentile P5 in each sampling station, and RC is the value for the reference conditions. We established the boundaries between classes according to the method proposed by OSPAR (2003): the lower boundary of the high status class is a deviation of 50% from the RC level; the boundary between the high and the good status classes is again a deviation of 50%. These calculations correspond to the following values of the quality rations: RC = 1; high status class range between 1 and 0.83 and the good status class, between 0.83 and 0.67. The upper boundary of the moderate status class is therefore 0.67.
Gholizadeh, M. H., et al.	2016	DO, BOD and COD cannot be determined with a high level of confidence by remote sensing
Giordani, G., et al.	2009	Discrete sampling. DO was converted to saturation percentage. DO was rated with a weighing factors of 0.15, assuming that its values depend primarily on benthic vegetation and phytoplankton production. The QV assigned to DO (QVDO) increased from 0 to 100, spanning complete anoxia to 100–125% oxygen saturation. DO values higher than 125%, common in highly productive transitional ecosystems, were also considered critical. For oygen saturation greater than 125%, QVDO decreased with QVDO = 0 at 250%.
Greenwood, N., et al.	2019	Dissolved oxygen. Discrete sampling +7-day average buoy data + model data. Indicators followed the OSPAR harmonized criteria. See scheme in supplement: \\winfs-proj\data\proj\havgem\Mo-PROJEKTKATALOG\Uppdrag\HaV\2019-02-18_HELCOM_IN_EUT_2019\arb\Syreindikator\Litteratur\WebofScience_EndNote\GreenwoodEtAl_2019_supplement.docx
Greenwood, N., et al.	2010	Dissolved oxygen and oxygen saturation. Discrete sampling + high frequency measurements were made at

		the surface, mid water and on seabed landers (incl ADCP). A correlation-based principal components analysis (PCA) was applied to bottom data in order to investigate the relationship between the variables measured.
Hatzikos, E., et al.	2009	No specific oxygen indicator.
Iqbal, M. M., et al.	2018	Dissolved oxygen. Model data (incl validation data). Qi is the water quality rating (Qi = 100[(Oi - Ii)/(Pi - Ii)]) where Oi indicates an observed value of each parameter, Pi is the standard allowable value of each variable, and Ii is the ideal value of each parameter in a clean ecosystem. Li is not mentioned but seems to be the saturation value.
Kamyab-Talesh, F., et al.	2019	DO sat (%). SUPPORT VECTOR MACHINES were originally developed for pattern recognition. For designing the model, the measured data were used. National Sanitation Foundation Water Quality Index: Convert dissolved oxygen (%sat) to water quality index. Note: If dissolved oxygen is greater than 140%, the quality index equals 50.
Khalit, S. I., et al.	2017	Dissolved oxygen. Marine Water Quality Index. Quality rating (q) is calculated using the formula, qni = {[(Vactual – Videal) / (Vstandard – Videal)] * 100} See eg. NarayananEtAl_2015 https://www.researchgate.net/publication/311707629_Development_of_Integrated_Marine_Water_Quality_Index_-_A_GIS_Approach
Kong, X. Y., et al.	2018	Dissolved oxygen. Multimetric trophic index TRIX (TRIX=[log 10 (Chl- a * aD%O * TN * TP)+ k]/ m) . aD%O=oxygen as an absolute percentage deviation from saturation.

McQuatters-Gollop, A., et al.	2009	Indicators for which long time-series were available. Area of hypoxia or Bottom dissolved oxygen. Trends.
Stoicescu, S. T., et al.	2019	Dissolved oxygen. High resolution vertical profiles. Test oxygen debt value just below the halocline, “Oxygen consumption” and Area of hypoxia.
Tallar, R. Y. and J. P. Suen	2016	Dissolved oxygen. Three different WQI methods (NSF, RPI, and MDE) compared. Standardized subindices (C) were transformed and developed to have the same scale and the same upper and lower limits. **Table 7** Standardization of se Government Regulation No. 8 Parameter: DO Unit: mg/L *Standardization factor (Ci)* 100: ≥6 90: $5.5 \le x < 6$ 80: $5 \le x < 5.5$ 70: $4.5 \le x < 5$ 60: $4 \le x < 4.5$ 50: $3.5 \le x < 4$ 40: $3 \le x < 3.5$ 30: $2.5 \le x < 3$ 20: $2 \le x < 2.5$ 10: $1.5 \le x < 2$ 0: <1.5
Tugrul, S., et al.	2019	Dissolved oxygen. Four different classification tools (TRIX ([log 10 (Chl- a * aD%O * TN * TP)+ k]/ m), E.I. (combination of nutrients and chl-a), chl-a, HEAT (without oxygen debt)) were examined. Deviations from oxygen saturation (%) are discussed.
Wan, Y. S., et al.	2012	Dissolved oxygen. 3D model data (incl validation data). Hypoxic and anoxic conditions.
Wang, X., et al.	2016	Dissolved oxygen. 3D process-based models and data assimilation. Model validation.
Wu, Z. X., et al.	2013	Dissolved oxygen. Discrete sampling. Bottom DO threshold, criteria and ranges. The indicator scores are based on the assessment concentration value, the spatial coverage and frequency of occurrence of concentrations that are considered a problem (episodic, periodic, persistent), rather than only on concentration values of indicators. For the secondary (DO and HABs) ecological response, the level of expression value of each single indicator over the whole area was also obtained by summation of the expression values over all the salinity zones. The level of expression values of the secondary ecological

		response for the whole area was determined by choosing the higher of the two expression values to highlight the fully developed eutrophication symptom(s) (DO or HABs).

RESULTS/DISCUSSION

General overview of the literature study

This section summarizes the literature shown in Table 1. Dissolved oxygen is often used together with other parameters such as Chl *a* to determine eutrophication status and typically not as a single assessment criteria or as a single parameter in a statistical method or model framework. Models used for eutrophication status assessment range from simple statistical linear regression and multivariate models to more complex model frameworks with several parameters and complex mathematical equations in which several model parameters have to be assumed and/or guessed. Both for simple statistical methods and more complex models there is a need to discuss how natural variation in seasonality such as the temporal dynamics of primary production affects DO. We also need to keep in mind the effect of natural oceanographic dynamics such as upwelling or inflows that affects DO. Skill assessments of complex eutrophication models are, however, necessary to demonstrate that the models reproduce or capture some of the temporal or spatial patterns observed in the data. How do we discern natural dynamics from those caused by anthropogenic climate change leading to eutrophication? It is noteworthy that both simple statistical methods and model frameworks with several "water quality" parameters regularly outperforms those with single parameters, even though the variation for each parameter can be substantial.

Literature study from the oxygen indicator point of view

This section concludes the review of oxygen indicators used in the literature shown in Table 2. The basis of all indicators summarized in Fig.1 is based on the dissolved oxygen concentration (DO) or the oxygen consumption in water and the evaluations are based on some kind of critical thresholds.

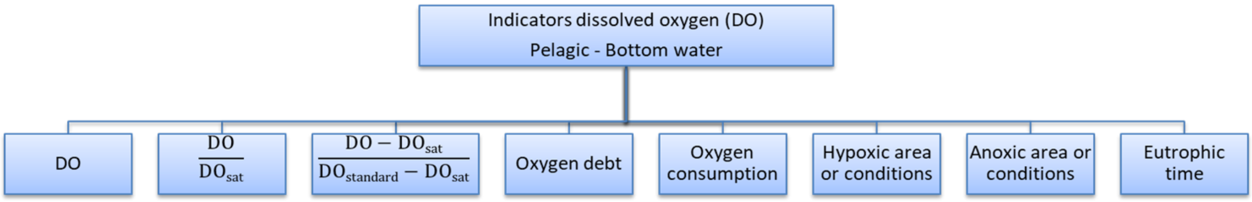


Figure 1. *Scheme of the oxygen indicators used or studied in the papers shown in Table 2. DO is dissolved oxygen.* DO_{sat} *is the oxygen saturation concentration.* $DO_{standard}$ *is the standard allowable value. Oxygen debt is the HELCOM indicator (the cumulative lack of oxygen [annual oxygen debt] below halocline) used for status evaluations in stagnant deep waters. Oxygen consumption is the decrease of DO caused by biologically driven oxidation processes. Hypoxia and anoxia are oxygen deficiency defined by certain low DO levels, e.g. 2 ml/l and 0 ml/l. Hypoxic/Anoxic area is the extension of hypoxic/anoxic bottom area. Eutrophic time is defined as the time (or frequency) of occurrence of concentrations/conditions that are considered a problem.*

The thresholds can be given as concentrations or in terms of discrete deviations from the actual oxygen saturation concentration (DO_{sat}) or compared to a given background (standard) deviation from the saturation ($DO_{standard}$- DO_{sat}). The literature cover examples where oxygen indicators are used both in shallow and deep areas, in surface and bottom waters as well as integrated vertically and horizontally. Oxygen consumption as an indicator was evaluated from high frequency oxygen profiling but showed problems with the impact from advection on changing oxygen concentrations. Eutrophic time is a concept used to evaluate the time a system is considered to have a problematic status as defined by some criteria or critical thresholds.

For most cases, except perhaps in the stagnant deep waters where the extent of hypoxic and anoxic conditions together with the oxygen debt indicator are used, an important issue is related to the differentiation between natural changes and eutrophication-related impacts. Another issue is related to the lack of temporal and/or spatial coverage in observations. To overcome these issues different modelling approaches, including e.g. mechanistic hydrodynamic and biogeochemical models and statistical models, are used as complementary tools to evaluate status and relate changes to certain forcing parameters where observations data are used to validate or support model simulations via data assimilations.

REFERENCES

All high-ranking literature, n=51 papers, is included below and the most relevant papers included in the analyses, n=27 papers, are marked with asterisk (*).

Albayrak, S., Balkis, N., Balkis, H., Zenetos, A., Kurun, A., Karhan, S. U., . . . Balci, M. (2010). Golden Horn Estuary: Description of the ecosystem and an attempt to assess its ecological quality status using various classification metrics. Mediterranean Marine Science, 11(2), 295-313. doi:10.12681/mms.78

*Bejaoui, B., Armi, Z., Ottaviani, E., Barelli, E., Gargouri-Ellouz, E., Cherif, R., . . . Aleya, L. (2016). Random Forest model and TRIX used in combination to assess and diagnose the trophic status of Bizerte Lagoon, southern Mediterranean. Ecological Indicators, 71, 293-301. doi:10.1016/j.ecolind.2016.07.010

*Bonometto, A., Giordani, G., Ponis, E., Facca, C., Brusa, R. B., Sfriso, A., & Viaroli, P. (2019). Assessing eutrophication in transitional waters: A performance analysis of the Transitional Water Quality Index (TWQI) under seasonal fluctuations. Estuarine Coastal and Shelf Science, 216, 218-228. doi:10.1016/j.ecss.2017.08.008

Braga, E. D., Chiozzini, V. G., & Berbel, G. B. B. (2018). Oligotrophic water conditions associated with organic matter regeneration support life and indicate pollution on the western side of Fernando de Noronha Island - NE, Brazil (3 degrees S). Brazilian Journal of Oceanography, 66(1), 73-90. doi:10.1590/s1679-87592018148306601

Brewer, P. G., & Hofmann, A. F. (2014). A Plea for Temperature in Descriptions of the Oceanic Oxygen Status. Oceanography, 27(1), 160-167. doi:10.5670/oceanog.2014.19

*Brockmann, U., Topcu, D., Schutt, M., & Leujak, W. (2018). Eutrophication assessment in the transit area German Bight (North Sea) 2006-2014-Stagnation and limitations. Marine Pollution Bulletin, 136, 68-78. doi:10.1016/j.marpolbul.2018.08.060

*Brown, C. A., & Nelson, W. G. (2015). A method to identify estuarine water quality exceedances associated with ocean conditions. Environmental Monitoring and Assessment, 187(3). doi:10.1007/s10661-015-4347-3

Brown, C. A., & Power, J. H. (2011). Historic and recent patterns of dissolved oxygen in the Yaquina Estuary (Oregon, USA): Importance of anthropogenic activities and oceanic conditions. Estuarine Coastal and Shelf Science, 92(3), 446-455. doi:10.1016/j.ecss.2011.01.018

Brugnoli, E., Muniz, P., Venturini, N., Brena, B., Rodriguez, A., & Garcia-Rodriguez, F. (2019). Assessing multimetric trophic state variability during an ENSO event in a large estuary (Rio de la Plata, South America). Regional Studies in Marine Science, 28. doi:10.1016/j.rsma.2019.100565

Cajaraville, M. P., Orive, E., Villate, F., Laza-Martinez, A., Uriarte, I., Garmendia, L., . . . Marigomez, I. (2016). Health status of the Bilbao estuary: A review of data from a multidisciplinary approach. Estuarine Coastal and Shelf Science, 179, 124-134. doi:10.1016/j.ecss.2016.01.013

Camarillo, M. K., Weissmann, G. A., Gulati, S., Herr, J., Sheeder, S., & Stringfellow, W. T. (2016). Pairing high-frequency data with a link-nodemodel tomanage dissolved oxygen impairment in a dredged estuary. Environmental Monitoring and Assessment, 188(8). doi:10.1007/s10661-016-5458-1

Cervantes-Martinez, A., Gutierrez-Aguirre, M. A., & Alvarez-Legorreta, T. (2015). Water quality indicators of coastal lagoons with toursim influence: Cozumel and Isla Mujeres, Quintana Roo, Mexico. Teoria Y Praxis, 11, 60-83. Retrieved from <Go to ISI>://WOS:000389035900004

Claussen, U., Zevenboom, W., Brockmann, U., Topcu, D., & Bot, P. (2009). Assessment of the eutrophication status of transitional, coastal and marine waters within OSPAR. Hydrobiologia, 629(1), 49-58. doi:10.1007/s10750-009-9763-3

*Coffin, M. R. S., Courtenay, S. C., Pater, C. C., & van den Heuvel, M. R. (2018). An empirical model using dissolved oxygen as an indicator for eutrophication at a regional scale. Marine Pollution Bulletin, 133, 261-270. doi:10.1016/j.marpolbul.2018.05.041

*Cosme, N., Koski, M., & Hauschild, M. Z. (2015). Exposure factors for marine eutrophication impacts assessment based on a mechanistic biological model. Ecological Modelling, 317, 50-63. doi:10.1016/j.ecolmodel.2015.09.005

Costa, C. R., Costa, M. F., Dantas, D. V., & Barletta, M. (2018). Interannual and Seasonal Variations in Estuarine Water Quality. Frontiers in Marine Science, 5. doi:10.3389/fmars.2018.00301

Costa, C. R., da Costa, M. F., Barletta, M., & Alves, L. H. B. (2017). Interannual water quality changes at the head of a tropical estuary. Environmental Monitoring and Assessment, 189(12). doi:10.1007/s10661-017-6343-2

*Ferreira, J. G., Andersen, J. H., Borja, A., Bricker, S. B., Camp, J., da Silva, M. C., . . . Claussen, U. (2011). Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive. Estuarine Coastal and Shelf Science, 93(2), 117-131. doi:10.1016/j.ecss.2011.03.014

*Fitzpatrick, J. J. (2009). Assessing skill of estuarine and coastal eutrophication models for water quality managers. Journal of Marine Systems, 76(1-2), 195-211. doi:10.1016/j.jmarsys.2008.05.018

*Fleming-Lehtinen, V., Andersen, J. H., Carstensen, J., Lysiak-Pastuszak, E., Murray, C., Pyhala, M., & Laamanen, M. (2015). Recent developments in assessment methodology reveal that the Baltic Sea eutrophication problem is expanding. Ecological Indicators, 48, 380-388. doi:10.1016/j.ecolind.2014.08.022

*Foden, J., Devlin, M. J., Mills, D. K., & Malcolm, S. J. (2011). Searching for undesirable disturbance: an application of the OSPAR eutrophication assessment method to marine waters of England and Wales. Biogeochemistry, 106(2), 157-175. doi:10.1007/s10533-010-9475-9

*Garcia, P., Santin, C., Colubi, A., & Gutierrez, L. M. (2010). Nutrient and oxygenation conditions in transitional and coastal waters: Proposing metrics for status assessment. Ecological Indicators, 10(6), 1184-1192. doi:10.1016/j.ecolind.2010.04.004

*Gholizadeh, M. H., Melesse, A. M., & Reddi, L. (2016). A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. Sensors, 16(8). doi:10.3390/s16081298

*Giordani, G., Zaldivar, J. M., & Viaroli, P. (2009). Simple tools for assessing water quality and trophic status in transitional water ecosystems. Ecological Indicators, 9(5), 982-991. doi:10.1016/j.ecolind.2008.11.007

*Greenwood, N., Devlin, M. J., Best, M., Fronkova, L., Graves, C. A., Milligan, A., . . . van Leeuwen, S. M. (2019). Utilizing Eutrophication Assessment Directives From Transitional to Marine Systems in the Thames Estuary and Liverpool Bay, UK. Frontiers in Marine Science, 6. doi:10.3389/fmars.2019.00116

*Greenwood, N., Parker, E. R., Fernand, L., Sivyer, D. B., Weston, K., Painting, S. J., . . . Laane, R. (2010). Detection of low bottom water oxygen concentrations in the North Sea; implications for monitoring and assessment of ecosystem health. Biogeosciences, 7(4), 1357-1373. doi:10.5194/bg-7-1357-2010

Harding, L. W., Mallonee, M. E., Perry, E. S., Miller, W. D., Adolf, J. E., Gallegos, C. L., & Paerl, H. W. (2019). Long-term trends, current status, and transitions of water quality in Chesapeake Bay. Scientific Reports, 9. doi:10.1038/s41598-019-43036-6

*Hatzikos, E., Hatonen, J., Bassiliades, N., Vlahavas, I., & Fournou, E. (2009). Applying adaptive prediction to sea-water quality measurements. Expert Systems with Applications, 36(3), 6773-6779. doi:10.1016/j.eswa.2008.08.051

*Iqbal, M. M., Shoaib, M., Farid, H. U., & Lee, J. L. (2018). Assessment of Water Quality Profile Using Numerical Modeling Approach in Major Climate Classes of Asia. International Journal of Environmental Research and Public Health, 15(10). doi:10.3390/ijerph15102258

Irby, I. D., Friedrichs, M. A. M., Friedrichs, C. T., Bever, A. J., Hood, R. R., Lanerolle, L. W. J., . . . Xia, M. (2016). Challenges associated with modeling low-oxygen waters in

Chesapeake Bay: a multiple model comparison. Biogeosciences, 13(7), 2011-2028. doi:10.5194/bg-13-2011-2016

Jiang, Q., He, J., Wu, J., Hu, X., Ye, G., & Christakos, G. (2019). Assessing the severe eutrophication status and spatial trend in the coastal waters of Zhejiang province (China). Limnology and Oceanography, 64(1), 3-17. doi:10.1002/lno.11013

*Kamyab-Talesh, F., Mousavi, S. F., Khaledian, M., Yousefi-Falakdehi, O., & Norouzi-Masir, M. (2019). Prediction of Water Quality Index by Support Vector Machine: a Case Study in the Sefidrud Basin, Northern Iran. Water Resources, 46(1), 112-116. doi:10.1134/s0097807819010056

*Khalit, S. I., Samsudin, M. S., Azid, A., Yunus, K., Zaudi, M. A., Sharip, Z., . . . Husin, T. M. (2017). A preliminary study of marine water quality status using principal component analysis at three selected mangrove estuaries in East Coast Peninsular Malaysia. Malaysian Journal of Fundamental and Applied Sciences, 13(4), 764-768. doi:10.11113/mjfas.v13n4.693

*Kong, X. Y., Che, X. W., Su, R. G., Zhang, C. S., Yao, Q. Z., & Shi, X. Y. (2018). A new technique for rapid assessment of eutrophication status of coastal waters using a support vector machine. Journal of Oceanology and Limnology, 36(2), 249-262. doi:10.1007/s00343-017-6224-0

*McQuatters-Gollop, A., Gilbert, A. J., Mee, L. D., Vermaat, J. E., Artioli, Y., Humborg, C., & Wulff, F. (2009). How well do ecosystem indicators communicate the effects of anthropogenic eutrophication? Estuarine Coastal and Shelf Science, 82(4), 583-596. doi:10.1016/j.ecss.2009.02.017

Mizerkowski, B. D., Machado, E. D., Brandini, N., Nazario, M. G., & Bonfim, K. V. (2012). ENVIRONMENTAL WATER QUALITY ASSESSMENT IN GUARATUBA BAY, STATE OF PARANA, SOUTHERN BRAZIL. Brazilian Journal of Oceanography, 60(2), 109-115. doi:10.1590/s1679-87592012000200001

Mokhova, O. N., Makedonskaya, I. Y., Novikova, Y. V., & Mel'nik, R. A. (2018). Environmental State of Water in the Blagopoluchiya Bay of Solovetskii Island According to Hydrochemical and Hydrobiological Parameters.

Russian Journal of General Chemistry, 88(13), 2967-2975. doi:10.1134/s1070363218130236

Narayanan, R. M., Sharmila, K. J., & Dharanirajan, K. (2016). Evaluation of marine water quality - a case study between cuddalore and pondicherry coast, India. Indian Journal of Geo-Marine Sciences, 45(4), 517-532. Retrieved from <Go to ISI>://WOS:000383219000007

Picart, S. S., Allen, J. I., Butenschon, M., Artioli, Y., de Mora, L., Wakelin, S., & Holt, J. (2015). What can ecosystem models tell us about the risk of eutrophication in the North Sea? Climatic Change, 132(1), 111-125. doi:10.1007/s10584-014-1071-x

Shumchenia, E. J., & King, J. W. (2010). Evaluation of sediment profile imagery as a tool for assessing water quality in Greenwich Bay, Rhode Island, USA. Ecological Indicators, 10(4), 818-825. doi:10.1016/j.ecolind.2010.01.003

Soetaert, K., & Middelburg, J. J. (2009). Modeling eutrophication and oligotrophication of shallow-water marine systems: the importance of sediments under stratified and well-mixed conditions. Hydrobiologia, 629(1), 239-254. doi:10.1007/s10750-009-9777-x

*Stoicescu, S. T., Lips, U., & Liblik, T. (2019). Assessment of Eutrophication Status Based on Sub-Surface Oxygen Conditions in the Gulf of Finland (Baltic Sea). Frontiers in Marine Science, 6. doi:10.3389/fmars.2019.00054

*Tallar, R. Y., & Suen, J. P. (2016). Aquaculture Water Quality Index: a low-cost index to accelerate aquaculture development in Indonesia. Aquaculture International, 24(1), 295-312. doi:10.1007/s10499-015-9926-3

Tian, X. G., Ju, M. T., Shao, C. F., & Fang, Z. L. (2011). Developing a new grey dynamic modeling system for evaluation of biology and pollution indicators of the marine environment in coastal areas. Ocean & Coastal Management, 54(10), 750-759. doi:10.1016/j.ocecoaman.2011.08.003

Topcu, D., Brockmann, U., & Claussen, U. (2009). Relationship between eutrophication reference conditions and boundary settings considering OSPAR recommendations and the Water Framework Directive-examples from the German Bight. Hydrobiologia, 629(1), 91-106. doi:10.1007/s10750-009-9778-9

*Tugrul, S., Ozhan, K., & Akcay, I. (2019). Assessment of trophic status of the northeastern Mediterranean coastal waters: eutrophication classification tools revisited. Environmental Science and Pollution Research, 26(15), 14742-14754. doi:10.1007/s11356-018-2529-6

*Wan, Y. S., Ji, Z. G., Shen, J., Hu, G. D., & Sun, D. T. (2012). Three dimensional water quality modeling of a shallow subtropical estuary. Marine Environmental Research, 82, 76-86. doi:10.1016/j.marenvres.2012.09.007

Wang, T. P., Yang, Z. Q., & Copping, A. (2015). A Modeling Study of the Potential Water Quality Impacts from In-Stream Tidal Energy Extraction. Estuaries and Coasts, 38, S173-S186. doi:10.1007/s12237-013-9718-9

*Wang, X., Zhang, J. J., & Babovic, V. (2016). Improving real-time forecasting of water quality indicators with combination of process-based models and data assimilation technique. Ecological Indicators, 66, 428-439. doi:10.1016/j.ecolind.2016.02.016

*Wu, Z. X., Yu, Z. M., Song, X. X., Yuan, Y. Q., Cao, X. H., & Liang, Y. B. (2013). Application of an integrated methodology for eutrophication assessment: a case study in the Bohai Sea. Chinese Journal of Oceanology and Limnology, 31(5), 1064-1078. doi:10.1007/s00343-013-2286-9

Additional references:

HELCOM 2013 Baltic Sea Environment Proceedings No. 133

HELCOM 2016 4-2Corr Shallow-Water Oxygen pre-core indicator

HELCOM 2018 Near-bottom Oxygen Concentrations in Shallow Waters

Wesslander 2015 Development of an oxygen consumption

Viktorsson 2016 SMHI uppdrag syreindikator