УДК 551.464.3:502.1

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ОЦЕНКА УРОВНЯ ЭВТРОФИКАЦИИ В МОРСКИХ ВОДАХ ЭСТОНИИ

Статья поступила в редакцию 01.02.2018, после доработки 25.04.2018.

Балтийское море находится под влиянием антропогенной эвтрофикации. Согласно требованиям «Плана действий по Балтийскому морю» и соответствующих директив Европейского Союза статус морских районов оценивается на основе индикаторов, показывающих, достигнут ли хороший экологический статус или нет. Основным результатом настоящей работы является то, что на основе данных национального мониторинга за 2011-2016 годы и использованных индикаторов, характеризующих концентрацию биогенных веществ, а также прямых и косвенных эффектов эвтрофикации, вся эстонская морская акватория находится под влиянием эвтрофикации. Общий статус в основном определяется концентрациями биогенных веществ или прямыми эффектами эвтрофикации (хлорофилл-а, биомасса фитопланктона и прозрачность воды). Нехорошее состояние в мелководном Моонзунд определяется в основном только общим фосфором, что указывает на необходимость анализа используемого порогового значения этого индикатора. Результаты оценки, полученные на основе предложенных порогов для минеральных биогенных веществ в прибрежных водах Эстонии, хорошо согласуются с результатами оценки в соседних частях открытого моря. Согласно предложенной схеме оценки достоверности, общий результат оценки в основном имеет среднюю достоверность, но достоверность высокая в открытой части Финского залива и прибрежных районах, где мониторинг осуществляется ежегодно. Средняя достоверность оценок состояния и высокая изменчивость результатов оценки в бассейнах, где мониторинг проводится всего один раз за шесть лет, указывают на необходимость увеличения частоты мониторинга.

Ключевые слова: эвтрофикация, Балтийское море, хороший экологический статус, морской мониторинг.

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ASSESSING THE EUTROPHICATION STATUS OF ESTONIAN MARINE WATERS

Received 01.02.2018, in final form 25.04.2018.

The Baltic Sea is a sea basin affected by human-induced eutrophication. As required by the Baltic Sea Action Plan and Marine Strategy Framework Directive, the status of the marine areas is assessed based on indicators showing whether the good environmental status (GES) is achieved or not. The main result of the present work is that based on the national monitoring data from 2011-2016 and used nutrients, direct effects and indirect effects indicators, the entire Estonian marine area is affected by eutrophication. The overall eutrophication status is mostly defined by nutrient concentrations in the water or direct effects of eutrophication (chlorophyll-a, phytoplankton biomass, and water transparency). The non-GES result in the shallow Moonsund area is mostly determined by total phosphorus (TP) suggesting that threshold values for TP should be studied in more detail. The assessment results derived based on the proposed dissolved inorganic nutrients thresholds for the Estonian coastal waters agree well with the adjacent offshore assessment results. According to the suggested confidence evaluation scheme, the overall assessment result has mostly intermediate confidence, but high confidence in the open Gulf of Finland and coastal water bodies covered with yearly monitoring. Intermediate confidence in status assessment and the noticed high variability in the assessment results in the basins with monitoring data from only one year, point to the need for an increase of monitoring frequency there.

Key words: eutrophication; Baltic Sea; good environmental status, marine monitoring.

Ссылка для цитирования: *Стойческу С.-Т., Липс У., Липс И.* Оценка уровня эвтрофикации в морских водах Эстонии // Фундаментальная и прикладная гидрофизика. 2018. Т. 11, № 2. С. 62—74.

For citation: *Stoicescu S.-T., Lips U., Lips I.* Assessing the eutrophication status of Estonian marine waters. *Fundamentalnaya i Prikladnaya Gidrofizika.* 2018, 11, 2, 62—74.

doi: 10.7868/S2073667318020053

1. Introduction. The Baltic Sea is a sea basin affected by human-induced eutrophication [1, 2]. Eutrophication is driven by excessive inputs of nutrients from rivers and atmosphere (mostly land-based sources) which lead to increased biological activity (phytoplankton, opportunistic macro algae), decreased water transparency, increased sedimentation of organic material, and therefore, oxygen depletion in the bottom layer and internal loading of phosphorus [3]. Nutrient loads to the Baltic Sea have been estimated as large as 840 773 t/a of nitrogen and 30 902 t/a of phosphorus based on data from 2012—2014 [4], and the loads have been mostly decreasing compared to the estimates from 1997—2003. An exception is in the Gulf of Riga where phosphorus input has increased 3.2 % between the two mentioned assessment periods [4].

Joint monitoring and assessment of the Baltic Sea, including assessment of eutrophication status, is carried out and coordinated by the Helsinki Commission (HELCOM) since 1979 [5]. After the adoption of the Baltic Sea Action Plan in 2007 [6] and Marine Strategy Framework Directive in 2008 (MSFD; [7]), the eutrophication status is assessed based on indicators of good environmental status (GES). A recent guidance document (Commission Decision, further on as COM DEC; [8]) for implementation of MSFD requires the assessment of European sea areas regarding human-induced eutrophication (Descriptor D5 of MSFD) using three primary criteria and five secondary criteria. COM DEC also defines criteria elements (indicators), principles how to define threshold values for GES, the scale of the assessment, and how to use indicators to characterize the status.

For the coastal waters, COM DEC guides to use the assessment methodology in accordance with the requirements of the Water Framework Directive (WFD; ([9]). It means, the assessment units should correspond to the defined coastal waterbodies, the indicators adopted by national legislation and/or internationally intercalibrated have to be used, and the good-moderate border of water quality classes have to be applied as threshold values. For the Estonian coastal waters, the indicators and water quality classes are fixed by Environmental minister regulation ([10, 11]). For the open sea areas, the assessment methods (indicators, assessment units, etc.) developed and adopted regionally, i.e., by HELCOM have to be used.

To get the final eutrophication assessment, aggregation of indicator-based assessment results is needed. The indicator results have to be aggregated to the criteria level and the criteria results to the descriptor level. COM DEC also defines that the aggregation methodology should be agreed upon at the regional level. Thus, an obvious choice would be to apply the HELCOM Eutrophication Assessment Tool (HEAT; [12]). The latest version of the HEAT (HEAT 3.0) compares estimated indicator values with a predefined threshold value, aggregates the indicator results to the criteria level using weighted averages and produces a final assessment together with the confidence of the assessment. In HEAT 3.0, the following three sub-groups of criteria are defined: the nutrients, direct effects and indirect effects of eutrophication [13].

In the frames of WFD, Estonia has developed a similar tool when assessing the ecological status, but here the emphasis is on the biological parameters while nutrients and water transparency are used as supportive indicators. So, the important difference between the MSFD and WFD assessments is that in MSFD the eutrophication input to the final assessment is greater compared to the supportive status of most of the eutrophication parameters in WFD based assessments.

Based on HELCOM methods, the confidence of the eutrophication assessment is ranked on a three-level scale and it is based on the confidence of the defined threshold value and the amount of data used for the status assessment. The confidence of the WFD based ecological status is also assessed on three levels and it is mostly dependent on data availability, but also the distance between the estimated indicator value and the threshold — if the obtained assessment result is close to the class boundary, then this would reduce the confidence [10]. These two confidence rating schemes seem to be oversimplified, and a more thorough approach is needed.

The aim of this work is to give an indicator-based assessment of the Estonian open sea and coastal areas regarding eutrophication effects using monitoring data from 2011—2016. Threshold values for some indicators are developed for assessment units where such borders were absent (e.g., winter nutrients DIN and DIP in coastal waters), and the confidence of the assessment results is discussed. We analyse the results in regard to the found differences in the assessment results in the adjacent assessment units, and discuss what would be the reasons of such differences and suggest possible improvement of the assessment methodology.

2. Material and methods

2.1. Indicators and assessment units. Indicators used in this work to assess the eutrophication status cover all primary criteria and two secondary criteria listed in the COM DEC [8]. Indicators belonging to primary criteria are under criterion D5C1 (nutrient concentrations), D5C2 (chlorophyll-a concentrations), and D5C5 (concentration of dissolved oxygen). The secondary criterion D5C4 describes the photic limit of the water column and criterion D5C8 the species composition and relative abundance of macrofaunal communities (table 1). The indicators under criterion D5C1 describe nutrient levels, D5C2 and D5C4 direct effects and D5C5 and D5C8 indirect effects of eutrophication.

The HELCOM oxygen debt indicator has been developed for deep basins where a permanent halocline is present which means all Estonian coastal areas and the Gulf of Riga cannot be assessed using this indicator. For coastal areas, we use zoobenthos index [14]. Furthermore, it has to be mentioned that HELCOM uses yearly average values for total nutrients while for the Estonian coastal waters summer average values are used.

Assessment units are defined in the coastal waters according to Estonian legislation [11] as coastal water bodies and off-shore areas according to the HELCOM division of open sea areas adopted by the HELCOM monitoring and assessment strategy [16] (fig. 1).

2.2. Threshold values. For coastal assessment units, we used threshold values corresponding to type-specific values of the border between good and moderate water quality classes set according to the WFD requirements by Estonian legislation [10]. Note that 16 waterbodies (we use 17 since one water body is divided into two) and six coastal water types are defined for Estonian coastal waters. For open sea areas, we used threshold values set by HELCOM [15]. In tables 2 and 3, the threshold values are displayed per assessment unit and indicator.

Table 1

Indicators used for the eutrophication assessment, their relevance in regard to COM DEC criteria, and references to the indicator documentation

Индикаторы, используемые для оценки эвтрофикации, их соотношение с критериями ЕС и ссылки на соответствующие документы

COM DEC criterion	Criterion relevance	Indicator	Estonian methods	HELCOM methods
D5C1 Nutrient concentrations	Primary	TN	Summer (June-September) mean value of the surface layer (0-10 m) [11]	Yearly average value of the surface layer [15]
		TP		
		DIN	Winter (December - February) mean value of the surface layer (thresholds are suggested in this paper)	Winter (December - February) mean value of the surface layer [15]
		DIP		
D5C2 Chlorophyll a concentrations	Primary	Chlorophyll-a	Summer median value of the surface layer [11]	Summer mean value of the surface layer [15]
		Phytoplankton biomass	Summer median value of the surface layer [11]	Summer median value of the surface layer (thresholds are suggested in this paper)
D5C4 Photic limit (transparency) of the water column	Secondary	Secchi depth	Summer mean value [11], [15]	
D5C5 Concentration of dissolved oxygen	Primary	Oxygen debt	n/a	Yearly mean value below the halocline [15]
D5C8 Species composition and relative abundance of macrofaunal communities	Secondary	Zoobenthos community index	Spring, early summer (May-June) index value [11]	n/a

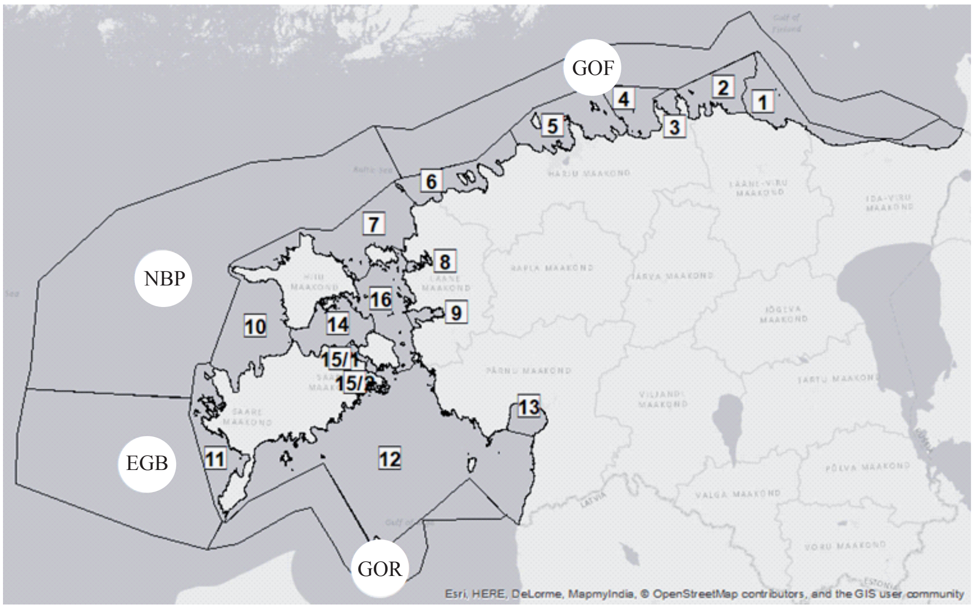

Fig. 1. Coastal and offshore division of Estonian marine waters. Coastal water bodies are marked with numbers and offshore sub-areas with abbreviations corresponding to the HELCOM division (borders only in Estonian waters are indicated). GOF means Gulf of Finland, NBP – northern Baltic Proper, EGB – eastern Gotland Basin, and GOR – Gulf of Riga.

Рис. 1. Разделение вод Эстонии на подбассейны в прибрежной и открытой частях моря. Прибрежные подбассейны обозначены цифрами, а открытые подбассейны – аббревиатурами в соответствии с районированием ХЕЛКОМ. GOF – Финский залив, NBP – северная часть Балтики, EGB – восточная часть Готландского бассейна и GOR – Рижский залив.

Thresholds were not defined or agreed yet for dissolved inorganic nutrients (DIN, DIP) in coastal areas, total nutrients (TN, TP) in Eastern Gotland Basin, and phytoplankton biomass in open sea areas.

Since ZKI and ODEBT may substitute each other as the indicators for indirect effects of eutrophication, we do not have an urgent need to develop their thresholds – at least one of them exists for all assessment units except GOR. However, we will suggest threshold values for phytoplankton biomass (FBIOM) in the open sea areas based on adjacent coastal waterbody thresholds and develop thresholds of dissolved inorganic nutrients (DIN, DIP) for coastal areas (see sub-chapter 3.1).

2.3. Eutrophication ratio and aggregation of the results. For the illustration and aggregation purposes, first, the eutrophication ratio (ER) is calculated for each indicator result using the HELCOM method where it is defined as the ratio between the indicator values calculated based on monitoring data and set threshold value [13]. Thus, the ER value 1 corresponds to the assessment results equal to the set threshold. To illustrate how far the assessment results are from the threshold, we use five classes: very good — ER <= 0.5; good — 1 <= ER > 0.5, moderate — 1.5 <= ER > 1, poor — 2 <= ER > 1.5, bad — ER > 2.

Aggregation of indicator results on the criteria level is made by weighted averaging of indicator ER values. In the present study, we used the weights which have been set in HELCOM HOLAS II process for the open sea indicators. These weights characterize the size of the impact of each indicator has in its criterion. Nutrients include DIN, DIP, TN and TP, and in most sub-basins and coastal areas, their weights were distributed evenly. An exception is made for GOR, where DIN and TN have both 17 % of the weight and DIP and TP 33 % both because phosphorus is considered the limiting nutrient in this basin [17]. Equal weights have been used for the indicators in coastal waters.

To give an overall eutrophication assessment, we grouped the criteria into three criteria groups: nutrients, direct effects of eutrophication and indirect effects of eutrophication. No aggregation of assessment results was needed for nutrients and indirect effects of eutrophication, since the indirect effects were described by oxygen conditions (D5C5) in open sea areas and by ZKI (D5C8) in coastal waterbodies. Direct effects of eutrophication include criterion D5C2 that combines indicators on chlorophyll-a and phytoplankton biomass and criterion D5C4 (includes Secchi depth indicator). The weights for direct effects criteria are divided evenly for most Baltic sub-basins and coastal areas, except for GOF and GOR, where photic depth criterion has 26 % and 20 %, respectively, and the residual percentage is assigned to criterion D5C2. When aggregating the results on the criteria-group level to the final eutrophication assessment the so-called "one-out-all-out principle" is used, i.e., the worst criteria group assessment is applied. When a criterion cannot be assessed, then the final assessment will be based on the available criteria, but it will have an effect on the confidence of the final assessment.

2.4. Data. Data used to estimate eutrophication status was gathered from Estonian environmental monitoring information system KESE [18]. After quality checking of the data, the number of measurements per indicator and sub-basin in the period of 2011—2016 ranged from 0 to 905 (details in Results section).

Already calculated values of zoobenthos index (ZKI), which were gathered from yearly monitoring reports [19], were used under criterion D5C8 for the coastal waters. In the national monitoring programme, oxygen is only measured in the surface layer and near the bottom, but to calculate the indicator value, we need profiles from the entire water column. Therefore, we used data from autonomous profilers, which were deployed in the GOF and NBP in 2014—2016 [20]. For GOF, we have data from 2014 and 2016 with 955 (gathered from 16.04—24.10) and 930 profiles (01.03—23.12), respectively. For NBP we have data from 2015 with 382 profiles gathered from 02.06 to 18.09.

2.5. Confidence. Supplementary information to the eutrophication assessment results is the confidence rating. HELCOM HEAT system evaluates the confidence based on the temporal coverage of monitoring data [21]. High confidence (value 1.0) is applied if every year of the assessment period for a certain assessment unit has >15 measurements. If there are >=5 and <=15 measurements, then the confidence is intermediate (value 0.5), and if <5 measurements, then the confidence is low (value 0.0).

In the present study, we also use other aspects of confidence, such as spatial representability, distance from the threshold, and methodological confidence suggested in HELCOM biodiversity assessment tool (BEAT) [22]. The spatial representability is high for an indicator and assessment unit pair if during the assessment period we had data from three or more stations. Intermediate confidence is given if data are from at least two stations and low if from only one station was available. The confidence based on the difference between the status assessment and the set threshold value is found using standard error of the used parameter. We assign high confidence if the difference between the indicator result and threshold divided by the standard error is >=2, intermediate if it was between <2 and >=1, and low if <1. High methodological confidence is assigned to an indicator which has data from monitoring conducted according to the HELCOM guidelines and the data quality is assured according to the HELCOM or other internationally accepted guidelines. If these requirements are partly met, then the methodological confidence is intermediate, and if the HELCOM and quality assurance guidelines are not followed, then the methodological confidence is low.

To aggregate the found four confidence components per indicator and assessment unit, we calculated the mean value. To get confidence results per criteria, we used the weighted average, where the weights are the same as in status assessment calculations. To get the final confidence rating, we found the mean of all three criteria groups. If the found mean was >=0.75, then the final result would be high, if it is >=0.5 and <0.75, then the result is intermediate, and if the mean was <0.5, then the final confidence rating would be low. In the cases, where we had a criterion with no indicators, the overall confidence was automatically set as low.

3. Results

3.1. Proposing indicator thresholds. To define threshold values for dissolved inorganic nutrient (DIN, DIP) in coastal areas, we used information on average salinity in the coastal water bodies and set nutrient thresholds in the adjacent freshwater bodies. This approach is similar to a study where thresholds for TN and TP in the North Sea were suggested [23]. The good-moderate border of TN (0.7 mg/l) and TP (0.06 mg/l) defined in Estonian legislation [10] for the river types contributing most to the freshwater discharge into the sea was taken as the threshold in freshwater. The problem here is that these values are set for total nutrients (TN, TP) measured in summer and we are looking for winter values for DIN and DIP in coastal waters. To convert TN and TP into DIN and DIP values we assumed that in nitrogen and phosphorus loading, DIN makes 74 % of TN and DIP makes 38 % of TP of the yearly average values as found by Korppoo et al. (2017) [24] for Finnish rivers. Based on these DIN/TN and DIP/TP ratios we get that the approximate DIN and DIP thresholds in the adjacent rivers should be 37.0 μmol/l and 0.74 μmol/l, respectively.

Based on coastal waterbody type average salinities (in psu: Type 1 — 5.09; 2 — 4.23; 3 — 6.10; 4 — 6.46; 5 — 5.42; 6 — 5.28), open sea basin average salinities (in psu: GOF west — 5.95; GOF east — 5.32; GOR — 5.71; NBP and EGB average — 6.95), and derived river and known open sea nutrient thresholds, we found approximate DIN and DIP thresholds for coastal water types (see in table 2). This scheme was applied to four water types, whereas it was slightly modified for the coastal types 3 and 5. In coastal water type 3, the average salinity was slightly higher than the open sea average salinity, and thus, in this coastal water type, the DIN and DIP thresholds were defined equal to those in the open sea area (GOF). In coastal water type 5, where at least two adjacent open sea-basins exist, the coastal DIN and DIP thresholds were defined as the average values found for the coastal water types 4 and 6.

We also had phytoplankton biomass (FBIOM) data from open sea areas, but no threshold values were available there. Therefore, we used adjacent coastal water body thresholds for open sea basins. For GOF, we used the threshold value of water type 3, for GOR type 6, and for NBP and EGB type 4.

3.2. Indicator results. The results of eutrophication assessment based on individual indicators are presented in Tables 2 and 3. National monitoring data on TN show that GES has been achieved in the coastal water bodies in the Gulf of Finland (water bodies 1 to 6) and the Moonsund (water body 16) and offshore areas of GOF and GOR (table 2). Based on TP indicator, only one coastal water body in the Gulf of Finland (2) is assessed as GES. All other assessment units had status as non-GES. From DIN and DIP results (table 2), it is seen that

Table 2

Indicator assessment results in the Estonian coastal and offshore assessment units with used thresholds and number of available data for total and inorganic nutrients. Results indicating GES are shown in bold

Результаты оценки индикаторов качества прибрежных и открытых частей вод Эстонии по общему количеству и неорганической части биогенных веществ с указанием пороговых значений и числа доступных данных. Результаты, указывающие «хорошее состояния среды» (the good environmental status, GES), выделены жирным шрифтом

Water-body	Type	TN µmol/l	TP µmol/l	DIN µmol/l	DIP µmol/l
		Threshold/ Result/ Data count	Threshold/ Result/ Data count	Threshold/ Result/ Data count	Threshold/ Result/ Data count
EE 1	1	**26.8/23.30/381**	0.84/0.92/385	5.2/8.72/39	0.60/1.21/37
EE 2	1	**26.8/20.82/36**	**0.84/0.52/36**	5.2/no data	0.60/no data
EE 3	3	**22.8/21.26/18**	0.72/1.16/18	3.8/no data	0.59/no data
EE 4	3	**22.8/19.71/85**	0.72/0.91/94	3.8/7.85/30	0.59/1.14/21
EE 5	3	**22.8/20.65/444**	0.72/0.90/441	3.8/6.86/42	0.59/0.98/42
EE 6	3	**22.8/19.67/72**	0.72/0.80/72	3.8/8.25/18	0.59/0.87/12
EE 7	4	18.3/19.94/23	0.42/0.80/23	5.1/8.60/9	0.30/0.67/6
EE 8	5	21.0/35.65/131	0.3/1.57/131	6.4/no data	0.37/no data
EE 9	5	21.0/26.46/5	0.3/0.65/5	6.4/no data	0.37/no data
EE 10	4	18.3/23.90/23	0.42/0.57/17	5.1/no data	0.30/no data
EE 11	4	18.3/23.31/18	0.42/0.61/11	5.1/no data	0.30/no data
EE 12	6	23.7/26.62/288	0.5/0.94/288	7.6/14.06/18	0.44/1.13/12
EE 13	2	29.2/32.32/251	0.67/1.12/251	13.4/37.57/10	0.50/1.63/12
EE 14	5	21.0/21.52/39	0.3/0.45/37	6.4/no data	0.37/no data
EE 15/1	5	21.0/ 25.06/18	0.3/ 1.02/18	6.4/no data	0.37/no data
EE 15/2	6	23.7/ 45.75/18	0.5/ 1.54/18	7.6/no data	0.44/no data
EE 16	5	**21.0/19.99/40**	0.3/0.82/40	6.4/16.00/4	0.37/0.92/4
GOF	n/a	**21.3/20.34/905**	0.55/1.06/891	3.8/6.85/113	0.59/1.05/92
GOR	n/a	**28.0/24.57/358**	0.7/1.16/358	5.2/9.96/53	0.41/1.02/41
NBP	n/a	16.2/18.90/521	0.38/0.93/522	2.9/4.85/68	0.25/0.79/58
EGB	n/a	-/18.06/189	-/0.93/189	2.6/3.71/30	0.29/0.63/24

all basins, where monitoring data were available, have not achieved GES. A total of nine coastal water bodies have not been assessed due to the lack of winter nutrient data. In regards to total nutrients, Eastern Gotland basin could not be assessed because threshold values for TN and TP are missing. In general, phosphorus indicators gave lower assessment results (greater relative distance to the threshold) than nitrogen indicators. The largest distance from the GES was found for TP in the Haapsalu Bay (water body 8) where the result exceeded the threshold more than five times. We also note that all TP indicator results are very bad in water type 5 assessment units where the lowest threshold is set – it is 0.3 µmol/l while in all other coastal types and offshore areas, higher thresholds are defined.

Based on the chlorophyll-a indicator, most of the water bodies have been assessed as non-GES except water body 3 in the Gulf of Finland and 15/2 in the Moonsund area. Concerning phytoplankton biomass, the results show that GES has not been achieved in most of the sub-basins except coastal areas 3 and 4 in the Gulf of Finland and 11 in the eastern Gotland Basin (table 3). Coastal water body 13 in the Gulf of Riga has no FBIOM assessment because this indicator is not used in this water body. Secchi results show that GES is achieved in coastal areas 3 and 4 in the Gulf of Finland, but not in all other assessment units (table 3). Thus,

Table 3

Indicator assessment results in the Estonian coastal (CS) and offshore (OS) assessment units with used thresholds and number of available data for chlorophyll-a, phytoplankton biomass, Secchi depth, ZKI, and oxygen debt results. Results indicating GES are shown in bold

Результаты оценки индикаторов качества прибрежных и открытых частей вод Эстонии на основе данных о концентрации хлорофилла-а, биомассе фитопланктона, прозрачности воды, индексе зообентоса (ZKI) и концентрации кислорода с указанием пороговых значений и числа доступных данных. Результаты, указывающие «хорошее состояния среды», выделены жирным шрифтом

Water-body	Type	CHLA µg/l	FBIOM mg/l	SECCHI m	ZKI for CS and ODEBT mg/l for OS
		Threshold/ Result/ Data count	Threshold/ Result/ Data count	Threshold/ Result/ Data count	Threshold/ Result/ Data count
EE 1	1	3.7/4.46/144	0.67/0.75/138	3.6/2.78/99	**0.5/0.595/54**
EE 2	1	3.7/5.23/18	0.67/0.87/18	3.6/3.55/30	**0.5/0.552/9**
EE 3	3	**2.7/2.65/18**	**0.42/0.36/20**	**4.5/4.54/16**	**0.5/0.600/9**
EE 4	3	2.7/3.35/42	**0.42/0.31/21**	**4.5/4.56/31**	**0.5/0.591/9**
EE 5	3	2.7/3.89/259	0.42/0.64/231	4.5/3.80/108	**0.5/0.500/54**
EE 6	3	2.7/3.98/46	0.42/0.85/36	4.5/3.56/32	0.5/0.450/18
EE 7	4	1.6/2.28/23	0.44/0.53/17	6.5/3.45/4	**0.5/0.620/9**
EE 8	5	2.4/7.04/100	0.15/0.38/109	4.9/1.70/82	0.5/0.496/45
EE 9	5	2.4/2.83/18	0.15/0.33/18	4.9/1.60/18	**0.5/0.704/9**
EE 10	4	1.6/4.15/18	0.44/0.70/17	6.5/5.40/20	**0.5/0.581/9**
EE 11	4	1.6/2.45/18	**0.44/0.32/17**	6.5/5.81/18	**0.5/0.589/9**
EE 12	6	3.0/4.48/102	0.33/0.50/86	4.2/2.61/85	**0.5/0.505/9**
EE 13	2	4.5/6.63/123	-/0.42/41	3.2/1.27/110	0.5/0.496/54
EE 14	5	2.4/2.57/18	0.15/0.24/18	4.9/4.41/28	**0.5/0.563/9**
EE 15/1	5	2.4/ 2.60/18	0.15/ 0.65/19	4.9/ 2.33/17	**0.5/0.593/9**
EE 15/2	6	**3.0/ 3.00/18**	0.33/ 2.40/18	4.2/ 1.03/10	**0.5/0.593/9**
EE 16	5	2.4/2.51/34	0.15/0.24/30	4.9/3.35/26	**0.5/0.532/9**
GOF	n/a	2/4.08/244	-/0.74/174	5.5/3.77/43	8.66/9.87/1885
GOR	n/a	2.7/4.21/55	-/0.83/29	5/3.48/25	n/a
NBP	n/a	1.7/3.80/103	-/0.63/69	7.1/4.59/21	8.66/9.40/382
EGB	n/a	1.9/3.40/22	-/0.63/23	7.6/4.59/10	8.66/no data

mostly the results on all three indicators on direct effects agree with each other pointing to a coastal sea area in the central Gulf of Finland with GES. All other assessments units mostly failed to achieve GES as the direct eutrophication effects are concerned.

When assessing the status based on the chlorophyll-a indicator, HELCOM uses arithmetic mean values (open sea areas) and Estonian system uses median values (coastal areas). To illustrate how this methodological difference could influence the assessment results, we found chlorophyll-a status assessment based on both the mean and median values (fig. 2). From the comparison, it is seen that in many sub-basins the status assessment gets a higher class when using median values instead of arithmetic mean values. This exercise is not fully correct since we compared the two results with the mixed thresholds (either arithmetic mean or median). But it demonstrates that harmonization of approaches at local and regional levels would be desirable to get compatible assessment results for the coastal and offshore waters.

ZKI results indicate that GES has been achieved in most of the coastal areas except basins 5, 6 in the Gulf of Finland, 8 in the Moonsund area and 13 in the Gulf of Riga. In contrast, oxygen debt assessment results show that GES has not been achieved in neither of the two basins assessed. Since both indicators (ZKI and ODEBT) are developed to assess indirect effects of eutrophication, the results reveal mostly GES in the coastal and non-GES in the offshore areas.

To indicate temporal changes in eutrophication status we analysed historical data on nutrients in the GOF open sea area and coastal areas 1 and 5. Data on total nutrients were available from 1993 to 2017 and inorganic nutrients mostly from 2005 to 2017. For TN, the yearly averages show that GES has been met for the last 6—7 years (fig. 3). Concerning TP in waterbody 1 we see that GES has been achieved since 2014, but the overall assessment for period 2011-2016 is still sub-GES with an ER result close to GES. TP values in the two coastal areas have been slightly above and below the threshold. In GOF, TP values have been sub-GES after 1997. Concerning inorganic nutrients, the average values are mostly sub-GES and the 5-year moving average indicates an increase in winter nutrient values, especially for DIP.

3.3. Eutrophication assessment and its confidence. Almost every basin had four nutrient indicators (DIN, DIP, TN, and TP), three direct effect indicators (CHLA, FBIOM, and SECCHI) and one indirect effect indicator (ZKI for coastal areas and ODEBT for open sea areas). In the assessment units where not all indicators could be calculated, we aggregated the results based on available indicators. For instance, in the coastal water body 13 (in the Gulf of Riga) FBIOM is not used and some coastal water bodies lacked DIN and DIP data. In the latter case, the criteria-group assessment was based only on TN and TP results.

Nutrient criteria-group level assessment reveals bad status in the Northern Baltic Proper and a few coastal water bodies in the Moonsund area, and GES only in one coastal water body (2) in the Gulf of Finland (fig. 4). Direct effects criteria-group level assessment shows that a few semi-closed water bodies in the Moonsund area had bad status, and only one water body (4) in the Gulf of Finland had good status. It is interesting that water body 4 which had good status regarding direct effects had poor status (thus a difference of two classes exists) regarding nutrient levels.

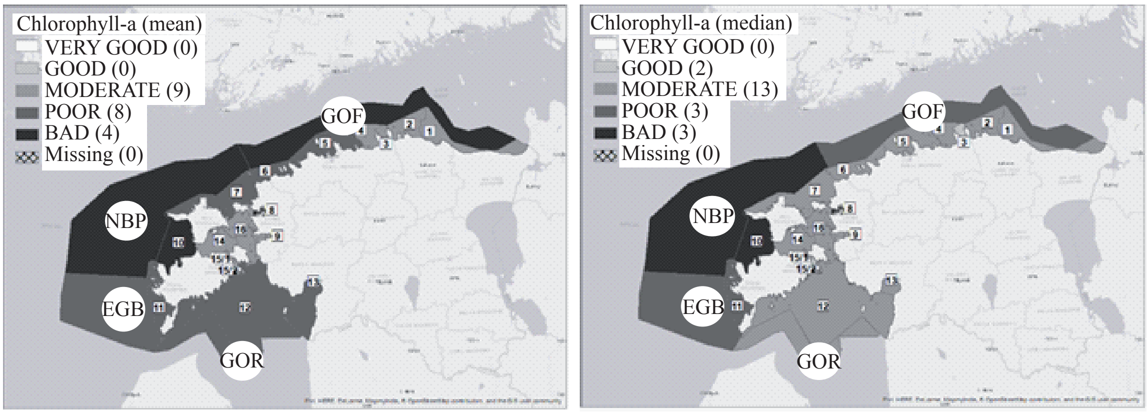

Fig. 2. Chlorophyll-a assessment results based on the arithmetic mean (left) and median (right) values. Five quality classes are shown as defined above in sub-section 2.3.

Рис. 2. Оценка качества вод по концентрации хлорофилла-а по средним арифметическим значениям (слева) и по медианным значениям (справа). Показаны пять классов качества вод, описанные в подразделе 2.3.

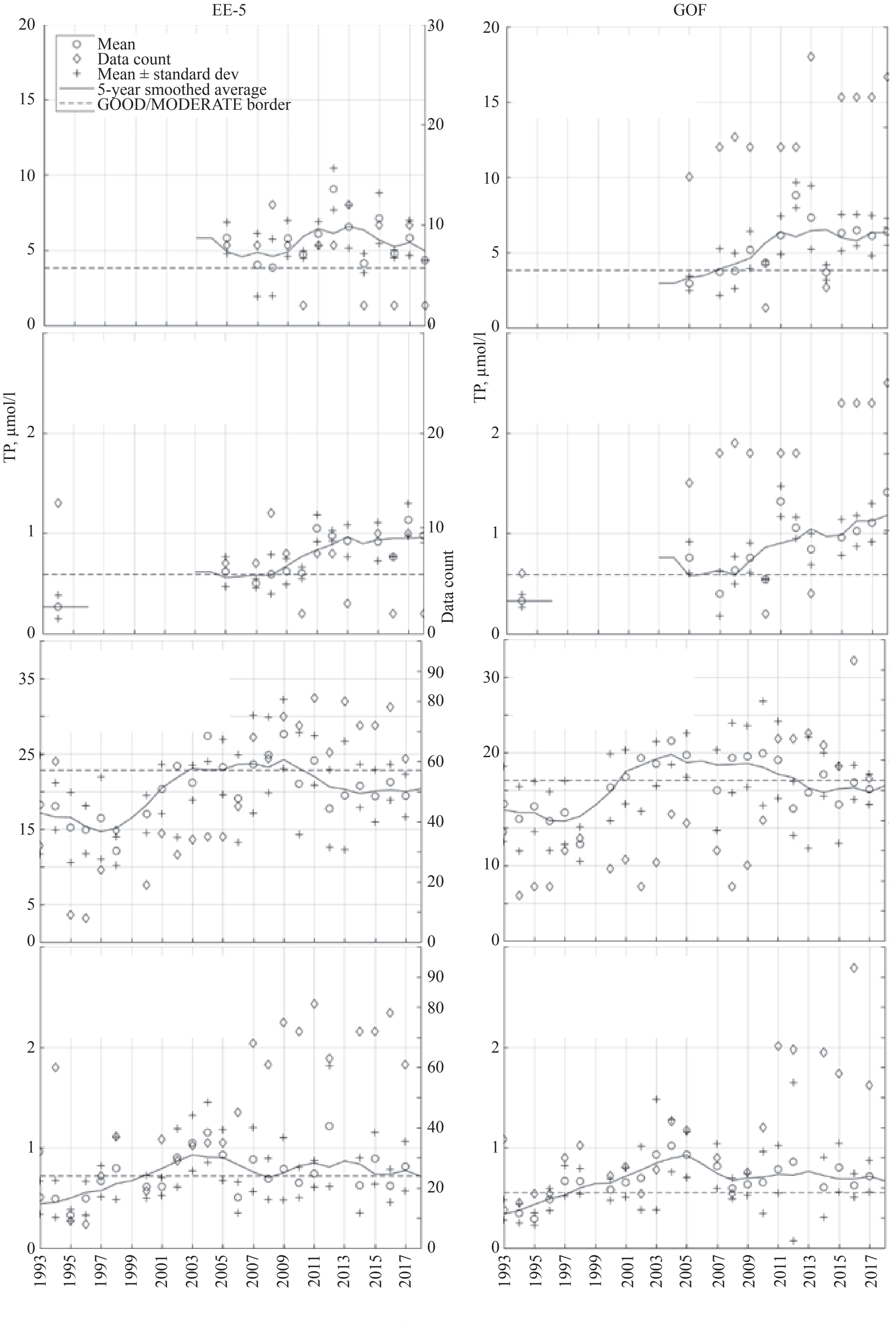

Fig. 3. Yearly mean values of DIN, DIP, TN, and TP in EE-5 and GOF.

Рис. 3. Средние годовые значения DIN, DIP, TN и TP в бассейнах EE-5 и GOF.

Since we assessed the indirect effects based only on one indicator, the criteria-group level assessment is equal to the indicator assessment. As highlighted above, the use of two different indicators led to the result

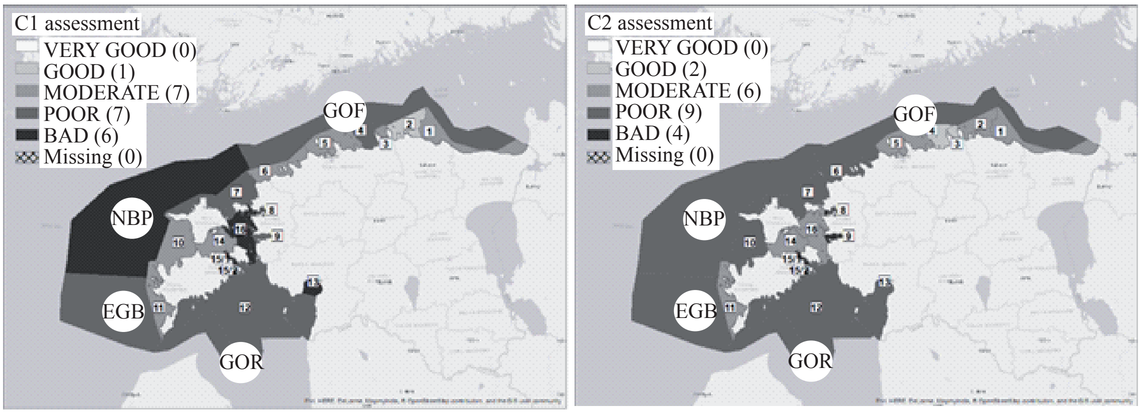

Fig. 4. Aggregated assessment results based on nutrient indicators (left) and direct effect indicators (right). Five quality classes are shown as defined above in sub-section 2.3.

Рис. 4. Обобщенные оценки качества вод на основе биогенных индикаторов (слева) и индикаторов прямых эффектов эвтрофикации (справа). Представлены пять классов качества вод, описанные в подразделе 2.3.

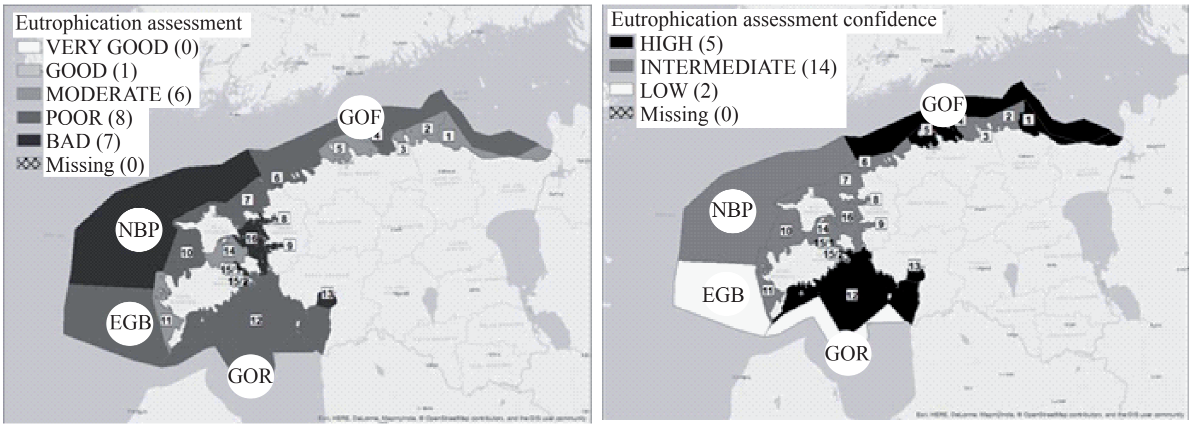

Fig. 5. Final eutrophication assessment (left) and its confidence (right). Quality classes are shown as defined above in sub-sections 2.3 and 2.5.

Рис. 5. Обобщенная оценка эвтрофикации (слева) и её достоверность (справа). Представлены классы качества вод, описанные в подразделах 2.3 и 2.5.

that regarding indirect effects of eutrophication, GES is achieved in most of the coastal water bodies (based on ZKI indicator) while not achieved in the offshore areas (ODEBT indicator). These results in the coastal waters differ from the assessment results on nutrients (aggregating indicators TN, TP, DIN, and DIP) and direct effects of eutrophication (aggregating indicators CHLA, FBIOM, and SECCHI) for most of the coastal areas (fig. 4).

Based on final eutrophication results it is seen that in the entire Estonian marine area GES has not been achieved (fig. 5). If we use the five-classes scheme, then bad status is revealed in coastal areas 8, 9, 15/1, 15/2 and 16 in the Moonsund area and 13 (Pärnu Bay) and in NBP (the only offshore area). Mostly the water bodies were in poor status except a few water bodies in the Gulf of Finland, one in the eastern Gotland Basin and one in the Moonsund area where moderate eutrophication status was revealed.

The confidence of eutrophication assessment results range from low to high, mostly being intermediate. Low confidence in GOR and EGB was revealed due to the lack of indirect effects criteria-group level assessments due to either no indicator or no data. The confidence was high in GOF and four coastal water bodies (1 and 5 in the Gulf of Finland and 12 and 13 in the Gulf of Riga) where the Estonian monitoring programme foresees measurements in every year.

4. Discussion and conclusions. The main outcome of the present indicator-based eutrophication assessment is that GES has not been achieved in the entire Estonian marine area (fig. 5). Since we used the “one-out-all-out” principle when aggregating the criteria-group results, at least one criteria-group gave non-GES result in every assessment unit. It is evident that the final results are based on either the nutrients or direct effects criteria-group assessment results because the indirect effects assessment results were almost always higher than the first two. The worst assessment result — bad status according to the 5-classes scheme or assessment value >2 (calculated by aggregating indicator ER-values) was found in the shallow coastal water bodies in the Moonsund area, the Pärnu Bay (water body 13) and the northern Baltic Proper. While the Pärnu Bay and the Haapsalu Bay (water body 8) were known earlier as the areas with poor status, this finding in regard to NBP and other water bodies in the Moonsund area has to be analysed in more detail.

The bad status of the Haapsalu Bay, which is an enclosed shallow water body, was revealed by indicators TP, CHLA, FBIOM, and SECCHI while the bad status of the Pärnu Bay, which is under influence of the Pärnu river discharge, by indicators DIN, DIP, and SECCHI. In coastal water body 9 (the Matsalu Bay in the Moonsund area) the bad result was due to the TP, FBIOM and SECCHI indicator results, which were assessed as bad. In water body 16 (Väinameri), the bad status was due to the bad status of both phosphorus indicators — DIP and TP, and DIN. In water bodies 15/1 and 15/2 (two parts of the Väike Väin), the bad status resulted from TP, FBIOM and SECCHI assessment results. Note that in all these results, total phosphorus was one or the only indicator pointing towards bad status. It has to be studied further whether this result could be scientifically justified or there is an issue with the set threshold value — officially it is 0.3 μmol/l, which is lower than in the adjacent coastal types of offshore basins.

We note that in most of the assessment units, TN indicator received higher results than TP indicator. If comparing TN/TP pair to DIN/DIP pair then it is seen that DIN/DIP assessment results are more uniform than TN/TP results. This finding might be one more reason to check the total phosphorus thresholds in the Estonian coastal waters. The other reason for bad TP assessment results might be related to the internal loading of phosphorus which is triggered by near-bottom hypoxia and/or anoxia [25, 3]. But this impact should be noticed mostly in the open sea areas, not in the coastal waters. For instance, higher DIP concentrations have been measured in the Gulf of Finland since 2011 (fig. 3) although the phosphorus load has been reduced [4]. We associate the observed increase of DIP and non-GES status with the internal phosphorus load and frequent collapses of stratification in the Gulf of Finland in winter [28] leading to the transport of phosphorus from the deep layer to the surface layer [29].

An interesting finding of the study was that the assessment results in some water bodies in the Gulf of Finland revealed good status based on two criteria-groups but moderate or poor status based on either nutrients or direct effects criteria-group. For instance, in water body 2, nutrients revealed good status, but direct effects showed moderate status. In contrast, in assessment unit 3, the direct and indirect effects criteria-groups revealed good status, but nutrients indicated moderate status (TN was good, but TP was poor). Since in the water bodies 1 (Narva Bay) and 5 (Tallinn Bay and adjacent coastal areas), the two criteria-group assessments coincided, we suggest that this diversity is mostly related to the monitoring frequency. In the Narva Bay and the Tallinn Bay, the monitoring is carried out every year while in the other coastal water bodies in the Gulf of Finland only once or twice during a 6-year period. This difference in monitoring programme is also reflected in the confidence evaluation scores – assessments results in water bodies 1 and 5 had high confidence while in 2—4 intermediate confidence. As shown in [26], the upwelling intensity and frequency reveal high inter-annual variability along the southern coast of the Gulf of Finland. Thus, the monitoring and assessment based only on one-year data set could be biased due to the natural variability caused by coastal upwelling events.

We also compared the assessment results found in this study with the eutrophication assessment results of HOLAS II [27]. Note that the available HOLAS II results were preliminary. NBP was assessed with poor status in HOLAS II and bad status in this study due to one class lower assessment result for TP, which changed the nutrients criteria-group and overall result to bad status compared to poor status in HOLAS II. Comparing DIN and DIP results in the open sea areas between HOLAS II and this study, we see that the results coincided in NBP, but the status based on DIP indicator was one class lower in this study in EGB, GOF and GOR while the status based on DIN was one class higher in GOF and GOR. Thus, we see that if only Estonian nutrient data are used the assessment results could change in the offshore areas.

Concerning the CHLA open sea mean value results and coastal area median value results, we see that NBP and the adjacent coastal area 10 and EGB with water body 11 have the same results, bad and poor, respectively. The bad assessment result in GOF (offshore area), on the other hand, is lower than in the adjacent coastal areas (1 to 6). The poor assessment result in GOR (offshore area) is also lower than the adjacent water body 12 result. Also waterbody 7, near NBP has a higher result than NBP. Thus, the coastal areas are mostly assessed with higher status than the open sea areas. This might be due to the set thresholds for the open sea areas being slightly lower or the same as coastal areas whereas the arithmetic mean values are used in the HELCOM offshore basins and median values in the Estonian coastal waters. Thus, also here more has to be done to harmonize the assessment schemes.

The confidence of assessment results in the open sea areas was assessed as low in EGB and GOR because there were no results for the indirect effects criteria group due to the lack of data and applicable indicator, respectively. The assessment confidence was high in GOF and intermediate in NBP since the number of stations for ODEBT indicator assessment was higher in GOF. Most of the coastal water bodies (except the Haapsalu Bay), where monitoring is conducted every year, were assessed with high confidence while the coastal areas, where monitoring is done once a year, were mostly assessed with intermediate confidence.

In conclusion, based on the national monitoring data from 2011—2016 and used nutrients, direct effects and indirect effects indicators, the entire Estonian marine area is affected by eutrophication. The overall eutrophication status is mostly defined by nutrient concentrations in the water or direct effects of eutrophication (chlorophyll-a, phytoplankton biomass, and water transparency). The non-GES result in the shallow Moonsund area is mostly determined by total phosphorus (TP) suggesting that threshold values for TP should be studied in more detail. The assessment results derived based on the proposed dissolved inorganic nutrients thresholds for the Estonian coastal waters agree well with the adjacent offshore assessment results. According to the suggested confidence evaluation scheme, the overall assessment result has mostly intermediate confidence, but high confidence in the open Gulf of Finland and in most coastal water bodies covered with yearly monitoring. Intermediate confidence in status assessment and the noticed high variability in the assessment results in the basins with monitoring data from only one year, point to the need for an increase of monitoring frequency there.

Most of the data used are collected in the frames of the Estonian national marine monitoring programme funded by the Ministry of the Environment. We acknowledge the work by the institutes carrying out the monitoring, especially the Estonian Marine Institute at the University of Tartu. The analysis was financially supported by the Estonian Ministry of the Environment and the institutional research funding IUT (IUT19-6) of the Estonian Ministry of Education and Research.

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