Response of submerged aquatic vegetation to eutrophication-related environment descriptors in coastal waters of the NE Baltic Sea

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Abstract. A national water quality classification system for surface waters based on type-specific reference conditions that fulfils the EU WFD requirements was established in Estonia in early 2007. The main objective of the current study was to test the Submerged Aquatic Vegetation (SAV) indicators included in the Estonian national assessment scheme against most commonly used parameters applied to describe the eutrophication situation. The aim was to detect possible regional differences in indicator response and to contribute to further development of those indicators. Depth distribution of phytobenthos, depth distribution of *Fucus vesiculosus*, and proportion of perennial plant species are currently used as SAV-related water quality indicators in the Estonian national system. All three indicators showed the strongest correlation with water transparency. The Southeastern Gulf of Finland was the water type showing in most cases the strongest relationship between eutrophication variables and the three tested SAV indicators. The performance between the tested variables was poorest in Pärnu Bay and the Väinameri area. Revision of the used indicator system is needed in these areas.

Key words: submerged aquatic vegetation, water quality assessment, Water Framework Directive, eutrophication, environmental variables.

INTRODUCTION

Aquatic macrophytes play a major structural and functional role in coastal ecosystems all over the world. They have an indicator role in the assessment of coastal water quality. According to the European Water Framework Directive (WFD) requirements, a water quality assessment system based on biological quality elements is to be established in all Member States (Anonymous, 2000). In this system the ecological state of the coastal water bodies should be assessed through three biological quality elements: phytoplankton, submerged aquatic vegetation (SAV), and zoobenthos.

Increasing eutrophication influences different aspects of SAV, of which decrease of biodiversity, increase in vegetation depth penetration, and substitution of perennial species by filamentous, short-living algae are well documented (Kotta et al., 2008). Due to the interactive effect of eutrophication and other physico-

chemico-biological factors (e.g. salinity, substrate composition, exposure, species competition), indicators that would fulfil the requirements of the WFD are not easy to establish. The developed biological indicators are expected to reflect in a sufficient way the effects of stressors of anthropogenic origin. Currently certain variability exists between assessment methods of Member States. Six out of the eight EU Member States around the Baltic Sea use depth distribution of selected species as a whole or part of the method (e.g. Krause-Jensen et al., 2005; Schories et al., 2009). Also the proportion of opportunistic or perennial algae, total cover and coverage or biomass of selected species are used (Krause-Jensen et al., 2007; Steinhardt et al., 2009).

Increased nutrient levels reduce macrophyte diversity and the biomass of perennial species and increase the biomass of ephemeral species (Coops et al., 2007). However, evaluation of the ecological status is often a difficult task because of spatial and temporal variability in communities. High nutrient concentrations in the water column do not necessarily indicate highly eutrophic conditions (Cloern, 2001). One of the reliable signals of increasing eutrophication is the replacement of late successional, perennial seaweeds with opportunistic species (Ofranidis et al., 2001 and references therein). Opportunistic macroalgae are generally favoured by short- or long-term high nutrient concentrations (Duarte, 1995). The ratio of the annual and perennial species expresses usually the stability of the environment and can be therefore used for the indication of the anthropogenic stress, for example, through addition of nutrients (Kautsky, 1988; Kautsky et al., 1999).

As SAV requires light for photosynthesis, its growth and depth penetration are directly related to light availability. Most of the studies on maximum depth penetration are concerned with perennial habitat forming species such as *Fucus vesiculosus* (Bäck & Ruuskanen, 2000; Torn et al., 2006) or seagrass meadows (Duarte, 1991; Nielsen et al., 2002; Krause-Jensen et al., 2005). However, degradation of submerged vegetation is indicated by the decrease in the depth distribution of all macrophytes (Selig et al., 2007). The best relationship between depth limits and water quality has been developed for the algal community as a whole. Depth limits of individual algal species are highly area-specific indicators (Kuuppo et al., 2006). For example, the maximum depth limits of *Fucus vesiculosus* correlate with Secchi depth only in the central Baltic Sea, but there is a very weak relationship at the entrance of the Baltic Sea (Torn et al., 2006). Therefore the assessment systems that include depth distributions of individual algal species should be tested and applied only at local scale.

A national water quality classification system for surface waters based on type-specific reference conditions that fulfils the requirements of the EU WFD was established in Estonia at the beginning of 2007. The main objective of the current study was to test the SAV indicators used in the Estonian national assessment scheme against the most common parameters used to describe the eutrophication situation, to detect possible regional differences in indicator response, and to contribute to further development of such indicators.

MATERIALS AND METHODS

The Estonian coastline has a very diverse structure and is influenced by the waters of several sea basins. The salinity of the Estonian coastal waters varies from 3.3 in the Gulf of Finland to 7.3 in the open sea areas along the shores of western Estonia. The coastal sea area is divided into six national types (Fig. 1). The coastal water types are distinguished on the basis of hydromorphological conditions such as salinity, depth, exposure to waves, mixing conditions, water residence time, dominating substratum, and duration of ice cover (Table 1).

Data for the analyses were collected from 65 transects in July or August from 1995 to 2009 (Fig. 1). Half of the transects were visited more often than once.
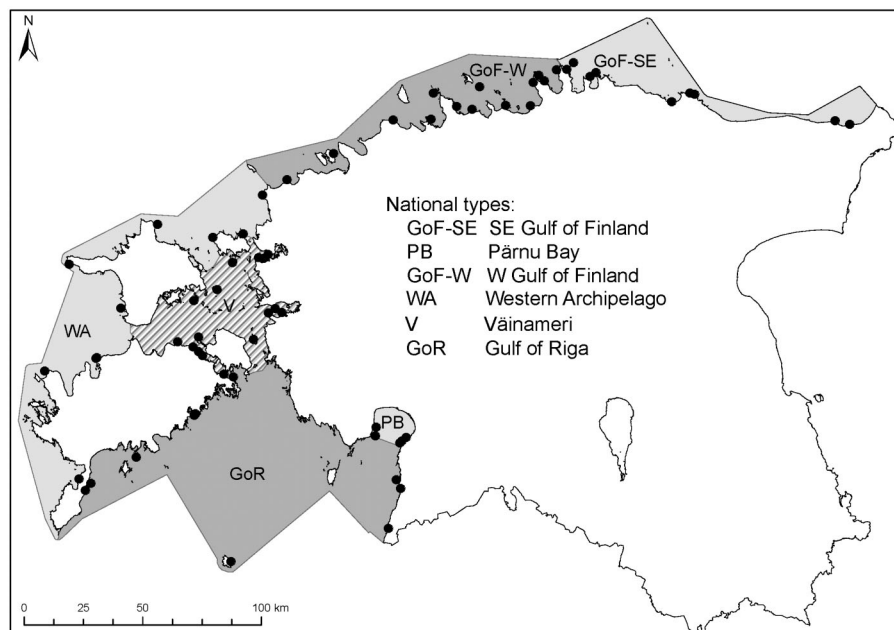

Fig. 1. Location of transects and national water types in the Estonian coastal area.

Table 1. Main characteristics of Estonian national types of coastal waters (Lips, 2005)

National type	Abbreviation	Description
Southeastern Gulf of Finland	GoF-SE	Oligohaline, exposed
Pärnu Bay	PB	Oligohaline, moderately exposed
Western Gulf of Finland	GoF-W	Mesohaline, deep, exposed
Western Archipelago	WA	Mesohaline, shallow, exposed
Väinameri	V	Mesohaline, shallow, sheltered, mixed
Gulf of Riga	GoR	Mesohaline, shallow, sheltered, seasonally mixed

The Estonian monitoring method is based on the HELCOM COMBINE guide-lines (www.helcom.fi). Monitoring is carried out along an imaginary transect line placed perpendicular to the shoreline from a predetermined starting point. Observations are carried out once inside a 1 m depth interval to the deepest limit of vegetation. When the deepest limit is reached, possible occurrence of vegetation deeper is checked by a 'drop' underwater video camera. A continuous transect line, often suggested for observations along Scandinavian rocky shores, is not used because of the small slope and the resulting length of transects.

Biomass samples are obtained from each different community type along the transect. Depending on the length of the transect, biomass samples are taken from 5–7 depths. Quantitative biomass samples are always taken in three replicates of 20 cm × 20 cm frames. Samples are stored in a deep freezer and later sorted in a laboratory. Then the dry weights of species are determined. Based on biomass data the proportion of annual and perennial plant species is calculated.

In Estonia three SAV-related metrics are used in the water quality classifi-cation system: (1) depth distribution of phytobenthos, (2) depth distribution of *Fucus vesiculosus*, and (3) proportion of perennial plant species. To determine the depth distribution of phytobenthos, the deepest occurrence of a single attached plant specimen is obtained by a scuba-diver or by a 'drop' underwater video camera. To determine the maximum depth distribution of *Fucus vesiculosus*, the deepest occurrence of single plant specimens is determined by a scuba-diver on the same monitoring transect. The proportions of perennial plant species are calculated based on dry biomass (Torn & Martin, 2011). Because of the scarcity of suitable substrates, the *Fucus* depth limit is not used in Pärnu Bay. The Väinameri area is too shallow to use maximum depth distribution.

For the above-mentioned metrics type-specific reference conditions were defined using a combination of historical data and expert judgement as a method. For some types a modelling approach was used, based on data from recent monitoring surveys and established functional relationships with pressure variables (nutrient concentrations, Secchi depth, etc.). This method was applied to model the reference conditions of SAV metrics on the basis of already established or estimated reference conditions of pressure variables (Torn & Martin, 2011). Type-specific reference values are presented in Table 2.

Table 2. Reference values of Estonian national types of coastal waters (for abbreviations see Table 1)

Type	Vegetation depth, m	*Fucus* depth, m	Perennials, %
GoF-SE	10	5	85
PB	5	–	60
GoF-W	15	7	90
WA	15	7	90
V	–	7	70
GoR	12	5	80

According to the WFD requirements, the ecological status of surface waters should be expressed as Ecological Quality Ratio (EQR). The EQR is the ratio of the actual level of a biological indicator and the reference value of the metrics. For the calculation of the Estonian Phytobenthos Index (EPI) the average of standardized EQRs of the three above-mentioned metrics is used.

The data on water transparency and chlorophyll *a* (chl *a*) concentration were extracted from the monitoring database of the Estonian Marine Institute. Measurements were performed at water chemistry monitoring stations neighbouring the vegetation sites and representing the period May–September of the same year as the vegetation data were collected. The data on the annual point sources and riverine loads of total N and total P to the coastal water bodies in 1995–2009 were obtained from the Estonian Ministry of the Environment. These data represent a proxy of the inter-annual variability in the amount of nutrients reaching the stations.

Pearson correlations between the pressure indices and biological indicators were computed (StatSoft, 2010). The relationships were established in two scales: on the level of all data and on coastal water type level with reference conditions determined type specifically.

RESULTS

Diversity of environmental conditions in coastal sea areas and SAV indicator values

The average chl *a* values in the Estonian coastal sea in 1995–2009 were the highest in Pärnu Bay (Table 3). Water transparency was the greatest in the exposed areas of the Gulf of Finland and in the outer Western Archipelago. The average values of point sources of total N and P were the highest in the Western Gulf of Finland. The highest riverine loads to the coastal water bodies were carried by the Narva River (SE Gulf of Finland) and the Pärnu River (Pärnu Bay).

Phytobenthos depth penetration was the highest (maximum 15 m) in the Western Archipelago. In Pärnu Bay only depths down to 4.8 m were colonized by SAV (Fig. 2). The depth limit of *Fucus vesiculosus* did not exceed 6 m in the Väinameri

Table 3. Descriptive statistics (average values) of environmental descriptors of Estonian national types of coastal waters. For abbreviations see Table 1

	Unit	GoF-SE	PB	GoF-W	WA	V	GoR
No. observ.		33	21	33	26	33	23
Chl *a*	mg m^{-3}	3.81	4.24	3.59	2.56	2.00	2.72
Transparency	m	3.86	1.85	4.92	6.01	2.98	3.64
Point N$_{tot}$	t y^{-1} km^{-2}	115.12	21.84	420.81	0.41	1.84	37.58
Point P$_{tot}$	t y^{-1} km^{-2}	5.30	4.27	30.44	0.10	0.17	6.14
River N$_{tot}$	t y^{-1} km^{-2}	2929.23	4907.85	1947.40	622.07	550.34	1104.83
River P$_{tot}$	t y^{-1} km^{-2}	113.85	119.90	35.45	20.91	13.16	43.52

area and showed generally higher values in the Western Archipelago (Fig. 2). In general the biomass ratios of perennial species (over 80%) were the highest in the Western and Southeastern Gulf of Finland (Fig. 2).
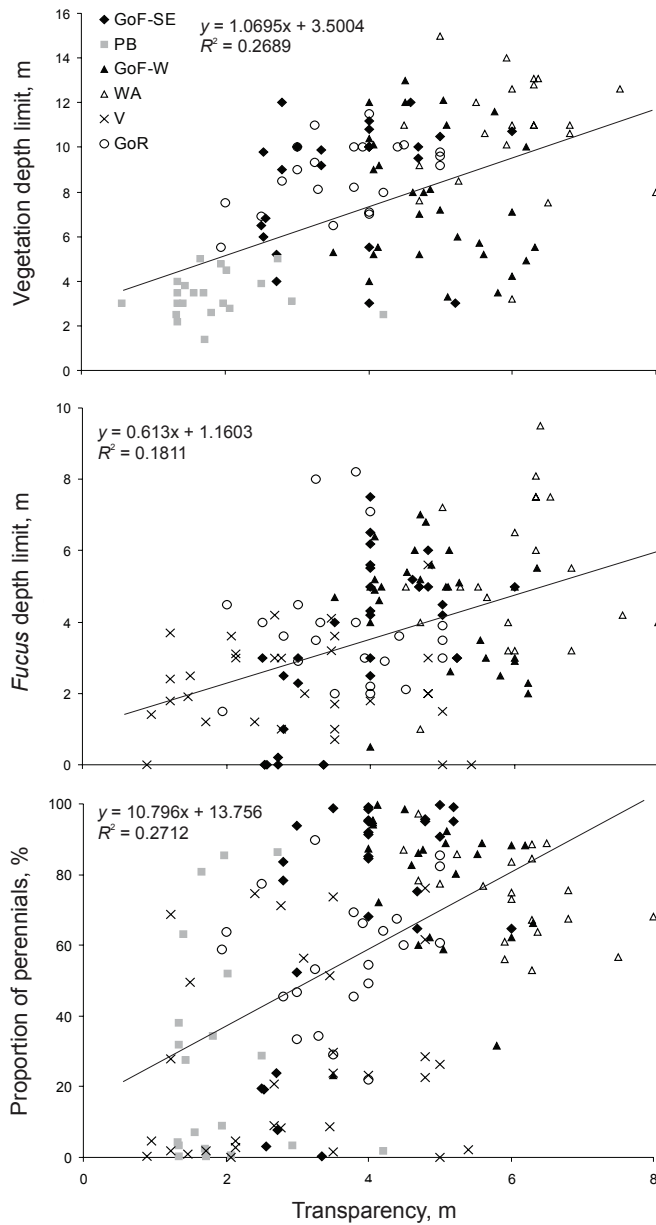

Fig. 2. Relations between SAV indicators and transparency (Secchi depth) from the Estonian coastal sea. Data from six national water types are shown. Regression lines are drawn to cover the whole data set.

SAV indicators in relation to environmental variables

The correlations between SAV indicators and selected eutrophication variables are shown in Table 4. This table also highlights the relationships on type level.

All three phytobenthos indicators correlated best with water transparency (Table 4). Depth limit of vegetation significantly correlated with riverine nutrient load when all data were pooled together.

Table 4. Results of Pearson correlation analysis between SAV indicators and selected eutrophication variables. Statistically significant relationships ($p < 0.05$) are in bold

Type*	Indicator	Chl a	Transparency	Point N_{tot}	Point P_{tot}	River N_{tot}	River P_{tot}
All	Vegetation depth limit	**−0.26**	**0.52**	**−0.23**	−0.18	**−0.52**	**−0.39**
	Fucus depth limit	0.02	**0.43**	−0.12	−0.07	**−0.33**	**−0.37**
	Proportion of perennials	0.04	**0.52**	**0.20**	0.16	**−0.22**	**−0.19**
GoF-SE	Vegetation depth limit	**−0.45**	0.20	**−0.73**	**−0.42**	−0.36	**−0.58**
	Fucus depth limit	**−0.39**	**0.66**	**−0.46**	**−0.68**	**−0.76**	**−0.77**
	Proportion of perennials	**−0.63**	**0.59**	−0.11	−0.32	**−0.47**	**−0.53**
PB	Vegetation depth limit	−0.10	0.06	0.37	0.17	−0.38	−0.28
	Proportion of perennials	−0.02	−0.03	0.08	−0.07	−0.31	−0.32
GoF-W	Vegetation depth limit	0.24	−0.23	−0.18	−0.09	−0.16	−0.11
	Fucus depth limit	0.20	−0.37	**−0.46**	−0.36	**−0.36**	**−0.37**
	Proportion of perennials	**0.39**	−0.08	0.07	0.05	**−0.44**	**−0.40**
WA	Vegetation depth limit	**0.45**	0.01	**−0.74**	**−0.68**	−0.05	−0.04
	Fucus depth limit	0.19	0.16	**−0.41**	−0.29	**−0.44**	**−0.53**
	Proportion of perennials	0.28	**−0.49**	0.19	0.07	0.24	0.22
V	*Fucus* depth limit	−0.20	−0.04	0.00	−0.33	−0.07	−0.09
	Proportion of perennials	−0.11	0.17	0.07	−0.01	−0.15	−0.12
GoR	Vegetation depth limit	**−0.58**	**0.46**	−0.03	0.21	−0.34	−0.39
	Fucus depth limit	−0.01	−0.05	0.06	0.00	−0.32	−0.23
	Proportion of perennials	0.03	0.22	−0.11	−0.15	0.12	0.05

* For abbreviations see Table 1.

Relationships between eutrophication variables and the three tested SAV indicators were established in most cases in the Southeastern Gulf of Finland (Table 4). No correlations between the tested variables were detected for Pärnu Bay and the Väinameri area. In other areas the depth distribution of *Fucus* and the proportion of perennial species were negatively influenced by nutrient loads. In the Gulf of Riga vegetation penetration was related with water transparency and chl *a* concentration.

Ecological Quality Ratio in relation to environmental variables

The correlations between the EQR (on metric level and average) and the selected eutrophication variables in different water types are shown in Table 5. In the Southeastern Gulf of Finland all variables showed statistically significant correlations

Table 5. Results of Pearson correlation analysis between SAV indicators' EQR values and selected eutrophication variables. Statistically significant relationships ($p < 0.05$) are in bold

Type*	Indicator	Chl a	Trans-parency	Point N_{tot}	Point P_{tot}	River N_{tot}	River P_{tot}
GoF-SE	EQR$_{Vegetation\ depth}$	**−0.44**	0.17	**−0.75**	**−0.44**	−0.36	**−0.58**
	EQR$_{Fucus\ depth}$	**−0.47**	**0.73**	**−0.44**	**−0.67**	**−0.78**	**−0.79**
	EQR$_{Perennials\ \%}$	**−0.65**	**0.60**	−0.17	−0.35	**−0.50**	**−0.57**
	EQR$_{EPI}$	**−0.60**	**0.69**	**−0.50**	**−0.61**	**−0.72**	**−0.80**
PB	EQR$_{Vegetation\ depth}$	−0.10	0.05	0.37	0.16	−0.36	−0.28
	EQR$_{Perennials\ \%}$	0.00	−0.09	0.08	−0.06	−0.30	−0.31
	EQR$_{EPI}$	−0.04	−0.06	0.20	0.04	−0.37	−0.34
GoF-W	EQR$_{Vegetation\ depth}$	0.23	−0.22	−0.16	−0.08	−0.15	−0.10
	EQR$_{Fucus\ depth}$	0.16	−0.35	**−0.50**	−0.41	**−0.42**	**−0.42**
	EQR$_{Perennials\ \%}$	0.33	−0.05	0.07	0.04	**−0.43**	**−0.41**
	EQR$_{EPI}$	0.33	−0.25	**−0.44**	−0.35	**−0.46**	**−0.44**
WA	EQR$_{Vegetation\ depth}$	**0.45**	0.01	**−0.72**	**−0.65**	−0.05	−0.04
	EQR$_{Fucus\ depth}$	0.24	0.15	**−0.42**	−0.30	**−0.43**	**−0.49**
	EQR$_{Perennials\ \%}$	0.31	−0.41	0.19	0.08	0.27	0.24
	EQR$_{EPI}$	**0.50**	0.00	**−0.46**	**−0.42**	−0.15	−0.20
V	EQR$_{Fucus\ depth}$	−0.24	−0.08	0.03	**−0.38**	−0.09	−0.10
	EQR$_{Perennials\ \%}$	−0.18	0.09	−0.09	−0.11	−0.18	−0.17
	EQR$_{EPI}$	−0.24	0.04	−0.06	−0.24	−0.17	−0.17
GoR	EQR$_{Vegetation\ depth}$	**−0.59**	**0.44**	−0.04	0.20	−0.32	−0.38
	EQR$_{Fucus\ depth}$	0.29	0.00	−0.14	−0.08	−0.34	−0.25
	EQR$_{Perennials\ \%}$	0.07	0.21	−0.13	−0.16	0.16	0.11
	EQR$_{EPI}$	0.00	0.29	−0.18	−0.08	−0.22	−0.22

* For abbreviations see Table 1.

with the final EQR, which is used for water quality estimations. In the Western Gulf of Finland and the Western Archipelago EQR values showed a closer coupling to point and riverine nutrient loads. Significant correlations were detected only in a few cases in the Väinameri and Gulf of Riga areas.

DISCUSSION

The diversity of environmental conditions in the Estonian coastal sea area reflects the major patterns in water circulation, nutrient loading by rivers (Pärnu and Narva bays), and anthropogenic nutrient load to the coastal ecosystem. In general our data showed that the Gulf of Riga had the highest background nutrient levels and the lowest water transparency, and the Western Archipelago had the lowest nutrient concentrations and the highest transparency. The Western Archipelago receives the smallest amount of freshwater inflows from land and is the least influenced by anthropogenic pollution. Environmental conditions of this area are controlled by general flow patterns and background nutrient levels of the Gulf of Riga, Gulf of Finland, and the Baltic Proper. Areas strongly influenced by riverine inflows were previously treated as 'hot-spots' in the coastal environment (HELCOM, 2003; Kotta et al., 2008). General patterns are well in accordance with previous information describing the eutrophication situation in the Baltic Sea (HELCOM, 2009).

Spatial differences in the distribution patterns of SAV parameters can be partly explained by major nutrient levels of the sea areas described. So the highest depth penetration values came from the areas least influenced by the runoff from land. The lowest values were characteristic of the areas with high nutrient and fresh-water inflows (e.g. Pärnu Bay). It is well documented that other factors besides freshwater inflow and amount of anthropogenic runoff influence SAV communities in coastal areas of the Baltic Sea. Among those the most powerful factors are seabed geomorphology, exposure to waves, and also water salinity at larger scales (Kautsky, 1989; Martin, 2000).

Of the tested environmental variables water transparency was the best eutrophication-related variable to be correlated with the SAV parameters. It is well documented in the literature that water transparency is related to the depth distribution of various species and total SAV communities (e.g. Nielsen et al., 2002). In most cases the depth penetration of the communities is set by perennial species. This study also demonstrated that water transparency was positively related to the proportion of perennial species. This relationship was present in the whole data set but was not detected in data sets covering certain types. Those types in which this relationship was missing usually occurred where the sea area was either very shallow or dominated by soft substrate (distribution of SAV communities is strongly substrate limited). Both factors either favour dominance of annual species or limit the distribution of perennial species.

Nutrient riverine load was a good environmental descriptor for the depth distribution of SAV communities when the whole data set was analysed. The load

from point sources however had no significant relationship with any SAV indicator when the whole data set was analysed but showed significant relationships in some of the water types. This phenomenon can be explained by the fact that in the case of the Estonian coastline the riverine nutrient load is in general a much more important environmental factor than the load from point sources.

The relationships described on type scale show an interesting pattern. For most of the types there were several environmental factors that had significant relationships with different SAV parameters. The largest number of significant relationships was established for the Southeastern Gulf of Finland. Here all tested environmental variables had significant relationships with at least some of the vegetation metrics. In other types (Western Gulf of Finland, Western Archipelago, and Gulf of Riga) the number of established significant relationships was smaller but still in each of those there were several eutrophication-related environmental variables that could be used to explain the behaviour of SAV descriptors.

Two types – the Väinameri and Pärnu Bay – demonstrated no significant relationships between any of the SAV descriptors and tested environmental variables. These two cases are areas where very special environmental conditions exist. The Väinameri (inner sea of the West Estonian Archipelago Sea) is a shallow area where in most sites vegetation can inhabit the seafloor. This area is influenced by water masses from the Gulf of Riga, Baltic Proper, or the entrance area of the Gulf of Finland with the origin of the water filling the area influenced by the prevailing wind direction. The area receives also a significant amount of fresh water through the Kasari River (Suursaar et al., 2001). All this causes high fluctuations in environmental conditions and interactions among environmental variables, which may prevent eutrophication to become responsible for the distribution pattern of SAV in the area.

Pärnu Bay is very strongly influenced by freshwater inflows. Here the major structuring factor is the Pärnu River. Besides supplying a huge amount of nutrients to the area the Pärnu River also affects Pärnu Bay through humic matter, changing the optical properties of the seawater and having a strong impact on light penetration (Kotta et al., 2008). Due to the low salinity and dominance of soft substrate in this area, SAV communities are limited by other environmental factors than those traditionally used to describe the eutrophication situation.

Application of the EQR instead of raw data is expected to improve the indicative power of the parameters as it includes type-specific adjustment of the indicator through the use of type-specific reference conditions. In our case the analyses performed on calculated EQR values increased the number of significant relationships with environmental characteristics. The general pattern of the established relationships however remained the same. For the coastal water types Pärnu Bay and Väinameri no significant relationships were established either when the SAV indicator EQR was used.

In Estonia three phytobenthos metrics are used in the water quality classification system: (1) depth distribution of phytobenthos, (2) depth distribution of *Fucus vesiculosus*, and (3) proportion of perennial plant species. All three responded

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to changes in transparency and nutrient levels and therefore can be used as indicators in water quality assessment systems developed for the purposes of the WFD. In our study we did not manage to establish significant correlations between all phytobenthic metrics and water quality variables in all coastal types. This may be caused by the small amount of reference data available for water quality variables (in some coastal water types the variability of water quality indicators is very high and a proper water quality monitoring scheme is missing).

Strong relationships were identified both on raw data level and calculated, type-specific EQR level. This means that the selected metrics are in general suitable for reflecting the eutrophication situation in coastal water bodies.

The following main conclusions can be drawn:

- The selected SAV metrics used in the Estonian National Water Quality assessment scheme generally respond to changes in eutrophication-related indicators.
- The strongest correlations of SAV indicators were established with water transparency.
- The selected indicators are not representative for areas with specific environmental conditions and thus revision of the used indicator system is needed.

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Põhjataimestiku ja eutrofeerumisega seotud näitajate vaheline seos Läänemere kirdeosas

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EL Veepoliitika Raamdirektiivi nõuetele vastav rannikumere veekvaliteedi hindamissüsteem töötati Eestis välja 2007. aastal. Meie töö eesmärgiks oli kasutatavate põhjataimestiku indikaatorite ja kõige tihedamini kasutatavate eutrofeerumisega seotud näitajate (klorofüll *a* kontsentratsioon, vee läbipaistvus, lämmastiku- ning fosforisisaldus) vaheliste seoste leidmine ja regionaalsete ise-ärasuste kirjeldamine. Põhjataimestiku indikaatoriteks on põhjataimestiku sügavus-levik, põisadru sügavuslevik ja mitmeaastaste liikide osakaal. Kõik nimetatud indi-kaatorid korreleerusid vee läbipaistvusega. Põhjataimestiku indikaatorid reageeri-vad eutrofeerumise näitajate muutustele sagedamini Soome lahe kaguosa tüüpalal. Seoseid ei leitud Pärnu lahe ja Väinamere tüüpalal. Sellest tingituna vajab nende piirkondade põhjataimestikul baseeruv hindamissüsteem täiendamist.