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Self-purification capacity and management of Baltic coastal ecosystems

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Abstract. It is expected that the Baltic region becomes a major centre of economic growth and prosperity in Europe already during this decade (Anon. 2000). Therefore, an Agenda 21 for the Baltic region (Baltic 21) was developed to ensure a sustainable development. Especially the coastal ecosystems are subject to increasing anthropogenic pressure e.g. eutrophication, traffic, harbours, tourism or offshore wind parks. Eutrophication remains the main ecological problem in the Baltic Sea and has serious negative social and economical consequences. Inner and outer coastal waters play an important role as buffers and filters for the Baltic proper. Consequently, the utilization and preservation of their self-purification capacity is of great importance.

Combined results of our own coastal research and of the international workshop 'Baltic coastal ecosystems: structure, function and coastal zone management' (Rostock University, November 2001) are presented here. Conclusions for an improved integrated coastal zone management of Baltic coastal ecosystems will be presented.

Keywords: Baltic region; Baltic Sea; Eutrophication; Hypertrophy; Integrated Coastal Zone Management.

Abbreviation: ICZM = Integrated Coastal Zone Management.

Introduction

The Baltic Sea covers an area of 412 000 km^2, has a volume of 21 700 km^3 and an average depth of 52 m. The Baltic Sea drainage basin has a size of 1 745 100 km^2 and is about four times larger than the Baltic Sea. 48% of the drainage basin is covered by forest, with low nitrogen and phosphorus loads into the Baltic Sea. Increased human activity during the 20th century caused an increase of riverine loads to the Baltic Sea and shift from mesotrophic towards a eutrophic system. Recent calculations by Elmgren & Larsson (2001) yield total annual nitrogen loads of 1 249 000 t and total annual phosphorus loads of 56 000 t. Despite successful combat measures, eutrophication, especially of the coastal waters, is still the main problem of the Baltic Sea.

With the fall of the 'Iron Curtain' and the extension of the European Union towards the East, the Baltic Sea becomes a central European sea of outstanding importance. Trade and traffic already increased again and the historical unity of the Baltic region is on the way to be restored. It is expected that the Baltic region becomes a major centre of economic growth and prosperity in Europe, already during this decade (Anon. 2000). The anthropogenic pressure on the coastal ecosystem will increase. Already 85 million people live in the Baltic drainage area (Fig. 1) and nearly 15 million people live within 10 km of the coast. The increase and further concentration of activities along the coast endanger the coastal ecosystems, and efforts towards a sustainable development of the region are imperative. Therefore strategies for an Integrated Coastal Zone Management (ICZM) are under intensive discussion.

The riverine loads have to pass the inner and outer coastal waters before they enter the open sea. The abundant shallow water bodies, with their high productivity and transformation abilities, are potentially efficient buffers and filter systems for the Baltic Sea. They protect the Baltic Sea from pollution. This self-purification ability of coastal waters is a result of different processes:

Fig. 1. The Baltic Sea drainage basin (modified from Anon. 2001).

sedimentation, deposition, erosion, transformation or simply transition, only diluting the loads and reducing the gradient. If the self-purification capacity is exceeded, coastal ecosystems can become a source of nutrients for the Baltic Sea themselves. It seems that in the present situation the self-purification capacity is exceeded, but our knowledge is still limited. A first more comprehensive approach to understanding these ecosystems was made by the BASYS project 1996/1999. The collected data are urgently needed for a realistic calculation of the necessary reduction of the anthropogenic loads.

Due to the high morphological diversity of the Baltic coastal zone we can expect a great diversity in function. Additionally, anthropogenic altered structures and loads have changed the buffering and filtering capacity of the coastal zones. This will be demonstrated in four different types of coastal zones, the semi-enclosed Greifswalder Bodden (Germany), the lagoon-like Darß-Zingst boddens (Germany), the open Pomeranian coast (Poland) and the river-dominated Neva Bay (Russia).

The WVU-workshop on Baltic coastal ecosystems and coastal zone management' (Schernewski & Schiewer 2002a) dealt with the analysis of potential conflicts in the southeastern Baltic, requirements and future challenges in coastal zone management, the promotion of information exchange in the Baltic region, the strategies for the establishment of a solid information base and the linking of stakeholders involved in coastal zone management. A comprehensive overview of the outcomes is given and suggestions towards an improved ICZM in the Baltic region are made.

Material and Methods

We focus on the southern and eastern Baltic coasts. Results of long-term studies (monitoring) in the Darß-Zingst boddens, Greifswalder Bodden and Salzhaff and comprehensive experimental approaches were analysed, e.g. in the Darß-Zingst boddens, Greifswalder Bodden and Salzhaff 1968/2001: 'Pelagial compartment experiments' (PEKOM), 'Shallow-water compartment experiments' (FLAK), 'Hypertrophy' (see Schiewer 1994); 'Ecosystem boddens – organisms and metabolism' (ÖKOBOD, 1996/1998); 'Greifswalder Bodden and Oder Estuary – Exchange Processes' (GOAP 1993/1997); 'Transport and transformation processes in the Pomeranian Bight – anthropogenic loaded transient waters between coastal zone and Baltic proper' (TRUMP 1994/1997); 'Baltic Sea System Studies' (BASYS 1996/1999) and 'Baltic coastal ecosystems – Structure, function and management' (Schernewski & Schiewer 2002). Details of the material and methods are given in Anon. (1999a, b), Jönsson et al. (1998), Schiewer et al. (1986), Schiewer & Jost (1991), Schumann & Schiewer (1994) and Schiewer et al. (2002).

Results

Northeastern German Coast

The morphologically differentiated German coast is characterized by inner coastal waters, called 'boddens' and 'haffs'. Due to its complex structure strong gradients exist. The DOC/POC-ratios (Fig. 2) are one example. (DOC = Dissolved Organic Carbon; POC = Particulate Organic Carbon.) The lowest ratio of 1 : 1 is found in the Darß-Zingst boddens (Görs et al. 2000; Estrum-Yousef

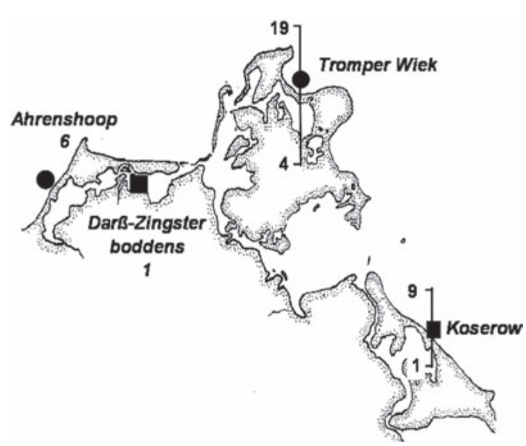

Fig. 2. DOC/POC-ratios in different coastal waters (modified from Estrum-Yousef 2001).

Table 1. Selected morphological-hydrological parameters of three German coastal waters along the Baltic Sea.

	Darß-Zingster Bodden chain	Greifswalder Bodden	Salzhaff
Surface area (km^2)	197.0	514.0	29.3
Volume (m^3)	$387 * 10^6$	$2960 * 10^6$	$67 * 10^6$
Catchment area (km^2)	1594	510	211
Surface /catchment area ratio	1 : 8	1 : 1	1 : 7
Mean depth (m)	2.0	5.6	2.5
Maximum depth (m)	12.0	13.5	10.0
Mean salinity PSU	4.5	7.5	10.5
Salinity range PSU	< 0.5-15.0	< 5.3-12.2	< 5.0-15.0
Present eutrophication status[1)]	4.5	3.5-3.0	2.0-1.5
Potential natural status[2)]	2.5-3.0	2.0	1.5

[1)]Scale 1-5; most oligotrophic conditions 1.0 (Schiewer et al. 1994)
[2)]Calculated from morphological and hydrological background (Schiewer et al. 1994)

2001), the most eutrophic coastal waters in this region.

The Salzhaff, located in the eastern part of the western Baltic Sea near the town of Wismar, can be regarded as a reference ecosystem for inner coastal waters. It is the smallest site studied (see Table 1) and barely influenced by direct anthropogenic activities. Only the minor river Hellbach and the small town Rerik are point sources for nutrients. The diffuse nutrient loads of the surrounding agricultural areas are not known. We can assume, that a considerable load is imposed on this system, compared to the small surface and large catchment area. Due to the efficient water exchange with the Baltic Sea the nutrient loads cause only a minor eutrophication. Relatively high salinity is another major element. The latter is due to the location of the Salzhaff in the western part of the Baltic Sea where a strong influence of the North Sea exists. Higher salinity allows a much greater diversity of the flora and fauna compared to the Baltic proper and the eastern coastal waters.

In general, the dominance of macrophytes, which can be expected in this shallow water type, has been preserved in large haff areas. Weber (1990) has documented the existence of an intact zoobenthos and epiphytic fauna in the littoral and a well developed sandy-bottom fauna in the benthal zone. This structural background is responsible for the predominance of the grazing food web. In combination with good oxygen supply of the benthos and an intensive grazing food web any excessive enrichment of organic matter in the sediment layer is obviously prevented. At the same time this creates a marked decreasing nutrient gradient from the shore towards the Baltic Sea.

As a result of the almost intact macrophyte colonization in the Salzhaff, there is still a stable filtering and buffering gradient from the shores to the Baltic Sea. A comparison with earlier data (cf. Benke 1997) shows that the present conditions are essentially similar to those found in the 1930s. The Salzhaff may be classified as a mesotrophic system, which is rare and therefore one of the major reference areas along the German Baltic Sea coast.

The Greifswalder Bodden is a semi-enclosed water body with good exchange possibilities with the Baltic proper (Fig. 2) and a surface/catchment-area relationship of 1:1. Therefore, it has potentially a natural mesotrophic status. Anthropogenic loads have transferred it into a eutrophic status. Before eutrophication started, around 80% of the bottom was covered by macrophytes. In the 1980s, the macrophytes covered only 15% of the bottom. The worst situation was found in the southwestern inner part, caused by a stronger impact of anthropogenic loads and reduced exchange rates with the Baltic Sea. The eutrophication process has altered the self-purification capacity during the last 40 years.

Nowadays, 10 years of restoration measures shows positive effects. Around 25% of the bottom surface are again covered by macrophytes. The eutrophication process in the shallow Baltic Greifswalder Bodden is shown in Fig. 3.

Completely different are the Darß-Zingst boddens (Table 1). The reduced water exchange rates with the Baltic Sea led to a more 'autonomous' ecosystem, which is even more favoured by the morphological division into sub-basins (Fig. 2). Such ecosystems are very sensitive to eutrophication (Schiewer 1998). A stepwise degradation in water quality took place over the last 50 years (Fig. 4).

Step I: Oligo-mesotrophic before 1969. Nutrient limitation, low phytoplankton biomass and dominance of diatoms. Dominance of submerse macrophytes (*Charophyceae*) in shallow parts.

Step II: Mesotrophic to eutrophic 1969/1989. Nutrient limitation, mainly nitrogen; higher phytoplankton biomass and dominance of green algae and cyanobacteria. Dominance of submerse macrophytes (*Charophyceae* and *Potamogetonaceae*) in shallow parts.

Step III: Eutrophic to polytrophic. Changes from nutrient to light limitation. Dominance of nano- and (pico)-phytoplankton (cyanobacteria and green algae) and microbial food webs. Dramatic loss of submerse

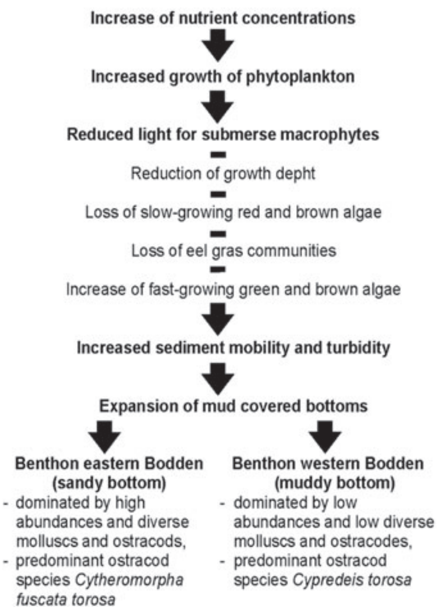

Fig. 3. The eutrophication process in the shallow Baltic Greifswalder Bodden.

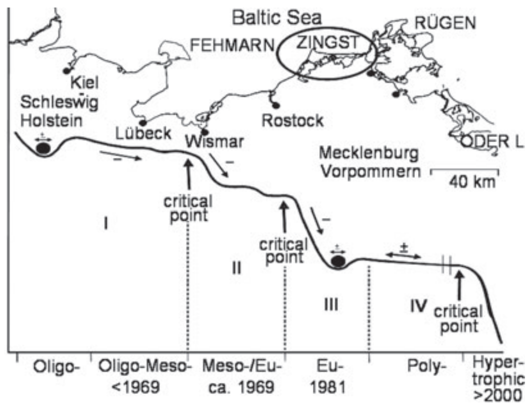

Fig. 4. The Darß-Zingst boddens: stepwise eutrophication of the Barther Bodden.

macrophytes.

Step IV: Polytrophic. From the end of the 1980s the most important feature was that the anthropogenic enhanced microbial food webs are concentrated on a very active fluffy sediment layer (Schumann et al. 2001).

Critical point: The change to hypertrophy is prevented by load reduction since 1991. Change from light to nutrient limitation will be expected between 2005 and 2010. Observed are already first recoveries of submerse macrophytes (*Potamogeton pectinatus* and some *Charophyceae*) in 2001 (H. Schubert pers. comm.).

The general consequences of this massive eutrophication are shown in Table 2. Eutrophication caused a degradation of the self-purification ability and the Darß-Zingst boddens became a nutrient source for the Baltic Sea itself.

Table 2. General consequences of heavy eutrophication in the Darß-Zingst Bodden.

- Predominance of nano- and (pico)-phytoplankton
- Predominance of microbial food webs
- Enhanced turnover of organic matter
- Accumulation of POC (aggregates, fluffy sediment layer)
- Higher remineralisation rates
- Stronger "internal"-eutrophication
- Increase of stochastic reactions and reduced predictability
- Enhanced ecosystem stability
- Restoration more elaborated
- Reduced buffer and filter capacity for the Baltic proper

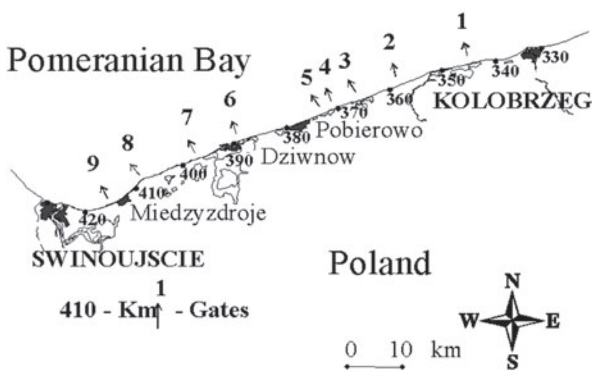

Fig. 5. Location of 'gates' along the Polish coast of the Pommerian Bight (Furmanczyk & Musielak 2002).

Polish Western Pomeranian Coast

In contrast to the German coast, the western Pomeranian coast of Poland is morphological nearly uniform (Fig. 1). Driven by predominating southwestern winds the nutrient loads entering the Baltic Sea with the Oder river are often transported with coastal currents far towards east. These 'coastal jets' maintain a gradient of nutrient concentrations from west toward east. High current velocities and intensive wave action ensure an effective water exchange along this exposed coast. Wave action and currents are not uniform, but create complex structures of 'gates' and 'nodules' along this coast (Fig. 5). These 'gates' are areas with a width of up to 3 km, where water is transported from the coast towards the open sea (Furmanczyk & Musielak 2002). It is uncertain, to what extent these processes contribute to the water exchange between coast and open sea and whether the assumed flow is a permanent feature. However, these structures have impact on the spatial sediment distribution, create a certain habitat patchiness along this apparently uniform coast and are well visible on air photographs.

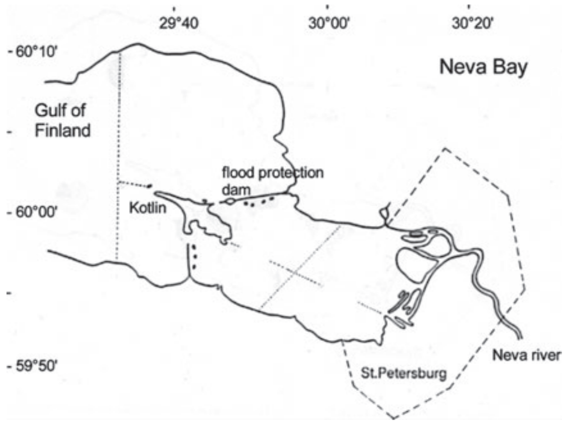

Fig. 6. Neva Bay, from St. Petersburg to the flood protection dam (Panov et al. 2002).

The Neva Bay

The Neva Bay (Panov et al. 2002) is the most eastern part of the Gulf of Finland (Fig. 6). In contrast to the other water bodies mentioned, the bay is dominated by freshwater discharge of the Neva river. Selected characteristics are shown in Table 3. In spite of the high nutrient load the trophic status is meso- to eutrophic. Caused by extremely high freshwater inflow and the short residence time the bay is a transition zone, reflecting the properties of the Neva river. The impact of the nutrient load is well visible in terms of an increased

Table 3. Selected characteristics of the Neva Bay.

Area (km^2)	329
Volume (10^6 m^3)	1200
Average depth (m)	3.5-4.0
Maximum depth (m)	12 (shipping channel)
Catchment area (km^2)	304 000
Area/catchment relation	1:920
Average freshwater inflow (10^6 $m^3.yr^{-1}$)	79 000
Residence time (d)	5.5
Salinity (PSU)	freshwater
Nutrient input ($t.yr^{-1}$)	3 300 total P 24 000 total N
Chlorophyll a ($\mu g.l^{-1}$)	2.1-19.7
Primary productivity phytoplankton (mg-C.$m^{-2}.d^{-1}$)	720
Metazoa (mg ww l^{-1}) (rotifers, copepods, cladocerans)	< 1.1
Seston (mg-dw.l^{-1})	14.5 - 28.9
Macrozoobenthos (g-ww.m^{-2})	< 134
Macrofauna species (number)	210
Trophic status	meso- to eutrophic

Table 4. Control factors for the self-purification of coastal waters.

1. ***Morphology and hydrology***
- Average depth
- Surface/catchment area
- Exchange with the Baltic Sea
- River discharge
- Water residence time

2. ***Physical-chemical processes***
- Salinity
- Nutrient loads
- Sedimentation/resuspension
- Accumulation

3. ***Biological processes and regulations***
- Changes in phytoplankton, e.g. decline of diatoms
- Phytoplankton versus submerse macrophytes dominance
- Grazing versus microbial food web dominance
- Formation of fluffy sediment-layer
- Decline of diversity
- Deterministic versus stochastic regulation
- Stepwise changes of trophic levels

productivity in the Neva estuary and the eastern Gulf of Finland.

Changes took place after the construction of the storm-surge barrier in the estuary in the 1980s. It changed the natural hydrodynamics in the Neva Bay and caused sedimentation, wetland formation, the development of emergent macrophytes, mainly *Phragmites australis* and *Scirpus lacustris* and overwhelming growth of *Cladophora glomerata* in the northern area of the Bay. The latter will have changed the ecosystem structure and function at least in the northern part of the Bay. Consequently, the self-purification capacity will be altered, but experimental data are not yet available.

As shown by these selected examples the 'self'-purification ability of the inner and outer coastal waters of the Baltic Sea is very different. It depends on different ecosystem characteristics (Table 4).

In general, the influences caused by anthropogenic increased nutrient loads are more pronounced in 'autonomous' shallow waters. River-dominated coastal zones, however, are often subject to structural changes with dramatic effects on the ecosystems.

Besides eutrophication, potential pollution, harmful algal blooms and the intrusion of non-native species from other brackish or fresh waters worldwide into the Baltic Sea are further important problems. There are a lot of gaps in the ecological knowledge of coastal ecosystems, e.g. there is an urgent need for a more detailed investigation and calculation of the self-purification ability of the coastal zone along the salinity gradient. It should also consider the time- and season-dependent transport, sedimentation, deposition, transformation and degradation of organic matter and nutrients.

Table 5. Important uses and user needs in the Baltic coastal zone of Mecklenburg-Vorpommern (Obenaus & Köhn 2002).

Main user interests	Superior and additional types of uses
Business	**Transportation**
	• Sea-born transportation
	• Roads
	Mining and sea-water
	• Sand / gravel
	• Oil / natural gas
	• Sea-water use
	Maritime tourism
	• Beach tourism
	• Water sports / sailing
	• Coastal passenger shipping
	Fisheries / aquaculture
	• Coastal fishery
	• Aquaculture
Defence	**Uses for military purposes**
	• Exercise voyage above and below the sea surface
	• Military shooting
Nature	**Nature and landscape protection**
	• Protection of ecosystems (fauna, flora)
	• Protection in accordance to European
	• Law and HELCOM Recommendations
	Coastal protection
Other needs	**Other user needs**
	• Dumping of dredged material
	• Conservation of monuments
	• Sea funeral
	• Marine research / monitoring restrictions
	• Wrecks and other impediments
	• Ammunition

Discussion

The unique coastal ecosystems play an important role in reducing the amount of natural and anthropogenic loads for the open sea. The self-purification capacity of coastal waters is the last barrier before pollutants and nutrients enter the Baltic Sea. The structure and behaviour of coastal waters are very different and only detailed regional analyses will give reliable results.

On the other hand, there is a general approach for coastal water management and restoration, considering the restoration of the catchment area, supporting the self-purification capacity and establishing adequate measurements for water quality assessments:

1. Restoration of the catchment area by direct intervention: Rehabilitation of 'hot spots'; reduction of small point loads by low-tech treatment plants; using best managing practice, e.g. critical area planing, crop rotation, streamside vegetative buffers and nutrient management; changing of land use; re-establishing of water exchange activities.

2. Supporting the self-purification of the coastal ecosystem by enhancement of the existing self-purification potential by ensuring the multivalent use of the coastal ecosystem; determination of critical loads; precautionary principle in industry and agriculture; minimum standards for waste water treatment; restrictions of use for sensitive water-management areas; establishing marine parks to provide reserve stocks for re-colonisation; adequate legislation for environment protection; education of the public.

3. Adequate measurements for water quality monitoring and evaluation: Use of the EU directives for the protection of inland surface water, transitional waters, coastal waters and groundwater, e.g. for preventing further deterioration and enhancing the status of aquatic ecosystems and terrestrial ecosystems and wetlands directly depending on the aquatic ecosystem, promoting sustainable water use based on a long-term protection of available water resources and contributing to mitigate the effects of floods and droughts.

Activities on Integrated Coastal Zone Management (ICZM) in Europe are closely linked to the Agenda 21 process, resulting from the Rio de Janeiro declaration on a sustainable development, which was signed in 1992. Follow up regional Agenda 21, like the Baltic 21 for the Baltic region, always mention ICZM explicitly in their action programme. The Agenda 21 has a 'green' background, aiming at the protection and preservation the natural environment. Sustainable development nowadays means more and is based on three basic pillars: Nature protection, economic development and social aspects. These three aspects require an integration and harmonisation. Obenaus & Köhn (2002) give an overview of the uses in the coastal waters of the southeastern German Baltic coast (Table 5).

Table 5 clearly shows that all kind of activities and problems are concentrated in the coastal zone. This and the lack of national strategies forced the European Commission to evaluate the state of ICZM in Europe and to develop a European strategy. Especially the EU-recommendations on ICZM, released in 2002, increased the pressure on the member states to foster their ICZM activities. Other organisations, like Visions and Strategies around the Baltic Sea 2010 (VASAB) or the Helsinki Commission (HELCOM) followed. HELCOM adopted its recommendations (24/10) on the implementation of integrated marine and coastal management of human activities in the Baltic Sea area in 2003. Other legislations, like the European Water Framework Directive or the Habitat Directive (Natura 2000) aim towards a sustainable development, a preservation of ecosystems and an integrated management, as well. But despite all efforts, we are still far away from a successfully implemented ICZM. The diversity and complexity of ecosystems and an insufficient knowledge about their functioning is only one reason. For the next future we see three major deficits, which should be overcome in the Baltic Sea Region (Schernewski & Schiewer 2002):

1. Lack of public participation: ICZM always requires a vision and aims for a regional development. A vision cannot be developed without public participation and the involvement of stakeholders. A vision serves as motivation for people to remain involved in an ICZM process, but is the exception in the Baltic. Experiences with open ICZM discussion forums are lacking and ICZM managers, who motivate, moderate and accompany an ICZM initiative are hard to find in the Baltic region. Still, hierarchical structures predominate the discussion and decision-making process. A promising way, at least for Germany, seems to be to use of active Agenda 21 processes for ICZM purposes. In the Oder estuary ICZM initiative (ICZM Oder), a regional Agenda 21 ensures the political commitment and provides a platform for participation.

2. Lack of communication and coordination: In the Baltic many actors deal with ICZM but the approaches are often developed independently, parallel and not well coordinated. The recently started joint approach of HELCOM, VASAB and Baltic 21 to establish a joint platform aims in the right direction. In most countries spatial planning is a major actor in ICZM. Planning has already the task to integrate different uses, but at least in German, is restricted to the land. In Germany spatial planning will be extended towards the sea, too. This confirms the leading role of spatial planning in ICZM initiatives. Science can play the role as mediators and advisor. The lack of communication is not limited to high-ranking national and international bodies but is visible between scientists, administrations, managers and decision makers, too. In the Baltic Region language barriers are still an additional obstacle.

3. Lack of information: Basis for decision-making and active involvement in planning is knowledge and information. On the Baltic level there are several Internet platforms, which can be regarded as a platform for ICZM. But a regular international, interdisciplinary Baltic ICZM forum with open meetings or conferences is still lacking. Therefore, ICZM on Baltic level remains intransparent. On the regional level this is even more problematic. Very often, large amounts of regional information are available at very different sources and are practically not accessible and available for ICZM initiatives. This hampers regional ICZM. Within the ICZM Oder initiative, an exemplary regional prototype of a comprehensive internet-based information network and database will be developed.

Conclusions

It is stressed that the Baltic coastal ecosystem is unique, as it is characterised by high diversity in structure and function. Consequently, ICZM can be efficient only, if the regional differences are considered and respected. There is an urgently need for a more comprehensive approach to understanding and managing the self-purification ability of the coastal zone along the salinity gradient, the time- and season-dependent transport, sedimentation, deposition, transformation and degradation of organic matter and nutrients as well as a joint sustainable coastal zone management.

In general, a well-developed gradient of floral, faunal and micro-organismic elements ranging from the river mouth offshore to the light compensation point of the coastal water, seems to be the best guarantee for efficient self-purification and protection of the Baltic proper.

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