Eutrophication of the Baltic Sea: Nutrient cycling and management

Bo Gustafsson
The Baltic Sea

9 riparian countries

Area = 420,000 km²
Mean depth = 50 m
Max depth = 459 m

Relatively large shallow entrance area with two shallow sills

Freshwater supply = 500 km³ yr⁻¹
Residence time 33 yrs

No tides!

Strong seasonality – ice in winter to up to 20 °C in summer
Cross-section through the Baltic Sea

Salinity

Oxygen
Long-term development of oxygen

Hypoxic  Anoxic

Conley et al. 2009
Cyanobacteria blooms are a nuisance to the public and a particularly nasty bloom occurred in 2005.
HELCOM (regional convention for protection of the Baltic Sea environment)

Baltic Sea Action Plan

Four priority areas:
- Hazardous substances
- Biodiversity and nature conservation
- Maritime activities
- Eutrophication

The plan was adopted by the Ministers in Nov 2007
Clear water
- Nutrient concentrations close to natural levels
- Natural occurrences of algal blooms
- Natural abundances of plants and animals
- Oxygen concentrations close to natural levels

### Environmental objectives

### Targets

### Maximum Allowable Inputs

### Country-wise reduction allocation

<table>
<thead>
<tr>
<th>Country</th>
<th>Phosphorus</th>
</tr>
</thead>
<tbody>
<tr>
<td>DK</td>
<td>38</td>
</tr>
<tr>
<td>EE</td>
<td>320</td>
</tr>
<tr>
<td>FI</td>
<td>360 (330+30)</td>
</tr>
<tr>
<td>DE</td>
<td>170 (110+60)</td>
</tr>
<tr>
<td>LV</td>
<td>220</td>
</tr>
<tr>
<td>LT</td>
<td>1470</td>
</tr>
<tr>
<td>PL</td>
<td>7480</td>
</tr>
<tr>
<td>RU</td>
<td>3790</td>
</tr>
<tr>
<td>SE</td>
<td>530</td>
</tr>
</tbody>
</table>

[Legend: Politics/Policy, Science]
Resolution

7 sub-basins
The catchment of each sub-basin is shown in colors
Environmental targets

<table>
<thead>
<tr>
<th>Basin</th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DIN</td>
<td>DIP</td>
</tr>
<tr>
<td>KT</td>
<td>5.0</td>
<td>0.49</td>
</tr>
<tr>
<td>DS</td>
<td>5.0</td>
<td>0.56</td>
</tr>
<tr>
<td>BP</td>
<td>2.6</td>
<td>0.30</td>
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<tr>
<td>BS</td>
<td>2.8</td>
<td>0.19</td>
</tr>
<tr>
<td>BB</td>
<td>5.2</td>
<td>0.07</td>
</tr>
<tr>
<td>GR</td>
<td>5.2</td>
<td>0.41</td>
</tr>
<tr>
<td>GF</td>
<td>3.8</td>
<td>0.59</td>
</tr>
</tbody>
</table>

+ targets on oxygen
Main characteristics:
- 13 sub-basins
- High vertical resolution
- Full circulation dynamics
- Mechanistic biogeochemical cycles including sediments
- Forced by meteorology, river runoff and boundary conditions to the Skagerrak
- And nutrient loads from Land and Air
- Typical simulation times on a high-end workstation 200 simulation years in 30 - 60 minutes

Publically available to run on-line in Nest:
http://nest.su.se
Method to determine Maximum Allowable Inputs

Question to be answered is:

*What combination of loads to the basins satisfies both targets and provides the maximal loads?* -> *optimization problem*

1. Determine relationships between loads and indicator response from a large amount (1000nds) of cleverly chosen model simulations

2. Find the solution to the optimization problem from the data base of relationships

Additional constrains that need to be considered are: model limitations and ecological relevance
$N$ load to BP = 325 kT yr$^{-1}$

Red: Secchi BP = 7.4 m  
Blue: O2 debt = 8.66 g m$^{-3}$  
Green: DIP GR = 0.41 mmol m$^{-3}$  
Yellow: DIP GF = 0.59 mmol m$^{-3}$  
Cyan: DIP BP = 0.3 mmol m$^{-3}$  
White: DIN BP = 2.6 mmol m$^{-3}$
WE RECOGNIZE that the revised Maximum Allowable Inputs represent best available scientific knowledge base and data, and characterize the HELCOM long-term vision of the Baltic Sea unaffected by eutrophication that we aspire;

<table>
<thead>
<tr>
<th>Baltic Sea Sub-basin</th>
<th>Maximum Allowable Inputs</th>
<th>Reference inputs</th>
<th>Needed reductions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TN tons</td>
<td>TP tons</td>
<td>TN tons</td>
</tr>
<tr>
<td>Kattegat</td>
<td>74,000</td>
<td>1,687</td>
<td>78,761</td>
</tr>
<tr>
<td>Danish Straits</td>
<td>65,998</td>
<td>1,601</td>
<td>65,998</td>
</tr>
<tr>
<td>Baltic Proper</td>
<td>325,000</td>
<td>7,360</td>
<td>423,921</td>
</tr>
<tr>
<td>Bothnian Sea</td>
<td>79,372</td>
<td>2,773</td>
<td>79,372</td>
</tr>
<tr>
<td>Bothnian Bay</td>
<td>57,622</td>
<td>2,675</td>
<td>57,622</td>
</tr>
<tr>
<td>Gulf of Riga</td>
<td>88,417</td>
<td>2,020</td>
<td>88,417</td>
</tr>
<tr>
<td>Gulf of Finland</td>
<td>101,800</td>
<td>3,600</td>
<td>116,252</td>
</tr>
<tr>
<td>Baltic Sea</td>
<td>792,209</td>
<td>21,716</td>
<td>910,343</td>
</tr>
</tbody>
</table>
How to share the reduction burden

Prerequisites:

- Inputs from land per country and basin are computed from monitoring.
- Country-wise contributions of airborne nitrogen deposition to each basin is modeled by EMEP.

Allocation:

- Reductions are shared in proportion to each country’s contribution to the basin-wise input.
- Contributions are expected from non-HELCOM countries as well.
The Copenhagen Ministerial Declaration including the new reduction scheme was signed on Oct 3, 2013
Loads has continued to decrease substantially since then.

River loads to Baltic Proper (Normalized)

- Nitrogen load (kT/yr)
- Phosphorus load (kT/yr)


 Loads in balance with burial! ‡
Further reductions leads to improvement

Source: HELCOM PLC + BNI

P burial (2000) in Baltic proper:
17 000 ton/yr (Mort et al., 2010, Gustafsson et al., 2012)
Continued depressing state of main Baltic Basins cause frustration
Spatial average DIP and TP concentrations (Observations and BALTSEM simulations)

The general development of the nutrient pools can be relatively accurately modeled.

Gustafsson et al., 2017
The model shows that an improvement are to be expected even by present day loads.
Conclusions

- BALTSEM indicates that recovery is underway, but will take decades to detect
- Natural variability is large and can mask recovery over extended period of time
- Pelagic processes are also quite important! For example:
  - Low winter DIN/DIP ratio gives less spring bloom and more cyanobacteria and summer production
  - High winter DIN/DIP ratio gives larger spring bloom and potentially higher sedimentation