

## Chapter 19

# Pelagic eutrophication in the Gulf of Riga



Paul Wassmann  
Norwegian College of Fishery Science  
University of Tromsø  
N-9037 Tromsø, NORWAY  
[paulw@nfh.uit.no](mailto:paulw@nfh.uit.no)

### 19.1 Introduction

Quantitative estimates of the fluxes and dynamics in the nutrient load on marine environments, their distribution and channelling through the food web and the effect on the increase of new production, are fundamental and constitute a prerequisite for the planning of actions for water protection measures. The Gulf of Riga is no exception. The Gulf is a semi-enclosed part of the eastern Baltic Sea, surrounded by Estonia and Latvia and has one major outlet, the Irbe Straight Sound, and one minor one, the Muhu Sound. The Gulf of Riga has a surface area of 19,000 km<sup>2</sup>, is up to 67 m deep, has

a relatively simple topography and a volume of 420 km<sup>3</sup> (Figure 19.1). The Gulf is eutrophicated and most of the pollution loads in the Gulf can be attributed to human activities in the drainage basin, which covers 135,700 km<sup>2</sup>, or more than seven times the surface area of the Gulf itself. In pelagic environments the fate of organic matter produced by an increased supply of nutrients, the regulation of vertical flux and in particular the pelagic-benthic coupling are not well known in general, let alone in the Gulf of Riga. Since the beginning of this century Estonian, Latvian, Lithuanian and Russian scientists have already carried out a substantial body of work in various disciplines in the Gulf of Riga and its drainage area (summarised by Ojaveer 1995). From 1993–1997 Nordic and Baltic scientists joined forces in an international project, the ‘Environmental Research in the Baltic Sea’, also referred to as the ‘Gulf of Riga Project’ (GoR). The objective was to study environmental problems in the Gulf and its drainage area, and to determine their impact on the rest of the Baltic Sea in general and the Baltic Proper in particular (Figure 19.2).

The investigations reviewed here aim at to understand the Gulf of Riga as an ecosystem by analysing

1. the dynamics of the runoff of nutrients and their supply to the Gulf
2. the distribution of nutrients in the Gulf

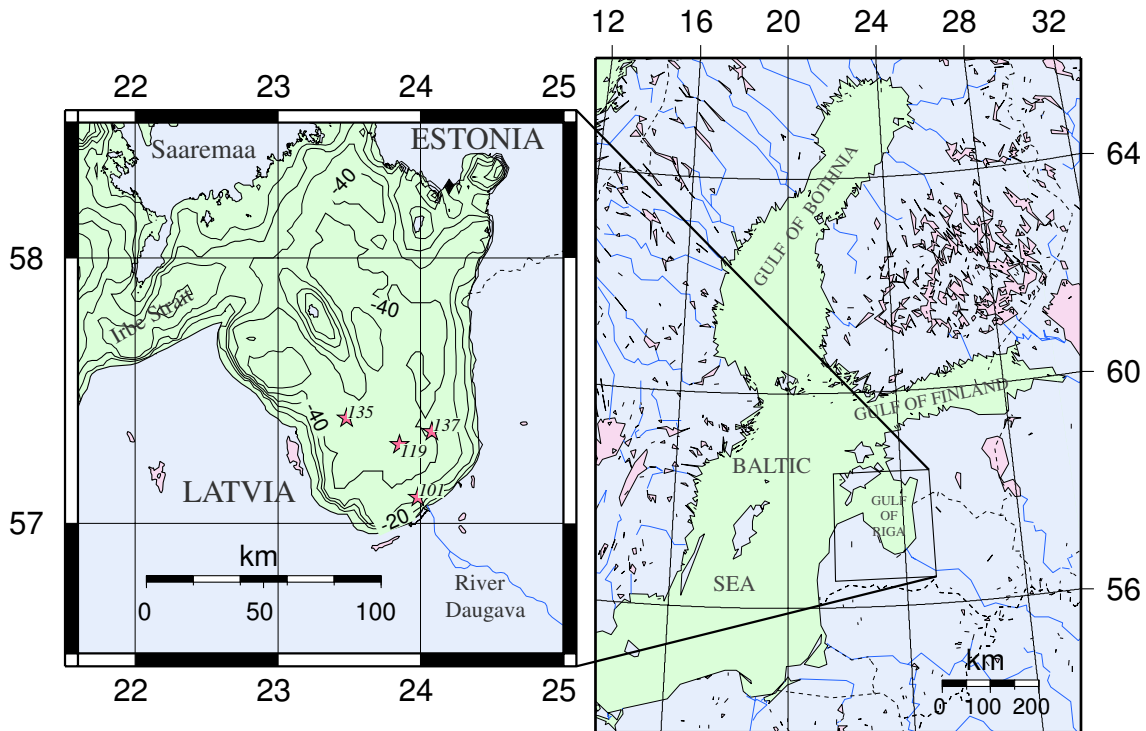


Figure 19.1: The Gulf of Riga between Estonia and Latvia. Also shown are some of the stations that were investigated

3. the production and distribution of plankton and organic matter and
4. the processes involved in settling and the vertical export of organic matter

This chapter rests upon 14 publications from the project ‘Pelagic eutrophication and sedimentation’ (Wassmann & Tamminen, 1999); see also *J. Mar. Syst.*, Vol 23.

## 19.2 The riverine input of nutrients is high, area-specific loads are low

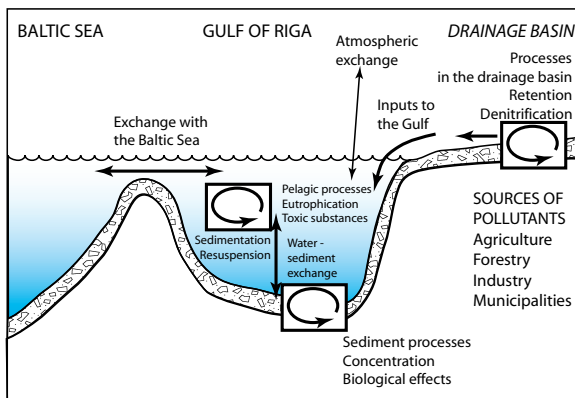


Figure 19.2: A conceptual scheme of the Gulf of Riga project.

The Gulf of Riga receives more than 140,000 t of nitrogen and 3,000 t of phosphorus annually (Laznik *et al.*, 1999). Most of this pollution load can be attributed to the activities in the drainage basin of the Gulf of Riga. The two largest drainage basins are those of the Daugava and Lielupe River,

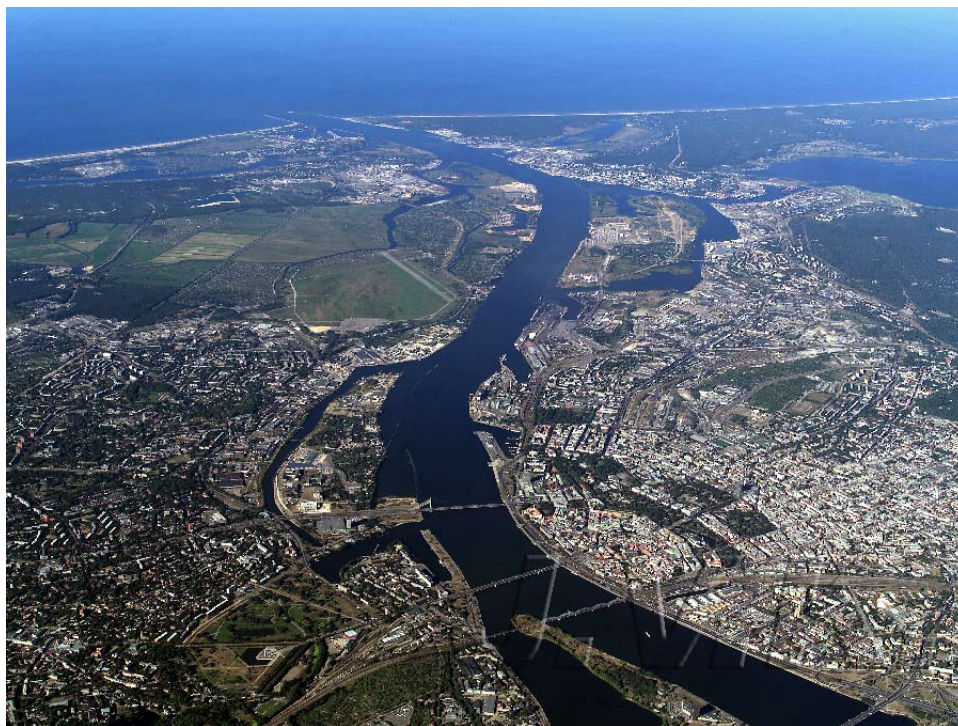


Figure 19.3: The town of Riga, the river Daugava and the adjacent coast in the southern coast of the Gulf of Riga.

which cover 78% of the total drainage area (Figure 19.4). On an annual basis, runoff corresponds to 9% of the total water volume of the Gulf. Thus, the impact of the rivers on the Gulf of Riga is substantial. River supply to the Gulf of Riga is by far the most important pathway of nutrients. Approximately 113,000 t of nitrogen (79% of the total load) and 2,050 t of phosphorus (68% of the total load) are annually transported by the rivers to the Gulf. In addition, the Gulf receives approximately 65,000 t yr<sup>-1</sup> of silica. Bio-available forms of nitrogen and phosphorus were shown to be responsible for 55% and 74% of the total loads of nitrogen and phosphorus, respectively. The share for the inorganic nitrogen is comparable with other Baltic Sea rivers, whereas the share for phosphate is somewhat higher (P. Stålnacke, pers. comm.). The high N:P ratio (>50 on an average annual basis, w:w) suggests that rivers entering the Gulf of Riga are phosphorus-limited, and that their discharge contributes to phosphorus limitation in the Gulf, which was suggested by Yurkovskis et al. (1993).

Although the riverine input of nutrients is high, the area-specific load from the catchment area of the Gulf of Riga is low or moderate compared to loads from other areas in the Baltic Sea region. For example, Stålnacke (1996) reported annual area-specific riverine exports of 12.2 kg ha<sup>-1</sup> for nitrogen and 0.42 kg ha<sup>-1</sup> for phosphorus in the Western Baltic sub-basin (i.e. Kattegat, The Belts, Øresund) compared to 8.3 kg ha<sup>-1</sup> for nitrogen and 0.15 kg ha<sup>-1</sup> for P reported for the Gulf of Riga catchment area by Laznik et al. (1999). These relatively low values are unexpected in view of the generally inefficient sewage treatment for the 4.5 million inhabitants in the drainage basin and the previously intensive agriculture (approximately 40% of the catchment area is used for agricultural production) with e.g. inefficient and inappropriate handling and spreading of manure and commercial fertilisers.

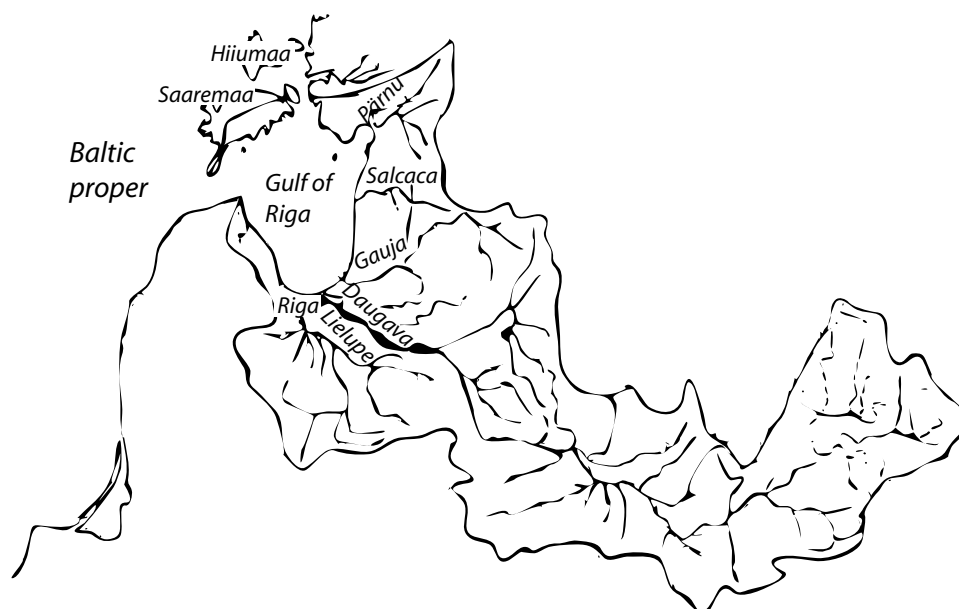


Figure 19.4: The water shed of the rivers discharging into the Gulf of Riga.

### 19.3 Temporal variation in riverine loads is substantial

The temporal variation in riverine loads of nutrients to the Gulf of Riga is substantial and characterised by both large interannual and seasonal variations. Most of these variations can be explained by natural fluctuations in runoff (Laznik *et al.*, 1999). The large interannual variation in the nutrient loads can be exemplified by the nutrient loads for 1984 and 1990, which differed by a factor of two for all major nutrient constituents. The seasonal distribution in load also correlates well with the variability in runoff. Comparatively low loads normally follow a pronounced peak during the spring flood during the low-flow period in summer. For example, the phosphorus load of the Daugava River in April usually accounts for 20% of the total annual load, whereas the corresponding loading during summer is much lower.

The annual loads in the period investigated (1993–1995) were, when compared with a 20-year average, relatively normal. Thus the biological investigations of the present study were carried out in a runoff scenario that resembles the average

over the last 20 years. However, in recent years increased nitrate concentrations were observed in the Daugava River (P. Stålnacke, pers. comm.). No definite and clear evidence of downward trends in the nutrient loadings related to the rapid economical recession (particular agriculture: fertiliser application decreased to 20%) in the catchment area in the former republics of the Soviet Union (i.e. Baltic Republics and Belarus) can be noted. The decrease in annual loadings that can be observed in certain periods is almost solely due to a decrease from the high runoff observed during other periods.

### 19.4 Riverine runoff dominates hydrography in spring, variable atmospheric forcing during summer — a shift from lateral to vertical processes

At the beginning of the annual plankton succession, the spring flood period dominates the growth conditions of phytoplankton not only because of

the nutrient supply factor, but also because of the physical conditions. The density difference between the high riverine runoff and the well-mixed basin water results in a strong, diffusive river plume. Salinity differences are the main agent for springtime stratification, and the buoyancy transport from springtime river runoff can re-stratify the Gulf after winter homogenisation in a period of about 5 weeks. During summer this would take about 1 year, indicating that the river runoff plays a major role in the creation of stratification only in spring (Stipa *et al.*, 1999).

The springtime river plume implies a formation of distinct horizontal gradients within the basin, whereas during summer conditions the weak river plume quickly dissolves and creates spatial variability in the southernmost basin only. The horizontal stratification gradients during spring have significant effects on the depletion of wintertime nutrients from the water column, and thus on the forthcoming growth conditions of planktonic communities during the stratified period. The areas in the middle and northern Gulf are mixed down to the bottom far later than the southern basin, which is under immediate river plume influence (Stipa *et al.*, 1999). Therefore significant nutrient reserves remain in the intermediate and deep layers of the southern basin after spring, whereas the northern basin is depleted of nitrate and especially phosphate down to deep layers (Tamminen & Seppälä, 1999).

After the establishment of thermal stratification the surface fluxes take over the buoyancy forcing by lateral freshwater eddy fluxes, and the mixed layer starts to deepen due to more variable atmospheric forcing. This implies higher temporal variability in the growth conditions of the planktonic community, and also more variability of lateral heterogeneity than during spring. An especially important feature of the vertical processes is the relation between mixed layer deepening and the depth of the euphotic zone, which in the Gulf of Riga is typically around 10 m as in adjacent Baltic Sea. Towards early autumn, the depth of the mixed layer clearly exceeded the euphotic zone, with dramatic consequences for the nutri-

tional and production preconditions of the planktonic biota (Tamminen & Seppälä, 1999; Olesen *et al.*, 1999).

## 19.5 The Gulf is basically nitrogen-limited

The total nutrient pools in the Gulf of Riga show significant seasonal changes. Springtime levels of ca. 400  $\mu\text{g N l}^{-1}$  and 30  $\mu\text{g P l}^{-1}$  in the whole basin (1995) except for the southern River Daugava plume, where concentrations of  $>>600 \mu\text{g N l}^{-1}$  and up to 40  $\mu\text{g P l}^{-1}$  have been detected. During the summer stages, total nutrient pools levels are lowest (on average, 270  $\mu\text{g N l}^{-1}$  and 17  $\mu\text{g P l}^{-1}$  in June 1994), increasing slightly from midsummer and onwards (Tamminen & Seppälä, 1999). The annual cycle of total nutrients with maximum in spring, minimum in early summer and gradual increase towards autumn is well established for adjacent Baltic areas like the Gulf of Finland, and overall total nutrient levels were comparable to long-term data from the coastal areas of the middle and eastern Gulf of Finland (HELCOM, 1996). Thus the total nutrient pools of the Gulf of Riga indicate a rather similar overall degree of eutrophy as other Baltic subareas.

The early spring 1995 nutrient distributions clearly indicated that the spring bloom period in the Gulf of Riga is potentially N-limited, since during the homothermal and deep-mixing season, inorganic N/P ratios were markedly and uniformly below the Redfield ratio in the whole basin, with the exception of the River Daugava plume (Tamminen & Seppälä, 1999). In early summer 1994, the mixed surface layer was effectively depleted of inorganic nutrients (both phosphate, nitrate and ammonium), yielding low ( $<$ Redfield) inorganic N/P ratios, except for the southernmost basin, which had high ammonium levels because of a strong mixing event. In mid-July 1994, very low inorganic nutrient concentrations and very low inorganic N/P ratios prevailed over the whole Gulf in the surface layer. Under this strongly N-limited productive layer, cumulative mineralization of am-

monium and phosphate took place in the relatively warm intermediate layers, as well as near to the bottom. A strongly N-limited productive layer, and equally strongly N-surplus deeper strata below the mixed layer characterize the summer stages in the Gulf of Riga as long as distinct separation of these layers prevail (Tamminen & Seppälä, 1999).

It is obvious that physical mixing events can produce drastic temporary fluctuations in the limitation pattern by introducing the significant nitrogen reserves from deeper water into the euphotic zone. When the effectively mixed surface layer depth exceeds significantly the depth of the euphotic zone towards the end of the stratified period, the production preconditions of planktonic autotrophs deteriorate, and consequently so do their capacity to utilise the nutrient pool of the mixed surface layer. As the considerable accumulations of nutrients in deep layers are also mixed into the surface layer, a combined result could be a sharp increase of inorganic nutrients in the euphotic zone.

Deep mixing during the stratified period promotes P-limitation, whereas a thin or moderate mixed layer promotes N-limitation, as previously observed in the outer estuary of the River Neva, eastern Gulf of Finland (Pitkänen & Tamminen, 1995). During the stratified period, strong mixing events due to physical forcing can abruptly change the prevailing N limitation into a P-limited phase, but unless deep mixing is prolonged, N-limitation is likely to be re-established in the surface layer. The probability of P-limited phases should increase towards the end of the stratified season, both due to the hydrographical development towards deep mixing, and to cumulative increase of subthermocline N reserves. The Gulf of Riga appears therefore to be characterized by considerable, hydrographically driven interannual and within-season variability with regard to surface layer inorganic nutrient concentrations and limitation patterns, in spite of the essential N limitation of the basin. The limitation scenario suggested by Tamminen and Seppälä (1999), which contradicts the conclusions of Yurkovskis et al. (1993)



Figure 19.5: *Cladophora*, a filamentous algae that is characteristic species in eutrophicated, marine and brackish water regions, growing on a stone in the Gulf of Riga.

and Suursaar (1995) suggesting P limitation of the Gulf, is supported by experimental evaluation of nutrient limitation of the natural planktonic communities (Seppälä et al., 1999).

## 19.6 Spatial variability of phytoplankton and pigments of the entire Gulf is high

During the spring bloom in 1995, the spatial structures of the high phytoplankton biomass and chlorophyll a were well explained by common factors such as inorganic N, total N and P, salinity and the depth of the mixed layer (Seppälä & Balode, 1999). Contrary to our expectations, the SW part of the Gulf was more influenced by the freshwater flow from the river Daugava than the SE part. Furthermore, the bloom was more pronounced in the SW part of the Gulf. Also in the central region of the southern gulf are influenced by the freshwater load. The river plume can move towards the centre and the western part of the Gulf instead of the anticipated north-easterly direction suggested by the general circulation pattern. This is obviously caused by the predominating wind strength and direction and suggests that wind plays a significant role for the spreading of surface and river plume water in the Gulf of Riga.

During the middle of the spring bloom diatoms

prevail over the entire Gulf, but algal biomass and chlorophyll *a* can quickly decrease during week-long periods, although considerable amounts of inorganic N and P are still available (Seppälä & Balode, 1999; Tamminen & Seppälä, 1999). The dinoflagellate *Peridiniella catenata* can be an important constituent of the phytoplankton spring community. The reduction of the silicate pool over the last ten years in the Gulf of Riga (Yurkovskis & Kostrichkina, 1996), which is probably the result of decreased runoff (Laznik *et al.*, 1999), could be one of the factors stimulating the development of dinoflagellates in late spring, as dissolved silicate becomes a limiting nutrient for diatoms. The proportion of diatoms/non-silicate demanding phytoplankton species varies in accordance to the annual and climatological variations in runoff. Strong stratification of the water column appeared to enhance sedimentation of diatoms while the motile dinoflagellates controlled their position in the water column in spring (Olli, 1999; Olli & Heiskanen, 1999). In the most stratified region in the southern Gulf a clear dominance of diatoms, however, remained.

The early summer stage is characterized by a homogenous distribution of algal biomass and low concentrations of inorganic N and P. Picoplankton was dominating the phytoplankton community in the outer Gulf (Seppälä & Balode, 1999). The small relative fraction of picoplankton in the regions affected by nutrient load in the southern part of the Gulf is in accordance with the conclusions of Kuparinen and Kuosa (1993). The dominating species of green algae, *Monoraphidium contortum* was probably favoured by eutrophic conditions (Kononen, 1988); the opposite seemed to be true for dinoflagellates.

An intense bloom of the cyanobacterium *Aphanizomenon* sp. took place in the middle of the summer of 1994 after an increase in temperature of the surface layer. Similar to the situation in spring, the abundance of *Aphanizomenon* sp. was related to the common structure of N, P and freshwater, and the bloom was most dense in the southern Gulf (Seppälä & Balode, 1999). It has been postulated that the recent increase

of cyanobacteria blooms is caused by the decreasing DIN/DIP ratio (Balode, 1994; Balode & Purina, 1996). During the cyanobacteria bloom in 1994, the DIN/DIP ratio was rather low (0.7–6.4 w:w). As during the early summer stage, the contribution of picoplankton was lower in the most eutrophicated, southernmost areas (Tamminen & Seppälä, 1999). Cyanobacteria are obviously supported by the high nutrient status of the river runoff. Less eutrophic conditions in the central and northern parts of the Gulf favoured the growth of cryptomonads and diatoms.

The early autumn phase in 1993 (after an intense bloom of cyanobacteria which covered the entire Gulf; Kahru *et al.*, 1994) was characterized by high heterotrophic activity and the phytoplankton community was dominated by cryptomonads (on average 50% of the total biomass). Diatoms were relatively more abundant in the most nutrient-rich southern Gulf. Cryptomonads, as main constituents of the phytoplankton community, were most abundant on the western side of the Gulf or generally in areas with less total N or P.

Basin-wide the distribution of phytoplankton variables correlated clearly, except during the early autumn stage, with environmental factors such as salinity, stratification and nutrients. Thus, the distribution of phytoplankton variables followed closely the patterns of nutrient-rich freshwater (Seppälä & Balode, 1999). The nutrient load from the rivers obviously generates a south-north gradient of phytoplankton biomass while the east-west gradient is more variable, probably depending on the predominating winds. The differences in phytoplankton biomass or chlorophyll *a* along the north-south axis were 3 to 6 fold. It seems to be clear that the nutrient load from rivers in the southern Gulf of Riga is the reason for higher phytoplankton biomass in the southern Gulf, especially during blooms.

### 19.7 Temporal variability dominates over spatial variability in the central and southern Gulf

High seasonal differences in the phytoplankton community structure and sedimentation characterise the southern Gulf of Riga (Olli & Heiskanen, 1999). However, the high within-season temporal variability dominates over the variability between different areas of the southern Gulf. For most of the suspended and sedimented parameters studied at the spatial stations, the recorded variability is significant in all seasons (Lundsgaard *et al.*, 1999; Reigstad *et al.*, 1999). The temporal variation found in the centre of the Gulf was even higher than the spatial variation. The situation off the mouth of the Daugava river is, however, different. This station is affected by resuspended matter at depth and by the suspended loads from the river runoff in the upper water column.

The sedimentation in the southern and central Gulf of Riga is influenced by river discharge, stratification and wind (Reigstad *et al.*, 1999). Wind causes high temporal variability in nutrients, suspended matter and vertical fluxes. In particular the wind direction changes the concentration of suspended matter and influenced stratification of the surface water that is influenced by both the river Daugava and by water entering through the Irbe Strait. The influence from the river on the sedimentation rates and retention of nutrients in the Gulf is difficult to evaluate since short-term variation exceeded the spatial variation in the Gulf.

### 19.8 Moderate primary production and high community respiration rates

Plankton community production and respiration rates in relation to wind, solar radiation, biomass and nutrients revealed that the predominant limiting factor for phytoplankton growth is nutrient

supply during spring and summer (Olesen *et al.*, 1999). In autumn, the combination of low light levels and deep vertical mixing due to wind leads to conditions of light limitation. The growth conditions are in all three situations, however, strongly affected by the stabilising (solar heating) and destabilising (wind) forces acting on the system. Depending on the relative strength of these forces, day-to-day primary production varies by a factor of two. Under conditions of nutrient limitation mixing may lead to increased photosynthesis, which is a consequence of improved exploitation of incident light and of available nutrients in the deeper mixed layer.

Primary production and respiration measurements indicate that the gross primary production is generally high during the productive season, on average about  $2 \text{ g C m}^{-2} \text{ d}^{-1}$  (Olesen *et al.*, 1999). Assuming that this estimate is representative for a presumed growth period March/April to October (approximately 200 days), the total annual primary production is estimated to range between 300 and  $400 \text{ g C m}^{-2}$  (Olesen *et al.*, 1999). High respiration estimates (on average about  $4 \text{ g C m}^{-2} \text{ d}^{-1}$ ) demonstrates that the pelagic system is rather based on regenerated than on new production. This is supported by simultaneous vertical flux measurements (Lundsgaard *et al.*, 1999) that indicate that the export of autochthonous matter out of the euphotic zone, relative to the standing stock and primary production, is small. Compared to many other coastal areas, the pelagic system of the Gulf of Riga appears exceptionally efficient in recycling and its ability to retain biogenic matter and nutrients in the upper layers.

### 19.9 Phytoplankton assemblages and the limited vertical export of phytoplankton cells

During spring the Gulf is characterised by an intensive dinoflagellate (mainly *Peridiniella catenata*) dominated spring bloom while the diatom



*Thalassiosira baltica* contributed most (80 to 90%) to the settling phytoplankton biomass. As mineral nutrients are abundant during the bloom it is suggested that the differential sedimentation of species is caused by physical factors (Olli & Heiskanen, 1999).

During summer the phytoplankton biomass is dominated by high abundance of the filamentous cyanobacterium *Aphanizomenon* sp., autotrophic nanoflagellates and picoplankton. The primary vertical flux of phytoplankton is mainly due to non-motile species and aggregate-bound picoplankton and *Aphanizomenon* sp. Below the pycnocline, resuspended dormant diatom populations cause a significant secondary flux. Large heterotrophic dinoflagellates (*Gyrodinium/Gymnodinium*) are abundant in the middle layers and associated with ammonium regeneration. The phytoplankton assemblage appears to have three major functional groups, which build up roughly equal parts of the total biomass (Olli & Heiskanen, 1999):

1. Large filamentous cyanobacteria (*Aphanizomenon* sp.). These are mainly inedible by the majority of the ambient zooplankton community in the Baltic Sea (Sellner *et al.*, 1994, 1996). As with the grazing losses, the sedimentation loss rates of this group are very low. Consequently, the fate of this biomass is probably to disintegrate in the water column and to fuel the detrital and microbial pathways of the food web.
2. Nanoflagellates (e.g. *Teleaulax* spp., *Plagioselmis prolonga*, *Pyramimonas* spp., *Pedinella* spp. and *Pseudopedinella* spp., *Chrysochromulina* spp., *Heterocapsa rotundata*). These are usually considered as readily available for mesozooplankton grazing. Their abundance points at the importance of the grazing food chain and represents the 'efficient' part of the energy transfer in the food web to higher trophic levels. The sedimentation of this compartment is also insignificant. It is suggested

that most of the nanoflagellates are grazed, and that their abundance is the result of an equilibrium between their growth and herbivory.

3. Picoplankton. This includes picocyanobacteria and pico-sized eucaryotes. The abundance of picocyanobacteria is quite common everywhere in the Baltic during summer. It is suggested that this compartment is an important food source for ciliates and cladocerans. Surprisingly, the sedimentation of picocyanobacteria was consistent. A likely mechanism is sedimentation within detrital aggregates.

The only significant sedimentation of fresh phytoplankton biomass took place in spring, in particular for *Thalassiosira baltica*. In the other seasons phytoplankton sedimentation appears unimportant. The matter that sedimented was detritus. Consequently, there must be mechanisms that prevent vertical export of phytoplankton cells and promote recycling of bioelements in the pelagic ecosystem of the Gulf of Riga.

## 19.10 The importance of microbial and viral loops in carbon cycling

In the planktonic ecosystem bacteria are the main consumers of dissolved organic carbon, and bacterial carbon production can be as much as half, or at times even higher than the primary production because carbon can be recycled several times through the microbial loop (Giorgio *et al.*, 1997). This seems to be the case in the Gulf of Riga during summer, when bacterial production was as high as primary production (Tuomi *et al.*, 1999). The carbon fixed by the phytoplankton is released by direct exudation, cell lysis and directly from the higher trophic levels (e.g. sloppy feeding). All this dissolved organic matter can be utilised by bacteria. Viral lysis of bacterioplankton is thought to make the bacteria-DOM-bacteria loop even more important (Thingstad *et al.*, 1993). Thus, there

are several routes by which the carbon from the primary producers ends up in bacteria and can be cycled several times through bacteria. One important route is the lysis of the cells due to viral infection. On average more than half of the bacterial production in the Gulf of Riga was lost through viral lysis (Tuomi *et al.*, 1999). This bacterial carbon is recycled back to bacteria. Unfortunately it is not possible to estimate how much of the other planktoners in the Gulf were lysed. In particular phytoplankton blooms may be attacked by viral infection.

Grazing by heterotrophic nanoflagellates and viral lysis have been recognised as two main reasons for bacterial mortality in aquatic ecosystems (e.g. Fuhrman & Noble 1995). Viral lysis of bacterial biomass produces dissolved organic matter to be utilised again by bacteria, while grazing can transfer bacterial carbon and other elements to higher trophic levels. In the Gulf of Riga heterotrophic nanoflagellates were estimated to consume on average one third of the bacterial production (Tuomi *et al.*, 1999). Due to respiration and sloppy feeding, only part of this carbon finally ends up to higher trophic levels.

It appears that a larger proportion of the carbon channelled into bacteria is recycled among the bacteria than is transferred to the higher trophic levels in the Gulf of Riga. Between trophic levels bacteria are thus more a sink than a link. Viral lysis of the cells seems to be very important at least among the bacteria. This results in the consumption of carbon among the bacteria and fast turnover of mineral nutrients. While the amount of carbon recycled through bacteria is as high as the primary production during summer, the bacterial production is lower during the other seasons, where bacterial production comprised 13 to 45% of primary production (Tuomi *et al.*, 1999). Thus the importance of the microbial loop in the carbon cycling of the whole plankton community is less pronounced.

## 19.11 P retention depends on the complexity of the pelagic food web

indexphosphorus!retention indexpelagic!nutrient retention

Although increased vertical export of C and N was recorded along with the export of phytoplankton cells at the end of the spring bloom (Olli & Heiskanen, 1999), pelagic retention of P is already high in late spring, resulting in low vertical loss rates of P. It is suggested that increased export of C, N and P to the benthos may take place during the spring bloom *before* the pelagic system develops sufficient complexity to greatly reduce vertical losses. The main supply of phytoplankton biomass to the benthos in the Gulf of Riga is thus determined by the time window characterised by low trophic complexity in spring. Retention of P was also high during summer and early autumn. In regions where nutrients are continuously supplied both from allochthonous and autochthonous sources, C and N are lost in excess while P is recycled from the pelagic system throughout the productive season (Heiskanen *et al.*, 1996). However, species-specific differences in bloom dynamics and sedimentation (i.e. dinoflagellates vs. diatoms) give rise to episodic events which are crucial for the further channelling of the assimilated nutrients and produced biomass into pelagic or benthic food webs (Heiskanen, 1998). Seasonal and annual variations in nutrient supply through rivers (Laznik *et al.*, 1999), in particular with regard to dissolved silicate, will possibly contribute to the differences in dinoflagellates vs. diatoms prevalence and thus induce interannual changes in the pelagic-benthic coupling.

The efficiency of P retention depends on the complexity of the pelagic food web and is enhanced by the increasing complexity of the trophic structure in the system over time. Increased P retention will also counteract the P deficiency induced by river runoff (Laznik *et al.*, 1999) and contribute to the complex N vs. P limitation scenarios recorded from the southernmost Gulf (Seppälä

*et al.*, 1999). Through this response P limitation may be eliminated and the P requirements of phytoplankton are adequate. The trophic complexity of the planktonic community in the southern and central Gulf of Riga and the variable, but continuous supply of nutrients by rivers such as Daugava give rise to a high 'buffering capacity' of the pelagic ecosystem throughout the productive season. Thus retention rather than export food chains are favoured and the effect of external perturbations, such as increased nutrient supply, is reduced.

### 19.12 Sources of settling material: Aggregation and zooplankton mediated fluxes

Despite the relatively high suspended biomass during summer situation, and the presence of suitable physical conditions, significant aggregate formation and export did not take place (Lundsgaard *et al.*, 1999). Contrary to expectations aggregation was not involved during mass sedimentation of diatoms during spring (Lundsgaard *et al.*, 1999). A positive correlation between sedimentation of detritus aggregates, sedimentation rates of biogenic matter and sedimentation velocities/specific loss rates of POC and phaeopigments is encountered. Aggregation of detritus may thus partly control the sedimentation dynamics, but it did not correlate with turbulent shear as expected according to classical coagulation theory. The aggregates are possibly fragile and form only during periods of low turbulence. The correlation between phaeopigments and aggregate sedimentation, the observed disintegration of faecal pellets into amorphous detritus, and the inclusion of pellets in the larger aggregates indicate that faecal matter constitutes an important component of sedimenting matter (Lundsgaard *et al.*, 1999). This points at the significance of the larger planktonic heterotrophs in the food web of the Gulf.

The food web composition in spring is characterised by a relatively high biomass of large phytoplankton and a dominance of protozoa (mainly

ciliates), while mesozooplankton are almost absent. During midsummer a medium phytoplankton biomass is encountered with significant quantities of mesozooplankton (both copepods, cladocerans and rotifers). However, all other heterotrophic components increase their biomass as well, and a complicated food web prevails. The early autumn is characterised by low phytoplankton biomass and a heterotrophic system with decreasing biomass. Protozoa (ciliates) increase their importance relative to metazoa. Bacterial production is reduced.

The relative export of biogenic matter in summer is possibly low due to a high potential for retention, disintegration and decomposition of detritus by heterotrophic organisms. The high concentrations of mesozooplankton during summer result in a disintegration of the larger detritus particles and aggregates. Or they disintegrate or ingest faecal pellets by mechanisms such as coprophagy or coprorhexy (*sensu* Noju 1991). Strong wind action may also affect the disintegration of aggregates. Furthermore, picoplankton and the microbial food web are important in the organic carbon flow and for regeneration. Ciliates were dominant among the large protozoa, and cladocerans as well as rotifers constitute a significant fraction of the metazoa. Contrary to copepods, these organisms produce faecal particles that easily disintegrate.

### 19.13 Eutrophication in the Gulf of Riga: fiction or reality?

Assuming that the bioavailable N and P from the rivers (Laznik *et al.*, 1999) would be spread over the entire Gulf, the annual supply would be 0.57 and 0.016 g m<sup>-2</sup> for N and P, respectively. Assuming further that the euphotic zone is 10 m deep and that the nitrate and phosphate concentrations at the end of the winter are 20 and 0.6 μM, respectively (Suursaar, 1995), it becomes obvious that the river supply to the winter-accumulated N and P in the euphotic zone is moderate: 20 and 15%, respectively. However, as the spreading of fresh-



Figure 19.6: A river meets coast of the Gulf of Riga in winter

water in the Gulf is dependent on runoff variations and meteorological forcing (Stipa *et al.*, 1999), the effect of nutrient supply (Turner & Rabalais, 1994) and suspended biomass (Reigstad *et al.*, 1999; Babichenko *et al.*, 1999) in the southern part can vary considerably. Also, wind mixing induces new nutrients to the euphotic zone. The greatest impact of nutrients is confined to the southern area and consequently new production is significantly increased.

A rough estimate of the autochthonous supply of P to the euphotic zone shows that it is less than half of what is delivered to the Kattegat. As compared to the high primary production rate (Olesen *et al.*, 1999), the relatively small vertical export of biogenic matter from the euphotic zone (Lundsgaard *et al.*, 1999), the small new production (Olesen *et al.*, 1999), the insignificant contribution of phytoplankton cells to the vertical export after the vernal bloom (Olli & Heiskanen, 1999) and the prevalence of detritus and faecal matter (Lundsgaard *et al.*, 1999) point at high

pelagic recycling efficiency in the Gulf. The buffering capacity of excess suspended biomass in the pelagial causes the prevalence of retention rather than export food chains. Consequently, the effect of external perturbations such as increased nutrient supply is reduced accordingly. The main supply of fresh biogenic matter to the benthos is defined by the extent of the vernal bloom and the complexity and efficiency of the seasonal development of the planktonic community structure. As the duration and start of the spring bloom can change as a consequence of variable seasonal and annual nutrient discharge to the Gulf as well as climatic factors such as ice-cover, wind forcing, solar radiation and the spectral light composition (clouds, fog etc.), the time window in which vernal phytoplankton is exported to the benthos is variable.

As the supply of nutrients to the Gulf depends strongly on the seasonal and interannual variability in river runoff, which can double during years of increased precipitation as compared to dry years, the allochthonous supply of nutrients varies accordingly. Thus also the interannual new production and the extent of eutrophication vary. Nutrient removal of bioavailable N and P from coastal point sources would only relieve the N budget of the Gulf by 9%, that of P however by 44% (Laznik *et al.*, 1999). Obviously a removal of P from coastal point sources would reduce the P budget of the Gulf significantly and even N removal would to some extent mitigate the N burden.

Nutrient removal from point sources such as the city of Riga will reduce the eutrophication in both the southern littoral zone as well as in those offshore areas of the Gulf that are under direct influence of the river Daugava. Clear evidence of downward trends in the nutrient loadings of rivers related to the rapid economical recession in the catchment area were so far not recorded (Laznik *et al.*, 1999). Thus, the allochthonous supply of nutrients to the Gulf by rivers from diffuse sources (e.g. agriculture) will basically continue in the future. The general eutrophication of the Gulf will probably only decline when both nutrient re-

removal at coastal point sources is introduced and the use of fertilisers and manure is kept continuously low over lengthy periods of time. Also, measures ought to be taken to limit the effect of modern forestry on nutrient discharge, to constrain the introduction of deserted farms into modern agriculture, to eliminate drainage of former wetland areas and to increase the vegetation along rivers and small streams in intensive agricultural areas. These measures will jointly increase the denitrification in the drainage basin or constrain the discharge of nutrients to small catchment areas. Finally, reduced emissions of P and organic matter from point sources in the drainage basin may, under certain conditions, reduce the denitrification capacity in rivers (Chesterikoff *et al.*, 1992). Therefore, it cannot be ruled out that the N loads to the Gulf of Riga may increase in the future, regardless of modernisation in the agricultural sector and nutrient removal from point sources along rivers (Stålnacke *et al.*, 1999). Accordingly, it is difficult to predict changes in both the total nutrient discharge to the Gulf and the N-P-DSi composition of the waters in the Gulf.

Eutrophication in coastal waters is not only characterised by substantial additions of P and N, but also by the fact that the supply of DSi is more or less constant or subjected to natural runoff patterns (Skjoldal, 1993; van Bennekom & Salomons, 1981). There is also a tendency for DSi supply to the sea to decrease over time in many eutrophied rivers (Turner & Rabalais, 1994). This is explained by increased growth of freshwater diatoms in the river due to increased N and P concentration, and subsequent sedimentation of diatoms behind dams. There seems to be evidence for declining DSi supply also from the Gulf of Riga (Laznik *et al.*, 1999). However, there are several dams along the river Daugava that were built already before nutrient records became available. Thus, DSi supply to the Gulf must have been reduced already for several decades. Scenarios where the relative concentration of DSi is decreased while that of N and P is increased, favour the growth of non-DSi dependent forms such as flagellates. The resulting change in phytoplankton species compo-

sition results in increased residence times of the phytoplankton-derived organic matter in the upper layers because aggregate formation and the relative contribution of rapidly sedimenting diatom blooms decreases. DSi obviously plays an important role for eutrophication as emphasised by Officer and Ryther (1980), Conley *et al.* (1993); see also Chapter 13. The increasing gap between decreasing DSi, but increasing N supply results in a decreasing significance of diatom and increased potential of nuisance blooms.

The high buffering capacity of the pelagial confines the vertical supply of biogenic matter to the benthos. However, the supply of biogenic matter to the benthos and the main accumulation bottom derives probably from advective transport from the slope, the river plume and the littoral zone where erosion of fine biogenic matter results in a predominance of hard substrate (D. Conley, pers. comm.). The effect of frequent resuspension episodes, weather-controlled bottom currents which regularly and easily entrain organic matter from the sediment-water interface (Floderus *et al.*, 1991), as well as sediment focusing, add to the supply of food for the benthos at depth. Here biogenic matter from the surface accumulates on an area which is less than half that of the entire surface area, creating favourable growth conditions for the benthos.

Statements that regard the Gulf of Riga as an eutrophic to hypertrophic area seem not to be valid. The data of Laznik *et al.* (1999) and Tamminen and Seppälä (1999) indicate that the nutrient supply to the Gulf, as well as the concentrations in the water body, are similar to or less than that of other Baltic Sea areas (e.g. the middle/eastern Gulf of Finland or the Kattegat). In contrast to previous assumptions the Gulf of Riga is basically N- and only periodically P-limited. Furthermore, it has a high pelagic buffering capacity with regard to nutrient discharge induced by efficient recycling by the pelagic food web, which limits the occurrence of massive algal blooms. Nevertheless, the pollution loads from the rivers, in particular those originating from the catchments of the Daugava and the Lielupe rivers,

have contributed to an overall eutrophication of the Gulf of Riga, with a continuously shifting gradient between the southern and northern halves of the Gulf. As the simple and exposed topography of the basin makes it exceptionally prone to physical forcing, it is obvious that episodic mixing events can cause considerable interannual and within-season variability in the production preconditions and nutrient limitation of the planktonic community, especially towards late summer and early autumn.

### Literature

- BABICHENKO, S., KAITALA, S., LEEBEN, A., PORYVKINA, L., & SEPPÄLÄ, J. 1999. Phytoplankton and dissolved organic matter distribution in the Gulf of Riga. *Journal of Marine Systems*, **23**, 69–82.
- BALODE, M. 1994. Long-term changes of summer-autumn phytoplankton communities in the Gulf of Riga. *Pages 96–99 of: GUELORGET, O., & LEFÈVRE, A. (eds), Baltic Sea and Mediterranean Sea a comparative ecological approach of coastal environments and paralic ecosystems.*
- BALODE, M., & PURINA, I. 1996. Harmful phytoplankton in the Gulf of Riga (The Baltic Sea). *Pages 69–72 of: YASUMOTO, T., OSHIMA, Y., & FUKUYO, Y. (eds), Harmful and toxic algal blooms.* Intergovernmental Oceanographic Commission of UNESCO.
- CHESTERIKOFF, A., GARBAN, B., BILLEN, G., & POULIN, M. 1992. Inorganic nitrogen dynamics in the River Seine downstream from Paris (France). *Biogeochemistry*, **17**, 147–193.
- CONLEY, D. J., SCHELSKE, C. L., & STROEMER, E. F. 1993. Modification of the biogeochemical cycle of silica with eutrophication. *Marine Ecology Progress Series*, **101**, 179–192.
- FLODERUS, S., JÄHMLICH, S., EKEBOM, J., & SAARSO, M. 1991. Particle flux and properties affecting the fate of bacterial productivity in the benthic boundary layer at a mud-bottom site in the south-central Gulf of Riga. *Journal of Marine Systems*, **23**, 233–250.
- FUHRMAN, J. A., & NOBLE, R. T. 1995. Viruses and protists cause similar bacterial mortality in coastal seawater. *Limnology and Oceanography*, **40**, 1236–1242.
- GIORGIO, P. A., COLE, J. J., & CIMBLERIS, A. 1997. Respiration rates in bacteria exceed phytoplankton production in unproductive aquatic systems. *Nature*, **385**, 148–151.
- HEISKANEN, A.-S. 1998. Factors governing sedimentation and pelagic nutrient cycles in the northern Baltic Sea. *Monographs of the Boreal Environmental Research*, **8**, 1–80.
- HEISKANEN, A.-S., TAMMINEN, T., & GUNDERSEN, K. 1996. The impact of planktonic food web structure on nutrient retention and loss from a late summer pelagic system in the coastal northern Baltic Sea. *Marine Ecology Progress Series*, **145**, 195–208.
- HELCOM (ed). 1996. *Third periodic assessment of the state of the marine environment of the Baltic Sea, 1989–1993.* Baltic Sea Environment Proceedings 64 B.
- KAHRU, M., HORSTMANN, U., & RUD, O. 1994. Satellite detection of increased cyanobacteria blooms in the Baltic Sea: natural fluctuations or ecosystem change? *Ambio*, **23**, 469–472.
- KONONEN, K. 1988. Phytoplankton summer assemblages in relation to environmental factors at the entrance to the Gulf of Finland during 1972–1985. *Kieler Meeresforsch., Sonderh.*, **6**, 281–294.
- KUPARINEN, J., & KUOSA, H. 1993. Autotrophic and heterotrophic picoplankton in the Baltic Sea. *Advances in Marine Biology*, **29**, 73–12.
- LAZNIK, M., STÅLNACKE, P., GRIMVALL, A., & WITTGREN, H. B. 1999. Riverine input of nutrients to the Gulf of Riga: temporal and spatial variability. *Journal of Marine Systems*, **23**, 11–25.
- LUNDGAARD, C., OLESEN, M., REIGSTAD, M., & OLLI, K. 1999. Sources of settling material: Aggregation and zooplankton mediated fluxes in the Gulf of Riga. *Journal of Marine Systems*, **23**, 197–210.
- NOJI, T. T. 1991. The influence of macrozooplankton on vertical flux. *Sarsia*, **76**, 1–9.
- OFFICER, C. B., & RYTHER, J. H. 1980. The possible importance of silicon in marine eutrophication. *Marine Ecology Progress Series*, **3**, 83–91.
- OJAVEER, E. (ed). 1995. *Ecosystem of the Gulf of Riga between 1920 and 1990.* Estonian Academy of Sciences. Tallinn: Estonian Academy publishers.
- OLESEN, M., ANDRUSHAITIS, A., & LUNDGAARD, C. 1999. Primary production, community respiration, light and mixing dynamics. *Journal of Marine Systems*, **23**, 127–143.
- OLLI, K. 1999. Diel vertical migration of phytoplankton and heterotrophic flagellates in the Gulf of Riga. *Journal of Marine Systems*, **23**, 145–163.
- OLLI, K., & HEISKANEN, A.-S. 1999. Seasonal stages of phytoplankton community structure and sinking loss in the Gulf of Riga. *Journal of Marine Systems*, **23**, 165–184.
- PITKÄNEN, H., & TAMMINEN, T. 1995. Nitrogen and phosphorus as producing limiting factors in the estuarine waters of the eastern Gulf of Finland. *Marine Ecology Progress Series*, **129**, 283–294.



Figure 19.7: Spectacular sunsets are characteristic on the shores of the Gulf of Riga.

- REIGSTAD, M., HEISKANEN, A.-S., & WASSMANN, P. 1999. Seasonal and spatial variation of suspended and sedimented nutrients (C,N,P) in the pelagic system of the Gulf of Riga. *Journal of Marine Systems*, **23**, 211–232.
- SELLNER, K. G., OLSON, M. M., & KONONEN, K. 1994. Copepod grazing in a cyanobacterial bloom in the Gulf of Finland. *Hydrobiologia*, **292/293**, 249–254.
- SELLNER, K. G., OLSON, M. M., & OLLI, K. 1996. Copepod interactions with toxic and non-toxic cyanobacteria from the Gulf of Finland. *Phycologia*, **35**(6), 177–182.
- SEPPÄLÄ, J., & BALODE, M. 1999. Spatial distribution of phytoplankton in the Gulf of Riga during spring and summer stages. *Journal of Marine Systems*, **23**, 51–67.
- SEPPÄLÄ, J., TAMMINEN, T., & KAITALA, S. 1999. Experimental evaluation of nutrient limitation of phytoplankton communities in the Gulf of Riga. *Journal of Marine Systems*, **23**, 107–126.
- SKJOLDAL, H. R. 1993. Eutrophication and algal growth in the North Sea. *Pages 445–478 of: DELLA GROCE, N. F. R. (ed), Symposium Mediterranean Seas 2000*. Genova, Italy, September 1991: Instituto Scienza Ambientale Marina Santa Margherita Ligure.
- STÅLNACKE, P. 1996. *Nutrient loads to the Baltic Sea*. PhD thesis, Linköping University, Linköping Studies in Arts and Science 146.
- STÅLNACKE, P., VAGSTAD, N., TAMMINEN, T., WASSMANN, P., JANSON, V., & LOIGU, E. 1999. Nutrient runoff and transfer from land and rivers to the Gulf of Riga. *Hydrobiologia*, **410**, 103–110.
- STIPA, T., TAMMINEN, T., & SEPPÄLÄ, J. 1999. On creation and maintenance of stratification in the Gulf of Riga. *Journal of Marine Systems*, **23**, 27–49.
- SUURSAAR, Ü. 1995. Nutrients in the Gulf of Riga. *Pages 41–50 of: OJAVEER, E. (ed), Ecosystem of the Gulf of Riga between 1920 - 1990*. Tallinn: Estonian Academy of Sciences, Estonian Academy Publishers.
- TAMMINEN, T., & SEPPÄLÄ, J. 1999. Nutrient pools, transformation, ratios, and limitation in the Gulf of Riga, Baltic Sea, during four successional stages. *Journal of Marine Systems*, **23**, 83–106.
- THINGSTAD, T. F., HELDAL, M., BRATBAK, G., & DUNDAS, I. 1993. Are viruses important partners in pelagic food webs? *Trends in Ecology and Evolution*, **8**, 209–213.
- TUOMI, P., LUNDSGAARD, C., EKEBOM, J., OLLI, K., & KÜNNIS, K. 1999. The productivity and potential loss mechanisms of bacterial biomass in the southern Gulf of Riga. *Journal of Marine Systems*, **23**, 185–196.
- TURNER, R. E., & RABBALAIS, N. N. 1994. Changes in the Mississippi River nutrient supply and offshore silicate-based phytoplankton community response. *Pages 147–150 of: DYER, K. R., & ORTH, R. J. (eds), Changes in fluxes in estuaries: implications from Science Management*. Fredensborg: Olsen and Olsen.
- VAN BENNEKOM, A. J., & SALOMONS, W. 1981. Pathways of nutrients and organic matter from land to ocean through rivers. *Pages 33–51 of: MARTIN, J. M., BUR-*

- TON, J. D., & EISMA, D. (eds), *River inputs to ocean systems*. Rome: UNEP/UNESCO.
- WASSMANN, P., & TAMMINEN, T. 1999. Eutrophication and sedimentation in the Gulf of Riga: An introduction. *Journal of Marine Systems*, **23**, 1–10.
- YURKOVSKIS, A., & KOSTRICHKINA, E. 1996. A long-term ecosystem response to man-made impact in the Gulf of Riga. *Pages 22–23 of: Baltic Marine Science Conference, October 22–26*.
- YURKOVSKIS, A., WULFF, F., RAHM, L., ANDRUZAITIS, A., & RODRIGUEZ-MEDINA, M. 1993. A nutrient budget of the Gulf of Riga, Baltic Sea. *Estuarine, Coastal and Shelf Science*, **37**, 113–127.