25 years of pollution abatement and environmental improvement in the

GUDENAA

- a Danish lake-river-estuary system

GUDENAA COMMITTEE - REPORT NO. 21
MAY 1999

GUDENAA COMMITTEE

The Gudenaa Committee was established following a major study of pollution sources and water quality in the Gudenaa river system in 1973-75. The Committee's first task was to issue recommendations on pollution abatement based on the results of the 1973-75 study. Since then, the Gudenaa Committee has served as an advisory body for the 35 local (municipal) and 3 regional (county) authorities within the catchment area. The Committee coordinates and issues recommendations on all environmental protection and management issues pertaining to the streams, lakes and estuary of the Gudenaa river system, including

- Wastewater treatment
- Abatement of pollution from freshwater fish farms
- Removal of dams preventing fish passage
- Stream restoration
- Monitoring and reporting activities.

Members of the Committee

The Committee comprises:
One representative of Aarhus County Council (Chairman)
One representative of Viborg County Council
One representative of Vejle County Council
One representative of a municipal council within Aarhus County
One representative of a municipal council within Viborg County
One representative of a municipal council within Vejle County.

In addition to these six elected politicians, the Committee includes one representative from the technical administrations of each of the three counties. The Secretary of the Committee is an employee of Aarhus County.

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SUMMARY

Pollution of Danish rivers, lakes and estuarine fjords became evident in the 1970s and led to adoption of the Environmental Protection Act in 1974. Coordinated efforts to reduce pollution were rapidly implemented in the Gudenaa catchment area, primarily based on the results of a detailed monitoring programme in 1973-75.

Organic pollution

In the 1970s and earlier, many streams were heavily polluted with degradable organic matter discharged in the wastewater from towns and industry, in slurry from farms and in effluent from freshwater fish farms. During the 1970s and 1980s, biological treatment was established in all towns and industries, agricultural discharges were curtailed, and discharges from fish farms were reduced. As a consequence virtually no heavily polluted streams remain in the Gudenaa river system, although some are still polluted by sewage from rural dwellings and by algal blooms in lakes.

Eutrophication

The estuary and all the lakes receiving wastewater or runoff from agricultural catchments are eutrophic due to nutrient loading. Phosphorus removal from wastewater was established at most treatment plants around 1980. The phosphorus concentration of lake water has not decreased concomitantly, however, due to the slow release of phosphorus accumulated in the sediments. Moreover, although agriculture is the dominant source of nitrogen loading and an important source of phosphorus loading, nutrient input from cultivated fields has not yet been reduced to any great extent. As a consequence there has so far only been moderate improvement in water quality in the lakes and estuary of the Gudenaa river system.

Physical quality

The surface waters of the Gudenaa river system are affected by channelization and damming. Restoration is proceeding slowly due to agricultural demands for stream maintenance and flood protection, and to differing wishes and priorities regarding dams, e.g. protection of cultural heritage, removal or construction of fish passes and hydroelectric power stations.

The lesson gained from the Gudenaa river system is that profound improvement in surface water quality is possible through wastewater treatment and improved agricultural practices, although pristine water quality cannot be achieved in densely populated and highly cultivated catchments.

INTRODUCTION

Objective

The objective of this report is to describe 25 years of pollution abatement efforts in the catchment area of the Gudenaa river system and the resultant improvement in the environmental quality of the streams, lakes and estuary.

Description of the Gudenaa river system

The river Gudenaa drains 3,200 km^2 of Danish lowland moraine landscape formed during the last glacial period. About 70% of the catchment area is cultivated farmland and the catchment population numbers about 350,000.

The catchment is characterized by numerous (70) lakes differing markedly in trophic level, and by very diverse soil quality, ranging from diluvial sand plains to hilly areas with dense, thick clay strata. The river Gudenaa discharges into the sea through the shallow estuary, Randers Fjord, where the river water mixes with brackish water from Kattegat (Fig. 1). Annual freshwater discharge is approximately 10^9 m^3/y.

Because of geological differences within the catchment, the streams of the river system also differ. In the western part, close to the border of maximum glacial extension during the last Ice Age, discharge is high and almost constant. In the streams in the eastern, clayey areas, in contrast, discharge is very low during summer.

Fig. 1.
Gudenaa river system indicating the catchment area (blue) and the county borders (brown).

These differences influence the water pollution situation. The streams with a low summer discharge are easily polluted, also because the population density in these areas is generally high. In contrast, the high, constant discharge in the western streams makes trout farming profitable alongside the streams, with resultant downstream pollution.

Monitoring

Nutrient and organic matter transport from the sources and through the streams are calculated from chemical analyses of 12-24 water samples and simultaneous measurement of water discharge. Transport is determined annually at all the wastewater treatment plants in the catchment, in five of the lakes, at about 25 river stations, and in the estuary. At the remaining lake and river stations, measurements are made every 3-10 years.

The ecological quality of the streams is monitored by field or laboratory investigations of the invertebrate fauna at about 2,000 monitoring stations, a few hundred of which are visited annually with the remainder being visited every five years. The degree of pollution at each station is given on a scale of I (unpolluted) to IV (very badly polluted) (Kirkegaard et al. 1992). The method is the standard method for biological assessment of river pollution in Denmark, and is a development of the saprobic index first described by Kolkwitz and Marsson (1909). The fish populations in the smaller streams are monitored by electrofishing, usually every 3-6 years.

The investigations of ecological quality and the impact of pollution in the lakes and estuary encompass nutrients, transparency and chlorophyll, and the number and biomass of the individual species of phytoplankton, zooplankton and submerged macrophytes. Fish populations are also monitored in some lakes, and benthic invertebrates in the estuary.

The water discharge monitoring station at Tvilum Bridge north of Silkeborg was established in 1917. Photo: Jens Møller Andersen

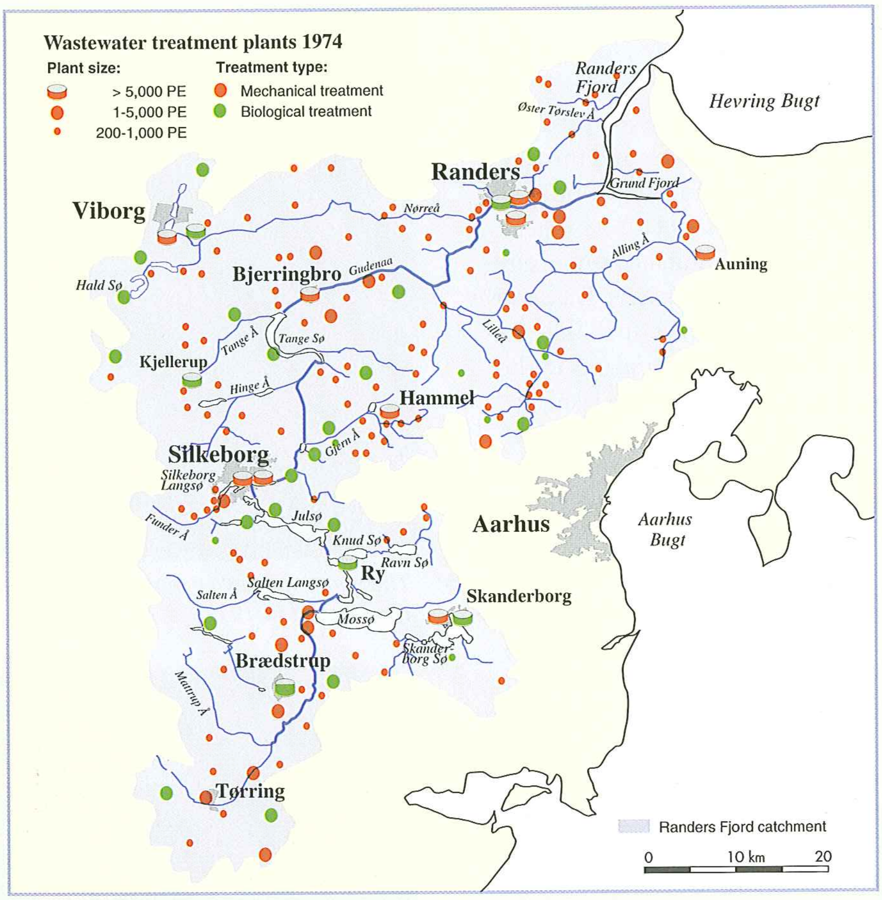
Fish populations and spawning results are monitored by electrofishing. Photo: Jens Møller Andersen

WASTEWATER

Wastewater treatment plants

Wastewater production in the parts of the catchment serviced by sewerage systems approximately corresponds to untreated wastewater from 600,000 persons (Person Equivalents, PE). This includes industrial wastewater, almost all of which is treated in municipal wastewater treatment plants along with sewage from the towns.

The first estimates of nutrient and organic matter discharges from wastewater treatment plants were made in 1974, when less than 50% of the wastewater was biologically treated and phosphorus removal was unknown (Fig. 2). Since then, biological treatment and phosphorus removal have been established in almost all towns exceeding 200 PE (Fig. 3), and sometimes also in even smaller towns. In line with the 1987 Action Plan on the Aquatic Environment, nitrogen removal is also undertaken at most wastewater treatment plants with a capacity exceeding 5,000 PE.



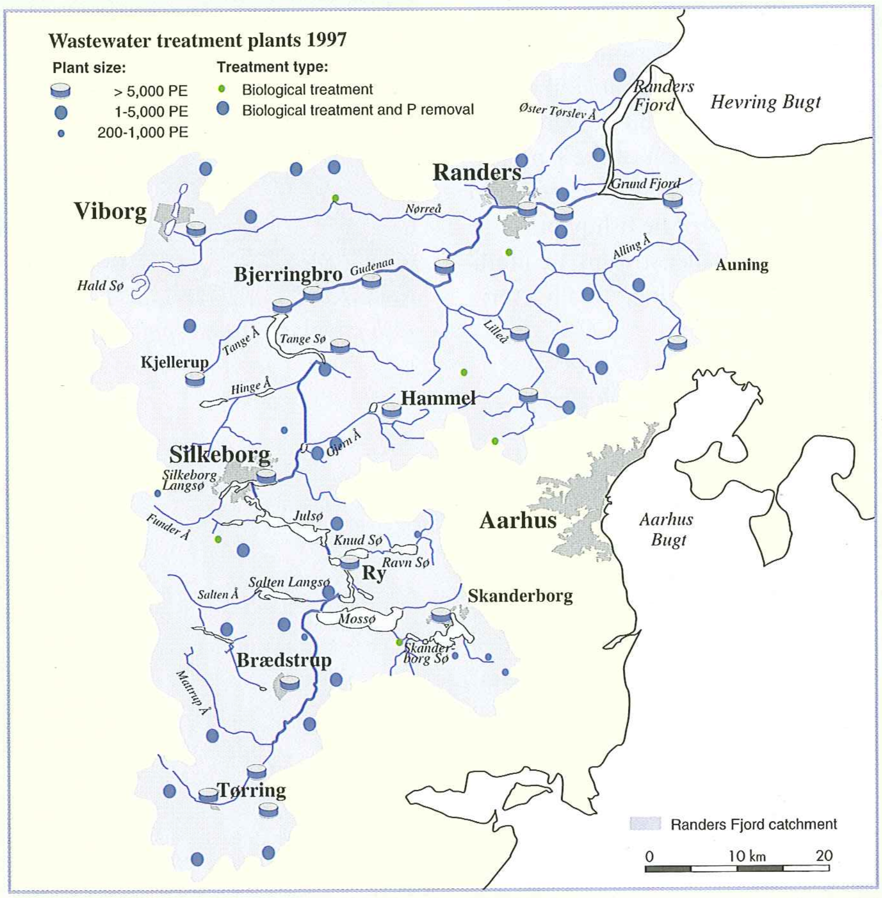


Fig.2.
Wastewater treatment plants in the Gudenaa river system in 1974 indicating plant size and treatment type. Most of the wastewater is only treated mechanically.

Fig. 3.
Wastewater treatment plants in the Gudenaa river system in 1997 indicating plant size and treatment type. Almost all the wastewater is subjected to biological treatment and phosphorus removal. Plants with a capacity exceeding 5,000 PE also remove nitrogen.

Since 1974, phosphorus and organic matter loading from wastewater treatment plants have been reduced by around 90% and nitrogen loading by about 50% (Fig. 4). This has occurred during a period where increasing amounts of wastewater and pollutants are being transported through the sewers to the wastewater treatment plants. The quality of wastewater treatment is currently good with respect to removal of organic matter (BOD) and reasonably good with respect to phosphorus and nitrogen (Table 1).

Katrinedal Fish Farm on the tributary Salten Aa.

Fish farms

Fish farm production of rainbow trout increased from 1,400 tonnes/y in 1974 to more than 3,200 tonnes/y in 1989, and was to 2,300 tonnes/y in 1997. Due to improved production technology and treatment of effluent from the fish ponds, organic matter pollution has decreased by about 90% while discharges of phosphorus and nitrogen have decreased by about 80% and 70%, respectively (Fig.5). This is of considerable importance for the streams and lakes where fish farms are concentrated.

	Untreated wastewater	Treated wastewater	% Removal
Organic matter (BOD)	10,400 tonnes/y	273 tonnes/y	97%
Total phosphorus	390 tonnes/y	23 tonnes/y	94%
Total nitrogen	1,720 tonnes/y	302 tonnes/y	82%

Table 1. Total wastewater input to treatment plants in the Gudenaa river system together with discharges of organic matter (BOD), phosphorus and nitrogen in treated wastewater.

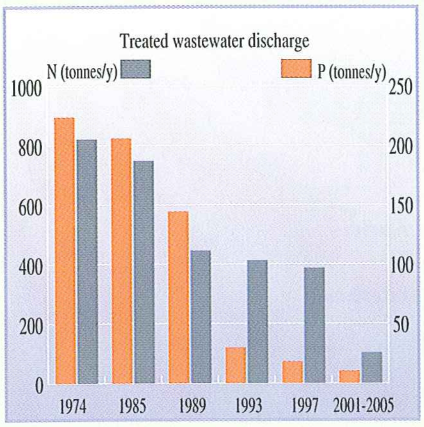


Fig. 4. Annual discharge of nitrogen and phosphorus from all wastewater treatment plants in the Gudenaa river system 1974-97. Estimated future discharges are indicated for the period 2001-2005.

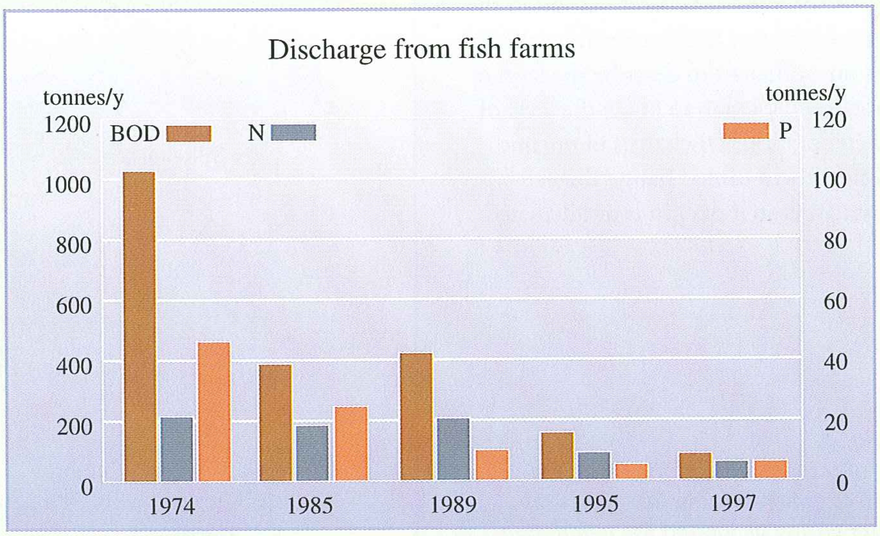


Fig. 5. Annual discharge of organic matter (BOD), nitrogen and phosphorus from all fish farms in the Gudenaa river system 1974-97.

ORGANIC MATTER POLLUTION

Streams

Stream pollution used mainly to be attributable to the discharge of degradable organic matter in inadequately treated wastewater, to polluting slurries from farms or to effluent from fish farms. Before municipal treatment of their wastewater was introduced, very substantial pollution was also seen downstream of food processing plants such as dairies and slaughterhouses.

Wastewater discharge from a slaughterhouse to Lilleaa 1976. Photo: Bent Lauge Madsen

Organic matter pollution has always been restricted in geographical extent, with impact zones limited to about 10 km downstream of major wastewater outfalls and about 1 km or less downstream of minor outfalls.

The environmental impact of organic matter pollution is particularly severe in small streams with little dilution of the discharged wastewater. In large rivers, the problem mainly relates to oxygen depletion caused by decaying organic matter, as described as early as 1925 by Streeter and Phelps.

Oxygen depletion is also an important cause of ecosystem deterioration in the small streams. In this case, however, it is not sufficient to describe the level of oxygen depletion to know the level of deterioration. Discharges of organic matter will often change the ecosystem even if oxygen is not depleted.

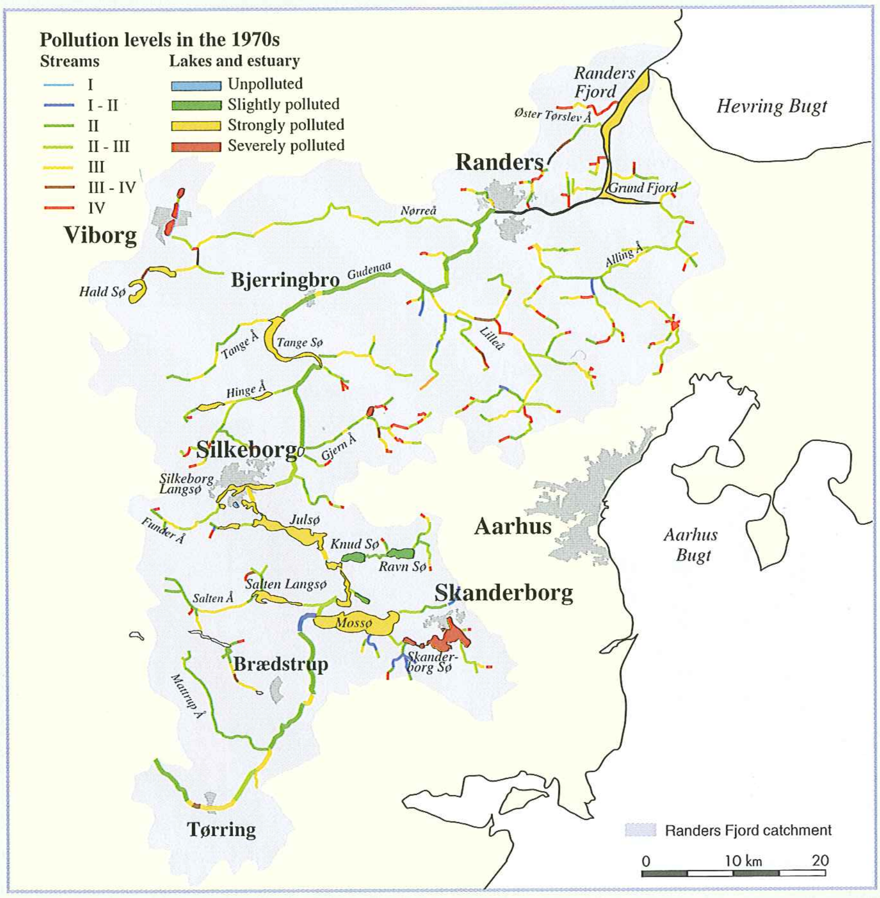


Fig. 6.
Pollutional state of the Gudenaa river system streams, lakes and estuary during the period when pollution levels were highest in the 1970s and early 1980s.

This is because the organic matter covers the stream bottom with sludge, thereby eliminating the substrate for clean-water animals. Moreover, pollution-tolerant species are stimulated by the excessive amounts of food in the form of wastewater organic matter (see, e.g. Hynes 1960).

The reduction in wastewater organic matter loading during the 1970s and 1980s resulted in rapid changes in the pollutional state of the streams. Thus while many of the streams were badly polluted in the 1970s, with degrees of pollution (saprobic levels) ranging from III to IV (Fig. 6), such levels of pollution were rarely found in the 1990s except in a few very small streams, usually polluted by discharges of wastewater from individual rural dwellings outside the sewerage catchments (Fig. 7).

The rapid improvement in stream pollutional state is attributable to the rapid wash-out of sludge deposits from the stream beds and rapid recolonization of clean-water fauna from elsewhere in the river system following restoration of appropriate physical and chemical conditions.

The upper parts of the river Gudenaa are almost unpolluted and intensively used for recreation.
Photo: Jens Møller Andersen

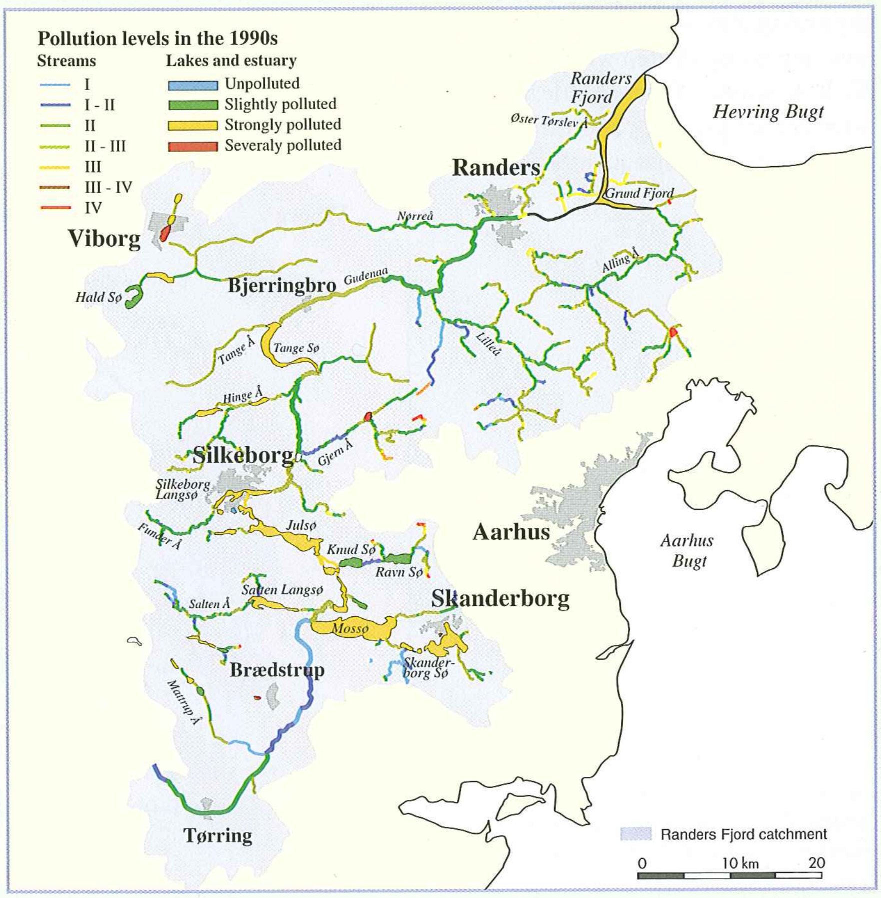
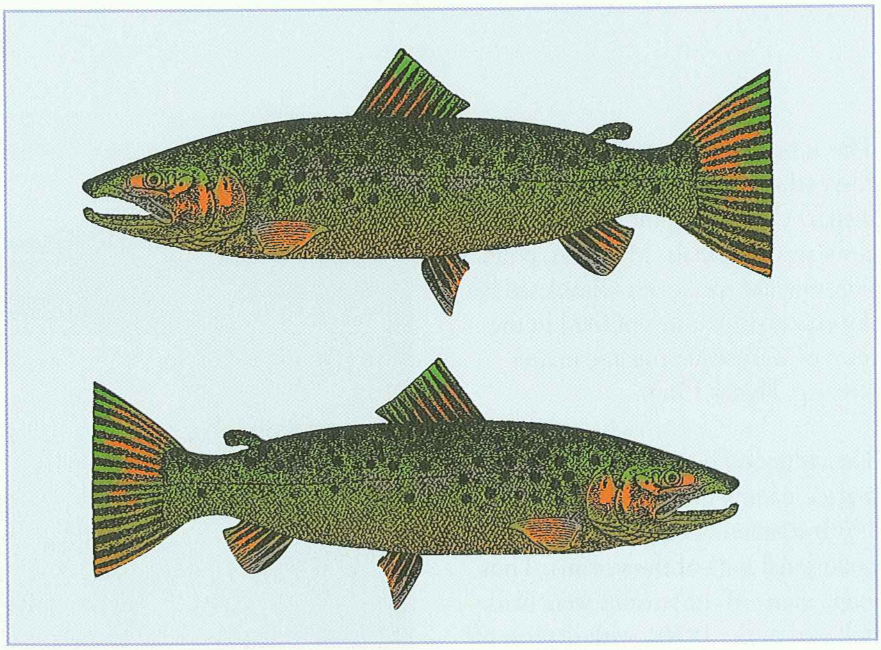


Fig. 7.
Pollutional state of the streams, lakes and estuary of the Gudenaa river system 1997.

Trout populations in small streams

The reduction in organic matter pollution of the streams has improved habitat conditions for the brown trout, *Salmo trutta*, which is the naturally dominant fish in small Danish streams. Trout population densities in 1973-75 and in 1992 are shown semi-quantitatively in Fig. 8 and Fig. 9.

In several streams, the trout population increased during this period, mainly because of improved (biological) wastewater treatment. In most streams, though, the trout populations are much below the environmental quality objectives stipulated in the regional water quality plans, mainly as a result of former stream regulation and maintenance undertaken to meet agricultural demands for drainage of adjacent farmland. However, the physical quality of the streams is now improving in step with the implementation of more gentle stream maintenance practices, and the trout populations are consequently increasing.



Brown trout

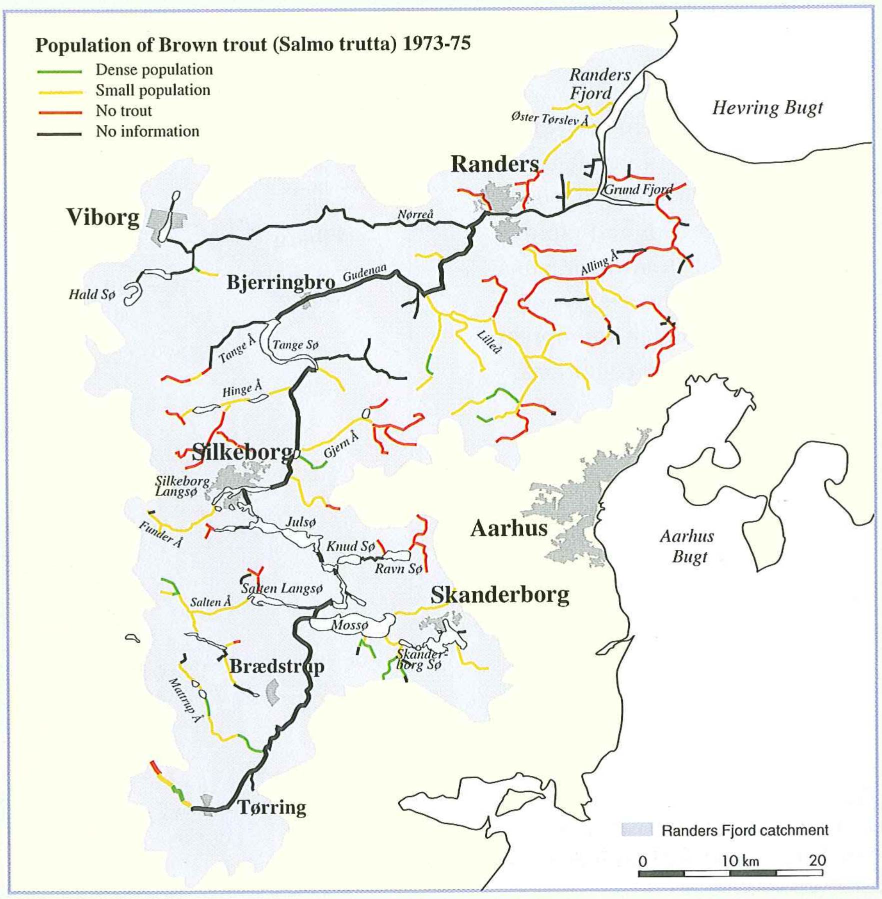


Fig. 8.
Brown trout population density in the smaller streams of the Gudenaa river system in 1973-75.

Lakes and the estuary

Organic matter pollution of the lakes in the Gudenaa river system from wastewater treatment plants has not posed any problem because the level of direct discharges has been low and usually insignificant compared to the eutrophication impact of nutrient loading.

In the estuary, Randers Fjord, direct discharge of organic matter in wastewater was high enough to cause sludge deposition and oxygen depletion in the inner part of the estuary, thereby affecting the benthic invertebrates. Since the establishment of effective removal of organic matter from wastewater, organic matter loading of the estuary has mainly been attributable to algal production in the upstream lakes.

Before the establishment of biological wastewater treatment in the town of Randers the inner part of the estuary was polluted by organic matter. *Photo: Erik W. Olsson*

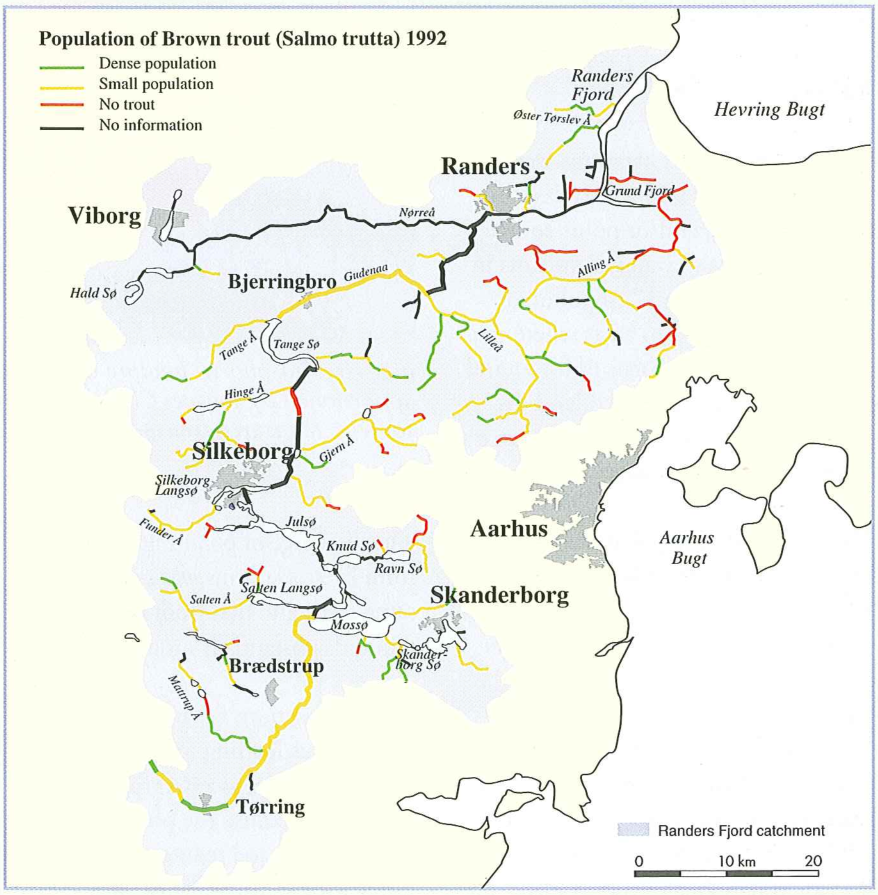


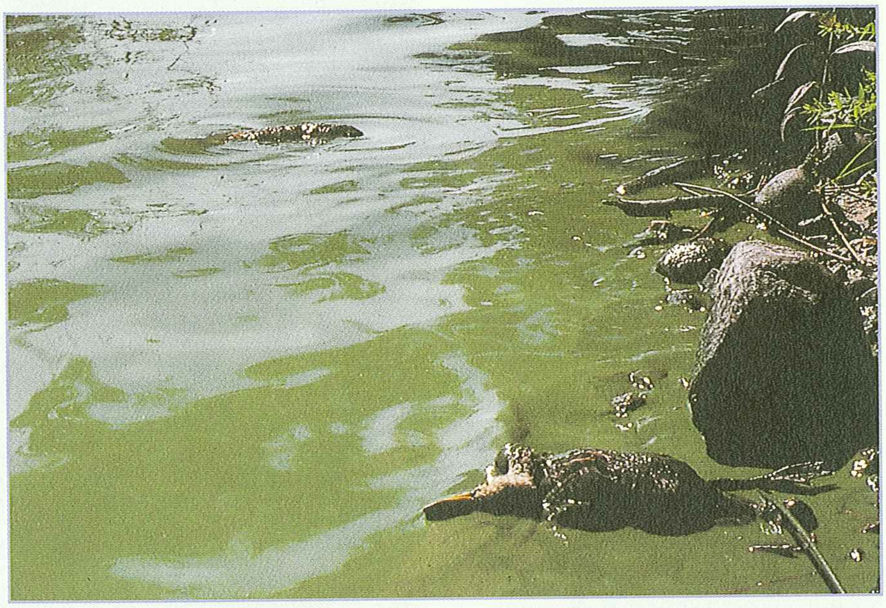
Fig. 9.
Brown trout population density in the smaller streams of the Gudenaa river system in 1992.

EUTROPHICATION OF LAKES AND THE ESTUARY

Nutrient pollution

While organic matter is the main pollutant in the streams of the Gudenaa river system, the lakes and estuary are polluted by excessive nitrogen and phosphorus loading from wastewater sources and runoff from agricultural land. The longer residence time of the water compared to streams allows planktonic algae to develop into nuisance blooms if the concentration of nutrients is sufficient for algal growth.

The excessive growth of planktonic algae leads to low lake water transparency, loss or depletion of submerged macrophytes, oxygen deficit during summer in the deep lakes and during winter ice cover in the shallow lakes, and to profound changes in the entire ecosystem, including the fish populations.



Nutrient loading often leads to blooms of blue-green algae in the lakes.
Photo: Jens Møller Andersen

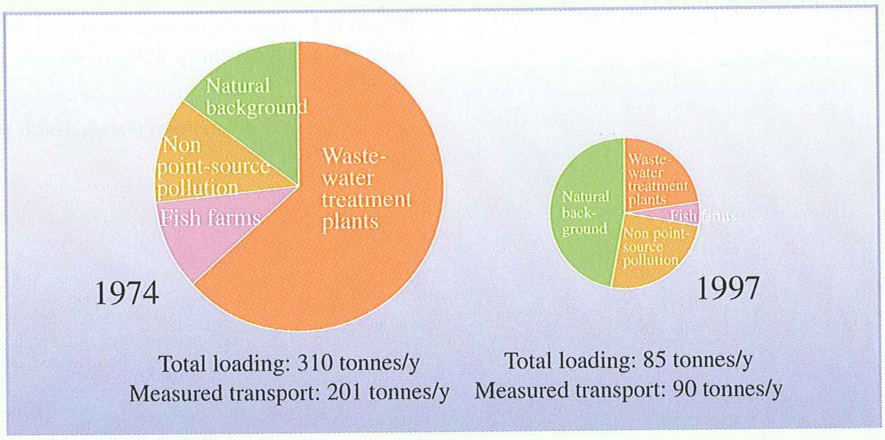


Fig. 10. Phosphorus loading of the Gudenaa river system in 1974 and 1997 apportioned by source. Circle area is proportional to total loading from all sources. Measured transport is also shown.

Lakes

High nutrient concentrations were found in all lakes with cultivated catchment areas and/or point-source discharges of wastewater to streams in the catchment. The 17 unpolluted lakes are all located in areas where the entire catchment consists of forest and other types of uncultivated land devoid of settlements with point-source discharges of wastewater.

The key to reducing pollution of the lakes is to reduce phosphorus loading. In 1979 it was therefore decided that all wastewater from the towns and villages in the catchment area of the lakes in the Gudenaa river system was to be subjected to phosphorus removal. The upgrading of the treatment plants was completed in the larger towns in the 1980s and in the remaining villages in the catchment area in the 1990s.

The discharge of polluting effluents from livestock farms was ceased at the same time, and that from fish farms was reduced substantially around 1990.

The implications of the reduction in phosphorus loading for the individual lakes have to be assessed for each lake separately because the phosphorus concentration and reduction in loading differ widely from lake to lake.

The importance of the reduction in phosphorus loading for the lakes along the main watercourse is illustrated in Fig. 10, which shows catchment phosphorus sources and transport in 1974 and 1997. Lake water quality and incipient improvement in water quality is illustrated in Fig. 11.
The percentage of the phosphorus pollution attributable to wastewater treatment plants and fish farms has decreased, and total phosphorus loading has fallen from

310 tonnes/y in 1974 to about 85 tonnes/y in 1997. Natural background loading and diffuse loading from agricultural land and non-sewered areas therefore constitute a larger percentage of total loading in 1997 than in 1974.

Delayed response caused by phosphorus accumulation in lake sediments

Lake water phosphorus concentration is decreasing following the reduction in external loading, but with a substantial time lag. During the preceding decades with high phosphorus loading, phosphorus has accumulated in the lake sediments. Some of this accumulated phosphorus is slowly being released into the lake water, where it can sometimes support excessive algal growth for decades after external loading has ceased or been reduced. Inertia in biological changes in a lake, for example in the composition of the fish stock, will delay improvement in lake quality (Jeppesen 1998).

As of 1997 the phosphorus concentration has decreased in about 24 of the 48 lakes monitored. Transparency has increased significantly in 12 of these lakes. Lake water quality has only deteriorated in one of the lakes, probably because of changes in the composition of the fish stock. Further improvement is expected during the coming decades without further reduction in phosphorus loading from the catchment area. Because of the very broad quality groups used, comparison of Figures 6 and 7 will only reveal major changes in lake water quality.

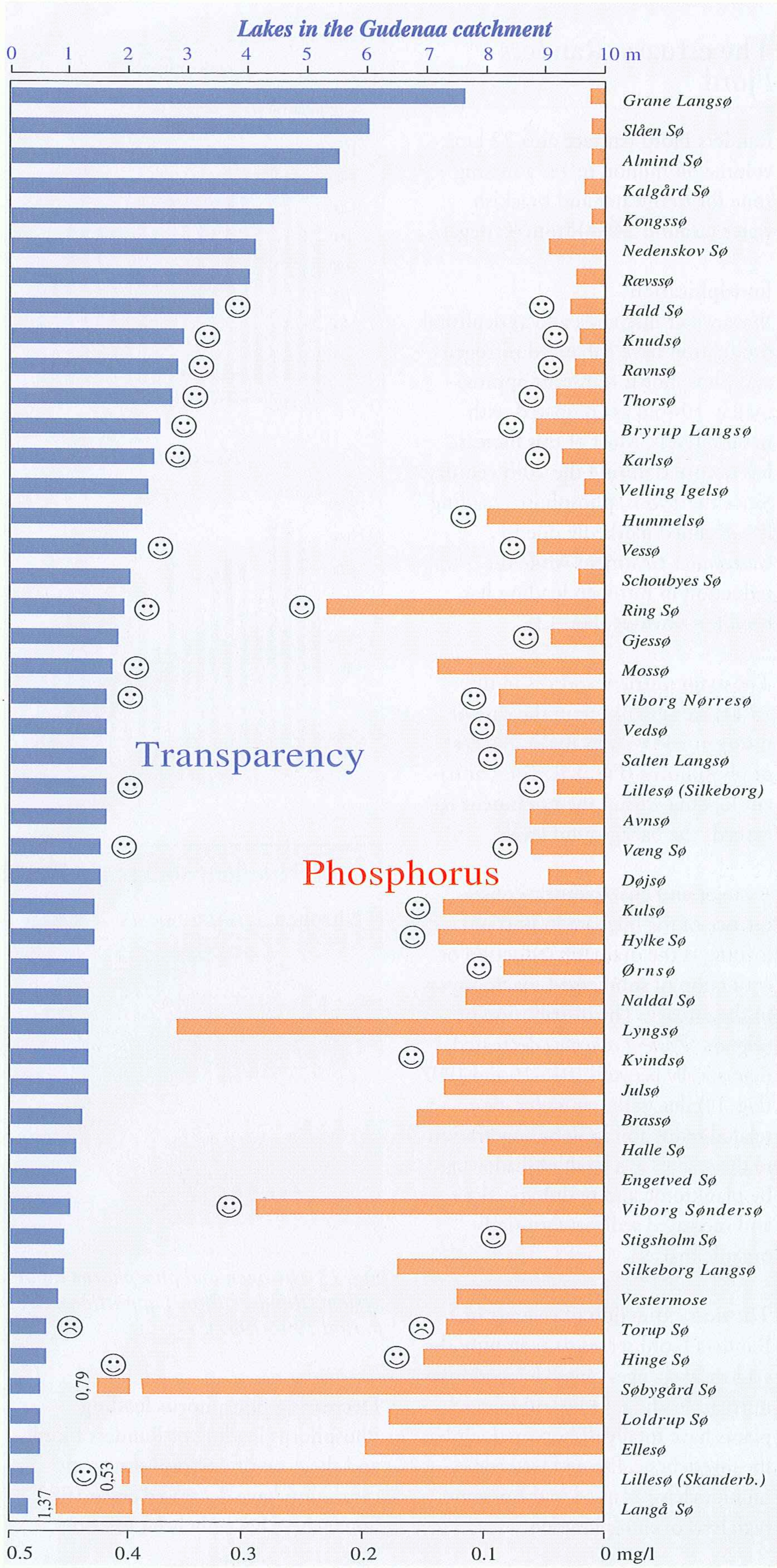


Fig. 11. Annual average phosphorus concentrations and average summer transparency in lakes in the Gudenaa catchment. A happy face indicates improvement in water quality since 1974. Deterioration in lake water quality was only seen in one lake, and was probably due to changes in the fish population.

The estuary, Randers Fjord

Randers Fjord (surface area 22 km², volume 34 million m³) is a mixing zone for freshwater and brackish water (around 24‰) from Kattegat.

Eutrophication

Wastewater discharge and agricultural production have enhanced nitrogen and phosphorus transport approximately 10-fold as compared with natural levels. Most of this increase has occurred during the 20th century. Since the 1980s, phosphorus loading has declined markedly due to wastewater treatment while the reduction in nitrogen loading has been less obvious (Fig. 12).

The main nutrient sources in the 1990s are agriculture in the case of nitrogen and wastewater in the case of phosphorus (Fig. 13). Total nutrient loading within the catchment far exceeds the background levels.

A major and characteristic consequence of the increase in nutrient loading is the dramatic reduction or extinction of submerged macrophytes in the estuary. The distribution of eelgrass *(Zostera marina)* decreased dramatically between 1915-16 and 1997 (Fig. 14) due to the eutrophication-related reduction in light penetration to the eelgrass as a result of shadowing by planktonic and periphytic algae and increased sedimentation of organic matter.

The near extinction of eelgrass in Randers Fjord serves to exemplify the ecological changes caused by increasing nutrient loading. Other submerged plants have totally disappeared while the invertebrate, fish and bird communities have adapted to the present high level of eutrophication.

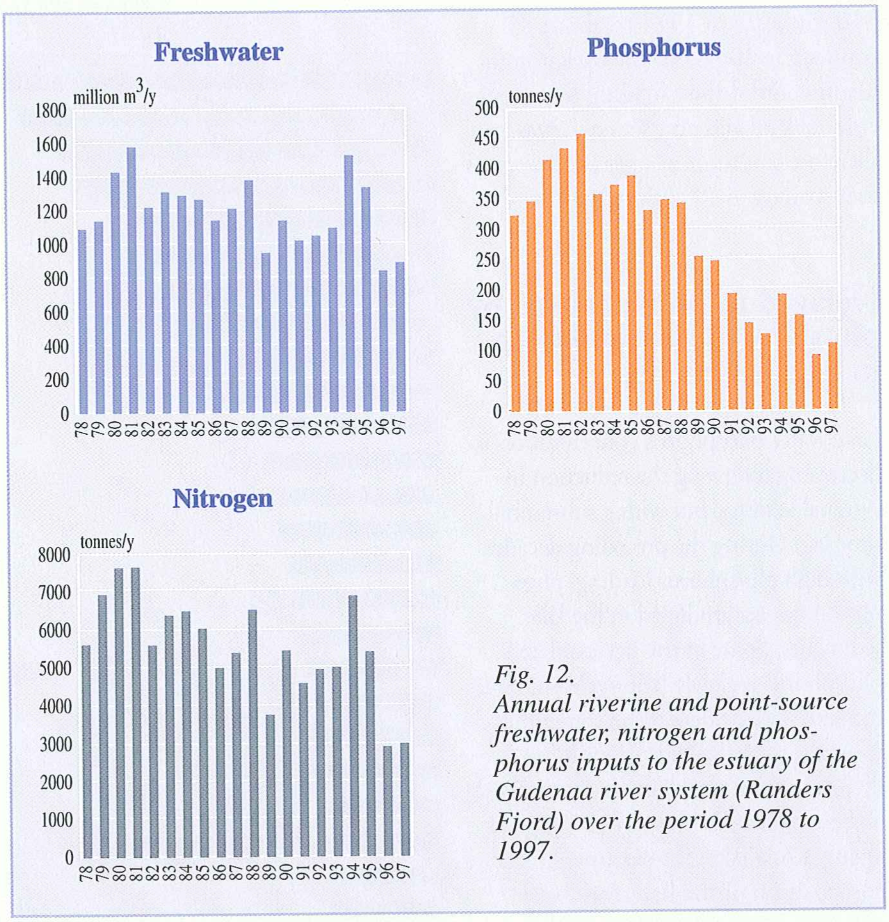


Fig. 12. Annual riverine and point-source freshwater, nitrogen and phosphorus inputs to the estuary of the Gudenaa river system (Randers Fjord) over the period 1978 to 1997.

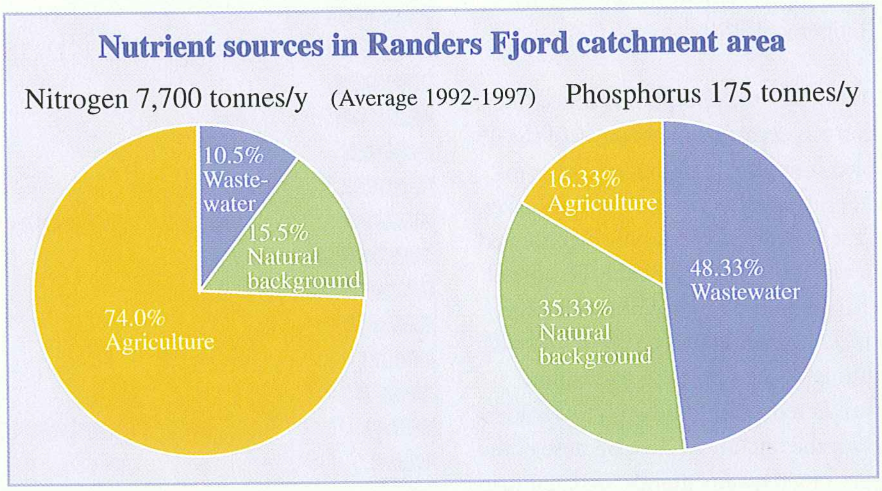


Fig. 13. Nitrogen and phosphorus input to the estuary of the Gudenaa river system (Randers Fjord) apportioned by source (annual average values for the period 1992-1997).

Decreasing phosphorus loading

Phosphorus loading of Randers Fjord and the estuarine phosphorus concentration have decreased since 1982. So far there has only been minor improvement in water quality, however. A major reduction in phytoplankton and anchored algae will require further reduction in the phosphorus concentration of the estuarine

The outer part of the estuary, Randers Fjord, is a shallow waterbody where freshwater from the river Gudenaa mixes with saline water from Kattegat. *Photo: Erik W. Olsson*

The inner part of the estuary, Randers Fjord, is a narrow navigation channel. *Photo: Erik W. Olsson*

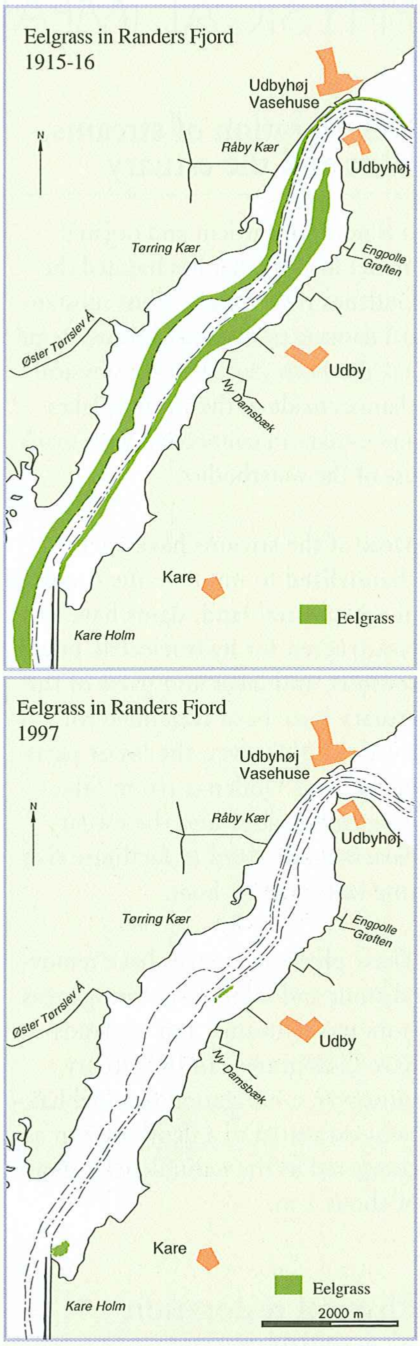


Fig. 14. Distribution of eelgrass (Zostera marina) in the Gudenaa river system estuary (Randers Fjord) in 1915-16, before the estuary became extremely eutrophic, and again in 1997.

water, and this will not occur until the phosphorus accumulated in the up-stream lake sediments has been exhausted. The transport of phyto-plankton produced in upstream lakes via the river Gudenaa will simultaneously decrease because of phosphorus limitation of algal growth in the lakes.

Water quality can be expected to improve still further when nitrogen loading from agricultural land and wastewater discharges of phosphorus have been reduced even more, cf. Fig. 13. According to the 1987 Action Plan on the Aquatic Environment, nitrogen loading from agricultural sources is to be reduced by 50%.

PHYSICAL IMPACT ON SURFACE WATERS

Deterioration of streams, lakes and the estuary

It is not just nutrient and organic matter loading that has harmed the Gudenaa river system. Thus substantial damage to the aquatic ecosystems has also been caused by the physical changes made to the streams, lakes and estuary in connection with man's use of the waterbodies.

Most of the streams have been channelized to improve the drainage of agricultural land, dams have been constructed for hydroelectric power stations, and lakes and parts of the estuary have been reclaimed for cultivation. Moreover, the lower parts of the river Gudenaa (from Silkeborg to Randers) and the estuary have been dredged to facilitate riverine transport by boat.

These physical changes have removed trout and salmon spawning areas from most streams, and wetlands have disappeared. In the estuary, moreover, a navigation channel has been excavated to a depth of 7 m as compared to the natural water depth of about 1 m.

Dams at old mills have prevented fish migration. According to the Gudenaa Committee recommendation, most of these fish passage obstacles have been removed.
Photo: Jens Møller Andersen

Until the 1980s the stream ecosystems were often destroyed by stream maintenance undertaken to improve the drainage of water from agricultural fields in the stream valleys.
Photo: Jens Møller Andersen

Physical restoration of streams

Since the 1980s the environmental authorities (Counties and Municipalities) have restored many of the stream ecosystems formerly destroyed by this physical "pollution" and the stream maintenance undertaken to protect farmland from flooding.

The removal of dams preventing fish passage to spawning grounds etc. is also important. Dam removal is not always possible, however, for example if it involves a cultural heritage or hydroelectric power station. In such cases, a parallel fish pass can usually be constructed. Progress in the removal of major obstacles to the passage of fish in the Gudenaa river system is summarized in Fig. 15.

Restoration of wetlands

Many wetlands were reclaimed for agricultural cultivation during the 20th century. This practice has now ceased, however, and attempts are being made to restore some of the wetlands. There are two main objectives: Firstly, to regain a type of ecosystem lacking in the Danish landscape, which is presently dominated by agricultural land, and secondly, to exploit the ability of such wetlands to serve as sinks for nutrients and suspended matter transported by the streams, thereby reducing the nutrient loading of downstream lakes and coastal waters.

Under the 1998 Action Plan on the Aquatic Environment II, 16,000 ha of agricultural land is to be restored to wetland before 2004 in order to reduce the nitrogen transport to the sea by 5,600 tonnes N per year.

Most streams have been channelized to improve the agricultural use of the stream valleys. Restoration of streams and wetlands will reduce the nutrient transport through the streams and improve the ecological qualities of the streams and valleys. Photo: E. W. Olsson

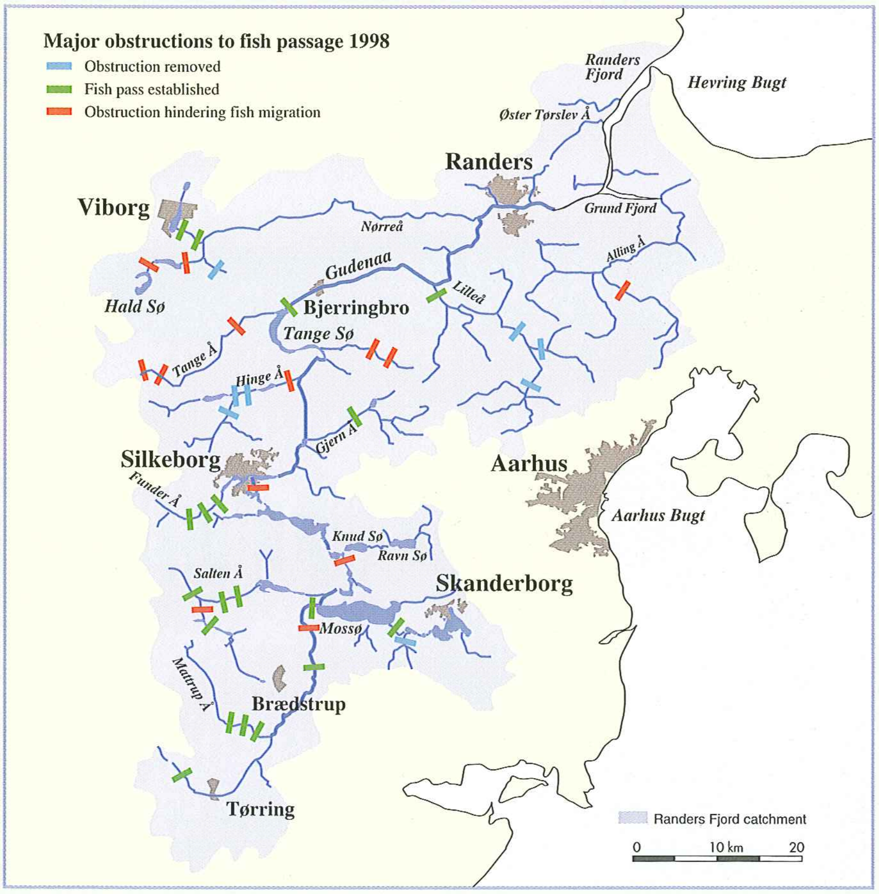


Fig. 15.
Major obstructions to fish passage in the Gudenaa river system. The map indicates intact obstructions, obstructions where a fish pass has been established, and obstructions that have been completely removed since 1974.

CONCLUSIONS

Regional water quality planning undertaken by the Counties and coordinated by the Gudenaa Committee has substantially improved water quality in the Gudenaa river system.

The reduction in organic matter loading has rapidly improved river water quality. However, despite the establishment of phosphorus removal at wastewater treatment plants, improvement in the lakes and estuary has been delayed for decades due to the slow release of accumulated phosphorus from the lake sediments. Besides improving conditions within the river system itself, the reduction in loading has also reduced phosphorus loading of the adjacent open marine waters.

The ecological damage to aquatic ecosystems caused by physical changes such as stream regulation and land reclamation are as severe as the damage caused by pollution. More environmentally sound stream maintenance practices have been implemented and major efforts are being made to remove obstacles preventing fish migration and to restore streams and wetlands.

The lesson gained from the Gudenaa river system is that profound improvement in surface water quality is possible through wastewater treatment and improved agricultural practices, although pristine water quality cannot be achieved in densely populated and highly cultivated catchments.

Sunset at Randers Fjord

Photo: Jens Møller Andersen

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