Urban Impact in the History of Water Quality in the Stockholm Archipelago

From the historical perspective, the increasing number of inhabitants in the city of Stockholm has had a negative effect on water quality in the surrounding lakes and coastal region. Government control and measures taken to improve water quality have been in progress since the mid-19th century. Water conditions in the 19th century, compared to later years is difficult to assess from the first chemical and biological investigations, due to infrequent sampling and the different parameters and methods used. However, a retrospective evaluation of water quality can be made on the basis of results from plankton investigations, which began in the early 20th century. The occurrence of the cyanobacteria *Planktothrix agardhii*, which indicates nutrient-rich conditions, was surveyed during summers with similar temperature conditions throughout the 20th century. The results show that eutrophied conditions probably prevailed in the Stockholm archipelago from the beginning of 20th century until the early 1990s. In the last decade of the 20th century, water quality appeared to be better than 100 years earlier. Today’s better water conditions are most probably an effect of proper measures taken in wastewater treatment.

INTRODUCTION

Since the city of Stockholm was founded in the 13th century, it has grown from a small country town to a large metropolis. Its surrounding waters have always been of vital importance to the everyday life of its inhabitants, while also being the recipient of wastewater from the growing community. Hence, water quality must have spurred public concern early on, even though the actions of governing authorities before the mid-19th century are not known (1). Analyses of sediment cores (2) and estimations of nutrient loading for 1900–1970 (3) indicate that eutrophied conditions have prevailed in the Stockholm archipelago for many years. But what can we say about changes in water quality? Were water conditions better at the beginning than at the end of the 20th century? In this study, governmental control and measures taken to improve water quality in the Stockholm archipelago are presented. Water quality in the 20th century is studied in terms of phytoplankton species composition and with a focus on the occurrence of the cyanobacteria *Planktothrix agardhii*, an indicator of nutrient-rich conditions (4). Both published information and material from unpublished sources have been taken into consideration.

STOCKHOLM’S INNER ARCHIPELAGO

The city of Stockholm is situated at the outflow of Lake Mälaren into the Baltic Sea. The stream Norrström constitutes the main connection between lake and sea (Fig. 1). Originally constituting an inlet from the Baltic Sea, due to land uplift Lake Mälaren has gradually come to be cut off from the sea. This connection with the sea was still evident in the 20th century, with causal inflow of brackish water into the lake in connection with a high water level in the Baltic Sea. In order to stop the influence of brackish water, as well as to keep constant water level in Lake Mälaren, a conclusive end was put to the westward transport of water in 1968 through the construction of a large floodgate at Norrström. The adjacent brackish water area in the center of Stockholm is called Lake Saltsjön. East of Stockholm, an archipelago some 80 km wide, with thousands of islands, makes a varying water landscape of large inlets and narrow passages. The steep topography yields deep bottom areas shielded by shallow sills.

Water from Lake Mälaren flows past the archipelago in an eastward direction into the open waters of the Baltic Sea (Fig. 1). This surface outflow of freshwater causes a deep counterflow of more saline water (approx. 4%), contributing to water exchange between the outer and inner areas of the archipelago. Due to the protective sills, the bottom water of the innermost part of archipelago has a higher retention time than the area further out (5). A natural border between the inner and outer archipelago, the Oxjupet sill (Fig. 1), plays a central role in the exchange of water between the two areas. Oxjupet has been deepened three times during the 20th century, increasing its depth from 8 to 20 m, in order to increase water exchange (Table 1).

The inner archipelago receives nutrients transported from Lake Mälaren, from direct sewage outlets, runoff from land, and precipitation. The two far largest nutrient sources in the inner archipelago are the outflow from Lake Mälaren and from sewage-treatment plants. The total mean loads from these sources in 1976–1999 were 8000 tonnes of nitrogen and 230 tonnes of phosphorus per year (6). The relative contribution from Lake Mälaren and the treatment plants vary from year to year but, on average, Lake Mälaren contributed 73% of the phosphorus while...
the nitrogen load was more equally distributed among the sources compared (6).

**TREATMENT OF WASTEWATER THROUGHOUT HISTORY**

Stockholm’s use of freshwater and treatment of wastewater have been thoroughly described by Cronström (1) and will only briefly be summarized here. Some of the first evidence of wastewater planning in Stockholm is seen in connection with the formation of gutters, when the streets were covered with cobblestones in the 15th century. The gutters and collecting ditches together served as wastewater collectors until the mid-19th century. This system could be more or less endured as long as the water flow was high, but during dry, hot summers, the city could be choked with the terrible stench originating from these ditches. By way of further transport in soil and water systems, the wastewater outlets sooner or later affected the water quality of Stockholm’s coastal waters.

Before the 19th century, lakes that received wastewater were also often used as sources of drinking water. Until the mid-19th century, Årsta Bay (Fig. 1) was a main source of drinking water for the Stockholm area. At the same time, Årsta Bay received sewage water from a large part of the growing city, as well as wastewater from industry. Health problems were undoubtedly affected by this incompatible situation and certainly a key factor in the spread of two severe cholera epidemics in Stockholm, in 1834 and 1853.

In order to provide safe drinking water for Stockholmers, a waterworks and pipe system were built near Årsta Bay in 1861–1896. The water was led through a sand filter and a description from 28 August 1880 of the lake water gives us an idea of the water quality before filtration: “muddy, deeply coloured yellow, with a large amount of infusorians and an unpleasant odour” (7). The quality of the drinking water and the question of whether or not it was contaminated by wastewater were topics of discussion in the late 19th century. The Public Health Board proclaimed that health problems were not at all associated with wastewater contamination and that the waterworks provided faultless water (8). In time, however, the situation became precarious and the drinking water supply was improved through the construction of a new waterworks at Lake Mälaren (Norsborg in 1907, and Lovön in 1933).

With an increasing number of inhabitants, functional solutions for wastewaters were also sorely needed. After the early installation of a number of private sewer pipes in various areas, the first public sewage system was built in 1864 in the southern district of Stockholm (Södermalm). This new, underground wastewater network was gradually expanded and, in 1872, 3 sewage mains led wastewater into Lake Mälaren, Lake Saltsjön and a number of other smaller lakes.

In 1900, wastewater from about 200,000 city-dwellers was discharged into the inner archipelago. Water-closet toilets had come into common use and water conditions in the recipient deteriorated. The debris floating in the water, a high concentration of bacteria, and the stench from hydrogen sulfide were troublesome. In the beginning of the 20th century, the solution to this was to increase the length of the sewage pipes and to distance the outflow further out into deeper water (3). It soon became clear, however, that the sewage had to be treated in some way. The first wastewater-treatment plant, Åkeskov (Bromma), was built at Lake Mälaren in 1934 (Fig. 2). The second plant, Henriksdalsverket, which discharges into the inner archipelago, was built in 1942. Initially, only mechanical treatment of the sewage was applied.

During the 1960s and 1970s, the treatment of wastewater benefited from new biological methods and chemical precipitation of phosphorus (Table 1). Nitrogen reduction began in 1997 and is still under expansion. In the Stockholm area, there are now 8 wastewater-treatment plants, of which 7 discharge into the inner archipelago (Fig. 2). In total, 1.5 million people and a large number of industries are connected to the plants (9).

**CONTROL OF WATER QUALITY**

At the end of the 19th century, the Public Health Board of the municipality of Stockholm was responsible for the regulation of both drinking water and water quality in wastewater recipients. Starting in 1870, the Board began to publish annual health statistics for the inhabitants of Stockholm. Besides the number of residents, diseases, epidemics and mortality, meteorological data...
and data on variations in water level, and the chloride-content in Lake Mälaren and Lake Saltsjön were also given.

The first investigation program on water quality started in 1874. Being the main source for drinking water for the residents in Stockholm, the water quality of Ärsta Bay was of special interest, but the lakes Mälaren and Saltsjön were also included in the program. In addition to measurements of temperature and salinity, the program included measurements of bacteria (from 1888) and oxygen content (from 1895) (10, 11). Two special investigations worth mentioning, conducted toward the end of the 19th century, concerned the direction of wastewater flow (12) and the concentration of bacteria in different areas (13).

PLANKTON INVESTIGATIONS
The first investigation of plankton in the waters of Stockholm was carried out in 1909–1911 by the Public Health Board. The object was to obtain supplementary information regarding the assessment of water quality using existing chemical and bacteriological methods. Plankton was sampled at a total of 19 sites in Lake Mälaren and the inner archipelago. Both zoo- and phytoplankton were collected, using nets, during the ice-free season at different depth intervals. Dominating species of the plankton community were estimated on a relative scale of 8 classes.

Figure 4. Sampling equipment used in the early 20th century (15).

The results were assessed according to Kolkwitz and Marsson’s saprobic system, in which specific species are used as indicators of water pollution (14). In 1909–1911, plankton sampling and the said analyses were carried out by Dr. Cleve-Euler (Fig. 5) and the botanist at the Board’s laboratory, Dr. Huss (15).

Plankton investigations continued in 1913 with supplementary net sampling for quantitative determination of total organic material content. This was estimated by allowing the samples to settle in graded glass tubes (sesont tubes) for 4 months, after which the total volume of organic material was determined (16).

Partly contemporaneously, in 1910–1916, Stockholm Water Works performed plankton investigations in Lake Mälaren (17, 18). Further investigations, starting in 1936, were conducted under the charge of the biological laboratory at Stockholm Water Works (later Stockholm Water Co.). By this time, the inner archipelago was also included in the investigations. Sampling sites,
frequency of sampling and methods varied over the years, but most often included both quantitative and qualitative samples. Classification of plankton frequency was made according to methods in use in 1910–1911, and the results were classified according to the saprobic system (14) until the beginning of the 1940s. An important development in plankton investigations occurred in the 1960s when plankton analysis went from using ordinary to inverted microscopes (19). The results, up to 1971, are available as raw, sometimes incomplete, protocols. Some samples have not yet been analyzed, but are still stored at Stockholm Water Co.

Since 1972, qualitative and quantitative plankton samples have been collected regularly. Qualitative sampling has been made with a small plankton net (mesh size 25 μm), from a depth of 5 m to the surface. During some periods, quantitative samples were collected by means of a bucket, but since the 1980s samples have been taken using a 2-m tube. Since the 1990s, the analysis of plankton has been carried out using a semiquantitative method that includes sampling by net and estimation of the number of dominating species per volume unit (20). Results are presented in annual reports compiled by Stockholm Water Co.

Plankton was also studied in the archipelago from 1969–1976, as a part of a comprehensive research project, Nutrient Investigations in the Stockholm Archipelago. The aim of this project was to study the effects of nutrient variations on algal species composition and growth, following the introduction of biological treatment in Stockholm wastewater-treatment plants. Seasonal variation in plankton species composition, biomass of dominating species, and limiting nutrients for algal growth were studied in a gradient from the inner to the outer archipelago (21–25).

WATER QUALITY REFLECTED IN PHYTOPLANKTON

A study of the descriptions of phytoplankton species composition given in control programs and research has been carried out

Figure 7. Mean content of chlorophyll a (μg L⁻¹) in surface water for June–September, Stockholm archipelago. Samples taken at least once a month. Data from 6, 26–30. Sampling sites locations given in Figure 1.
to evaluate changes in water quality in the Stockholm archipelago during the 20th century. Special interest has been devoted to the occurrence of *Planktothrix agaridii* (earlier *Oscillatoria agaridii*), which indicates nutrient-rich water conditions (4). The studies were based on results from the very first plankton investigation in 1910–1911. The mean air temperature during these summers, 14.3–15.3°C, was lower than usual. As phytoplankton composition and biomass often vary with temperature, only years with similarly low temperatures have been taken into consideration. Because of periodically infrequent sampling, varying sampling sites and different methods used for sampling and analyses during the 20th century, only a limited number of investigations can be compared (Table 2). However, from the scattered information available, it is evident that *Planktothrix agaridii* was a characteristic, and very often dominating, species in the archipelago during summers throughout the century. Favoring both the high availability of nutrients and high water temperatures (27), the predominance of *Planktothrix agaridii* was probably more obvious in years with high summer temperatures.

A survey of biomass variations in the archipelago for the entire century cannot be made, due to noncomparable methods of sampling and analyses. Measurements of plankton biomass in terms of chlorophyll *a* in 1957–1985 show that the abundance of plankton was normally highest in the innermost archipelago, about 15 km east of Stockholm (22, 28). The highest biomass was recorded in the period 1969–1972, after which it has decreased (Fig. 7). In 1993, the biomass in the inner areas was still higher compared to the outer areas of the archipelago, whereas, in 1995 and 1999 it was more or less at the same level in the whole archipelago. *Planktothrix agaridii* was the overall dominating species until the early 1990s when only scattered blooms were recorded (6). From 1995–1999, other cyanobacter genera such as * Aphanoizomenon* and * Woronichinia* dominated (6).

The evaluation of water quality in the inner part of the Stockholm archipelago based on the occurrence of phytoplankton, thus, indicates that nutrient-rich conditions prevailed from the beginning of the century until the early 1990s. The occurrence of eutrophic conditions as early as at the beginning of the century is consistent with results from Bennerstedt (3), based on estimations of total nutrient load to the archipelago 1900-1970. The decrease in total biomass and change in phytoplankton dominance from *Planktothrix agaridii* to a more species-rich community, taking place at the end of the 20th century, is most likely a result of the effective reduction in the nutrient loads of wastewater-treatment plants.

References and Notes

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