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A quantitative analysis of discharges into the Helsinki urban sea area in 1850–1995

A city is the largest construction on earth, and it will become even larger and more complex in the 21st century. In fact, it has become impossible to plan sustainable human societies without considering the cities and their environmental impact. This article aims to study the change in the environmental impact of a city - Helsinki - from a historical point of view, specifically the changes in the load from urban areas to watercourses over time. A model of four stages of urban development is presented to provide a quantitative estimation of the change in discharges (P, N, BOD_7) into urban water bodies over the past 150 years.

INTRODUCTION

Urbanisation is, if anything, a fragmented process. Different cities in different places have their own particular history. Nevertheless the main characteristic of urbanisation is growth. Accordingly, it is tempting to evaluate the changes caused by urban domestic waste water only in terms of population growth. The inhabitants may be given certain contemporary values indicating relative to the loads produced and then these figures may be extrapolated backwards in time. The result is a logical curve showing the growth of the urban load. This approach could be recommended if cities had the same sanitary or environmental technology in the past as they have today. This assumption is, however, unrealistic.

To understand the large-scale structural changes that result from urban environmental impacts we should make an overview, a cross-section of the place and time we aim to study. In this way we may learn about the structures at given times instead of trying to capture their development. To facilitate a statistical evaluation we have chosen four different decades to be compared. Each time period is supposed to present a certain stage of urban development with different waste and waste water technologies.

- 1850s: the latrine town
- 1900s: the piped city
- 1950s: the networked city
- 1990s: the centralised system

To provide estimates for a given period, historical source material was integrated with present-day methods of calculating environmental loads. Due to gaps in the historical statistical data, the stages presented here are rather general models based on the estimates calculated by the authors.

The subject of this case study represents a medium-sized European city, Helsinki. This has been done on purpose, as large cities often give a distorted impression of the common basis of our urban history. Technical development in large cities has often been more rapid than in other cities. Yet most of the people in Europe live in medium or small cities where the technical and scientific developments have been slower or taken different ways.

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MATERIAL AND METHODS

Study area

The study area covers the present day Helsinki with its centre, suburbs and semi-rural areas. Helsinki, the capital of Finland, has 0.5 million inhabitants. It is a rather typical medium-sized Nordic city. The city is situated mainly on a narrow cape surrounded on three sides by the brackish water of the Baltic Sea. Today the land area of Helsinki is about 185 km^2. In the 19th century the administrative area of the city was less than 20 km^2.

The cape region has remained as a major source of pollutants. A great deal of the total load to the sea area off the city comes also from the drainage area of the Vantaa River, which empties into a bay east of Helsinki. This river collects nutrients from various points and diffuse sources from a total drainage area of almost 1,700 km^2. The share of present-day Helsinki of this area is only about 45 km^2 [1].

Loads

The aim of this paper is to point out the most significant changes in the waste water treatment systems and to quantify the total organic and nutrient loads (nitrogen N, phosphorus P and biochemical oxygen demand BOD_7) washed into the urban sea area during the past 150 years. The loads are also shown geographically in order to illustrate their distribution in the urban coastal zone.

In terms of urban water pollution history, the eutrophic loads originate from inhabitants' excrement and daily household sewage. To study the flow of household waste water into sea we must study 1) the toilet system, 2) the sewer system and 3) the purification system. Other sources of anthropogenic pollution, such as agriculture and industry have to be evaluated, too. And furthermore, by calculating the natural load from forests, meadows and other non-cultivated lands, we can distinguish the impact of human waste discharges from other natural sources.

In this study, the main focus is on point loads, which have been historically the most important ones. Diffuse loads are, however, also estimated, taking into consideration their inaccuracy. For simplification, atmospheric emission of nitrogen has not been taken into account.

Potential loads

Every activity, whether anthropogenic or natural, has a specific potential load. Potential loads can be obtained, to begin with, from specific pollutant loads, which are the loads specific to a certain source or activity, for example to inhabitants or domestic animals, factory production units, arable lands, forest soil etc. The daily potential load is computed as the product of the specific pollution load and the volume. For example the load of settlement origin nitrogen is calculated in the following way:

> POTENTIAL LOAD (gN/day) = SPECIFIC POLLUTION LOAD (gN/inhabitant/day) x VOLUME (number of inhabitants)

Specific pollutant loads are calculated or obtained from literature. These values are naturally average values, and they contain uncertainties.

Most of the nitrogen in domestic waste water comes from human excrement. Its specific per capita load has remained rather stable. The slight increase is a result of improved nutrition. The daily per capita pollution load of phosphorus has, on the other hand, approximately trebled, mainly due to the post-war introduction of synthetic polyphosphate detergents. Some recorded data on the changes of the specific loads of nitrogen and phosphorus can be seen in Figure 1. The population of Helsinki is presented in Table 1.

The specific organic load, which depends mainly on the size of the community and water consumption, has also increased over the years. It has ranged between 55 to 130 g/inh.*d according to various sources [2]. Besides, per capita loads the specific loads of domestic animals, industry and agriculture have increased as well, due to e.g. improvements in nutrition, industrial processes and fertilisation.

The values used in the calculations for the 1850s and 1900s are obtained from literature, as are the nutrient loads in 1950s. A more accurate approach in the case of the BOD load in the 1950s and 1995 is to calculate the weighted values from the operational records of the waste water treatment plants. The values used in this study have been gathered in Table 2.

Another factor we need to know is the volume of a source or an activity, for instance the number of inhabitants or domestic animals or the production volume of factories within the drainage area. Furthermore, if we intend to divide the loads into southern, western and eastern sections of the coastal area, we should know the number of inhabitants in each part of the city. This information is obtained from maps of drainage areas, demographic statistics and from sewage system maps from the period in question.

Cows, horses and pigs played an important part in urban history. Thus it is reasonable to include their contribution to residential discharges in the point load. Quite a few studies of the specific loads from domestic animals, and consequently rather diverse results, are available. It has been assumed in this study that a cow and a horse are both equivalent to three persons and a pig to 1.3 persons. This is again a rough simplification, as these ratios are actually dependant on the component (N, P or BOD) in question. The specific loads are presented in Table 3.

The numbers of domestic animals have been estimated as a ratio of animals to inhabitants. According to a statistical survey of 1876, there was approximately one cow for every

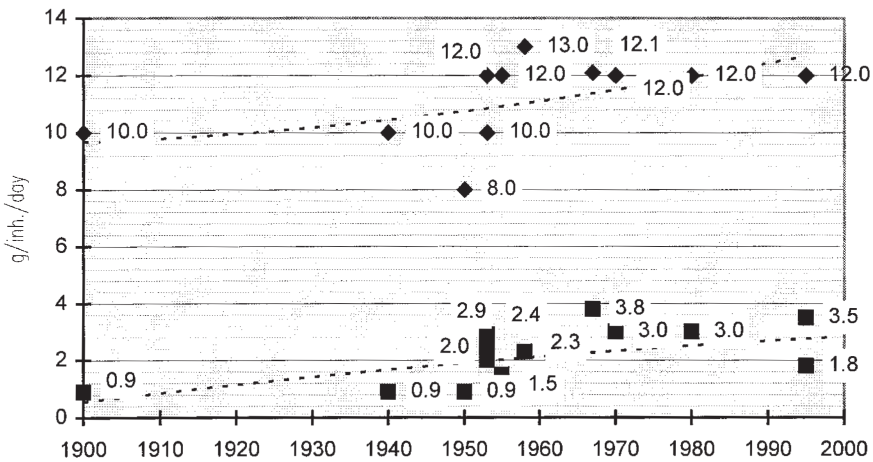

Figure 1. Some records of the development of average daily per capita loads of nitrogen and phosphorus

Table 1. Population of Helsinki in 1850–1995 according to approximate drainage area

	1850	1910	1950	1995
South	12,000	49,000	84,000	516,000
West	0	7,000	115,000	0
East	3,000	34,000	136,000	0
Central bay	5,000	30,000	6,000	0
Total population of the city	20,000	120,000	341,000	516,000
Scattered settlements	5,000	10,000	30,000	0
Total population of city environs	25,000	130,000	371,000	516,000

Table 2. Specific per capita pollution loads in 1850–1995

g/inh*day	1850	1900	1950	1995
BOD_7	55	55	61	71
N	10	10	10	13
P	0.9	0.9	2	2

Table 3. Specific pollutant loads of domestic animals

g/day	Cow	Horse	Pig
BOD_7	165	165	72
N	30	30	13
P	2.7	2.7	1.2

eighty residents, one horse for every fifty residents and one pig for every two hundred residents [3]. These data were used for the calculations for the 1850s.

Actual loads

Actual load denotes the load that in fact gets into the water. In order to calculate this we need to know how much of the load is reduced on its way from the source to the receiving water. The factor describing the ratio between actual and potential loads can be called the degree of dissemination, which is the opposite of the degree of purification.

The difference between potential and actual loads depends primarily on the sewer system. About 90% of household nutrients and organic load originate from excrement, the remaining 10% coming from other sources such as food preparation and waste from doing laundry. In the modern water closet system all of the excrement ends up going to the sewer. The proportion of phosphorus coming from human waste is only about 40%, the remaining 60% originates from other sources in the household [4]. A latrine, on the contrary, actually functioned as an automatic purification plant, as 90% of daily nitrogen and 40% of phosphorus ended up at dumping sites instead of in sewers and receiving water.

Secondly, besides the origin of the discharges, also the type of the sewer system (a ditch or a sewer pipe) affects the actual load. Unlike a modern sewer pipeline, which transports the waste water unpurified straight into the sea, an open ditch also acts in a way as a waste water treatment system. This purifying effect depends on for instance the length of the ditch, soil properties, flow rate and topography. In some measurements, for example, the phosphorus reduction in a 300 meter ditch was as high as 15%, the BOD_7 and nitrogen reductions even to over 40% [5]. These kinds of reductions require, however, rather ideal conditions; in this study the reduction is assumed to be less than 10% for all components.

At the beginning of the 20th century almost 90% of the houses in Helsinki were connected to a sewer system (See Figure 2). The sewers were equipped with small precipitation wells (or septic tanks), but their purification efficiency proved to quite modest [6]. According to a survey from 1917, the purification efficiency of BOD5 could be up to 10% and 0-20% for ammonia [7]. It has been assumed here, quite optimistically, that the reduction in a precipitation well varies between 10 and 20% for all components.

The first waste water treatment plant (an Imhoff tank) was built in Helsinki in 1910 for 3,000 people. It had a very limited impact on the total load [8]. According to reported operation measurements the purification efficiency for organic matter (COD_{Mn}) was about 40-50%, for nitrogen and phosphorus by estimation about 10-20% in both plants. In the beginning of the 1910s the influent COD concentration in Alppila plant was about 106 g/m^3 and the ammonia content was 21 g/m^3 [9].

Table 4. Different types of wastewater treatment and corresponding degrees of dissemination

Type of system	Degree of dissemination %		
	BOD_7	N	P
– Wastewater purification (depends on plant type)	10–80	60–90	10–80
– Water closet – Sewer pipe	80–90	80–90	80–90
– Earth closet – Sewer pipe	10–20	10–20	50–60
– Earth closet – Open ditch	0–10	0–10	0–10

The degree of dissemination varies theoretically between 0 and 100%. Theoretical degrees of dissemination of four distinct systems of waste water management are shown in Table 4.

The actual load can be obtained from the equation

ACTUAL LOAD (g/day) = POTENTIAL LOAD (g/ day) x DEGREE OF DISSEMINATION

In 1910 the population of Helsinki was almost 120,000. Only about 3% of the people were connected to the WWTP. About one third of the population had earth closets, i.e. they were connected to the barrel system. Approximately 42,000 people used water closets that conducted the sewage through precipitation wells into the sea. About 10% of the inhabitants in the city still lived at that time with latrines and open ditches. In addition, some thousands of people were living beyond what was then the city limits.

In 1950 the population was 370,000 inhabitants [13]. About 90% of the households were connected to the sewer system, and there was a water closet in almost 80% of them. There was a bathroom in 44% of the households in the city centre [17]. In the calculations the specific nutrient loads of inhabitants used are nitrogen 10 g/inh.*day and phosphorous 2 g/inh.*day [16]. The BOD7 load can be calculated when we know the discharges and the number of inhabitants connected to the treatment plants. According to the calculations the weighted average load in 1948-1952 was about 61 g/inh.*day.

The population of Helsinki is about 516,000 people nowadays. Practically all the domestic and the industrial sewage from Helsinki and other nearby municipalities is treated in a central biological waste water treatment plant. Instead of several old-style sewer pipes, all the purified waste water is pumped in a single tunnel which leads to the Baltic

Table 5. The purification parameters in the main wastewater treatment plant in 1995

	Influential load (kg/year)	Effluent load (kg/year)	Degree of purification (%)
BOD_7	20,805,000	861,000	96
N	3,208,000	2,449,000	24
P	526,000	32,000	94

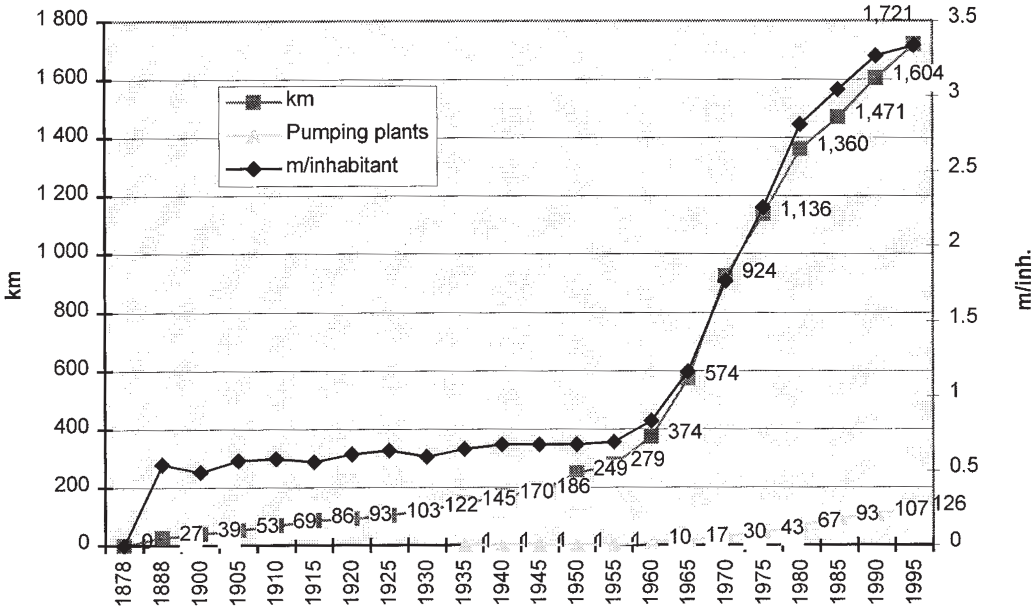

Figure 2. The length of the sewer system and the number of pumping plants [10–12]

Sea about 8 km south of Helsinki. The total waste water discharge in 1995 was 89,000,000 m^3 [19]. Other essential parameters are shown in Table 5.

Rainwater

The sewer system initially admitted both rainwater and domestic sewage. It was, however, soon observed that this system caused a severe overload to the waste water treatment plants and thus reduced the effectiveness of the purification processes. Consequently, the city council made a decision in 1938 that the new channels would be built on the basis of separate sewerage.

Despite this decision, overloading still caused serious problems in the 1950s because of the insufficient capacity of the treatment plants. In an overload situation, especially during heavy rain, the sewage flowing in the combined sewerage pipelines was led straight into the sea. A great deal of the waste water was led to the sea only mechanically purified or even completely unpurified. No accurate measurements were, however, made of the water flows or discharges.

Heikkonen [20] has studied the discharges in these kinds of overflow situations. The annual overflow in the late 1970s was circa 370,000 m^3 with a BOD_7 concentration of 100 g/m^3, a nitrogen concentration of 6 g/m^3 and a phosphorus concentration 1.4 g/m^3.

Industrial discharges

Today the BOD discharge of industrial waste water is about 15% of the total amount led to the treatment plants. The share of nitrogen is 6% and of phosphorus 9% [21]. The first larger industrial plants started to emerge in the 19th century. The biggest of these were a sugar factory (founded in 1830), a gas factory (1860), a brewery (1819) and a slaughterhouse (beginning in the middle of the 18th century).

The local Sinebrychoff brewery operated from the 1820s to the beginning of the 1990s. It led its waste water unpurified straight to the southern sea area at least until the 1950s. It has been assumed here that the brewery consumed 10–20 litres of water to produce one litre beer. Furthermore, it has been assumed that about 25% of the water used became waste water, which was led into the municipal sewer. Estimated average BOD, nitrogen and phosphorus concentrations in waste waters were N 50 g/m^3; P 20 g/m^3; BOD_7 1,200 g/m^3. Annual beer production in 1854 was 300 m^3, in 1899 5,500 m^3 and in 1950 20,300 m^3 [22–24].

Another important polluter was the gas factory, which produced gas from coal for street lighting, heating, industrial purposes and later for household consumption as well. It operated in the centre of the city from 1860 until August 1910 when it was moved to the eastern bay [25]. The discharges from the gas factory consisted of both eutrophicative and toxic components, ammonia, coal tar and hydrogen sulphide. It has been estimated that the combustion of one ton of coal produces waste water containing 1.8 kg ammonia, and circa 1.21 kg nitrogen [26; 27]. The estimated consumption of coal in 1910 and 1950 can be seen in the following [28]: in 1910 coal consumption was 11,900 t/a (the load being discharged into the central bay) and 5,600 t/a (the load being discharged into the eastern bay). In 1950 the coal consumption was 76,000 t/a.

A municipal slaughterhouse was built in 1880, but there are no statistical data available on the sewage from the slaughterhouse, and thus we have to cite literature values [29]. The slaughterhouse moved near the eastern bay in 1933 and was connected to the first activated sludge plant in Helsinki. Estimates on the annual amounts of sewage produced by animals are

	Cow/horse	Pig/sheep
Amount of sewage	1.5	0.54
M^3/animal		
BOD_7 G/animal	1,760	670
N G/animal	230	70
P G/animal	40	10

Diffuse loads

The aim here is to estimate the loads of scattered settlements, agriculture, livestock farming and natural soil leaching. This task includes a great deal of generalisation as well. Sufficient statistical and demographic information on the rural areas is available, but estimation of the discharges into each water basin is particularly demanding. The diffuse load of Helsinki at present is of minor importance. It has been assumed in this study that all the discharges from scattered settlements and other diffuse sources are included in the loads that end up to the sea from the brooks.

Scattered settlements

The population outside Helsinki was typically concentrated in small peasant villages. There were no dominating urban centres in the area. Agriculture was the most important source of livelihood, however at the beginning of the 18th century a small-scale sawmill industry emerged near the River Vantaa. The specific pollution loads of the inhabitants depended on the technical systems, soil quality, flow circumstances and the distance from the receiving water basin. According to Rontu and Santala [30] the daily actual discharges from households without a water closet in sparsely populated areas were on average: BOD_7 12 g/inh.*day; N 0.8 g/inh.*day; P 0.7 g/inh.*day. For simplification these values have been used in calculations for all time periods.

Arable land and domestic animals

The magnitude of nutrient leaching from fields depends on soil quality, the distance of settlement from receiving water areas, cultivation technique and ditching, and above all on fertilising, which has had a crucial impact in the development of agriculture. As for example underground drains and manure were used already in early times, the use of chemical fertilising is the primary difference between our times and the past.

The introduction of fertilisers did not take place until the 1870s and their use increased gradually in the next decades [31]. In the beginning of the 20th century the average use of nitrogen fertilisers was 0.5 kg and of phosphates 5.4 kg per hectare [32]. However, this amount was, until the middle of this century, so small that the plants could use all the nutrients, and the net leaching from fields was thus practically zero [33]. Nowadays the consumption is about 90-100 kg N/ha and 15-20 kg P/ha [34]. At the same time the average loads from fields have recently been 6-20 kg N/ha and 0.35-1.8 kg P/ha [35]. Since no exact values are available for the loads in the past, it has been assumed in this study that during the whole period the average leaching values are 6 kg N/ha and 0.35 kg P/ha. Phosphorus causes secondary oxygen consumption in receiving water bodies, which has been measured to be about 143 g per 1 g oxygen [36]. This effect has not been taken into account here.

In considering the point loads of the 1850s, we included the domestic animals in the calculations because they played such an important part in the settlements. When diffuse loads are studied, we take into account the animals outside the city. The approximated ratios between domestic animals and inhabitants of that area are presented in Table 6. The specific loads are the same as presented earlier. The degree of dissemination of the loads is roughly estimated to be 5%.

Table 6. Ratios between livestock animals and inhabitants

	Cows/inh.	Horses/inh.	Pigs/inh.
1850	0.58	0.21	0.10
1910	0.33	0.15	0.17
1950	0.001	0.002	0.001

Table 7. Development of surface area of forests and waste lands

	Western areas km2	Eastern areas km2
1876	26	88
1910	10	34
1950	6	50

Natural soil leaching

The amounts of nutrients are above all dependent on the quality of soil and on climatic conditions. In southern Finland the annual leaching of nitrogen is estimated to be 200 kg/km^2. According to different sources the phosphorus load ranges between 5 and 11 kg/km^2, of which the latter figure is used in this article. The estimated surface areas in "natural state" are represented in Table 7 [37].

RESULTS

Absolute loads

In this study three historical stages have been compared with the modern times. In the 1850s purification occurred rather unintentionally. In contrast, the contemporary purification system 150 years later is a highly specialised product of science and technology. How do these stages compare to each other despite the obvious growth of population? Figure 3 represents the increase of the total load into the sea during the years. It seems that even though the population until 1950 was much smaller, the BOD_7 and phosphorus loads were much bigger than today. The peak years were in the middle of the 20th century. The situation was best in the latrine town stage.

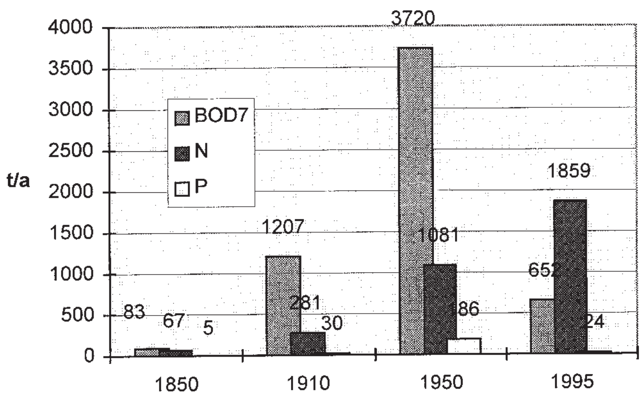

Figure 3. Development of the total loads in 1850–1995

Relative performance

There are basically three elements which affect the increase of loads that end up to the sea: standard of living, the volume of activity (population, industrial production, acreage of cultivated land, etc.) and the technical system through which the sewage flows. The effect of the technical system can be described with the changes in the degree of dissemination (see Table 8).

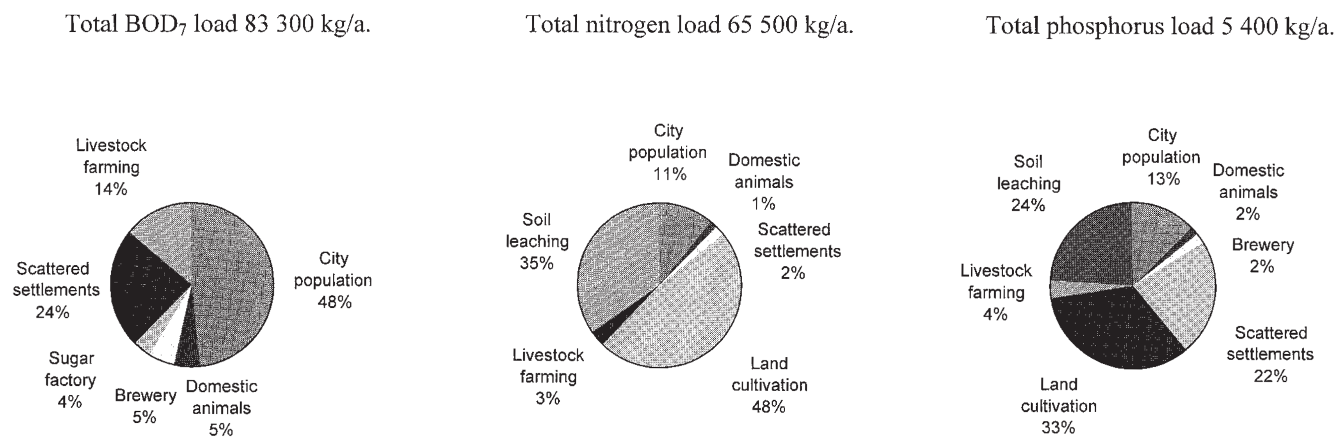

Figure 4. Total actual loads in 1850

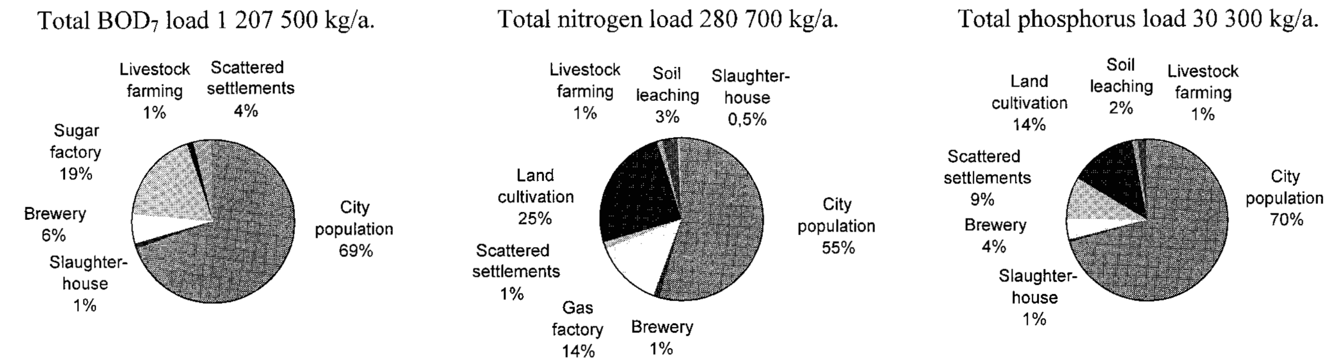

Figure 5. Total actual loads in 1910

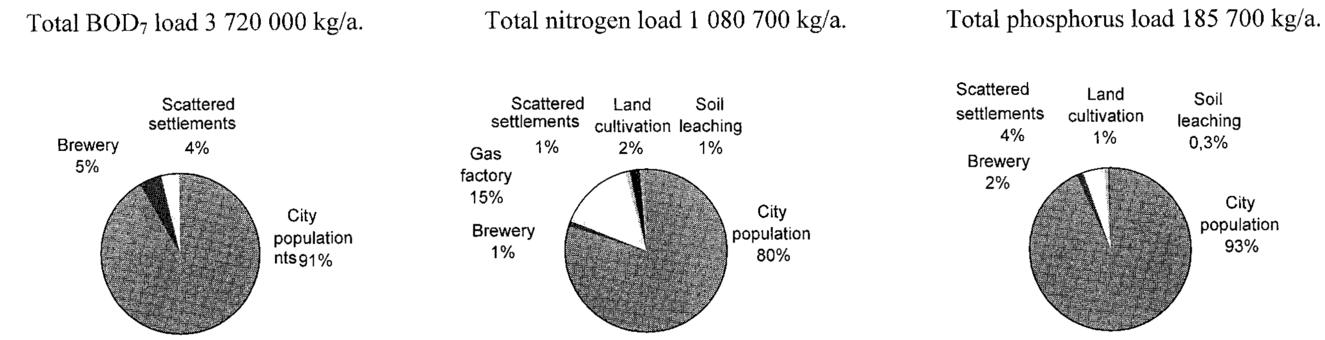

Figure 6. Total actual loads in 1950

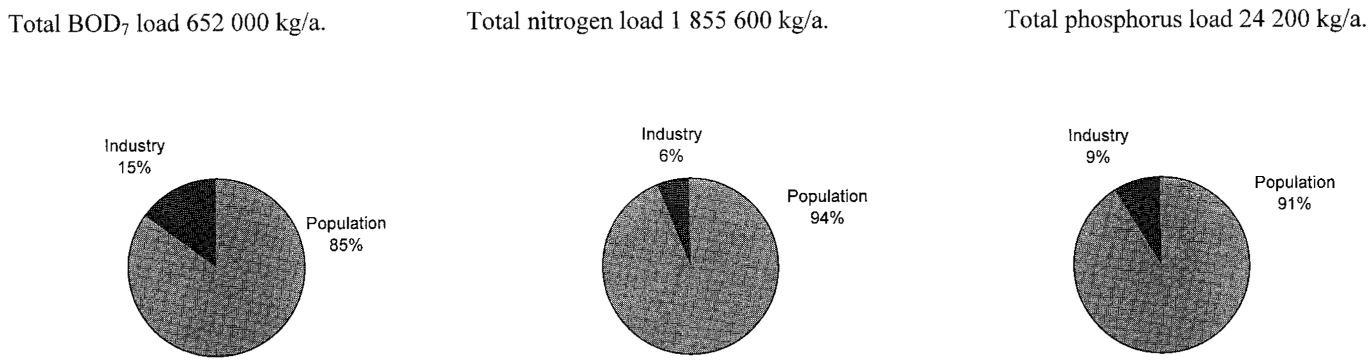

Figure 7. Total actual loads in 1995

Table 8. Development of average weighed degree of dissemination

%	1850	1910	1950	1995
BOD_7	0–10	35–45	70–80	0–10
N	0–10	35–45	70–80	70–80
P	0–10	55–65	75–85	0–10

Table 9. Industrial load as percentage of total load

	BOD_7 %	N %	p %
1850	16	0	13
1910	27	22	7
1950	5	17	2
1995	15	6	9

In relative terms the use of latrines in Helsinki produced the best statistical model for a sustainable city. The centralised city is second and the piped city third in terms of performance. The worst type was again the networked city, where the use of water closets and the sewer pipe system was already widespread, but the purification system did not yet function properly. Those inhabitants who where connected to the sewer system and had water closets, but who were not connected to the purification plants, were relatively the biggest polluters. According to estimates they produced about 70% of the total BOD load and about 45% of the nitrogen and phosphorus loads. Yet, they represented only 37% of the total population. The biggest group at that time were those sewage was conducted into purification plants; they produced about 25% of the total BOD load, 50% of the nitrogen load and 45% of the phosphorus load.

Figures 4-7 show the shares of the sources of the total actual loads. It seems that natural soil leaching had a major impact on the nutrient balance only in the 1850s. Also diffuse loads (scattered settlement, land cultivation and livestock farming) represent a large part in the case of nutrients. The constant increase of the share of the population of the polluters is notable. Pollution from the population dominates in the modern city, while there was a considerable diversity in pollution sources during the time in Helsinki when latrines were used. The figures also show clearly how anthropocentric a place the modern city has become compared, with the diversity of different lifestyles in different historical stages.

Before the beginning of the 20th century what had been a pre-urban agricultural community was gradually becoming an industrialised, rapidly growing city. The inhabitants of Helsinki were the major polluters. The gas factory on the eastern bay was an important source of nitrogen load. By 1950 Helsinki had become a rather modern industrialised city, in which the share of diffuse loads was at best about 5%.

The contribution of industry to pollution in modern Helsinki can not be compared with that of earlier periods of time, as there is not enough information available about the factories. Table 9 shows the relationships between industrial loads and total load.

Geographical distribution of loads

The urban sea area of Helsinki is presented in Figures 8, 9, 10 and 11 which show the distribution of the total loads into the receiving water areas. The eastern bay has been a major receiving water body over the years, especially because it has received a large share of the diffuse loads and natural soil leaching. Only later have the point sources turned out to be dominant, and the loads into southern and western

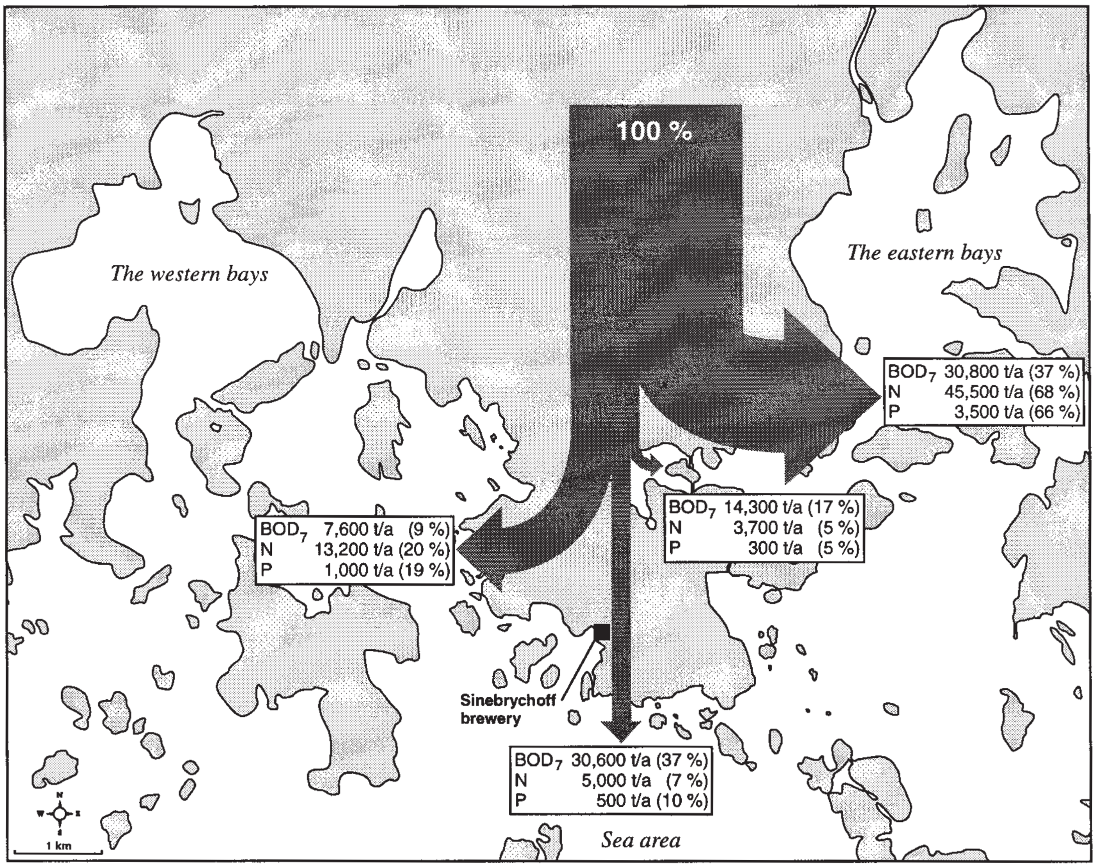

Figure 8. Total BOD_7, nitrogen and phosphorus loads in 1850

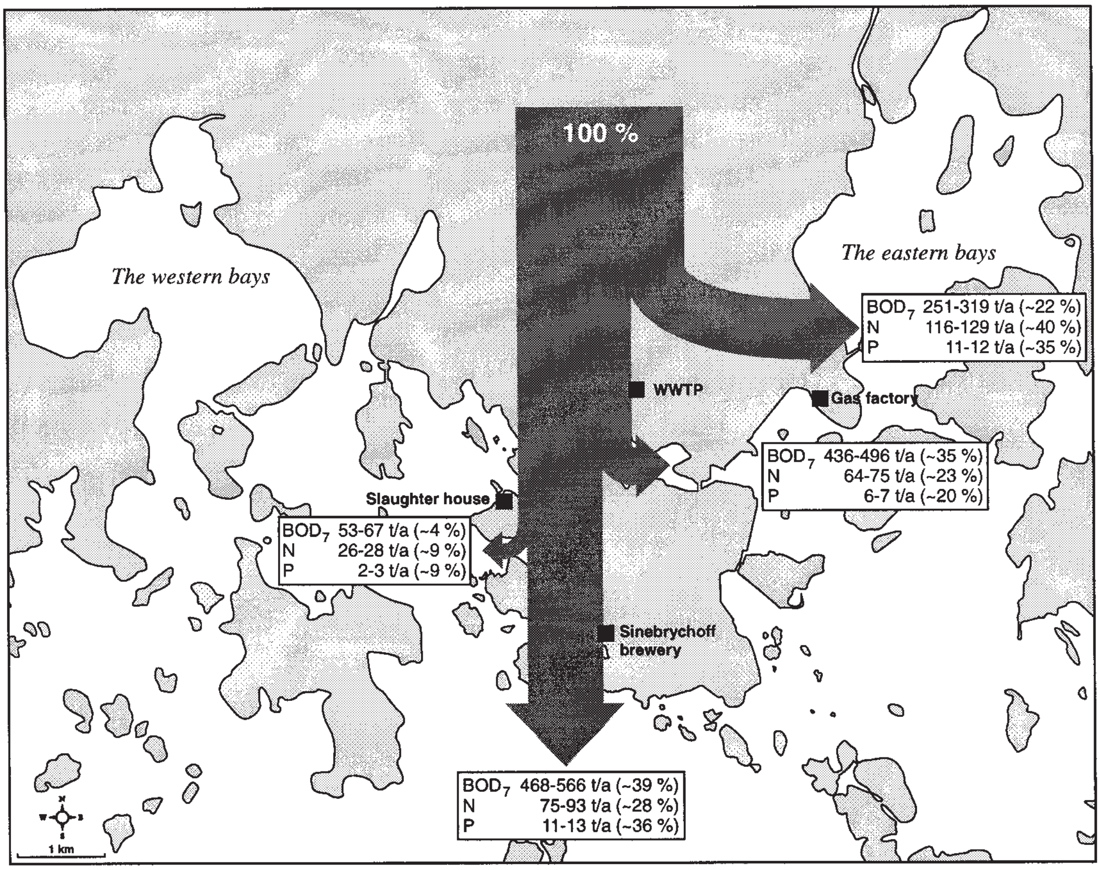

Figure 9. Total BOD_7, nitrogen and phosphorus loads in 1910

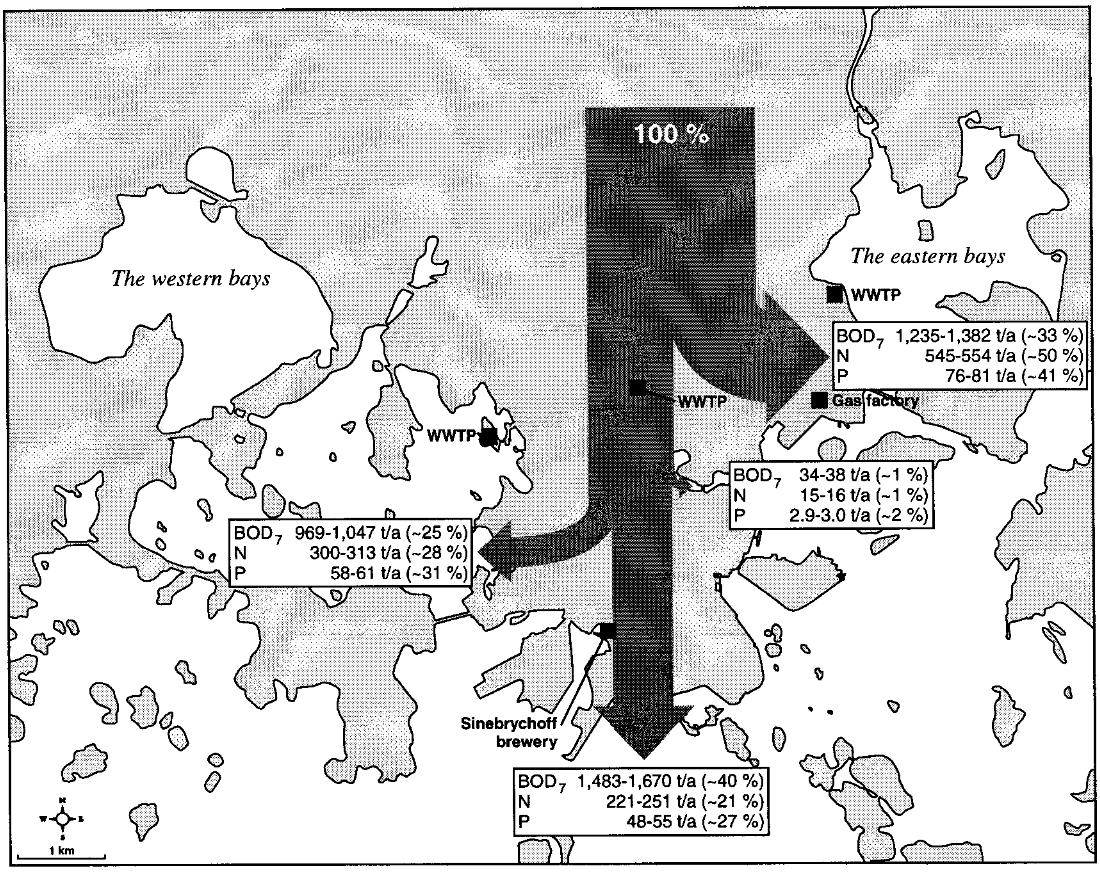

Figure 10. Total BOD_7, nitrogen and phosphorus loads in 1950

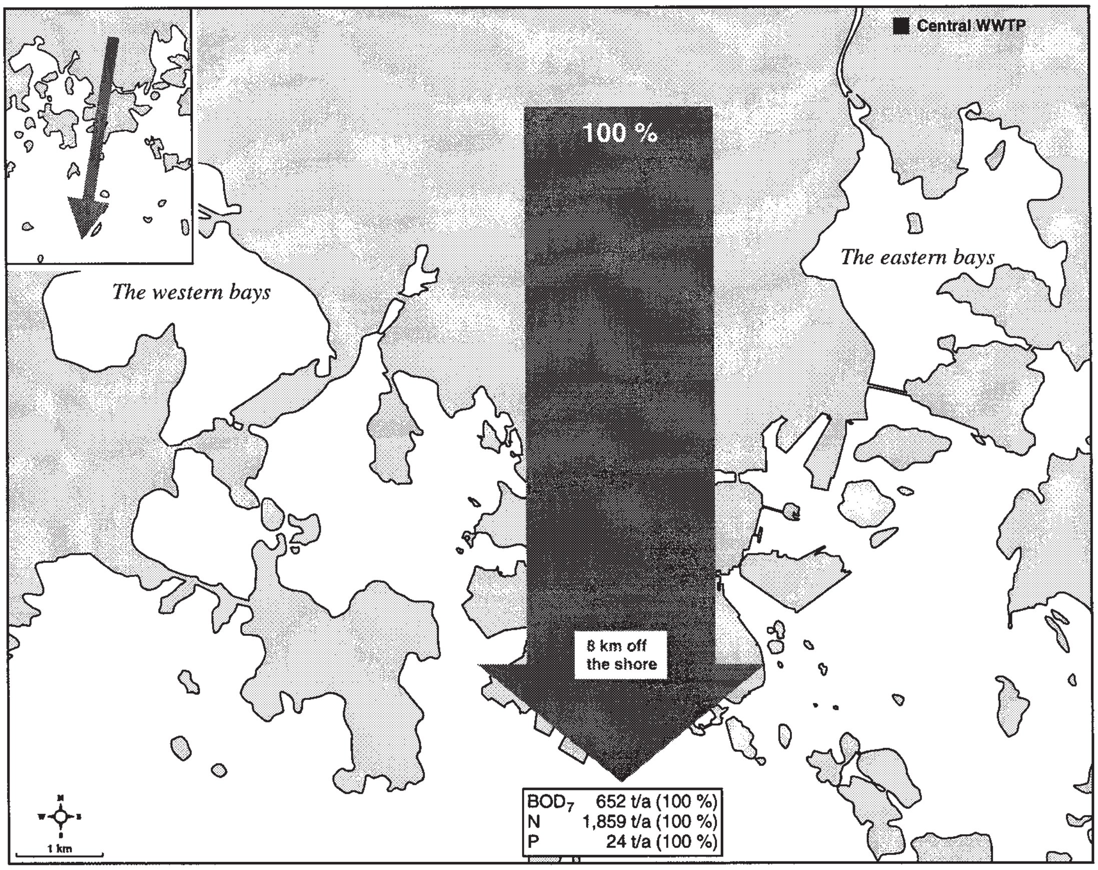

Figure 11. Total BOD_7, nitrogen and phosphorus loads in 1995

receiving water bodies have increased accordingly. Nowadays practically all the loads end up flowing to the southern high sea area, while the amounts of diffuse nutrient loads into western and eastern bays represent at most about 1% of the municipal loads.

CONCLUSIONS

In a famous essay, C. P. Snow claimed that the humanities and technical scientific studies are so deeply divided that they may be defined as two separate cultures. Our study has attempted to integrate these two approaches. A knowledge of historical changes and the systematic approach of science are both indispensable in efforts to reconstruct the long-term changes that have occurred in our environment.

Our study identifies a major interconnected change which has taken place in loads, technical systems and environmental impact: centralisation. All three of these factors have in principle evolved from diversified processes towards a centralised system. Since the second half of the 19th century in Helsinki the loads into the water courses have been done by human beings, animals, and factories. The technical system at the earlier stages consisted of a number of artificial or natural sewers with small catchment areas. Consequently, the load was distributed into various water bodies surrounding the city. In the late 20th century the urban population has become almost the sole source of load. The treated waste water is nowadays discharged to one point outside the city. Consequently, degradation of the marine environment has evolved from organic pollution of the shore zone towards eutrophication of the open sea.

The centralised systems have provided good results from the point of view of hygienic conditions and state of the urban water bodies. However, they offer rather limited possibilities of planning different technical systems to improve the conceptual paradigm of urban waste water management. Hence the diversity of the historical city should be studied more deeply in order to provide innovative solutions for the future sustainable city.

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