

# Springtime Episodic Acidification as a Regulatory Factor of Estuary Spawning Fish Recruitment

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Cover picture: In order to protect the declining fish stocks, the so called "kungsådran" Kings Lead, was established through a vast hearing proceedings in the late nineteenth century in the estuary of River Kyrönjoki. Fishing was prohibited in the Kings Lead. According to the regulations from that time, it was also forbidden to dump harmful substances in the water. The Kings Lead was marked by iron crosses. Remains of the markings are still visible hundred years later.  
Photo R.Hudd November 1981.

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## Abstract

Hatching and the earliest life stages of three studied species representing coastal fish with different modes of reproduction were shown to take place before, during or after a springtime acidification in a river estuary running through acid sulphate soils in the Gulf of Bothnia, the Baltic Sea. The three species all have a pelagic larval stage during which dispersal from the hatching sites takes place. Because of different spawning times and consequently different hatching times, the effect of temporarily variable springtime pH-minima as a regulating mechanism for coastal stocks could be established. For almost the entire study period, burbot was exposed to acidic water during the calculated hatching time, and the stock consequently suffered. The early developmental stages of perch were, especially in the latter part of the study period, not exposed to the worst annual acidification. The perch population at least doubled in size when the negative impact on recruitment was not occurring. Smelt could avoid negative influence by occupying non-acidified sea water areas in the outer parts of the estuary. Furthermore, in the latter part of the study period during favourable years, they were reoccupying suitable larval areas in the inner estuary, as well. For the smelt, comparatively good spatial and temporal matching ensured survival among larvae, which in turn ensured a high recruitment to the fisheries. This interpretation of acidification impacts on fish recruitment is strongly supported by the observations that the acidification in some periods reached lethal levels even for adult fish, indicating that very few other environmental factors could have been of decisive importance for the survival of fish larvae.

## Original papers of this thesis

This thesis is based on 9 papers which are referred to in the text by their Roman numerals. The thesis also contains unpublished material collected until 1997.

I. Hudd, R., Urho, L. and Hildén, M. 1983. Occurrence of burbot, *Lota lota* L., larvae at the mouth of the Kyrönjoki in Quarcken, Gulf of Bothnia. *Aquilo*, Ser. Zool. 22:127-130.

II. Hudd, R. and Lehtonen, H. 1987. Migration and home ranges of natural and transplanted burbot (*Lota lota*) off the coast of Finland. *Proc. V Congr. Europ. Ichtyol.*, Stockholm 1985. pp. 201-205.

III. Hudd, R., Hildén, M. and Urho, L. 1986. The effects of antropogenic acidification on the stocks and fisheries of bream and burbot in the sea area influenced by the River Kyrönjoki in the Gulf of Bothnia. *Publications of the Water Research Institute, National Board of Waters, Finland*, 68:134-138.

IV. Hudd, R. & Kålax, P. 1998. Effects of acidification on 0+ juvenile fish diversity and abundance in River Kyrönjoki, Finland. *Ital. J. Zool.* 65: 483 - 486.

V. Hudd, R., Leskelä, A., Kjellman, J., Rahikainen, M. and Karås, P. 1994. Effects of episodic acid runoff on the abundance of fish fry of spring spawning fish species and the perch (*Perca fluviatilis* #) stock in the estuary of the River Kyrönjoki. In: Müller, R. & Lloyd, R. *Sublethal and Chronic Toxic Effects of Pollutants on Freshwater Fish*. Cambridge: 301-310.

VI. Hudd, R., Kjellman, J. and Urho, L. 1996. The increase of coincidence in relative year-class strengths of coastal perch (*Perca fluviatilis* L.) stocks in the Baltic Sea. *Ann. Zool. Fennici* 33: 383 -387.

VII. Hudd, R. 1985. Assessment of the smelt (*Osmerus eperlanus* (L.)) stock in the Northern Quark, Gulf of Bothnia. *Finnish Fish. Res.* 5:55-68. *Monistettuja julkaisuja* 53: 88-102

VIII. Hudd, R. and Urho, L. 1985. Abundance and distribution of smelt (*Osmerus eperlanus* (L.)) yolk sac larvae in the Northern Quark, Gulf of Bothnia. *ICES C.M.* 1985/J:28.

IX. Hudd, R. and Leskelä, A. 1998. Acidification-induced Species Shifts in Coastal Fisheries off the River Kyrönjoki, Finland: A Case Study. *Ambio* 27: 535 - 538.

## I. Introduction

Sulphur rich layers, originating from bottom sediments of the former Littorina Sea, occur up to 80-90 meters above present sea level along the coasts of the Baltic Sea. Because of the low elevation, Littorina sediments can be found more than a hundred kilometers inland from the present coastline, especially in the Gulf of Bothnia (Purokoski 1959, Erviö 1975, Alasaarela 1983, Åström 1996). Presence of sulphur rich clays in the estuaries in the Gulf of Bothnia was described already at the end of the 1890's (Rosberg 1895). In the former sea bottom, the sulphur is present as sulphide, mostly ferromonosulphide (e.g. Purokoski 1958). When such soils are aerated, hydrogen ions are released into the soil water causing acidification in the soil as well as in the runoff water. This is also a start of reactions causing more acidification. Acid cations, especially  $Al^{3+}$ , are brought to the surface by capillary forces and form aluminiumsulphate salts, such as, alum (Purokoski 1958). From the soil surface, these are flushed into the waters by rain and floods. At the same time, due to the hydrolysis of aluminum and iron ions, hydrogen ions are released, i.e. acidification increases (Hartikainen & Yli-Halla 1985, Palko et al. 1985). During the last stage of acidification in the monosulphide soils, oxidation is catalysed by bacterial (*Thiobacillus ferrooxidans*) activity at a pH between 2.0 and 3.5. (Palko et al. 1985, Palko & Myllymaa 1987).

Large scale aeration of sediments takes place after ditching, excavation work and water level regulation. As a result of land reclamation programs spanning several decades (e.g. vonWillibrand 1908, Hildén & Rapport 1993), there is now probably not a single Finnish river emptying into the Gulf of Bothnia that hasn't been excavated, regulated (Hildén et al. 1982) or whose catchment area hasn't been ditched. To further complicate the situation, most of the small coastal creeks and other fresh waters have been lowered, excavated or ditched (Wistbacka 1986).

Although acidification originating from sulphur rich soils was documented already

in the latter part of the nineteenth century (Nordquist 1896), really bad conditions did not begin to occur frequently in the main streams and in the estuaries until the 1960s (e.g. Alasaarela 1983, Hudd et al. 1984). Mass kills of adult fish, caused by this type of acidification, have been documented along the entire Finnish coast. Most of them, however, have been reported only in newspapers and internal reports of governmental or municipal authorities. Little attention has been focused on the effects on fish population levels and still less on the fisheries off the rivers.

Since the bacteriological processes involved in the oxidation of the sulphides need the summer warmth, the levels of alum salts on the soil surface will be highest after the summer. In order for the sulphides to wash out, high water levels after snow melting or heavy rain are needed. That is the reason why most of the recorded acid periods are associated with floods (Palko et al. 1985, Lax et al. 1998). Originally, the most extensive mass kills of adult fish occurred in the latter part of the spring flood when pH levels were at their lowest. The spring flood also overlaps the early life period of most native fish. As the earliest stages are particularly vulnerable to acidification (e.g. Beamish 1975, Rask 1984, Tuunainen et al. 1991, Sayer et al. 1993, Vuorinen et al. 1993), this may function as a regulatory factor for coastal fish stocks reproducing in the rivers and their estuaries.

The large scale excavations and water regulation works in Finnish rivers have resulted in negative impacts on coastal stocks of fresh-water fish (e.g. Hildén et al. 1982, Lehtonen & Hudd 1990). The magnitude of the problem in the Gulf of Bothnia was demonstrated for example by a comparison of catch statistics between the Northern Quark Archipelago and the Archipelago Sea (Hildén et al. 1982). From the 1960s to the 1980s, catches of several freshwater fishes, e.g. perch and bream, developed differently. In the Northern Quark, the perch catch decreased continuously while the catches grew steadily in the Archipelago Sea. The bream catches remained more or less stable over the study period in the Archipelago Sea, while they dropped during the same period in

the Northern Quark. As changes in the market demand couldn't be the main reason for the observed changes in catches, other explanations, mainly acidification in spawning and nursery areas, were highlighted. The most favourable habitats for fish reproduction in the northern parts of the Gulf of Bothnia region are situated in estuaries, lower reaches of streams and rivers and in small lakes in immediate contact with the sea (Eriksson & Müller 1982, Wistbacka 1986, Lehtonen & Hudd 1990). These areas are most heavily exposed to the effects of dredging, ditching and excavation work, thus changing the water quality.

Local impacts, such as acidification in key habitats, can have a widespread influence in the surrounding coastal areas. A study was initiated at the beginning of the 1980s to analyse the development in the River Kyrönjoki estuary (Figure 1) and the surrounding archipelago, and to collect information for analysing river acidification impacts on a selected set of coastal freshwater fish depending upon the river for their recruitment. The results of the work are the basis for this thesis. The objectives of the thesis are as follows:

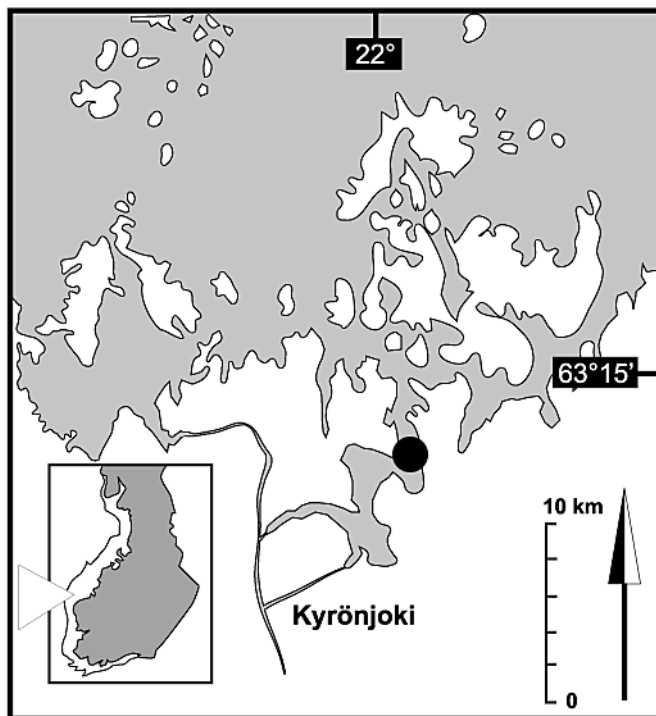


Figure 1. The River Kyrönjoki estuary. Inserted in the lower left corner is a map of the southern part of Finland. The area in which Littorina Sea sediments occur inside the present coast line is drawn in white. The arrow pointing from the left indicates the location of the River Kyrönjoki. The black dot indicates the station for routine water sampling from 1983 on.

- 1) Describe and analyse how episodic acidification, especially the timing of pH minima during the earliest life history periods, affect the population dynamics of coastal fish stocks reproducing in estuaries.
- 2) Describe and analyse how variable recruitment caused by this kind of acidification affects the structure of the coastal fishery.
- 3) Evaluate the need of long term monitoring for assessing population level reactions of fish stocks to local environmental impacts.

The study was focused on burbot, perch and smelt stocks in the Kyrönjoki estuary. The three selected species have different spawning times, spawning substrates and hatching times (Hudd et al. 1984, Urho et al. 1990). Their early life stages, however, have a similar tolerance to acidification (Table 1), and they all have a pelagic larval stage during which they can be acutely exposed to acidic outflow. Due to the different hatching times, they may have different possibilities to survive springtime acidification. In order to obtain reliable catch statistics and to perform adequate sampling, delimitation and definition of unit stocks and definition of their main reproduction areas was of crucial importance. The three species studied have been of fishery importance during the entire study period which enabled the gathering of information on catches for virtual population analysis to estimate year class strengths.

Table 1. Sensitivity of burbot, perch and smelt to low pH in egg and early larval stages.

Species	Egg sensitivity	Larvae sensitivity
burbot*	- no development below pH 5 (Volodin 1960)	- high mortality below pH 5 (Hudd et al.1984)  - tolerant due to lengthy yolk sac period and hatching in cold waters when metabolic activity is low (Keinänen 1997)
perch	- some eggs survive and hatch below pH 4.9-5 (Hudd et al.1984)  - some hatching even below pH 4 (Rask 1984)	- 50% survived labtests at pH 5.4-5.6 & low abundance in areas where pH is below 5.3 (Hudd et al. 1984)  - larvae from acid lakes more tolerant, some larvae survived even below pH 4.25 (Rask 1984, Vuorinen et al. 1994)  - some larvae survive even below pH 4 larvae from acid lakes more tolerant, (Rask 1984)
smelt**	- some eggs survive and hatch at pH c. 4.5 (Geffen 1990)	- sensitive (Geffen 1990)

\* Reproduction stops at pH 6.0 - 5.5 (Beamish 1976) in Canadian lakes

\*\* *Osmerus mordax*



## II. Material and methods

### 1. Description of study area

The River Kyrönjoki empties into the Northern Quark in the central part of the Gulf of Bothnia in the Baltic Sea (Figure 1). The drainage area of the river is 4920 km<sup>2</sup>. Due to the low percentage of lakes (1%) in the drainage area, the flow is highly variable. The maximum measured discharge is 480 m<sup>3</sup> per second. The mean high flow is 295 m<sup>3</sup> per second. The minimum observed flow is below 1 m<sup>3</sup> per second, but the mean minimum flow is nowadays regulated to 4 m<sup>3</sup> per second.

During spring floods, the freshwater flowing from the river can be observed more than 40-50 km off the mouth. Also during winter, the river water spreads under the ice cover over quite a large area. Since the wide archipelago off the river mouth is shallow, it is more or less filled with river water for some periods. Thus, acid water can spread widely. Due to the highly variable dynamic extension of river water, it is difficult to delimit the estuary or divide it into different zones. However, inside the archipelago, on the mainland side, one can talk about an inner estuary, which is filled with river water. This inner estuary is c. 10 km long. The main stream in the inner estuary is between 50 and 100 m wide, but large bays form wide shallow areas covered with macrophyte stands. Dominating plant genera are *Scirpus*, *Nuphar*, *Nymphaea* and *Phragmites* (Meriläinen 1984). The sea water salinity in the area off the river is 3 to 4 ‰ (Hudd et al. 1984, Sevola 1988). The inner estuary and the lower reaches are ice covered from November or December to late April. Mean ice break up occurs in the lower reaches on 24th April, while in the sea off the river it occurs on 11th May. Though the river and its catchment area have been highly influenced by human activities for several hundred years (e.g. Hildén & Rapport 1993), the largest excavation and flooding projects were started in the late 1960s. They continued until the late 1990s.

About forty fish species occur in the sea area off the river (Andreasson & Peterson 1982, Hudd & Svanbäck 1988). Of the abundant fish species reproducing in the outer estuary, only Baltic herring (*Clupea harengus membras*), four horned sculpin (*Myoxocephalus quadricornis*) and sand goby (*Pomatoschistus minutus*) do not continuously inhabit the river water. Large herring larvae, not yet metamorphosed, have been caught in the inner estuary (Hudd et al. 1984). The dominating part of the fish fauna consists of freshwater fish which, as in the Gulf of Bothnia in general, regularly move unimpeded from freshwater to seawater and vice versa. No fish species lives only in the estuary, but in the river, even in the lower reaches, the freshwater stone loach (*Noemacheilus barbatulus*) is found.

### 2. Unit stocks, fishing areas and catch statistics of burbot, perch and smelt

Unit stocks (Gulland 1969, Cushing 1981), dispersal and fishing areas and homing of stocks were delimited by tagging spawning fish at spawning sites (Hudd et al. 1984, II, Böhling & Lehtonen 1984, VII). Spawning burbot are nowadays caught outside the inner estuary, whilst still in the innermost parts of the archipelago which is more or less filled with river water during winter and high floods. Burbot fishing (Figure 2) in the dispersal area in the sea is insignificant except for times close to spawning. Intermixing with neighbouring stocks was obviously negligible (II, IX). The fisheries for ascending burbot in the inner parts of the estuary and lower reaches of the river ceased in the late 1960s and early 1970s (Hudd et al. 1984).

Perch has its main spawning and nursery areas in the inner part of the estuary (Hudd et al. 1984, Urho et al. 1990, Hudd et al. 1997). The fishing area is distributed in the archipelago in the vicinity of the estuary, in the estuary itself, and in the river (Hudd et al. 1984, Böhling & Lehtonen 1984, Lax et al. 1998) (Figure 2). Newly hatched larvae are scarce in the outer parts of the estuary, and 0+ juveniles are found in very low abundance in the archipelago off the estuary (Hudd et al. 1984, 1997, Urho et al. 1990). However, perch

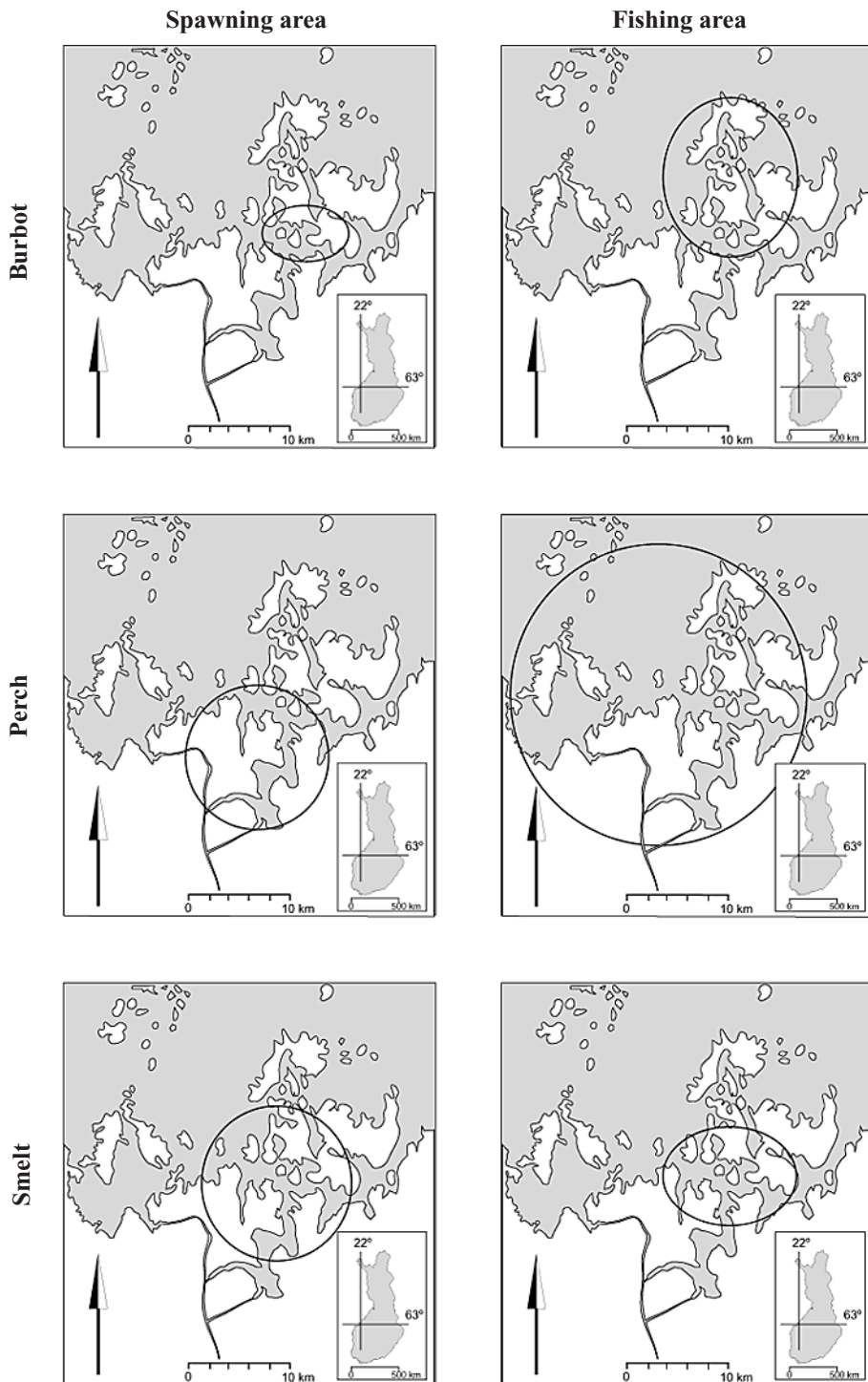


Figure 2. A key map of the spawning and fishing areas of burbot, perch and smelt in the estuary of Kyrönjoki. In the left column, the main reproduction areas of burbot, perch and smelt encircled. In the right column, the main fishery areas of burbot, perch and smelt encircled.

0+ juveniles are abundant in the river (Hudd & Kålax 1997, IV).

Smelt spawns mainly in the archipelago off the estuary, and the newly hatched larvae are predominantly found there (VIII). Although the smelts' dispersal area is wide, the concentrated fishing takes places within the vicinity of the spawning sites (VII) (Figure 2). Smelt fishing in the lower reaches of the river and in the inner part of the estuary ceased by the beginning of the 1970s, although during springs with favourable acidification conditions migration of smelt can be traced to the lower reaches of the river (Hudd et al. 1984). Although the smelt nowadays does not ascend high up into the river for spawning, its migration pattern (VII) is, by definition (McDowall 1997), anadromic. The adult smelt migrates to the sea after spawning. Ascendance to spawning sites takes place during ice break up (VII), and the duration of the spawning period is relatively short. The smelt stock off the River Kyrönjoki is clearly long-living (VII) and anadromous. The long-living and anadromous smelt stocks have, according to Belyanina (1969), relatively small fluctuations in year class strengths and stock sizes. Newly hatched smelt larvae occurred at their highest densities in the outer estuary in areas strongly affected by river water (VIII). Smelt yolk sac larvae occurred also in low abundance within the archipelago off the estuary branch cut off in the 1970s but not in the open water areas outside strong river influence (VIII, Urho et al. 1990).

Catch statistics (VII, IX) were collected within the area estimated from recoveries of tagged fish. For perch and burbot, besides the official statistics (Finnish Game and Fisheries Research Institute commercial fishery statistics), the purchases made by wholesalers and statistics of the fishermen's organisation (Österbottens Fiskarförbund yearly reports) were used. Total catches of burbot and perch were calculated by adding the catches of recreational fisheries to the commercial catches. As a consequence of the uncertain estimates of the recreational catches, they were assumed to be the same during the entire study period as assessed in Hudd et al. (1987). For

smelt, information from fodder industry purchases was collected by yearly telephone interviews. Being of minor importance, the recreational catch of smelt was ignored.

### **3. Water quality and calculation of acidity index**

In nature, the acidification phenomenon is a complex process, where not only the amount of dissolved hydrogen ions is of biological significance. The concentrations of several harmful metals also increase when acidification increases. Under natural conditions, it is complicated, time consuming and expensive to constantly identify the biologically significant components. In some cases, as for aluminum, the poisonous effects quickly increase over a narrow range of pH-values, for example, when acidified river water meets buffering sea water and the pH rises. In such cases, measurements of total aluminium concentration would be of little use. The situation and the role of metals is even more complicated in rivers with polyhumous water such as the River Kyrönjoki. Because of the complex, fickle and variable nature of the acidification, it is treated here as a whole including both the acids and the harmful metals, and the measure used to describe the acidification is the pH-value.

In the lower reaches, routine sampling of water quality started at the beginning of the 1960s. Samples were collected only 1-2 times per month (Official Water Quality Register of West Finland Regional Environmental Centre). In order to demonstrate the occurrence of the most acid periods, pH data were surveyed from the 1960s to 1997.

Until 1983, the acidification in the estuary had been monitored irregularly, but from April 1983 onwards, samples were collected 2-3 times per week (Official Water Quality Register of West Finland Regional Environmental Centre). Missing values, i.e., the values for days when no sampling was done, were interpolated by linear fill. Parallel temperature measurements were used, for example, in calculations of incubation times and growth indices of perch 0+ juveniles (V).

In order to increase the comparability of the yearly level of acidification during the earliest life stages, the duration of the most acidic periods was calculated and expressed as an annual index (V). Because of the different hatching times of the three species studied, two different time periods, 1 April -15 June and 1 May-1 August, were studied. Yearly pH-indices for the chosen period were calculated by subtracting the number of days when the pH value was below pH 5 multiplied by a factor of 2, and between pH 5 and pH 5.5 multiplied by 0.5, from the total number of days within the period in question. By multiplying by a factor of 2, the most acidic periods were given more weight (Formula 1). The weighting by factors 2 and 0.5 was originally determined and used for the perch stock (V). The pH-values 5.5 and 5.0 were chosen based on earlier observations of changes taking place at these pH-values, for example, disturbances in the survival of adult fish in fisheries, low abundance of 0+ juveniles, decreased survival of 0+ juveniles and decreased motility of spermatozoa's in waters with a pH value below 5.5 (Hudd et al. 1984, Urho et al. 1984), and was further supported by some literature data on the sensitivity of 0+ juveniles of fish (Table 1). Due to irregular monitoring, the possibility of calculating the pH-index for the period 1.4.-15.6. was restricted to the years 1983-1985 and 1987-1997.

Formula 1. Calculation of the pH-index (modified from V)

$$\text{pH index} = A - (b \times C) - (d \times E)$$

where:

A = number of days of the studied period

C = number of days of the studied period when  $\text{pH} < 5.0$

E = number of days of the studied period when  $5.0 < \text{pH} < 5.5$

b = 2

d = 0.5

#### 4. Sampling of fish and the virtual population analysis of studied stocks

In order to mitigate the risk of intermixing with fish from other stocks, the main sampling of the adult stocks of burbot, perch and smelt was concentrated on spawning fish which were assumed to be homing to their spawning sites (II, VII, Hudd et al. 1984, Böhling & Lehtonen 1984). Homing has been documented in burbot (e.g. Johnsson 1982, Müller 1984), perch (e.g. Willemssen 1977, Johnsson 1978) and smelt (e.g. McKenzie 1964).

Because most of the perch catch is taken outside the spawning time (e.g. Hudd et al. 1987, Moilanen 1994), there was a risk that year class strengths in samples from spawning fishery could diverge from the year class strengths of the entire catch. In order to reduce this risk, the age distribution in the spawning time samples was compared to samples from different fishing gears using a relative year class strength analysis (Svårdson 1961, Kempe 1962, Neuman 1974). Samples were taken from gill nets using the most commonly used mesh sizes of 35, 38 and 40 mm (bar length), as well as from coastal survey nets (Thoresson 1996). In the analysis, males and females were treated together.

The relative year class strength calculations were made for different age-group ranges, for example, 2-8, 2-9, 3-6, 3-9. The group revealing the lowest coefficient of variation (c.v.) for year class strength was used for further analysis (V). Because there were no statistical differences (t-test) between relative year class strengths of the contemporaneous year classes in catches from different fishing gears, the age composition from the longest series of samples (the wire trap net samples) was assumed to represent the entire age composition used for virtual population analysis. Ageing of burbot and smelt was done from sagittae otoliths (III, VII). Ageing of perch was done from the operculum bone (LeCren 1947) and, in difficult specimens, supported with ageing from scales (VII) to ensure adequate location of first annulus. The total number of fish in samples 1979 to 1997 are presented in Table 2.

Table 2. Numbers of sampled spawning burbot, perch and smelt in the Kyrönjoki estuary 1979-1997. No samples of burbot were taken in 1989-1991 due to lack of funding.

Year	Burbot	Perch	Smelt
1979	151	-	-
1980	214	-	79
1981	206	166	197
1982	132	132	269
1983	109	142	243
1984	98	144	203
1985	89	150	198
1986	84	154	312
1987	105	265	366
1988	113	332	226
1989	-	377	286
1990	-	504	122
1991	-	304	146
1992	151	204	105
1993	154	148	146
1994	169	371	192
1995	324	303	169
1996	530	371	174
1997	224	482	146
Total	2853	4549	3579

Virtual Population Analysis (VPA) (Ricker 1975, Gulland 1983, Hilborn and Walters 1992) was used to describe the variability in year class strengths and overall development of the populations. In all three VPAs, the natural mortality was set to 0.2. Setting the terminal fishing mortality too low will cause an overestimation of the stock size (e.g. Hilborn & Walters 1992). In this case, where the variability of year class strengths and the overall development were to be studied, terminal fishing mortality was set constant to 0.6 in burbot and 1.0 in perch and smelt. High terminal fishing mortality will lessen the effects of the few rare old fish found in perch and smelt catches but has less influence on the conception of the overall development of stocks (Hudd et al. 1997). In perch, which is fished with a variety of selective gears, weight at age was expressed as a mean of weight at age for all samples included. No specific weighting according to gear type was done. For all three species, the strength of fully recruited age groups, for example age group 5, belonging to the different year classes was correlated to the pH-index for the respective year of birth.

### 5. Calculation of hatching time in relation to development of spring acidification

The hatching time of burbot, perch and smelt was calculated using information from literature. Müller (1960) observed mass hatching ("Massentschlüpfen") in burbot at 117 to 131 day degrees. By setting the spawning peak to February 25th, the day degrees could be calculated from the temperature data collected in the estuary. February 25th was chosen as a result of interviews with fishermen and of observations made during sampling and tagging during the years between 1980 and 1997. For perch, the same procedure was applied, although the spawning was set to the date when the temperature rose sharply from 6 to 10 degrees (Karås 1987). The needed day degrees for hatching was set to 101 above 5°C (Guma'a 1978). In smelt, the spawning was set to take place when the spawning run was assumed to be at its peak, i.e., when the temperature rose over 2°C (VII). The day degrees needed for the incubation time

(140-180) were applied from the smelt originating from the River Neva in the Gulf of Finland (Belyanina 1969). The calculated hatching time for the three species was graphically charted against the springtime daily pH-values in order to reveal patterns indicating good or bad opportunities for survival.

Table 3. Observed very acid periods (pH =<5) in the lower reaches of River Kyrönjoki 1961-1997 (Official Water Quality Register of West Finland Regional Environmental Centre)

Year	n.	month											
		1	2	3	4	5	6	7	8	9	10	11	12
1961	10												
1962	18												
1963	17												
1964	14												
1965	14	X											
1966	15								X	X			
1967	15			X									
1968	16												
1969	19					X					X	X	
1970	43	X		X	X	X							X
1971	84				X	X				X	X	X	
1972	78			X	X	X					X	X	
1973	28			X	X					X	X		
1974	24			X	X			X	X				X
1975	43												
1976	32			X	X	X							
1977	16			X	X	X				X	X		
1978	16					X						X	
1979	17				X	X		X	X	X			X
1980	27	X			X					X			
1981	19			X	X					X	X	X	
1982	20												X
1983	17												
1984	41				X					X	X	X	
1985	21				X	X				X	X		
1986	14				X					X	X		
1987	16					X							
1988	15				X								
1989	17												
1990	22												
1991	14												
1992	6												
1993	12												
1994	24												X
1995	6												
1996	15										X	X	
1997	17		X	X	X						X	X	

### III. Results

#### 1. Acidification in the lower reaches and estuary of River Kyrönjoki

Low pH-values or very low pH-values ( $\text{pH} \leq 5$ ) were only sporadically observed until the end of the 1960s. From that time until the mid 1980s, very low pH-values were measured annually in spring and autumn, except for 1975 and 1983. Few observations of extremely low pH-values were recorded in 1978 and 1982. At the end of the 1980s and the beginning of the 1990s, pH-values below pH 5 were rare (Table 3). In the estuary, the measured pH was often lower than in the lower reaches. For example, in 1983, pH below 5 were observed several times (Figure 3).

From the end of the 1980s to the middle of the 1990s low or extremely low pH was not measured during springtime and early summer. These years, the most acid periods occurred in winter-time. In 1994, no real acid period was recorded at all.

Due to the time when the lowest pH occurred, the two calculated pH-indices diverged from each other some years. The differences were biggest in 1983, 1985, 1988, 1990 and 1992. The longer time pH-index was proportionally lower than the shorter time index in 1983, 1988, 1990 and 1997, whereas it was proportionally higher in 1985 and 1987. Other years showed coincidence (Figure 4).

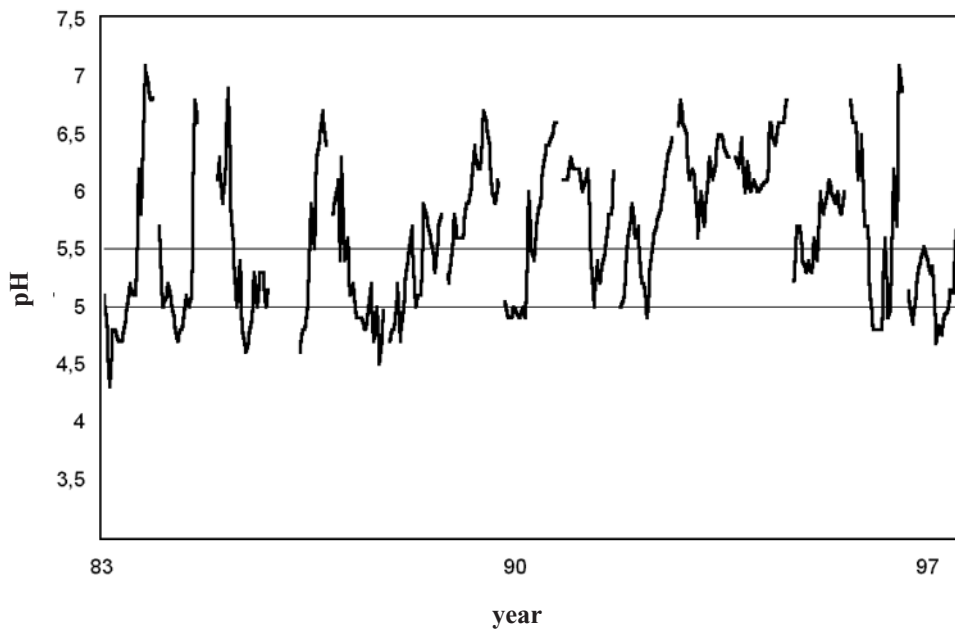


Figure 3. The yearly development of pH in the Kyrönjoki Estuary, 1983 to 1997 (Official Water Quality Register of West Finland Regional Environmental Centre).

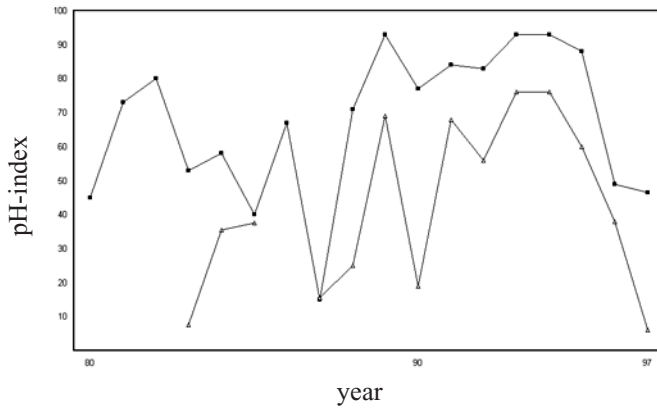


Figure 4. The pH-indices 1980 to 1997. Line with open triangles = pH indices calculated for the period 1.4. - 1.8. Line with black dots = pH indices calculated for the period 1.5. - 1.8.

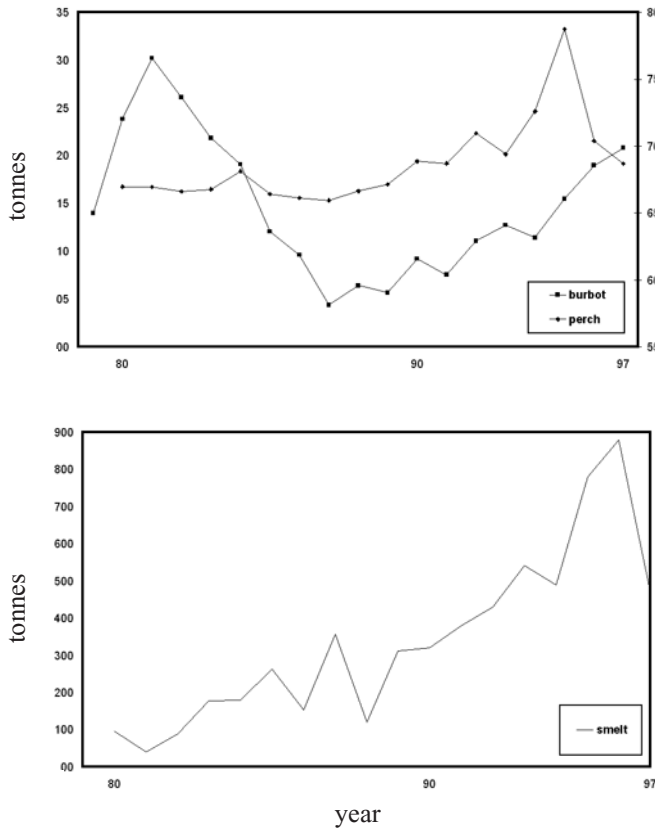


Figure 5. The development of the burbot, perch and smelt catches (in tons) in the Kyrönjoki Estuary 1979-1997.



## 2. Development of burbot, perch and smelt catches and stocks

The size of the burbot catch is assumed to have been stable prior to the large fish kills at the beginning of the 1970s (III). The total burbot catch decreased in 1982 - 1987 (III) followed by a small recovery in the latter part of the 1980s (Figure 5). In the late 1960s, the mean purchase by wholesalers was more than 16 tonnes. In the late 1980s, the commercial catch was smaller than 2 tonnes (IX). The commercial catch of perch has varied between 1 and 5 tonnes (IX). During the study period, the total perch catches seem to have been rather stable until the end of the 1980s, when they started to grow. The smelt fishery and smelt catches diminished during the entire 1970s (Hudd et al. 1984), but since the beginning of the 1980s, the smelt catches have recovered and grown continuously (Figure 5).

The burbot stock continued to decrease during the study period, except for a short period in the beginning of the 1990s (Figure 6).

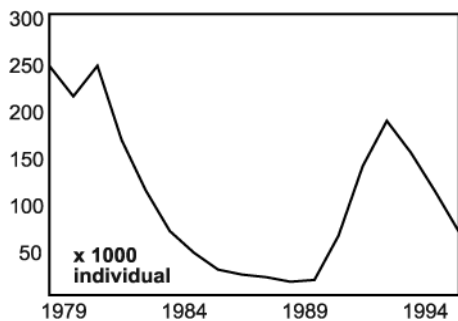


Figure 6. Development of the burbot stock in the Kyrönjoki Estuary 1979-1996.

The decrease in catches was due to fluctuations in the stock rather than changes, for example, in the market situation (IX). The perch stock was, until the beginning of the 1990s, at a low level but started to grow, at least to double in size, at the beginning of the 1990s (Figure 7).

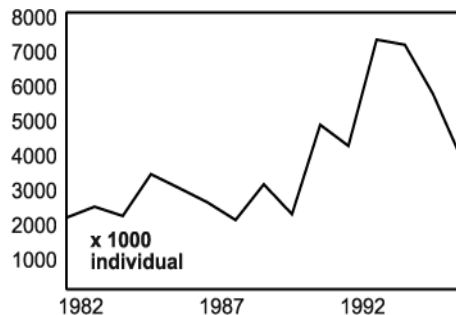


Figure 7. Development of the perch stock in the Kyrönjoki Estuary 1982-1996.

The smelt stock grew throughout the 1980s and the first half of the 1990s (Figure 8).

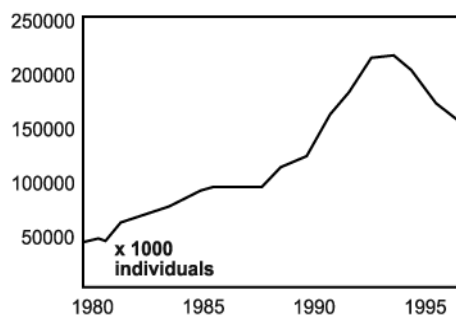


Figure 8. The development of the smelt stock in the Kyrönjoki Estuary 1980-1997.

## 3. Year class strengths and their relation to springtime levels of acidification

In burbot, strong year classes were born in 1975, 1978, 1989 and 1990 (Figure 9).

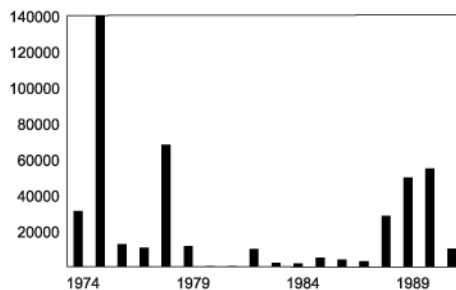


Figure 9. Year class strengths, number of individuals, of the burbot stock in the Kyrönjoki Estuary 1979-1996, according to VPA. At age 5.

Weak year classes were born in most other years, especially between 1980 - 1987 (IV). In perch,

strong year classes were 1982, 1986, 1988, 1990 and 1991 (Figure 10).

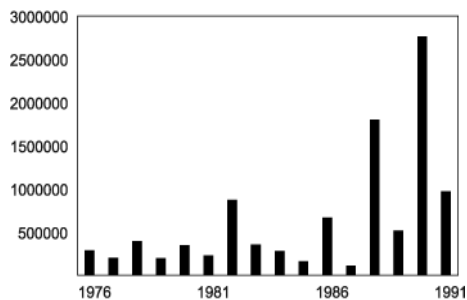


Figure 10. Year class strength, number of individuals, of the perch stock in the Kyrönjoki estuary, 1981-1996, according to VPA. At age 5.

The year classes of the smelt stock have grown during the entire study period (Figure 11).

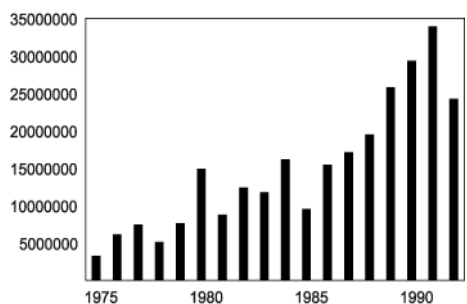


Figure 11. Year class strengths, number of individuals, in the smelt stock in the Kyrönjoki Estuary, 1980-1997, according to VPA. At age 5.

In relation to the pH-index, the year classes 1981, 1982, 1986 and 1991 were small in burbot. In perch, year classes 1981 and 1989 were small in relation to the pH-index. In smelt, year class 1987 deviates as strong, and 1981 and 1982 deviate as weak in relation to the pH-index (Figure 12).

In burbot the correlation between year class strength at age 5 and the pH-index calculated from 1.5 - 1.8. was 0.61 (Spearman,  $n = 12$ ,  $p < 0.05$ ). In perch, it was 0.72 (Spearman,  $n = 13$ ,  $p < 0.01$ ) and in smelt 0.55 (Spearman,  $n = 13$ ,  $p < 0.1$ ). There was no correlation between year class strengths and the pH-indexes calculated 1.4 - 1.8.

#### 4. Calculated hatching time in relation to yearly springtime development of acidification and subsequent year class strengths

The calculated hatching time for all three species was short and did not overlap. For burbot, it mostly took place during or before the lowest springtime pH (Figure 13). Only in some years, for example, in the middle of the 1990s, did the calculated hatching time take place at the end of or after the springtime pH-minima. Year class 1991, that was small in comparison to the pH-index (Figure 13) was exposed to falling pH after the hatching but not at any exceptional rate. Perch had the latest calculated hatching period time of the three species. Thus, the calculated hatching time of perch coincided, especially in the latter part of the study period, with a rising pH. At the beginning of the study period, the coincidence was variable. The calculated hatching time of the strong year classes 1986, 1988 and 1990 coincided with the timing of rising springtime pH (Figure 13). Year class 1991 deviates as a strong year class though the calculated hatching time coincides with a period of low pH, which was even falling afterwards. The calculated hatching time of the weak year classes 1985 and 1987 in perch coincided with a low or falling pH. The calculated hatching time of year class 1989 was not during low or falling pH. In smelt, hatching was calculated to take place also during low pH as in 1985, 1987 or 1990.

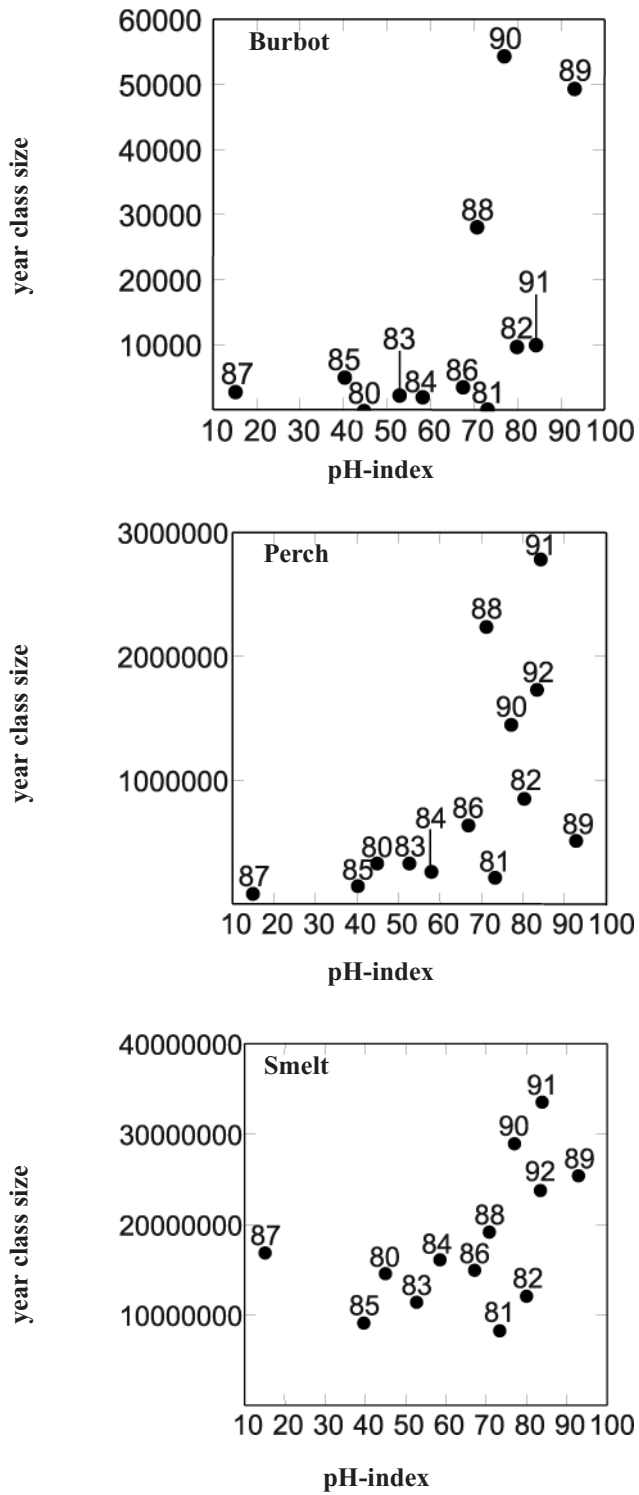


Figure 12. The year class strength of burbot, perch and smelt stocks in relation to the pH-index in the Kyrönjoki Estuary.

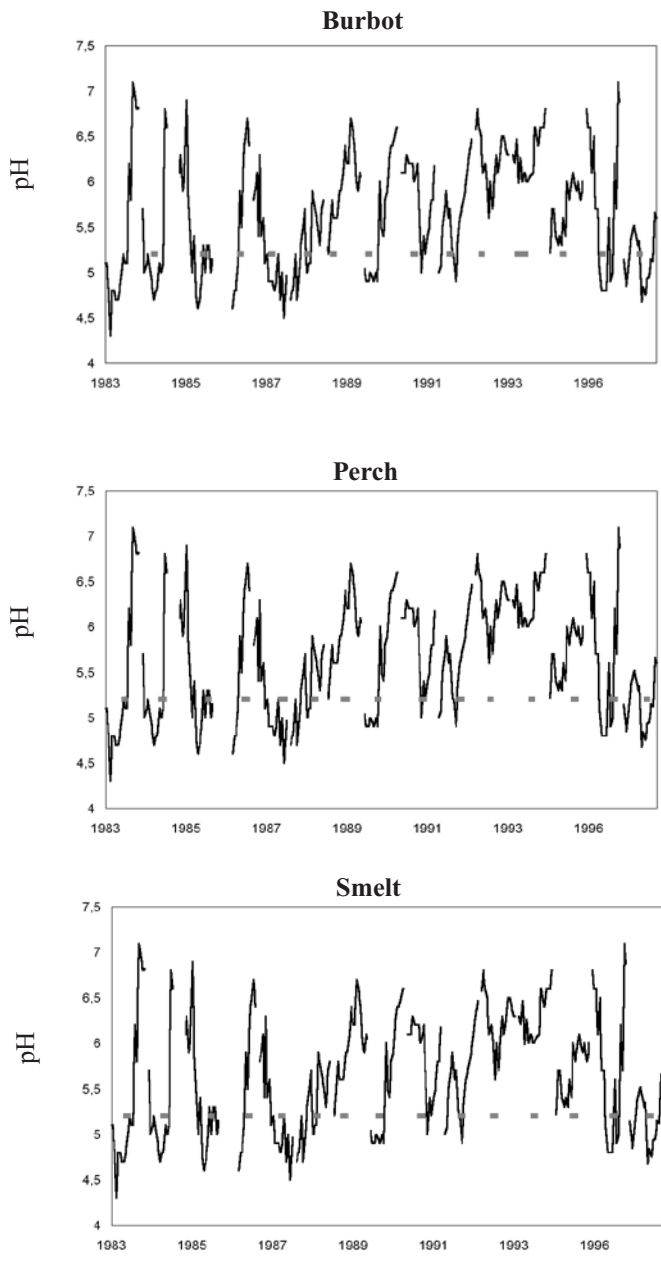


Figure 13 a. The calculated hatching time of burbot, perch and smelt in relation to the springtime (15.4.-15.6.) development of acidification in Kyrönjoki Estuary 1983-1997. Hatching time indicated by grey horizontal rectangles and pH indicated by a solid line.

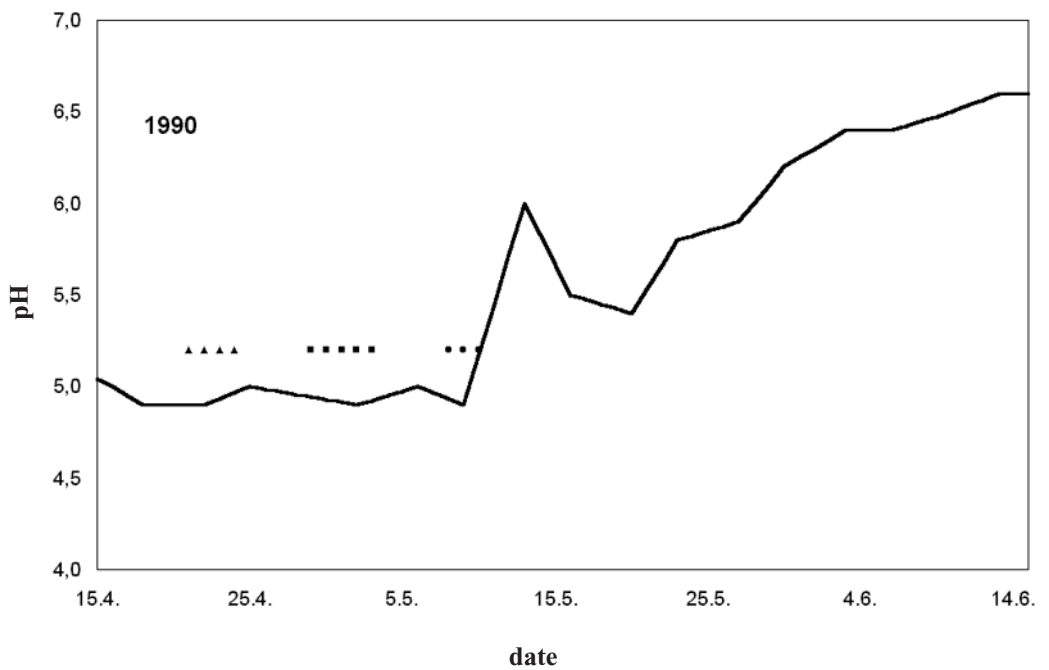
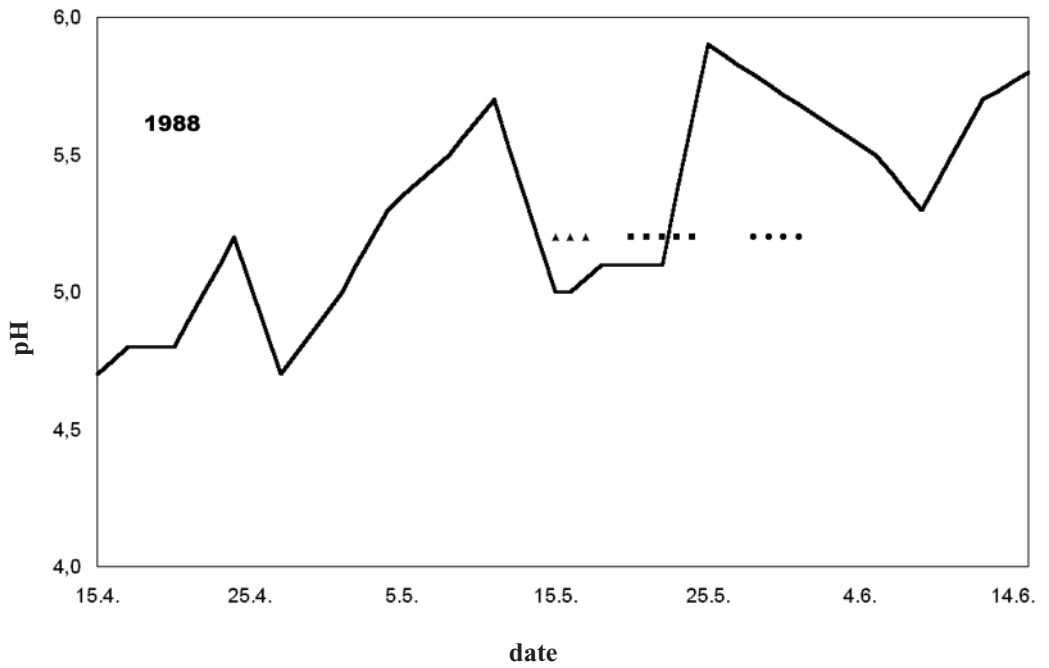


Figure 13b. Enlarged from Figure 13a. The years 1988 and 1990 as examples of calculated hatching time of burbot (triangles), smelt (squares) and perch (dots) in relation to springtime development of pH (solid line) in the Kyrönjoki estuary.

## IV. Discussion

Because of their early hatching or spawning time, Urho et al. (1990) suggested that offspring of burbot, coregonids and pike (*Esox lucius* L.) would be the first to be affected by the spring pH-minimum in acidified streams. The stocks of burbot, whitefish (*Coregonus lavaretus* (L.)) and vendace (*Coregonus albula*) present in several acidified estuaries have indeed suffered (e.g. Hudd et al. 1984, III, IX, Leskelä & Hudd 1993). The acidification in springtime has recurrently overlapped the early stages of River Kyrönjoki fish species spawning in autumn, winter and spring leading to low survival and low abundance of 0+ juveniles (V, IV, Urho et al. 1990). Consequently, abundance of 0+ juveniles has been variable both in the estuary as well as in the river (Hudd et al. 1984, 1997, V, Hudd & Kålx 1997, IV). In the late 1980s and beginning of the 1990s, the mild winters caused the snow to melt during the winter, meaning that no real spring flood took place (Lax et al. 1998). The most acid period was early occurring as it did during the winter. As a result of the early acidification peak, abundance of 0+ juveniles of spring spawning fish increased (Kjellman et al. 1996, Hudd et al. 1997, IV).

The calculated hatching times, put in relation to the pH development during the springtime, evidently influences the chances of survival for pelagic fish larvae. The results of this study indicate a temporal match - mismatch which is crucial, especially for species with pelagic larvae. Fish would have increased chances for a good seasonal match by having long spawning periods, several spawning groups or long hatching periods. Spawning time in burbot is clearly concentrated in a short period at the end of February. Newly hatched larvae have, however, been observed for a longer period (Hudd et al. 1984, II) than could be assumed by the calculated hatching time, indicating that the hatching period can be prolonged. This would potentially increase the chance for a better match and, consequently, for better survival of larvae. However, the early hatching, on the whole, causes fewer opportunities for burbot to take advantage of better con-

ditions later in the spring. Although burbot do occur in the uppermost parts of the river (Lax et al. 1998), sensitivity to acidification has probably limited the yearly expansion of burbot larvae into the more acidic lower reaches and estuary. Consequently, downdrift of burbot larvae cannot replace destroyed downstream reproduction.

Pelagic yolk-sac larvae of burbot, as well as a lack of stranded 0+ juveniles, were absent from the inner part of the estuary (I) supporting the assumption that the reproduction, both in the inner estuary and in the river itself, was damaged. 0+ and older juveniles were, according to electrical test fishing, also missing in the rapids of the lower reaches of the river (Hudd & Kålx 1997, West Finland Regional Environmental Centre unpublished results). Burbot could be found in low abundance only in the very uppermost tributaries (Lax et al. 1998) which were not so heavily acidified.

Perch has a relatively long spawning period (Thorpe 1977, Koli 1990). Therefore, chances of a good match for some of the larvae should exist nearly every year. However, the perch stock did not increase until the latter part of the study period when the year classes born during a good match of calculated hatching time and decreasing springtime acidification were recruiting to the stock. Strong year classes and a steplike increase in stock size followed after early pH-minima in mild winters in the late 1980s and early 1990s. These better conditions also partly explain the discrepancy in higher explanation rate of year class strengths and pH-index at the beginning of the study period (V) than throughout the entire study period. When pH-conditions were acceptable, other regulatory mechanisms came into force; for perch, especially, the temperature took over. In the beginning of the study period (V), the pH-index explained up to 66 % of the year class strength in the perch stock. When years with earlier acidification peaks were included, pH-index explained only about 30 % of the year class strength. Also, 0+juvenile abundance later in the summer coincided well with the pH-index at the beginning of the study period (V). However, since warm summers are most often dry,

and the run-off from acid tributaries and dredging areas is small, acidification also is low. It is, therefore, difficult to distinguish if strong recruitment is due to low acidification or high temperatures. But anyhow, in the studied stocks, no other strong year classes were born in acid years than the smelt year class 1987.

There is a conflict concerning poor year classes and the good pH indexes in 1981 and 1982 that needs deeper analysis. The year class 1981 was small in all three stocks studied. Since the pH-index was based on scarce water quality monitoring, it gave an overrealy positive picture of the water quality during some years. In late spring 1981, low pH was measured outside the routine monthly official sampling program. Ph below pH 5 was observed for a period in May and the beginning of June (Hudd et al. 1984). Consequently, early life stages and springtime acidification had once again overlapped, and a poor year class was born. Similar observations of episodically low pH-values were also noted for 1982 (Hudd et al. 1984). 1982 also gave birth to smaller year classes in perch and burbot, although the pH-index calculated for the year was good. However, the reasons for the poor perch year class 1989 cannot be explained by bad temporal matching with spring time acidification because the pH in spring and summer 1989 was good. The year class 1989 was poor also in non acidified areas in the Gulf of Bothnia (VI).

Because the perch hatching from later spawning have had a good match nearly every year, the results indicate that the offspring originating from early spawning was of higher importance for the increase in the stock. Perch also reproduce in the upper river (IV). Downward migration of 0+ juveniles or downdrift of larvae could, at least potentially, fill empty areas in the estuary. However, at the beginning of the study period, this potential filling from upstream spawning was evidently not enough to keep the coastal perch stock at a high level.

Newly hatched smelt larvae predominantly occurred further out in the estuary than the perch larvae (VIII, Urho et al. 1990). They are con-

sequently protected by the buffered sea water. Therefore, the smelt offspring had a better match, spatially, than newly hatched perch larvae. Since most of the suitable or high productive 0+ juvenile habitats of perch are not in the outer estuary (Hudd et al. 1984, Urho et al. 1990), the perch larvae are not protected against acidification by buffering sea water. Thus, the smelt stock had better chances to grow throughout the study period.

The "match-mismatch" theory was originally developed to explain the variations in survival of marine fish larvae. According to the theory, strong year classes are born when food plankton maxima occur simultaneously with the peak of first feeding fish larvae (e.g. Cushing 1982, 1990). The theory was developed from Hjort's (1914) hypothesis of a critical period existing in the early life history stages of marine fish larvae during which the year class strength was determined. Starvation was thought to be the mechanism regulating survival (Sinclair 1988). Starvation could be caused by bad temporal match or larval transport to poor food plankton environments (Cushing 1982, Fossum & Øiestad 1991, IX). However, the match-mismatch theory has been difficult to verify through testing (e.g. Sinclair 1988). When applying the terminology to stocks in acid waters, however, good matching of hatching in relation to springtime pH explains most of the year class strengths.

Different stocks, even of the same species, seem to have developed differently in different coastal regions. For example, while the catches and the smelt stock off the acidified River Kyrönjoki have been growing, the smelt fisheries in some other acidified estuaries in the Northern Quark, for example at Vaasa, have collapsed (VII). In comparison to the Kyrönjoki estuary, the acidification in the estuary at Vaasa is more severe. The duration of spring acidification, in particular, is normally much longer (Hudd & Wiik 1989). So, the chances for good survival for offspring of fish spawning in autumn, winter or spring are nowadays small. Bream, perch, and burbot fisheries have also collapsed (purchase statistics of the wholesalers Vasanejdens fiskandelslag, f:ma

Näsman, f.ma Snickars, f.ma Smirnoff).

After the better years in the late 1980s and early 1990s, the acidification pattern reverted, and large mass kills were documented again. For example, in 1996, more than 70 tonnes of adult spawning fish were counted floating on the surface or lying on the shores on one day in the Kyrönjoki estuary alone (West Finland Environmental Centre unpubl.). The effects on the bream stock of mass kills in the beginning of the 1970s was discussed in Hudd et al. 1984 and III, but very little is generally known about the population effects of mass kills among adult fish. The mass kills in the beginning of the 1970s were evaluated (Anon. 1973) as regards the amount of stranded dead fish. Sunken or eaten fish couldn't be evaluated. Since no data on fish stocks was available, population level effects from acidification was not documented properly. The effects of the mass kills on the fish populations were first-simulated for bream (Hudd et al. 1984, III) using population analysis. It was possible to make a retrospective simulation due to the high recruitment age and long life span in the bream stock. Some of the individuals present in the beginning of the 1980s had been adolescents when the biggest mass kills occurred in the 1970s. Fish kills caused by acidic soils have been documented in several Nordic waters (Nordqvist 1902, Arwidsson 1915, Högbom 1921, Olofsson 1930, Vallin 1953, Nilsson & Peterson 1964, Dahl 1963, Rasmussen 1967). Globally, similar phenomena have also occurred, for example, in Australia (Brown et al. 1983, Willet et al. 1993) and India (Pillai et al. 1983).

The importance of first summer water temperature and first summer growth for the strength of the coming year class is documented in several perch and other percid stocks (Kipling 1976, Koonce et al. 1977, Willemsen 1977, Neuman et al. 1996). In the Gulf of Bothnia, as in the whole Baltic Sea, the year class strength in perch populations normally coincides over larger coastal areas (Böhling et al. 1991). A high correlation between year class strength and the summer temperature conditions during the first summer of life (Neuman 1976) is probably due to fast

growth and survival during summer and better survival during the subsequent winter (Karås 1987). Weather conditions are not restricted to single water courses so for example, after the mild winters and warm summers at the end of the 1980s and early 1990s, several stocks of perch within the acidified area had covarying year class strengths. They even began to covariate with populations used as references for monitoring general year class fluctuations in the Baltic Sea (VI). Consequently, the recruitment was more adjusted to a normal pattern.

Hudd et al. (1984) found no similarity in year class strengths between the burbot stock from the Kyrönjoki estuary and two burbot stocks from the western part of the Northern Quark. Neither did Lehtonen et al. (1993) when comparing the stock from the Kyrönjoki estuary with the stock off Pori in the central Bothnian Sea. Lehtonen et al. (1993) assumed acidification to be the cause of the discrepancy between the compared stocks.

Lehtonen & Hudd (1990) suggested that the recruitment of several fish species caught on the coast very much depends upon spawning and nursery areas in rivers and their estuaries offering early and stable warmth, shelter, and rich food supplies in comparison with the sea. The use of estuaries, rivers and other fresh waters for reproduction makes the coastal stocks vulnerable to acidification. Those species that use only the estuaries or fresh waters are extremely vulnerable (Urho et al. 1990).

Step by step, the changes in the water courses leading to acidification have affected several stocks. The three studied species have suffered from acidification in coastal areas far beyond the Kyrönjoki estuary (Hildén et al. 1982). Several stocks in the region have collapsed (III, Lehtonen & Hudd 1990), and some species can even be considered extinct in the region due to acidification of their reproduction areas (e.g. Hildén et al. 1982). Even the smelt, which was successful in the Kyrönjoki estuary during the study period, suffered so much in some parts of the region that fisheries have collapsed (VII). It is also in



line with the known vulnerability to acidification found among cyprinides and burbot (Volodin 1960, Milbrink & Johansson 1975, Beamish 1976, Tuunainen et al. 1990) that burbot and bream fisheries have suffered greatly (III, IX).

Changes in reproduction areas can influence fisheries in a much larger area several years later, and the blame can be put on the wrong scapegoat. In the 1970s and beginning of the 1980s, there were voices raised to regulate the fisheries of burbot, perch and bream in the Northern Quark. The collapse of fish stocks in large areas (Hildén et al. 1982) was mysterious and acute, and the fisheries were made responsible. For those accusing the fisheries, the collapse of unfished stocks, e.g. several cyprinids, was difficult to explain. However, fish stocks can recover provided that their environmental requirements in all life stages, nota bene including those of the early life stages, are in order. The smelt and perch stocks in this study can serve as examples. The start of their recovery could easily be combined with changes independent of fisheries.

No baseline studies existed on fisheries and fish population dynamics in the estuary and influence area of the River Kyrönjoki when the project started in the early 1980s. There were only some data on low pH values and mass kills of fish, as well as plans for further water regulation works. Because the acidification in the region is so intimately coupled to water works, it was very soon understood that few or none of the fish stocks in the vicinity could serve as a good reference. All of the bigger rivers and their estuaries were also regulated or excavated. Especially during the 1960s, there had been large water work projects and forest ditching programs in Finland. The history of neighbourhood fish stocks would thus have been as problematic as the background of those from the River Kyrönjoki. Furthermore, only by increasing the number of years in the study would there be any possibilities to cover different abiotic conditions. The effects of variability in summer temperatures, especially, could then be distinguished from the effects of acidification.

The long time series started in 1979 - 1980 covered both good and bad periods when the end of the 1980s and beginning of the 1990s was included. Thanks to the included good years, it was obvious that the River Kyrönjoki had a potential to produce much fish offspring also for the coastal stocks. When acidification was low or appearing early in the winter, no other water quality factors were documented that destroyed the production of fish offspring, thus preventing strong year-classes from being born. Evidently, a complete analysis of the effects of stream acidification on coastal fish stocks could not have been made without the long term monitoring. This is assumably the case also for other variable impacts.

In open coastal systems, ignorance of the dispersion area and homing behaviour of fish reproducing in rivers and estuaries can cause underestimates of the geographic ranges involved. Consequently, the economic magnitude of the effects of an impact that at first looks very local can be underestimated. In line with this, the coastal fisheries have often been neglected and in many cases have been condescendingly treated (e.g. Suupohja 1965) in the water court proceedings of water construction programs. As a result, little effort has been focused on impact studies to elucidate the importance of healthy reproduction areas for the coastal fishery. The River Kyrönjoki studies are among the few in Finland in which the consequences for coastal fish species other than the big salmonides were also analysed.

The fisheries within the archipelago off the River Kyrönjoki, as in several other places in the Northern Quark, had until the 1970s been small scale relying on several species following each other in delimited seasons (IX). Most of the catches had been taken in the very vicinity of the fishermen's own shores. In summertime, the fishermen used small boats. In wintertime, they used kick sleds as transport devices. The variable stocks of traditionally caught fish led to an uncertain outcome. The outflow of acid water also affected the migration pattern of the fish schools (Hudd et al. 1984) which, in turn, also affected the fishing success. As a consequence new resources had to

be fished upon. The fishing of migratory whitefish, especially, grew rapidly (IX). Although still quite small, the boats grew in size and horse power and especially nowadays they are faster because fishing trips out at sea are so much longer. In wintertime, fast skidoos are used because fishing trips grew up to 40 times in length within a decade (Hudd et al. 1984). This process started before the changes in the Finnish fish market situation had occurred and the popularity of some fish species dropped. Still, in the beginning of the 1980s, catches of some of the freshwater fish species had even grown in other areas along the coast (Lehtonen & Hudd 1990). According to Setälä & Klemola (1992), the fish market in Finland is more or less one market, so development should have been similar all over the coast. According to Setälä & Partanen (1994), the commercial interest of some of the coastal species, e.g. the bream, has changed and is nowadays small. However, there is a good market for perch, and regionally, burbot is still a highly valued fish, fetching a good price. Although the fishing of whitefish has been successful, the low diversity in catches makes the fishery vulnerable to sudden fluctuations or failures in recruitment. The fishery is also more vulnerable to regulations. Earlier, when the fishermen fished on local species, they could more or less decide themselves over the management of the fisheries. Nowadays, when they fish on whitefish stocks migrating over the entire Gulf of Bothnia, management is lifted to a national level, in the future perhaps, to an international level. The fisheries in the region are not strategically prepared for that. Furthermore, the fishermen have to take larger risks in the more exposed open sea areas and variable ice conditions.

## Acknowledgements

My relative Gunnar Antill (†) told me when I was a little boy about the mysterious deaths of fish after ditching and water clearances. Gunnar knew about the poisonous alum. He had experienced it in everyday tasks on his farm. He connected the mass kills in the River Vörå to the outflow of alum. Kalle Wiklund told me how the pike, when spawning, avoided ascending newly ditched creeks for several years. So, when I started this project, I not only had the dramatic mass kills, as presented from the beginning of 1970s on the front pages of local press, but also the tales from my childhood in mind.

Among those who have taken part in the development of the project, I would particularly like to thank Pertti Sevola, Ole Storsved (†) and Kurt Blomqvist. Pertti Sevola was the first who, from a scientific viewpoint, raised the question concerning the long term consequences for fish stocks after large mass kills. I hope that my studies, at least to some extent, have given answer to some of the questions concerning what happens after acidification of reproduction areas. Ole Storsved (†) argued passionately that the burbot doesn't reproduce in archipelagos and that the crash in the stocks on the Finnish west coast was due to acidification of spawning rivers and creeks. Now, I have the same opinion that he had. Ole, it's too late for you to read this work, but I confess, I was wrong then. Kurt Blomqvist was the first to point out to me how beneficial it is for a coastal fishery to have several fish species to rely upon. The seasonality of the catches enabled full time fishing all around the year, and if one stock or species is decreasing, there is another to fall back on. In the estuaries in the Northern Quark, there were still, at that time, several stocks to fish. Nowadays, most fishing is very concentrated on only one species, and the fisheries are vulnerable to population fluctuations and regulations.

In my team and among my colleagues, I especially want to thank Jakob Kjellman, Pia Kålx, Lauri Urho, Ari Leskelä and Mikael Hildén. Without your combined intelligence, nothing would have succeeded. I would also like to

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