A MERCURY MODEL USED FOR ASSESSMENT OF DREDGING IMPACTS

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Abstract. The effects of dredging of contaminated sediments on the mercury (Hg) concentrations of prey and predatory fish were calculated for the Kokemäenjoki River and its estuary in Western Finland. The accumulation of Hg in fish is controlled by the Hg concentrations in water, zooplankton, zoobenthos and by suspended solids. Hg is accumulated into fish mainly through food web, eg. from perch (*Perca fluviatilis*) as prey and to pike (*Esox lucius*) as predator. In addition to dredging, temperature and flood situations have also increased the Hg accumulation and release from the bottom sediments.

The validity of the model has been tested with data recorded from earlier dredgings. Thereafter the model has been used to predict the Hg levels caused by dredging planned upstream in the river. The predictions are supported by the concentrations of total mercury (Tot.Hg) and methyl mercury (MeHg) measured in water and in sediments under several flow conditions. As a result, 30 % increase of Hg in pike - from 0.8 to 1.05 mg/kg - was expected. This was too high, and therefore dredging was not included in the final plan for flood protection.

1. Introduction

River sediments contaminated by mercury (Hg) are problematic since they are often distributed over wide areas and are easily transported and released by flows and floods. With dredging, even higher amounts of total mercury (Tot.Hg) can be released from the sediments. These releases will accumulate through the food web into fish as methyl mercury (MeHg), which can be toxic to birds and mammals, including man (Verta, 1990; Harris, 1991; Sjöblom and Häsänen, 1969; Jernelöv, 1970; Jernelöv and Lann, 1971; Huckabee *et al.*, 1979; Häkkilä, 1987).

The increased understanding of accumulation dynamics in fish, accumulation rates and fish growth dynamics has resulted in bioaccumulation models (Norstrom *et al.*, 1976), bioenergetic growth models (Hewett and Johnson, 1992) and combinations of these in bioenergetic bioaccumulation models (Korhonen *et al.*, 1994), respectively. These are useful aids in planning river management, e.g., dredging, in other construction efforts or regulation, in assessing their potential effects in advance, in designing the operations to mitigate harmful effects, and finally, in deciding their acceptability and ways of execution.

The aim of this paper is to describe the use of a bioenergetic bioaccumulation model in the practical planning, selections and decisions of real management problems. At first the application area, observations and management alternatives are reviewed, then the model is briefly presented and selection of model parameters is described, and the use of the model is explained. Model results are presented and their use and their meaning for decisions are described. More model details and validity tests are presented elsewhere, in Korhonen *et al.* (1994). The work is largely based on the long and strong tradition of environmental Hg research in Finland (Sjöblom and Häsänen, 1969; Häkkilä, 1987; Verta, 1990).

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2. Area of Application

The research area is located in Western Finland in the central parts of the Kokemäenjoki River, up to 60 km from the sea (Figure 1). The surface sediments (0 - 30 cm) are mainly clay and silt (about 85 %). Since the 1950's the sediments have been contaminated by Hg from a chlorine plant. The Hg loading was drastically reduced in the early 1970's and was recently eliminated almost totally. The concentrations of Hg in sediment in the area vary from 0.01 to 16.7 mg/kg (dry weight). The total amount of Hg in the sediment planned to be dredged is about 100 kg.

The Kokemäenjoki River is one of the biggest rivers in Finland. Its mean rate of flow (MQ) amounts to 220 m^3/s, the mean high flow (MHQ) to 600 m^3/s and the mean low flow (MNQ) to 37 m^3/s. The drainage area is 26 000 km^2 and almost 12 % of it is covered by lakes. The catchment of its middle reach and the Loimijoki River, the main tributary, is an important agricultural area. The rivers are regulated by several hydropower plants.

Wide areas around the central part of the river, including the Loimijoki River, often suffer from floods. The areas of planned remediation efforts, observations, estimation of model coefficients and model application are located at the central parts of the river (Figure 1). The model validity has been tested at the downstream parts near the river mouth (northwestern corner of Figure 1, Korhonen *et al.*, 1994).

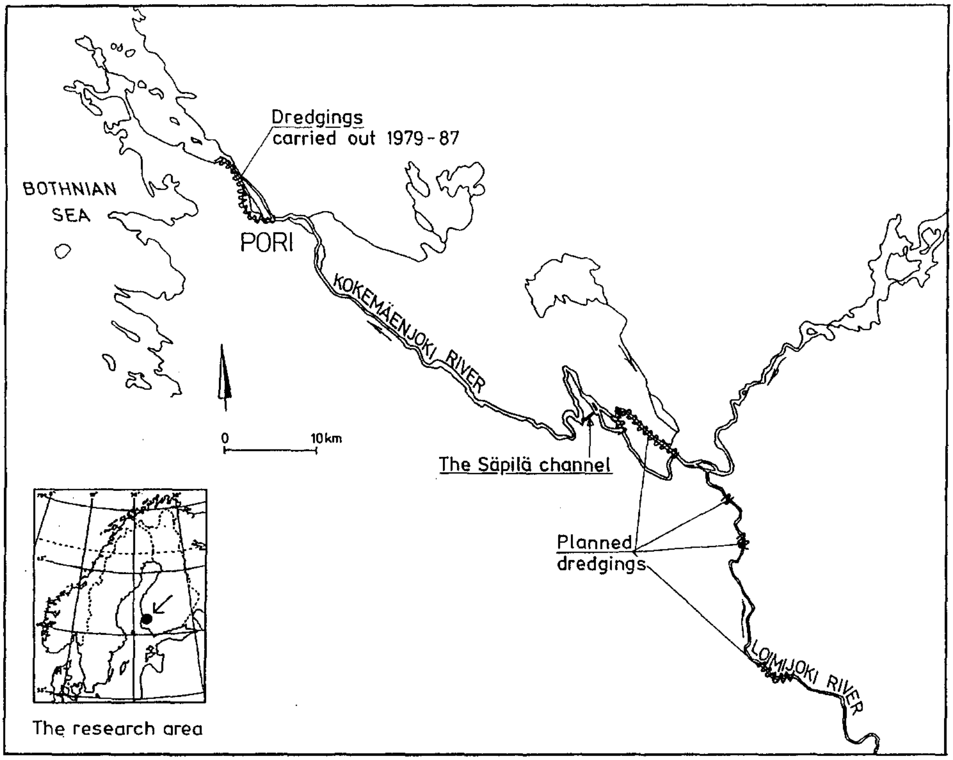

Figure 1. The research area in the central regions of the Kokemäenjoki River in Western Finland. The validity of the model has been tested in the downstream region near the river mouth (Korhonen *et al.*, 1994).

3. Plans for Dredging

Both the Kokemäenjoki River and the Loimijoki River are prone to flooding, which has caused substantial damage to agriculture. Some housing areas have also suffered from flooding. Severe flooding (>20 km^2) in the 1970's created demands for flood protection. The preliminary remediation plan presented in 1987 - 1988 contained dredging of a part of the river, clearing of some rapids and construction of a new artificial channel (the Säpilä channel, Figure 1). The remediation efforts would affect the use of the river for electricity production, because the middle reach of the Kokemäenjoki River is regulated by two hydropower stations. In addition to the desired economic impacts, the project has some controversial effects on the environment. Most important of these are impacts on the threatened fish asp (*Aspius aspius*), increase in the Hg content of fish and lowering of ground water level.

4. The Model Utilized

The model was developed and described by Korhonen *et al.* (1994). Its central elements are based on the bioenergetic calculation of food consumption and fish growth (Bevelhimer *at al.*, 1985; Hewett and Johnson, 1992) and on the bioaccumulation of MeHg into the fish from food and from water (Norstrom *et al.*, 1976). Its main steps and dynamics are schematilly shown in Figure 2.

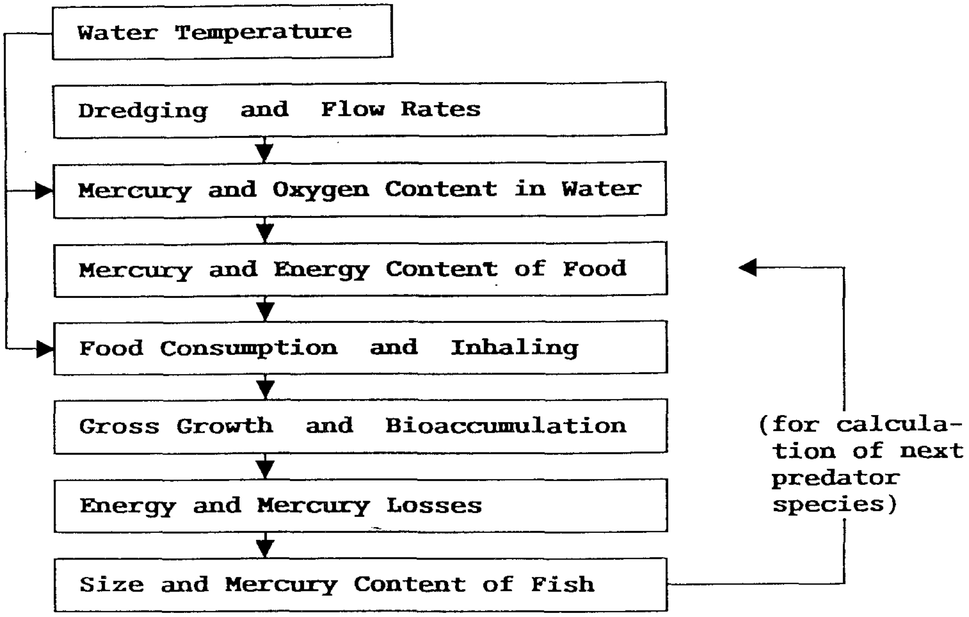

Figure 2. Main calculation steps of the bioenergetic mercury accumulation model.

5. Observations

The growth data for pike (*Esox lucius*) are based on a sample of 344 fish caught 1984 - 1987 in the Kokemäenjoki River and in its estuary (Figure 1). The growth of perch (*Perca fluviatilis*) is estimated from a sample of 761 fish caught 1987 - 1990 in the estuary.

The water temperatures were the monthly averages of 1970 - 1991 at the surface of the river and the estuary. They varied from 0.2 °C in winter to 20 °C at the end of July. The same temperatures were used for model validation (for 1970 - 1992, Korhonen *et al.*, 1994) and the present application. The oxygen concentrations in water varied from 8 in August to 12.6 mg/l in winter, and pH from 6.6 to 7.6.

The estimates of the Hg content in sediments are based on about 50 samples from different depths (0 - 50 cm) obtained between 1985 and 1993 (Häkkilä, 1987; Korhonen and Virtanen, 1993). Typically - but not regularly - the highest values are found near the shore at 10 - 30 cm below the surface of the sediment. In 52 % of the sediment samples there is Hg < 0.1 mg/kg, in 28 % of samples > 1 mg/kg. Hg concentrations in deeper bottom layers, more than 30 cm from the sediment surface, have not exceeded 0.06 mg/kg. The average concentration in the sediments planned to be dredged is about 0.3 mg/kg.

Concentrations of Tot.Hg and MeHg in water were measured 7 times in 1991 - 1992 at 5 places in the river and estuary. The concentrations of Tot.Hg varied from 1 to 20 ng/l and those of MeHg from 0.01 to 0.5 ng/l (Korhonen and Virtanen, 1993).

No recent observations were available from the concentrations of Hg in zooplankton and zoobenthos. In the 1970's and 1980's, Hg concentrations from < 1 mg/kg to > 100 mg/kg dry weight were measured for these groups (Häkkilä, 1987).

Concentrations of Hg in pike have been measured in the region since the end of 1960's. The number of annual samples varied from 2 to 100 fish. Between 1970 and 1992, the concentration of MeHg in 1 kg "standard" pike varied from 0.38 to 1.35 mg/kg fresh weight, depending on the area and time. In 1991 - 1992, the concentration of Hg in prey fish (mainly perch and roach, *Rutilus rutilus*) varied from 0.08 to 0.27 mg/kg, based on a sample of 60 fish of 5 to 20 cm in length (Korhonen and Virtanen, 1993).

6. Parameter Estimation

The coefficients of food consumption by perch are obtained directly from Kitchell *et al.* (1977). The coefficients for pike are modified from those of Bevelhimer *et al.* (1985) to represent the local conditions. The optimum temperature of food consumption has been reduced from 24 to 19 °C, and the maximum temperature from 34 to 26 °C, respectively.

The estimates of food composition and the relations between the sizes of predators and preys are based on detailed investigations by Korhonen and Heikinheimo-Schmid (1993). The coefficients of bioaccumulation are taken directly from Norstrom *et al.* (1976). The only exception was the steepness exponent r coupling Hg removal rate Lp to fish weight W (Lp/P proportional to W^r, when P is Hg concentration). For perch this was changed from -0.58 to -0.8 in order to avoid unnatural fluctuations. All coefficients of bioaccumulation are listed in Korhonen *et al.* (1994).

7. Approximations for Model Input and Use

Based on the observations and the selected model coefficients, the model was applied to earlier dredging under roughly natural flow conditions (Korhonen *et al.* 1994). Comparisons of the model results with the measured mercury levels in pike indicated qualitative similarity in the downstream section of the river (Figure 1 in Korhonen *et al.*, 1994).

With the same assumptions which were used in the validity tests, the model is applied to the planned dredging of the contaminated sediment areas. The concentrations of MeHg in fish used food are of interest mainly during the growth season from May to September. During that time, under the present conditions, the MeHg concentrations in water vary from their spring flood values of 0.5 to 0.1 - 0.2 ng/l for the rest of the summer. In the model input these are estimated as an average 0.2 ng/l for the whole season. Winter concentrations of 0.03 ng/l MeHg in water are not taken into account in the model for mercury accumulation to fish, because fish eat almost nothing during the winter season.

Tot.Hg released from the sediments and mixed to the MQ is estimated to increase the MeHg concentration of water with 50 % during the growth season (from May to September) if the works are carried out throughout all seasons at equal efficiency for three years. The average flow over three years is not expected to deviate very much from the MQ. The flood flows during the dry spell, from June to September, are assumed to increase MeHg in water with an extra 0.1 ng/l when the flow is stronger than twice the MQ (Figure 3).

The effects of dredging include both the direct releases from disturbed sediments and the overflow from the settling and drying areas to which the bottom masses are pumped or transported. In the region where the validity tests were made, suction pumping was used while showel digging has mainly been planned for the central parts of the river. This may slightly overestimate the predictions since the pumped wet masses can be more hazardous for strong overflows than the dryer showel masses, especially since the conditions in the settling basins (as warm, large, slowly flowing, turbid and perhaps anoxic) after pumping can be very favourable for methylation. Due to lack of direct observations no attempt was made to eliminate this possible overestimation from the predictions.

The relative increase of MeHg in water is assumed to appear immediately at equal relative strength in the MeHg of the plankton and zoobenthos perch eat. Compared with the concentration increases in water the effects in the food of younger (0 - 3 year) perch is 250 000 -fold and in that of the older (4 - 7 year) perch 500 000 -fold. From this assumption - i.e. 50 % increase of perch food MeHg for 3 years, and thereafter return to the present values again - the accumulation of MeHg into perch is calculated with its growth using the bioenergetic bioaccumulation model with a time step of one day.

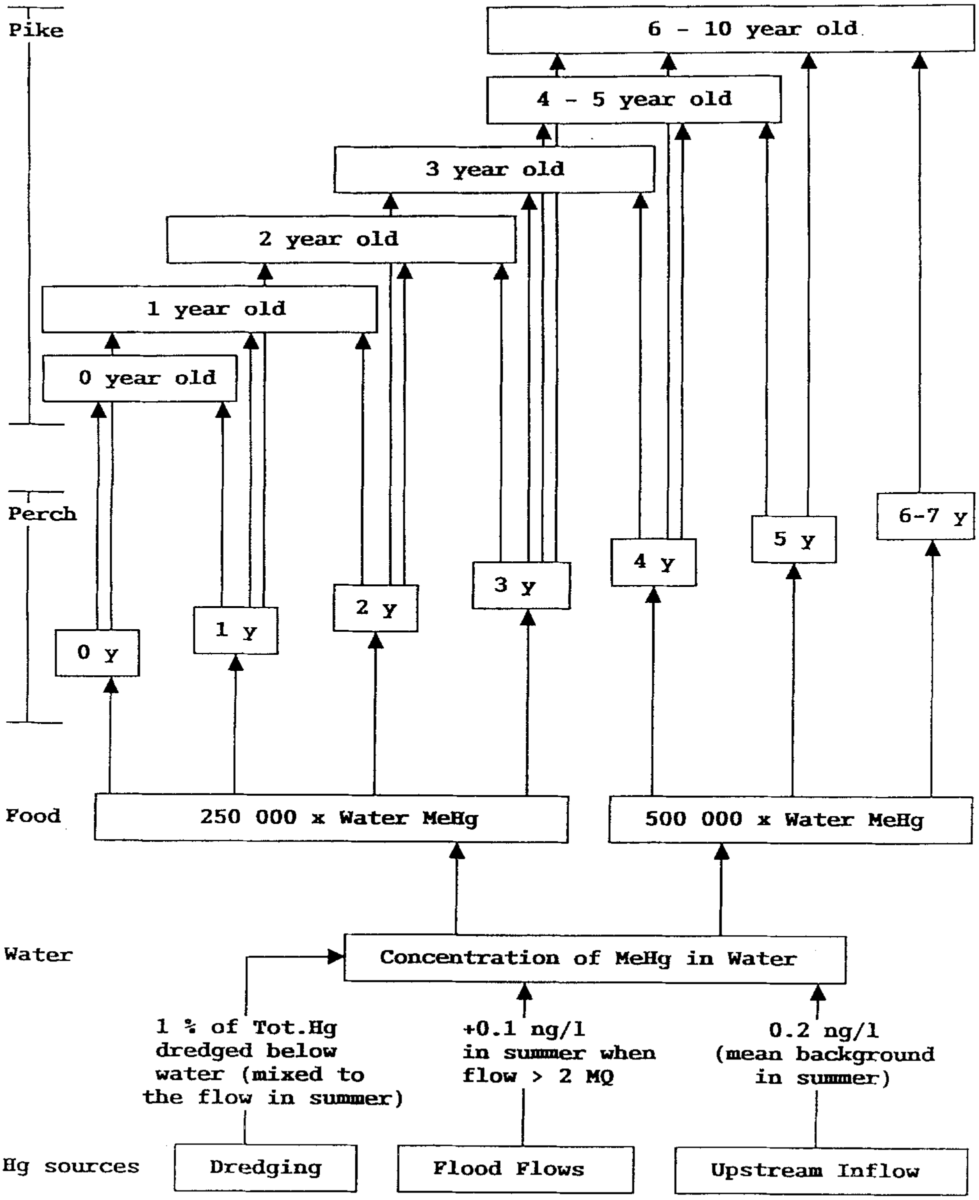

Figure 3. Basic assumptions behind and accumulation paths within the use of the bioenergetic bioaccumulation model (Korhonen *et al.*, 1994).

Based on the investigations of Korhonen and Heikinheimo-Schmid (1993), the perch are assumed to be eaten by pike according to age as follows:

Pike age (years)	0	1	2	3	4 - 5	6-10
Eaten perch age (years)						
0	+	+				
1	+	+	+			
2		+	+	+		
3			+	+	+	+
4				+	+	+
5					+	+
6-7						+.

I.e., pike eat fish already at the age of 0 years. The Hg accumulation to pike and their growth are calculated separately for male and female fish using recursively the bioenergetic bioaccumulation model with one day time steps. Schematic presentation of the accumulation paths within the food web as they are described in the model is shown in Figure 3.

8. Model Results

The highest relative increases of MeHg concentrations in perch, 60 %, are found in the 1 year old individuals during the two last years of dredging. In older perch the highest increases, 40 to 50 %, occur in the last year of dredging. The elevation of MeHg is evident in the oldest perch until 5 years after dredging (Figure 4).

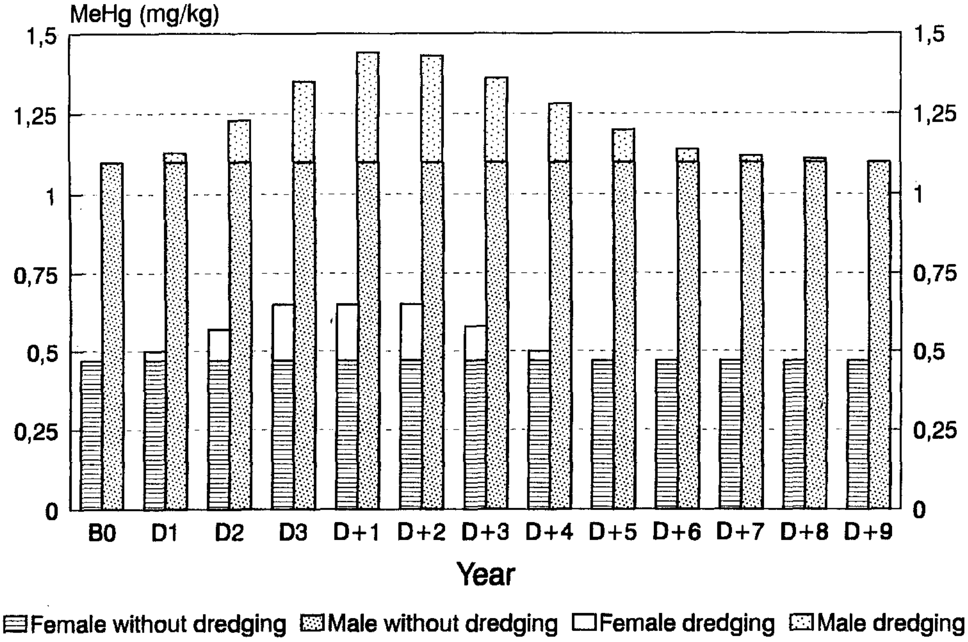

Figure 4. The effects of dredging on the MeHg in 1 year, 3 years, 5 years and 7 years perch in respect of time (years) before (B0), during (D1-D3) and after (D+1-D+7) the dredging.

Accumulation of MeHg into the pike is slower than that into perch. In a 1 kg pike the highest increases appear in the year following the three years of dredging. The effects on female and male pike are shown separately in Figure 5. As the average of males and females, the highest increase of MeHg is about 30 %, from 0.8 to 1.05 mg/kg, which is just above the recommended absolute limit of 1 mg/kg for selling and eating. Increased concentrations of MeHg persist in males for 8 years following the termination of dredging, while in females these last for 4 years only. Rapid growth rate of females decreases their Hg increase compared with the Hg increase in males.

In practice, all of the MeHg in fish is from their food. According to the results of the bioaccumulation model (Borgmann and Whittle, 1992; Korhonen *et al.*, 1994; Korhonen and Virtanen, 1993), only a small percentage of Hg is directly from water through gills with inhalation.

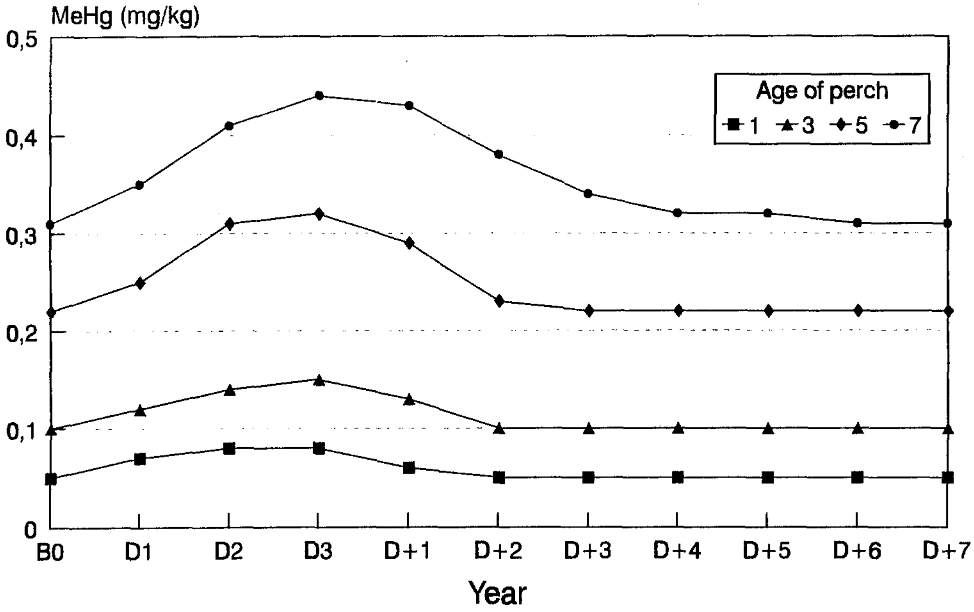

Figure 5. The effects of dredging on the MeHg in 1 kg female (right) and male (left bars) pike in respect of time (years) before (B0), during (D1-D3) and after (D+1-D+9) the dredging. Model results (total columns) compared with the prevailing values without dredging (the lower parts of the columns).

9. Use of Model Results in Impact Assessment

In Finland the Water Act requires that developers of large scale water regulation projects present investigations on the effects on the aquatic environment, fish stocks and fisheries. The assessment of the impacts of the flood protection project started in the late 1980's. In 1991 the National Board of Waters and the Environment decided that the international principles of environmental impact assessment (EIA) should be applied in the project. In Finland the law for EIA will come into force in the fall of 1994.

In the EIA process six different alternatives for flood protection were considered. Two of them included dredging of Hg contaminated sediments, two others restricted dredging to areas not contaminated by Hg, one alternative contained only opening of a new channel, and one was the zero alternative where nothing was planned to be done nor changed.

Results of the Hg model were used both in the EIA process and in preparing an application for the Water Court. Results of the Water Court Process are not yet known. During the EIA process ecological, social and economic impacts were examined (Hildén *et al.*, 1991; Hildén *et al.*, 1994; Hämäläinen and Marttunen, 1994). Some stake holders were interviewed, to find out their opinions about the impacts and the alternatives of the flood protection project, and to improve their involvement.

The release of Hg from sediments was one of the issues that caused public concern. This lead to development of the model described in Korhonen *et al.* (1994) and in this paper. The results of the model and other extensive investigations were useful in the interviews to assess the relative differences between the alternatives.

10. Conclusion

As a result of the EIA process the National Board of Waters and the Environment decided not to dredge the Hg contaminated sediments as part of the flood protection project. The decision was based on a combination of costs, benefits and potential harmful environmental effects. Thus accumulation of Hg in fish was one of the reasons presented in support of the decision not to carry out the dredging.

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