National Swedish Environmental Protection Board REPORT 3949

Radioecology in Nordic Limnic Systems.

- present knowledge and future prospects -

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Beställningsadress:
Naturvårdsverket
Informationsavdelningen
171 85 SOLNA
tel: 08-7991000

Distribution:
Svedish Environmental Protection Agency
Information Department
S—171 85 SOLNA
tel: (+46 8) 7991000

ISBN 91—620—3949—0
ISSN 0282—7298
NKS RAD—2(91)1
Upplaga 500
1991/09

Cover illustration: Wetzel; Limnology 1975.

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Preface

The Nordic Nuclear Safety Research (NKS) program for 1990-1993 supports radioecology research in four projects: Rad-1 methods and quality assurance, Rad-2 aquatic ecosystems, Rad-3 agricultural ecosystems and Rad-4 natural (terrestrial) ecosystems.

The following report was prepared during a meeting within the Rad-2 project in November 1990. The aim was to summarize experience drawn from post Chernobyl investigations concerning the behaviour of radionuclides in limnic ecosystems in the Nordic countries. An important task was also to identify particular issues requiring further research.

Participants 12-15 November 1990	Organisations
Subgroup for chapter 5.1	
John E. Brittain	Oslo University
Helge E. Björnstad	Agricultural University of Norway
Björn Sundblad	Studsvik Nuclear
Subgroup for chapter 5.2	
Tord Andersson	Umeå University
Anders Broberg	Uppsala University
Subgroup for chapter 5.3	
Markus Meili	Uppsala University
Torbjörn Forseth	NINA
Sture Nordlinder	Studsvik Nuclear
Ritva Saxén	STUK
Coordinators	
Manuela Notter	Swedish Environmental Protection Agency
Georg Neumann	Swedish Environmental Protection Agency
Secretary support	
Béatrice Andersson	Swedish Environmental Protection Agency
Layout	
Eva Sköld	Swedish Environmental Protection Agency

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Summary

This report from the aquatic radioecology project (RAD-2), being conducted within the Nordic Nuclear Safety programme (NKS), summarizes the results obtained by Nordic research subsequent to the Chernobyl accident within the subject area concerning limnic radioecology. The report gives a survey of the intentions and the sampling programme for the Nordic research projects initiated after the Chernobyl accident. The status for two international model development projects dealing with limnic radioecology—BIOMOVS and VAMP (IAEA)—is also reported. Finally, recommendations for continued research inputs in sectors where data are lacking are given, and where particular requirements are identified.

A number of different projects within Nordic research into limnic radioecology examine the migration of cesium in the ecosystem. National compilations have been made of ^{137}Cs concentration in fish muscle from different lakes with varying fallout. A number of projects with experimental inputs have also been conducted, mainly with regard to the uptake and excretion by fish of cesium.

The report identifies the most important factors. Their importance for the addition, mobility and biological availability of cesium in limnic ecosystem is discussed under three main headings: processes in the catchment area; influence of lake-specific parameters on the distribution of cesium in lakes; differences in uptake depending on fish ecology.

The most important factor for the cesium load on the lake was the initial, direct deposition on the lake surface and on the catchment area. During the first year, 1986, the leaching from the deposition in the catchment area was 0.6-8%. After the dynamic process during the first year, the cesium is now strongly bound in the catchment area. The lake is now supplied annually with a very small amount (ca. 0.007-0.1% of the amount deposited in the catchment area). The half-life of cesium in the water phase was relatively short during the first year after the accident ($T_{1/2}$≈50 d), but has since then increased markedly and is now (1990) more than a year. The turnover time of the water and the depth of the lake are of importance for the cesium content of the lake. Deep lakes with short turnover time has a lower cesium concentration in fish. In comparison with the factors mentioned earlier, the values in the lake water of parameters such as K^+ and pH are of less importance for the cesium concentration in fish.

Of the total cesium content in the lake, the completely dominating part today (1990) is in the sediment (ca. 99%). Sediment-chemical and biological conditions are of great importance for the future cesium level of the lake. After the surface contamination of the sediment during the first year, many lakes show a more homogenous, vertical distribution where different mixing processes have had an influence. Shallow lakes have a relatively comprehensive recirculation of cesium from the sediment. This causes a removal of cesium from the lake but also a higher biological availability in the lake's cesium pool. Rapid recirculation, in the same way as comprehensive bioturbation, has the result that the cesium concentration in fish is kept at a relatively high level and decreases slowly.

The maximum transfer factor to fish from the deposited load (Bq(kg f.w.)$^{-1}$/Bq m^{-2}) was in the range 0.03-0.3 and was reached within four years for all observed fish species. The transfer factor may vary up to 10-fold depending on the characteristics of the lake. The maximum value depends on the diet and the feed intake. For the fish species which first

reached the maximum, small, rapidly-growing fish, it is calculated that a certain equilibrium will occur 5-10 years after the accident. Then the transfer factor is estimated to be about 5-10% of the maximum value. In predator fish the concentrations will be enhanced for many years in the future, and will decrease considerably more slowly.

The concentration factor (Bq(kg f.w. in fish)$^{-1}$/Bq l^{-1} in water) has been calculated to 1000-10000 based on values from 1988-1990.

Sammanfattning.

Projektet akvatisk radioekologi (RAD-2) inom det nordiska kärnsäkerhetsprogrammet (NKS) ger i denna rapport en sammanfattning av de resultat som nordisk forskning efter olyckan i Tjernobyl har givit inom området limnisk radioekologi. Rapporten ger en översikt över syften och provtagningsprogram för nordiska forskningsprojekt initierade efter olyckan i Tjernobyl. Status för två internationella modellutvecklings-projekt som behandlar limnisk radioekologi; BIOMOVS och VAMP (IAEA) redovisas också. Slutligen ges även rekommendationer för fortsatta forskningsinsatser på områden där data saknas, och där särskilda behov har konstaterats.

En rad olika projekt inom den nordiska limniska radioekologiforskningen belyser cesiums vandring i ekosystemet. Det har också gjorts nationella sammanställningar av ^{137}Cs koncentrationen i fiskmuskel från olika sjöar med varierande nedfall. Även några projekt med experimentell inriktning har genomförts, främst rörande fiskars upptag och utsöndring av cesium.

I rapporten har de mest betydelsefulla faktorerna identifierats. Deras betydelse för tillförsel, mobilitet och biologisk tillgänglighet av cesium i det limniska ekosystemet diskuteras under tre huvudrubriker: processer i avrinningsområdet; sjöspecifika parametrars inverkan på fördelningen av cesium i sjön; fysiologiska och ekologiska faktorers inverkan på cesiumhalter i fisk.

Den viktigaste faktorn för sjöns cesiumbelastning var storleksordningen på det direkta nedfallet på sjöytan och i avrinningsområdet. Under första året (1986), var urtvättningen från markbeläggningen i avrinningsområdet 0.6-8%. Efter det första årets dynamiska förlopp, är cesium hårt fastlagt i markskiktet, och årlig tillförsel från avrinningsområdet är nu liten (0.007-0.1%). Halveringstiden för cesium i vattenfasen var relativt kort under det första året ($T_{1/2} \approx 50$ d), men har sedan ökat markant och är nu (1990) längre än ett år. Vattnets omsättningstid har stor betydelse för sjöns cesiuminnehåll. Undersökningar visar att det finns samband mellan omsättningstiden och cesiumkoncentrationen i fisk. Kort omsättningstid ger lägre koncentration i fisk. Efter nedfallet från Tjernobyl hade sjöns omsättningstid större betydelse för cesiumkoncentration i fisk, än sjövattentes värden på parametrar som K^+ och pH.

Av sjöns totala cesiuminnehåll finns nu (1990), den helt övervägande delen i sedimentet (ca 99%). På längre sikt kommer de sedimentkemiska och biologiska förhållandena att få ökad

betydelse för koncentrationen i fisk. Efter första årets ytkontaminering av sedimenten visar många sjöar under senare år en mer homogen, vertikal fördelning, där olika blandningsprocesser har inverkat. Grunda sjöar har en relativt omfattande recirkulation av cesium från sedimenten. Det orsakar borttransport av cesium från sjön, men också en högre biologisk tillgänglighet av cesiumpoolen i sjön. Snabb recirkulation, liksom omfattande bioturbation, orsakar att cesiumkoncentrationen i fisk hålls på en relativt hög nivå och avtar mycket långsamt.

Maximal överföringsfaktor till fisk från deponerad belastning (Bq(kg f.v.)$^{-1}$/Bq m^{-2}) uppnåddes för alla observerade fiskarter inom fyra år. Överföringsfaktorn kan variera upp till 10 ggr beroende på sjöns karaktäristika. Små snabbväxande fiskar uppnådde maximum först (0.03-0.3) och en relativ jämnvikt beräknas inställa sig 5-10 år efter olyckan. Överföringsfaktorn uppskattas då till ca 5-10 % av maxvärdet . Det maximala värdet beror på dieten och födointaget. Hos rovfisk kommer halterna att vara förhöjda många år framöver, och minska betydligt långsammare.

Koncentrationsfaktorn (Bq(kg f.v.)$^{-1}$/Bq l^{-1} i vatten) har beräknats till mellan 1000 -10000 baserat på värden från 1988 -1990.

1. Introduction

The two most important radionuclides in human food chains are ^{90}Sr and ^{137}Cs. Both have a physical half-life of about 30 years. ^{90}Sr enters and accumulates in bone tissue. Together with its daughter nuclide Yttrium-90 ($t_{1/2}$ - 60 h), a much stronger β-emittor, the nuclides affect the red bone marrow and can therefore cause leukemia. The biological half-life of ^{90}Sr in man is about 5-10 years (Hansen & Aarkrog 1990). ^{137}Cs, on the other hand, to a certain extent follows potassium and enters the cells (Na/K-pump) and mainly accumulates in muscle tissue. It has a biological half-life of about 30-100 days, .

Among the fission products in the fallout from Chernobyl that reached the Nordic countries, ^{137}Cs must be considered to be the most important from a radioecological standpoint. This justifies the fact that main topics of the present meeting were processes related to this nuclide.

During the period between 1960 and the Chernobyl event (April 26, 1986), Nordic scientists were rather active in studying phenomena connected with the transport of fallout radionuclides through limnic systems. One may be reminded of a few of these earlier radioecological projects by mentioning for example the work of Hannerz (1968) on the role of feeding habits in the accumulation of fallout radionuclides in fish, the study by Kolehmainen, Häsänen and Miettinen (1968) of ^{137}Cs in fish, plankton and plants in Finnish lakes and Carlsson's (1976) investigation of ^{137}Cs in a dysoligotrophic lake (Lake Ulkesjön).

From these studies, which were mainly concerned with the transport of radiocesium (and in some investigations also with ^{90}Sr) through different lake compartments, some valuable observations were made. A number of good estimates of biological half-lives under different conditions were obtained, and transport-pathways through limnic systems were identified and quantified. Many of these quantitative results are still regarded as of considerable value and are frequently used, for example, in modelling.

After the Chernobyl event, the interest in limnic systems was strongly vitalized. At several meetings, including the Fifth Nordic Radioecological Meeting in Rättvik, Sweden (1988), a number of results were reported concerning the fate of radiocesium in Nordic limnic systems. Due to the rapid contamination and the quite high surface load of ^{137}Cs in some Nordic regions, the Chernobyl accident naturally strongly stimulated the launching of several ambitious projects entailing large and detailed sampling series as well as much work on modelling nuclide transport. Some studies were also aimed at the possibility of reducing the content of ^{137}Cs in fish by adding chemicals to catchments or lake waters, in this way changing conditions which were considered to influence the uptake of radiocesium.

In recent years mathematical modelling has become an increasingly important tool in understanding the complex processes which determine the distribution of radionuclides in lakes.

The VAMP project (initiated by IAEA) as well as the BIOMOVS project (launched in 1986 and terminated in October 1990 as concerns aquatic systems) are both international projects on model validation in which Nordic scientists are active.

Finally, the large quantity of Nordic radioecological data now published at a steadily increasing rate, renders the need for an efficient and versatile data base. A data base of this kind developed at Risø, Denmark (the Nordic Chernobyl Data Base, NCDB), was demonstrated at the meeting.

2. International model-validation projects

VAMP and BIOMOVS have both provided extensive possibilities for modellers from different institutions to communicate with each other as well as with field scientists. Nordic participation in these projects has been quite extensive, and two oral contributions (B. Sundblad and S. Nordlinder) on this topic were given at the meeting.

2.1 BIOMOVS

A short introduction to the BIOMOVS project (BIOspheric MOdel Validation Study) was given by B. Sundblad. He briefly described the history of this project which was officially launched in 1986 on the initiative of NIRP (National Institute for Radiation Protection, Stockholm). It was pointed out that organisations from 14 countries participate in the BIOMOVS project. Twelve organizations are represented in the BIOMOVS coordinating group. A list of participating countries and organizations is given in Table 2.1.1.

Organisations represented in the BIOMOVS study

Organisations	Countries
National Research Institute for Radiobiology and Radiohygiene *	Hungary
Comitato Nazionale per l'Energia Atomica-Disp *	Italy
National Cooperative for the Storage of Radioactive Vaste *	Switzerland
National Radiological Protection Board *	United Kingdom
National Institute of Radiation Protection *	Sweden
Risø National Laborarory *	Denmark
Technical Research Centre of Finland *	Finland
Tokai Research Establishment *	Japan
Department of Energy *	USA
Atomic Energy of Canada Limited *	Canada
Studiecentrum voor Kernenenergie, SCK/CEN *	Belgum
Department of Environment/ANS	United Kingdom
Ministry of Agriculture, Fisheries and Food	United Kingdom
Institute of Radiation Hygiene	West Germany
General Electricity Generating Board	United Kingdom
Swiss Federal Institute for Reactor Research	Switzerland
Gesellschaft für Stralen- und Umwelt Forschung	West Germany
Japan Atomic Energy Research Institute	Japan
Oak Ridge National Laborarory	USA
Laboratory of Radiation Research	The Netherlands
Empresa Nacional de Residous Radioactivos *	Spain
Studsvik Energiteknik AB	Sweden

* members of the BIOMOVS coordinating group

Table 2.1.1 Organisations represented in the BIOMOVS study.

Two lines of approach have been followed in this project:

Approach A, in which validation was attempted by using independent observ-ational data which were not accessible to the modellers until the final delivery of the model results, in order to avoid different types of pre-calibrations.

Approach B, in which model predictions and related uncertainty estimates for specific artificially constructed test scenarios of importance for dose assessments were compared.

The primary objectives of the BIOMOVS (NIRP 1986) study are to estimate the extent of uncertainty associated with model predictions of the transfer, accumulation and re-mobilisation of environ-mentally significant radio-nuclides or trace substances in the biosphere and to recom-mend procedures for improving predictive accuracy.

There are generally two types of uncertainties to be considered in the BIOMOVS-modelling:

- Uncertainties in the input parameters
- Uncertainties in the model structure

Whereas the former type may be studied by means of a number of different methods (generally of a stochastical character), the second type is best considered by testing the model against different sets of independent data. Another very important, and probably in general a more powerful way of validating model structures is to make intercomparisons between results obtained from different models, preferably developed by different modellers.

Within the BIOMOVS study, limnic systems have been treated within the sub-project "Dynamics within Lake Ecosystems" (subproject A5). Other subprojects dealing with lakes have been "Release of Radium-226 and Thorium-230 to a Lake" (subproject B3) and "Ageing of lakes" (subproject B5).

As to models relating to the Chernobyl accident it was noticed that in some cases, rather encouraging predictions for shorter time-perspectives were obtained in modelling the transfer to fish from primary surface contamination on drainage areas and lake surfaces. Dynamic methods were found much superior, especially in the inital phase, to other methods which at least in part utilized empirical transfer factors, such as between sediments and water. It was also noticed that the techniques for modelling physical and chemical processes (e.g. sedimentation) in limnic systems still need improvement.

In summarizing, it must be pointed out that within the BIOMOVS project special interest has gradually been concentrated on different aspects of uncertainty in analyses of modelling.

It should finally be mentioned that future BIOMOVS studies probably will not concentrate on problems associated with lake ecosystems. On the other hand, there are many parallels to the VAMP project which will be discussed below.

2.2 VAMP

The Chernobyl accident fallout has resulted in a single pulse, which has been detected and measured in a variety of environments, mainly in the European parts of the USSR and in Europe.

The acquisition of these new data sets justified the establishment of an international programme aimed at collating data from different IAEA Member States and a co-ordinating work on model testing studies.

In 1988, IAEA established a coordinated Research Programme "Validation of Models for the transfer of Radionuclides in Terrestrial, Urban and Aquatic Environment" (acronym VAMP). Since January 1989, VAMP has been co-sponsored by the CEC (IAEA 1988, 1989, 1990). A short introduction to the VAMP program was given by J.E. Brittain.

The scientific scope and objectives of VAMP are:

- to facilitate the validation of assessment models for radionuclide transfer in the terrestrial, aquatic and urban environments.

- to guide environmental research and monitoring efforts to acquire data for the validation of models used to assess the most significant radiological exposure pathways.

- to produce reports reviewing the current status of environmental assessment modelling, including a review of the improvements achieved as a result of post-Chernobyl validation efforts and identifying the principal remaining areas of uncertainty in models used for radiation dose assessments.

- to run "test scenarios" for model validations selected for their importance in relation to radiation dose assessments, particularly to improve the reliability of predictions of radinuclide transfer through the terrestrial environment and in food-chains, their transfer through surface waters (freshwater and seawater) and their transfer in urban environments.

Four working groups were established at the first meeting. The most significant here is the VAMP Aquatic Working Group.

The aquatic group intends to study the dynamic behaviour of radionuclides in watersheds and to focus on:

- Freshwater systems, lakes
- The causal relationships governing the uptake of ^{137}Cs in fish
- The factors regulating the decline of ^{137}Cs in fish (i.e. the factors regulating the transport of Cs from land to water and the factors in the river/lake regulating internal loading/ resuspension and possible remedial measures (to reduce the concentration of Cs in fish).

The following fluxes are found to be of fundamental importance for the modelling:

➤ The fallout onto the lake surface (primary load).

➤ The uptake of Cs from the primary lake load depends on
  - the water residence time.
  - the stratification and/or thermal regime.
  - sedimentation rate of Cs

➤ The flux of Cs from sediments (internal load). This flux is linked to two major processes:
  - diffusion, which is regulated by the concentration difference between Cs in sediment pore water and in deep lake waters.
  - resuspension, which may be divided into wind/wave induced resuspension in large and shallow lakes and slope induced resuspension in deep lakes with inclining bottoms.

➤ The flux of Cs from land to water (secondary load). This will depend on the tributary water discharge and the concentration of Cs in the tributary water, which in turn will depend on the characteristics of the drainage area.

- The amount of Cs leaving the lake per unit time (outflow). The outflow depends on the water discharge and the concentration of Cs in the lake water. In certain lakes, significant amounts of Cs may be lost through fishing.

Seven sets of data have been compiled and are available to the VAMP aquatic group. The 7 localities have been chosen to provide, as far as possible, the widest range of lake characteristics.

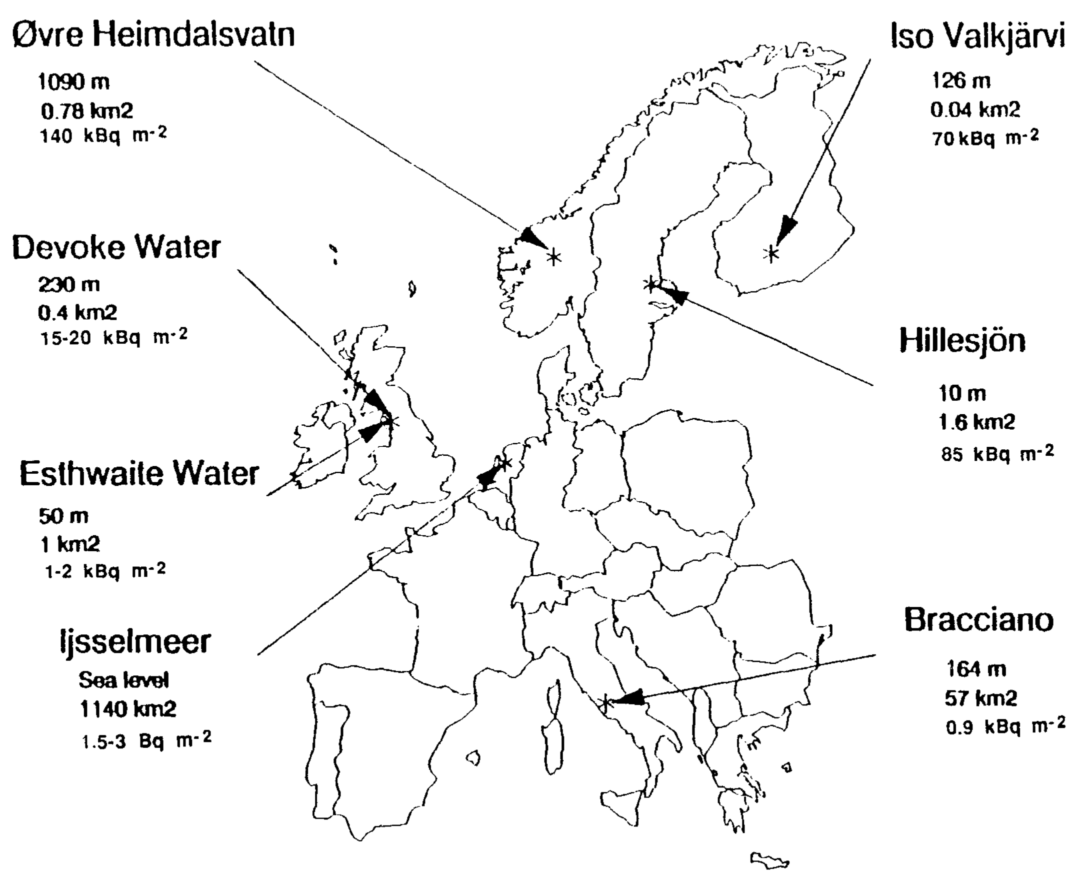

Fig. 2.2.1 Altitude (m), area (km2) and ^{137}Cs deposition (kBq/m2) of the lakes in the VAMP project.

In the study modellers are invited to model the behaviour of Cs within these lakes for comparison against the observations.

It is accepted that this selection does not include all possible lake types. The locations of the lakes and estimates of the cesium deposition at these sites from the Chernobyl plume are shown in Fig. 2.2.1.

The modelling part of the program will start in the beginning of 1991.

3. Nordic Post Chernobyl Research

The investigations performed in the Nordic countries on the behaviour of Chernobyl fallout radionuclides in different ecosystems are numerous, even if we restrict the field by just considering limnic systems.

Most investigations in the limnic field are from Finland, Norway and Sweden since Denmark and Iceland were not so heavily contaminated.

This type of research was initiated in different ways in the Nordic countries. Funding has mostly been provided by the state, although its distribution has been quite different. In Finland it has been more centrally controlled, and monitoring and research has been ordered by the state. In Norway and Sweden different institutions have designed their own projects and obtained additional financial support from the agency responsible for radiation protection and from other research councils.

Most investigations were principally aiming at gathering field data to obtain a better understanding of cesium transportation processes in the ecosystem, although a few experimental studies also have been carried out (most concerning ^{137}Cs uptake and excretion in fish).

A selection of the research projects is given below.

More details of the lectures presented on the first day of the meeting are included in Appendix 1.

3.1 Finland

In Finland, the Finnish Centre for Radiation and Nuclear Safety (STUK) is the authoritative institute concerning radiation protection. Besides the long-term nationwide environmental monitoring programmes, the Centre carries out special radioecological studies concerning transport and behaviour of radionuclides in terrestrial and aquatic ecosystems. Besides STUK, some other institutes in Finland, especially the Department of Radiochemistry at Helsinki University, are carrying out radioecological studies, also in the aquatic environment.

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Project:	A nationwide long-term study on the transfer of radiocesium in the aquatic environment. The study includes analyses of freshwater fish and surface water.
Organisation:	Finnish Centre for Radiation and Nuclear Safety. Contact persons: Ritva Saxén, Kristina Rissanen.
Finance:	Finnish Centre for Radiation and Nuclear Safety.
Objectives:	The main aim in monitoring freshwater fish is to get areal and temporal data for the estimation of radiation doses to Finnish fish consumers. One purpose of

monitoring surface water is to acquire areal data for intake estimations from drinking water. The other purpose of the study is to gather radioecological information on environmental factors affecting the behaviour of radionuclides in different drainage areas.

Sampling: Since 1986 several different fish species, generally perch, pike, vendace, whitefish, bream, burbot and roach have been collected and analysed twice a year from about 100 lakes from different parts of the country. Water samples have been taken four times a year since 1986.

References: Saxén, R. and Rantavaara, A., 1987; Saxén, R., Aaltonen, H., 1987; Rissanen, K. et al., 1987; Saxén, R., 1990; Saxén, R., Rantavaara, A., Arvela, H., Aaltonen, H., 1990.

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Project: A study on the transport of radiocesium from Chernobyl fallout in small oligotrophic lakes and their catchment areas. The lakes have different chemical and hydrological qualities and they are located in the area of high deposition from Chernobyl.

Organisation: Finnish Centre for Radiation and Nuclear Safety in cooperation with the Evo Inland Fisheries and Aquaculture Research Station and the Finnish Game and Fisheries Research Institute. Contact person: Ritva Saxén.

Finance: Finnish Centre for Radiation and Nuclear Safety.

Objectives: To study the transfer of radiocesium in freshwater ecosystems to find out factors affecting trophic transfer of radiocesium as well as interactions between water and sediment.

Sampling: Fish (perch, pike, whitefish) three times a year since 1987, water three times a year since 1987, zooplankton, *Asellus aquaticus*, sediment, soil from the catchment areas, measurements of external gamma radiation.

Data from one lake will be used within the VAMP project for validation purposes.

References: Not yet published.

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Project: A study on the transfer of gamma-emitting radionuclides into the bottom sediments of some Finnish lakes.

Organisation: Finnish Centre for Radiation and Nuclear Safety. Contact persons: Marketta Puhakainen, Erkki Ilus, Ritva Saxén.

Finance: Finnish Centre for Radiation and Nuclear Safety.

Objectives: To get data on transport of gamma-emitting radionuclides from the water phase into bottom sediments in different types of lakes. Eight large lakes were chosen for the study.

Sampling: Profiles of bottom sediments were taken once a year for two years (1988 and 1990) after the accident at Chernobyl. Water samples from the same lakes were also taken. The samples were analysed for gamma-emitting radionuclides.

References: Not yet published.

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3.2 Norway

Two major programmes were initiated. One was financed by the Norwegian Agricultural Science Research Council (NLVF) and focused on practical measures to reduce radioactivity in agricultural products and foodstuffs, to improve our understanding of processes determining levels of radioactivity in, for example, pasture, grazing animals and fish, and to monitor long-term trends in radioactivity in such biota. The other programme was located at the Norwegian Institute for Nature Research (NINA) and focused on ecological processes determining the turnover of radiocesium. Other institutions initiated smaller research programmes, also in the aquatic field.

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Project: Ecosystem studies of Chernobyl fallout in Øvre Heimdalsvatn and its catchment areas.

Organisation: Norwegian Agricultural University/University of Oslo. Contact persons: John E. Brittain and Helge E. Bjørnstad.

Finance: Norwegian Agricultural Science Research Council (NLVF).

Objectives: To study ^{90}Sr and ^{137}Cs radioecology in a typical montane catchment which received high levels of Chernobyl fallout. The aim is to identify and quantify major transport mechanisms for these isotopes within Øvre Heimdalsvatn and its catchment. Furthermore, to study transport in different size fractions both in the water phase and in particulate organic material in streams and in runoff, to investigate interactions between water and lake sediments and to study the pathways up through the food chain to brown trout. Levels of radioactivity in fish population have been monitored since 1986. Studies of isotope transport and plant and microbiological uptake in the catchment are also in progress.

The lake has earlier been included in the IBP programme and is presently part of VAMP.

Methods: A wide variety of methods, including field gamma spectrometry, chemical extraction (soil, sediments), ultrafiltration (lake water, runoff), particle traps and vegetation analyses, have been used.

Sampling: Sampling has been carried out in different seasons, i.e., winter, spring, summer and autumn. Samples include ultrafiltered water samples vegetation, soil, sediment cores and particulate organic matter, brown trout (muscle, gonads, stomach contents), zoobenthos (Gammarus, aquatic insects, etc.), zooplankton.

References: Brittain et al. in press; Salbu et al. in press; Haugen et al. (1990); Hongve et al. (1990); Olsen & Bakken (1990).

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Project: Radiocesium in brown trout and Arctic charr.

Organisation: Norwegian Institute for Nature Research (NINA), Trondheim. Contact person: Torbjørn Forseth

Finance: Norwegian Institute for Nature Research, Radioecological research programme.

Objectives: To study radiocesium distribution in freshwater ecosystems to identify and quantify the controlling factors for radiocesium turnover in brown trout and Arctic charr, and to study the long-term development of radiocesium in fish, zoobenthos and zooplankton. Furthermore, to study radiocesium distribution in sediments, horizontal and vertical distribution and changes with time.

Methods: Fish diet and habitat selection daily, ratio estimates, estimates of radiocesium intake and excretion in fish, temperature monitoring.

Sampling: Sampling has been carried out on five occasions in 1986 and 1987 and three occasions in 1988, 1989 and 1990. All sampling was done during the summer season except for one in 1987. Samples include vertebrates, water (only 1987), sediments (not 1990), macrophytes (only 1986) and phytoplankton (1986, 1987). Measurements of external gamma radiation were also carried out.

References: Forseth et al. (1991); Gaare and Ugedal (1989).

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Project: Radiocesium retention in brown trout.

Organisation: Norwegian Institute for Nature Research. Contact person: Ola Ugedal.

Finance: Norwegian Agricultural Science Research Council (NLVF).

Objectives: Experimental study of radiocesium retention in brown trout. Effects of temperature and body size on radiocesium retention.

Methods: Acute orally ^{134}Cs dosed brown trout were killed at intervals for radioactivity counting. The study was performed at four different temperatures and with four homogeneous size groups of fish.

References: Ugedal, O., Jonsson, B., Njåstad, O. & Næumann (1991): Effects of temperature

and body size on radiocesium retention in brown trout (*Salmo trutta* L.). — (manuscript). Gunnerød, T.B. & Garmo, T.H. (eds.) (1988): Forskningsprogram om radioaktivt nedfall. Foredrag och konklusjoner fra et seminar i Sem i Asker 22.-23. Nov. 1988. — Norges Landbruksvitenskaplige Forskningråd, Trondheim/Ås, Norge.

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Project: The addition of potassium chloride to a lake and its effect on the concentration of radiocesium in trout.

Organization: Institute for Energy Technology (IFE), Oppland County Environmental Administration, and Norwegian Institute for Nature Research (NINA). Contact person: Gordon C. Christensen (IFE).

Finance: Nordic Liaison Committee for Atomic Energy (NKA) and own funds.

Objectives: To study the influence of the potassium concentration of lake water on the concentration of radiocesium in trout.

Methods: Two "twin" mountain lakes were studied, one as reference, to the other was added potassium. Gamma spectrometric analyses of water, sediments and trout.

Sampling: Sampling of fish and water has been done 3-4 times in the summer and autumn every year from 1986 to 1990. Sediments were sampled in 1988.

References: NKA/NORD 1990:46 (1990), U. Tveten (Ed.); Blakar, G.C. Christensen and J. Skurdal (in prep.).

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3.3 Sweden:

In Sweden the National Institute for Radiation Protection (NIRP) has given financial support to several projects run by scientists at different institutions. Most investigations have focused on the cesium transport in ecosystems and the identification of the most important mechanisms involved in the pathways, responsible for dosage to man. A joint report of the results from the post-Chernobyl research supported by NIRP is planned to be published in 1991.

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Project: Long-term transfer of radionuclides from terrestrial to aquatic systems, a validation study.

Organisation: Studsvik Nuclear. Contact person: Björn Sundblad.

Finance: NIRP

Objectives: The aim of the project is to follow the long-term transfer radionuclides, mainly of ^{137}Cs from a terrestrial to an aquatic system. In addition, data for model validation studies of lake ecosystems are being collected.

Sampling: Sampling of water, suspended matter, plankton, macrophytes, invertebrates, roach, perch and pike has been carried out since June 1986. In addition, soil sampling, in-situ gamma-spectrometric and exposure rate measurements were carried out in the catchments of two lakes, Hillesjön and Sälgsjön.

Data has been used within the BIOMOVS study and will be used within the VAMP study for validation purposes.

References: Evans, S., S. Lampe and B. Sundblad (1988). One year after Chernobyl. Studsvik/ND-88/17, 1988. Sundblad, B., S. Evans and U. Bergström (1989). Sundblad, B., S. Evans and S. Lampe (in prep.).

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Project: Biological half-life of ^{137}Cs in fish exposed to the Chernobyl fallout.

Finance: NIRP

Organisation: Studsvik Nuclear. Contact person: Sverker Evans.

Objectives: An experimental study of the clearance of ^{137}Cs in roach exposed to various potassium concentrations in the water.

Methods: Fish and lake water were collected from a lake in the Gävle area. The water and fish were transferred in four aquaria. After three weeks of acclimatization potassium was added to three of the aquaria. At regular intervals fish were collected and their muscle tissues measured, individually by gamma spectrometry. The water was analysed for pH, conductivity, potassium and ^{137}Cs.

References: Evans, S. 1989

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Project: Distribution and circulation of ^{137}Cs in lake systems.

Organisation: Institute of Limnology, Uppsala University. Contact person: Anders Broberg.

Finance: National Institute of Radiation Protection (NIRP).

Objectives:
- To study the distribution of deposited ^{137}Cs in freshwater ecosystems.
- To study bioaccumulation processes during the first year after fallout.
- To study the importance of lake production and type of ecosystem on the circulation of Cs.
- To determine the time period for increased levels of ^{137}Cs at higher trophic levels (fish).
- To study the vertical and horizontal distribution of ^{137}Cs in lake sediment and its changes with time.

Sampling: Sampling has been carried out in three lakes of different type since June 1986, and in four lakes between May and October 1986. Material for analysis of ^{137}Cs has been collected from the abiotic environment, suspended matter from the inlet, surface water and outlet and sediments. Sediment cores have been taken to follow the areal as well as the vertical distribution of Cs. The number of cores taken on each sampling occasion varies between 4 and 10 depending on the purpose. At the same time biotic components have been sampled. These components are plankton (net of different mesh sizes), benthic algae, macrophytes from different sites in the lakes and divided into different parts, benthic animals mainly from the littoral zone, and fishes from different species and size classes. Sampling has been carried out 4 to 5 times a year since 1986, mainly during the ice-free period.

References: Andersson (1989); Andersson & Broberg (1990); Broberg (1989); Broberg & Andersson (1989); Meili et al. (1989); Broberg & Andersson (1990) (in prep.); Meili (1991); Meili (1991b).

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Project: Measures to reduce high levels of radioactive cesium in fish

Organisation: Project "Liming-Mercury-Cesium". Contact person: Tord Andersson and Lars Håkanson

Finance: Swedish National Institute for Radiation Protection and Swedish Environmental Protection Agency

Objectives: To study the factors which affect the content of ^{137}Cs in fish and evaluate different measures to reduce ^{137}Cs in fish.

Sampling: The studied lakes are 41 small, mainly oligotrophic Swedish lakes in an area with high fallout (4-70 $kBqm^{-2}$) from Chernobyl. Small perch (1+, <10 g) were collected annually during autumn (10-15 individuals/sample). Pike (0.5-1.5 kg) were caught during spring 1987-1989 (5-10 ind./sample). The first year was used as a reference year, and the remedial measures (lake liming, wet land liming, fertilisation, extensive fishing and in 13 lakes combined with potash treatment) were initiated in 1987. A broad set of data describing lake morphometry and drainage area was collected for each lake, standard water chemistry (pH, alk., cond., colour, tot-P, Fe, CaMg and K) was analysed monthly during the whole period. In 15 lakes the content of ^{137}Cs was measured in water, material collected in sediment traps and in surface sediments. In 1988-89 the sediment trap programme included all 41 lakes.

Subproject: Radioactive cesium in Swedish lakes after Chernobyl. Contact person: Tord Andersson.

Objectives: Collect and evaluate all available Swedish data from 1986-1988 as regards ^{137}Cs in fish, water and sediments and compatible limnological data. Obtain a picture of how the content of ^{137}Cs in different species varied geographically during the years 1986-1988 and which lake properties can be related to this variation.

References: Håkanson et al. (1988); Andersson et al. (1990); Håkanson et al. (1990).

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Project: ^{137}Cs in Arctic charr and brown trout.

Organisation: Swedish Environmental Protection Agency, Manuela Notter and Institute of Freshwater Research, Johan Hammar.

Finance: NIRP and own institutes.

Objectives: To quantify the amount of Chernobyl ^{137}Cs in the limnic environment, at different trophic levels, in a series of seven mountain lakes in northwest Jämtland, and to identify and describe significant elements in the transport of this radionuclide through the food chain to fish (Arctic charr and brown trout).

Sampling: Sampling was carried out two to three times a year, 1986-1988, and once a year 1989. Surface sediment: 3 samples per 2-4 localities per lake; filtered lakewater: (30 litres, 0.45 µm); filter (phytoplankton); zooplankton (net mesh 0.055-0.060 mm); macroinvertebrates (*Mysis, Pallasea, Gammarus*, insects, molluscs). Prey fish (minnow); brown trout and Arctic charr: 10-15 per period. Sediment traps: summer 1988, summer 1989, summer 1990. Water samples for total chemical analyses and radionuclides (^{137}Cs, ^{134}Cs, ^{40}K).

References: Hammar, J., Notter, M. and Neumann, G. (1990).

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Project: Uptake, turnover and transport of radioactive cesium in a boreal forest ecosystem.

Organisation: National Defence Research Establishment (FOA), Umeå, in cooperation with the Swedish University of Agricultural Sciences, Faculty of Forestry (SLU), Umeå.

Finance: The Center for Environmental Research, the EG Radiation Protection programme, the National Defence Research Establishment and the National Institute of Radiation Protection. Contact persons: Torbjörn Nylén and Thomas Palo.

Objectives: To study the time related run-off of radioactive cesium after wet -deposition on snowcovered areas, the distribution of the remaining amounts between soil, vegetation and animals; the turnover in and between these compartments.

Sampling: Sampling of run-off and throughfall waters, soil profiles, vegetation and mammalian animals has been carried out since 1986 by the Forest Research Station at Vindeln. In addition to this, in situ gamma-spectrometric measurements are being carried out.

References: Bergman, R., Nylén, T. and Palo, R.T. (1991) (in prep.); Bergman, R. et al. (1988) FOA rapport E 40040; Nylén, T. & Grip, H. (1991) (in prep.); Nylén, T. & Eriksson, A. (1991) (in prep.); Palo, R.T., Nelin, P., Nylén, T. and Wickman, G. (1991); Palo, R.T. & Nylén, T., (1991) (in prep.).

4. Nordic Chernobyl Data Base

The Nordic Chernobyl Data Base has been established with the purpose of collecting the large amount of data resulting from measurements made in several laboratories during the period following the Chernobyl accident.

The information is stored in the C-base data handling system which has been developed especially for this type of environmental data. The C-base handling system permits inputs from a variety of sources and outputs to other computer programs for further data treatment.

It has been decided that the responsibility for the data collecting is to be at a national level. In each Nordic country a certain agency has the task of encouraging scientists to deliver data to the data base. Up to the present this task has not been given sufficient priority, so very few data are stored.

The data base was demonstrated by J. Lippert during the meeting and several of the map-handling facilities were shown. Several participants also tried to transfer their own data files into the data base.

The possibility of using the data base for presenting some joint Nordic result was discussed. It was agreed that NCDB in its present form is best suited for the administration of large bulks of data, for instance obtaining regional overviews. On the other hand its capacity for storing multiparametric data sets, useful for instance in model testing, has not yet been fully tested and evaluated.

In this connection, credit was also given to the excellent work done during the autumn 1990 by Dr. Lena Carlson, Lund, in introducing data on radiocesium in Fucus into the NCDB. This work will certainly also add to a general experience of the potentialities of the NCDB.

Considering the present state of the NCDB, it was decided that much would be gained by a tentative introduction of a few data sets covering most of the Nordic territory. Thus it was agreed to introduce into the NCDB as much as practically possible (due to the limited resources) of Nordic data on some widespread fish species (perch, pike, brown trout and charr) together with relevant data on catchment, place and time, as well as size class. This would make it possible to compile an annual Nordic overview of the ^{137}Cs concentrations in selected fish species.

During the preparation of this report the work has been carried out by Lena Carlson as a consultant.

4.1 Extractions from NCDB

The effort to register postChernobyl results from fresh water fish in NCDB has resulted in 4535 records, about 2000 of the records are relatively evenly distributed over the three countries; Sweden (794), Norway (646) and Finland (636). The rest of the records (about 2500) originate from a Swedish scanning investigation during 1986-1988 in which numerous lakes from the middle of Sweden are represented (see also Figure 4.1).

The most commonly reported fish species are pike, perch and trout, but others are also represented,Table 4.1.

Species	no. of records	Species	no. of records	Species	no. of records	Species	no. of records
Bleak	1	Ide	8	Rainbow Trout	15	White Bream	6
Bream	68	Grayling	36	Roach	137	Whitefish	225
Burbot	87	Perch	1382	Smelt	10		
Char	466	Pike-perch	31	Trout	977		
Eel	3	Pike	982	Vendace	94		

Table 4.1 Fish species and number of records of each species registered in NCDB July 1st 1991.

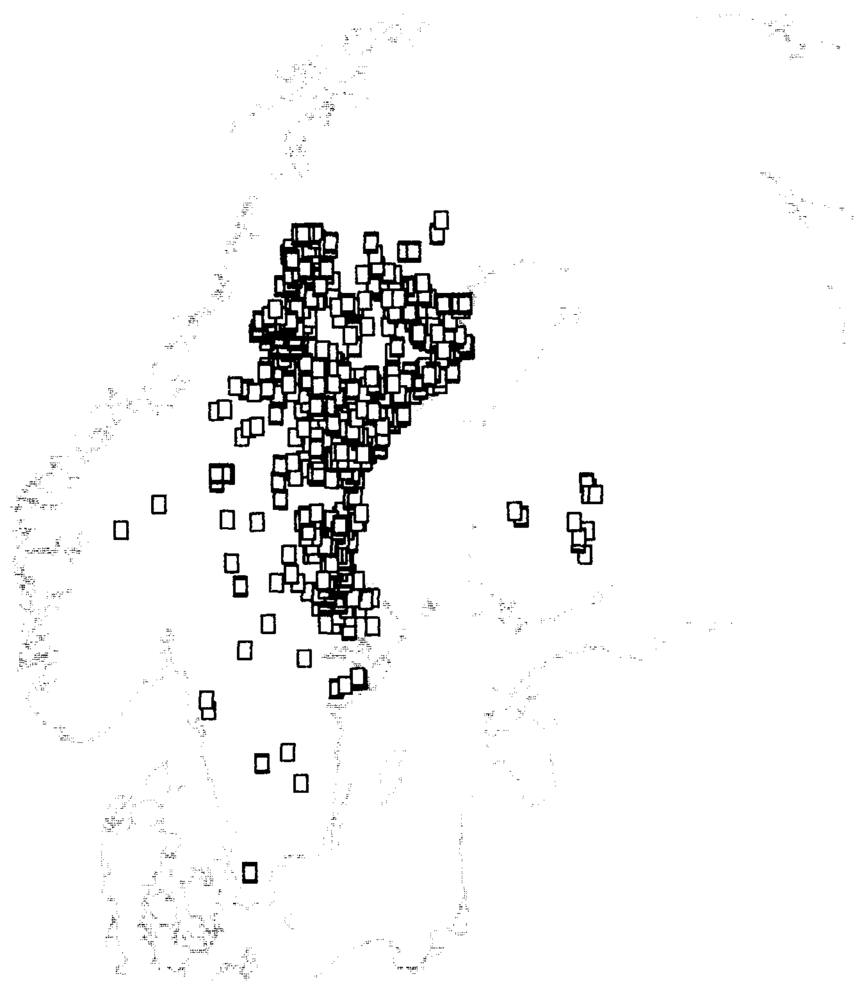


Fig. 4.1 All lakes registered in the NCDB by a ^{137}Cs value on fish muscle.

All lakes are given with coordinates but not all with names. Differences in reported values have occurred. In some cases the mean values of individual measurements are registered and in other cases the result refers to pooled samples.

In many cases each lake is registered just by one result, sometimes also only one fish species is measured, and in some extreme cases the value corresponds just to a single fish. Under these circumstances the values are not very representative for the lake and are not at all informative. If the lakes in the scanning investigation are excluded, the database contains two lakes from Norway and Finland respectively and 7 lakes from Sweden with longer time series (from 1986 to 1990).

The deposition rate of the nuclide has been shown to be a very important parameter for the cesium concentration in fish. The Chernobyl deposition varied considerably in the Nordic countries. This creates problems when comparing the values from different lakes in the database. It would be an improvement if the NCDB could be supplemented with deposition values for the Nordic region so the deposition could be mapped out (with a certain accuracy) together with the results from the biota. It would also be an advantage if the inserted values, with special preset calculations, could easily be normalized according to this important parameter.

Although the scientists could get assistance from the consultant fairly severe pressure was needed to get the results from the different laboratories on the required form. A further problem, which has not yet been considered, is the updating of the database. This experience underlines the statement below from the meeting:

> The meeting's opinion is that the database must be continuously maintained to facilitate its use by developing data treatment, processing and output in the required formats. Therefore, a serious attempt to find resources for such continuous work must be made.

5. Knowledge and experiences gained from post Chernobyl research

This chapter is based on Chernobyl fallout and the experience, data and predictions derived from this incident. The main aim in this chapter is to determine pathways, processes and factors of importance for radioactive inputs to freshwater ecosystems, and in the long run be able to generate better prognoses for the concentration of radioactive substances in fish for human consumption.

Evaluation and synthesis of data, conclusions and models are still in progress. The new data sets lead to continuously improved understanding of the behaviour of radiocesium in ecosystems. General findings are incorporated in models where the validation work encourages to a co-operation between experimentalists and modellers.

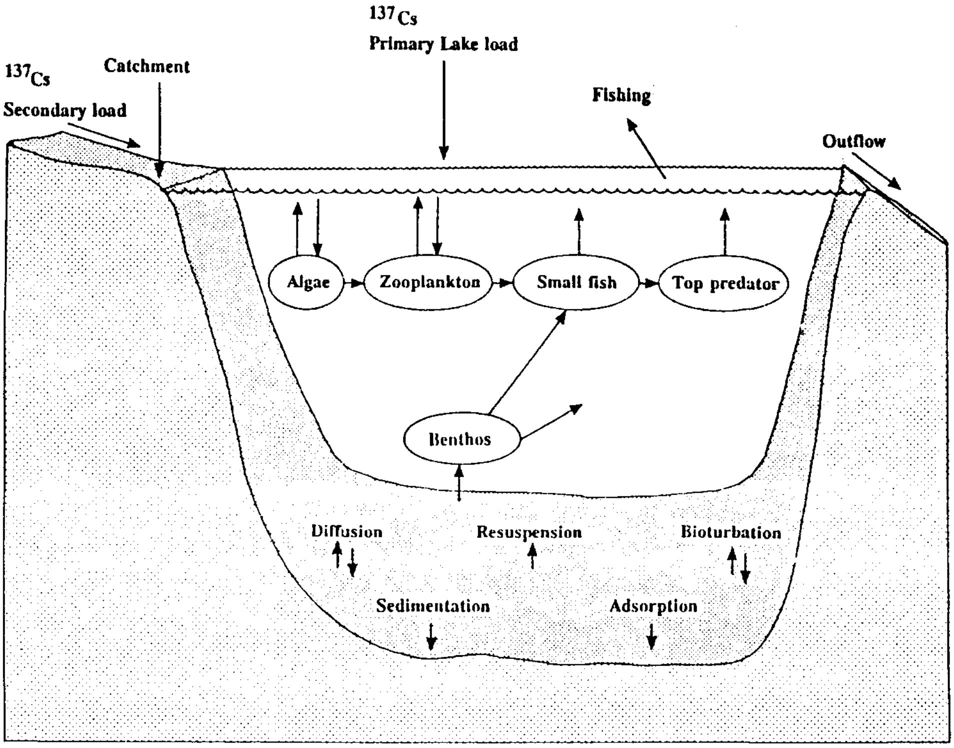


Fig. 5.1 Processes that affect the magnitude of the radionuclide concentration in biota within a limnic ecosytem.

Fig. 5.1 shows the general picture of the processes which affect the uptake of ^{137}Cs in biota. The experiences from the studies after Chernobyl will be used to give an estimate of the importance of the different processes and which lake-specific parameters can be related to each process.

This chapter summarizes present knowledge on the turnover of radiocesium in lakes from three different perspectives:

* transport to lakes
* turnover within lakes
* bioaccumulation in lakes

5.1 Deposition and transport of radionuclides from terrestrial catchments to lake ecosystems

Fallout characteristics

Fallout from the Chernobyl accident reached the Nordic countries, probably in two plumes, in late April and early May 1986 and in the form of both dry and wet (rain/snow) deposition. Hot particles have also been recorded (Salbu, 1988).

The nature of the fallout will affect its transport to and its role in aquatic systems. The following characteristics are considered to be important:

*The form of the fallout (e.g. particulate, aerosol) will depend on the reactor, the distance from the discharge and the meteorological conditions.

*The nature of the deposition (dry/wet) will depend on local meteorology and topography.

*The isotope composition will reflect the type of incident (reactor type/discharge source).

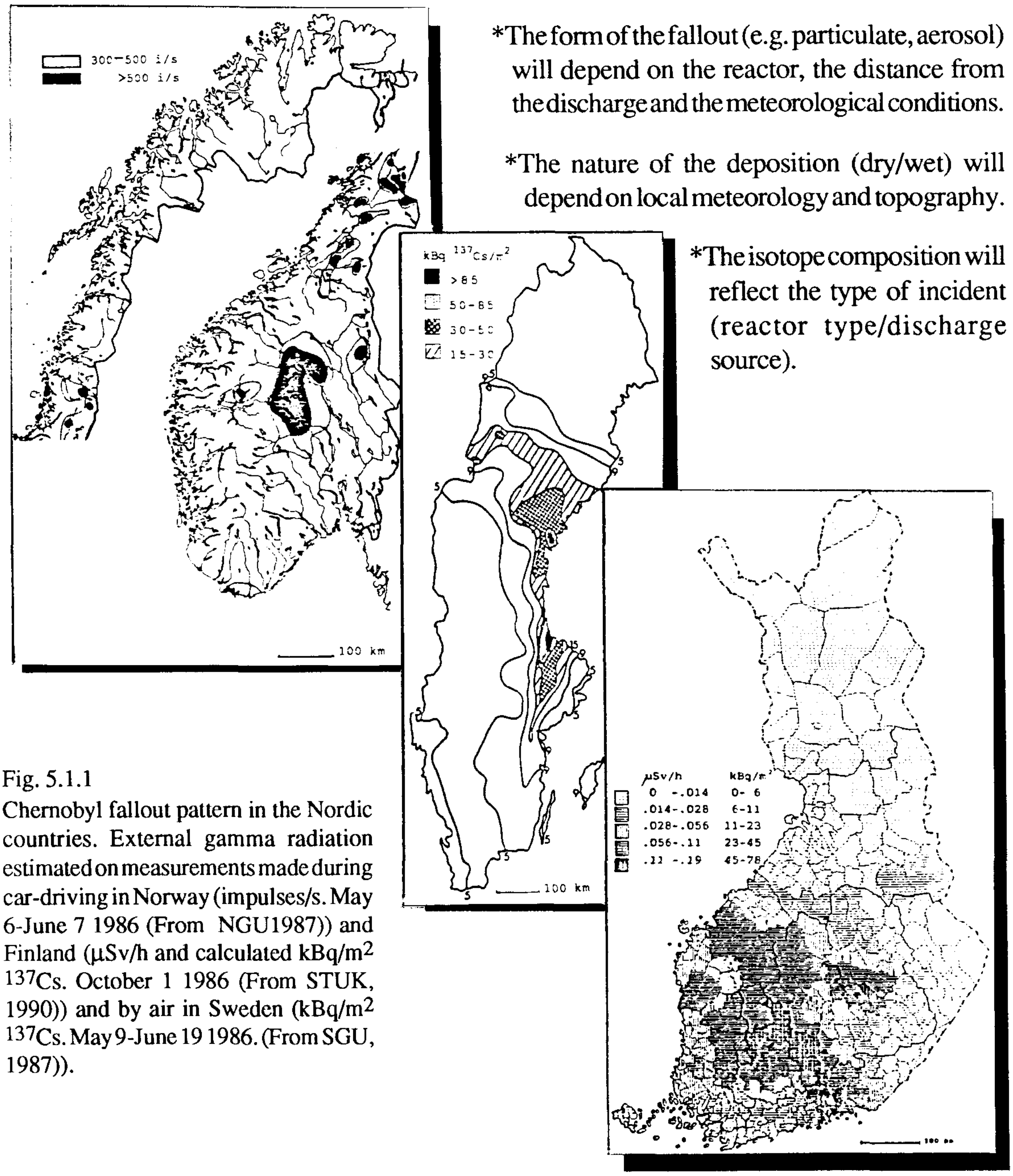


Fig. 5.1.1
Chernobyl fallout pattern in the Nordic countries. External gamma radiation estimated on measurements made during car-driving in Norway (impulses/s. May 6-June 7 1986 (From NGU1987)) and Finland (µSv/h and calculated kBq/m^2 ^{137}Cs. October 1 1986 (From STUK, 1990)) and by air in Sweden (kBq/m^2 ^{137}Cs. May 9-June 19 1986. (From SGU, 1987)).

Fallout deposition from Chernobyl was extremely variable both nationally (Fig. 5.1.1) and locally (Fig. 5.1.2). Even areas as small as 100 m^2 show high variability, and measurements taken 1 m apart can show differences in activity of up to fivefold. (e.g. Haugen et al., 1990).

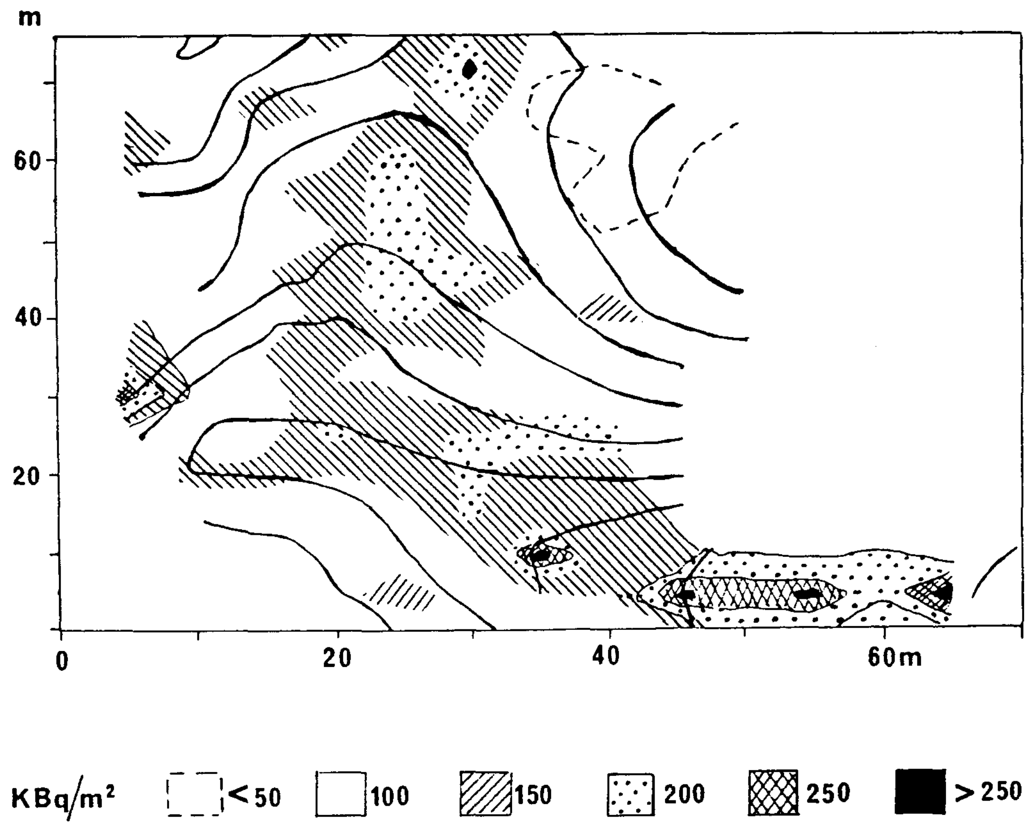


Fig. 5.1.2 Map of ^{137}Cs deposition in a small area (C. 70x70 m) in Øvre Heimdalen. 1m contour intervals. (From Haugen et al., 1990.)

Climate and catchment characteristics

Climatic conditions and the nature of the catchment will be of prime importance in determining the nature and levels of radioactive inputs to drainage systems. In northern Europe the following aspects should be considered:

1. Time of year, including extent and depth of snow cover. The following types of wet deposition can be distinguished:

a. Snow on snow	c. Rain on bare ground
b. Rain on snow	d. Snow on bare ground

2. Vegetation will act more or less as a filter for radioactive fallout depending on the extent and nature of the vegetation cover, e.g. forest (deciduous/conifer), marsh, mountain, urban, etc. (Fig. 5.1.3).

3. Topography (e.g. aspect, slope, relief) will affect deposition patterns.

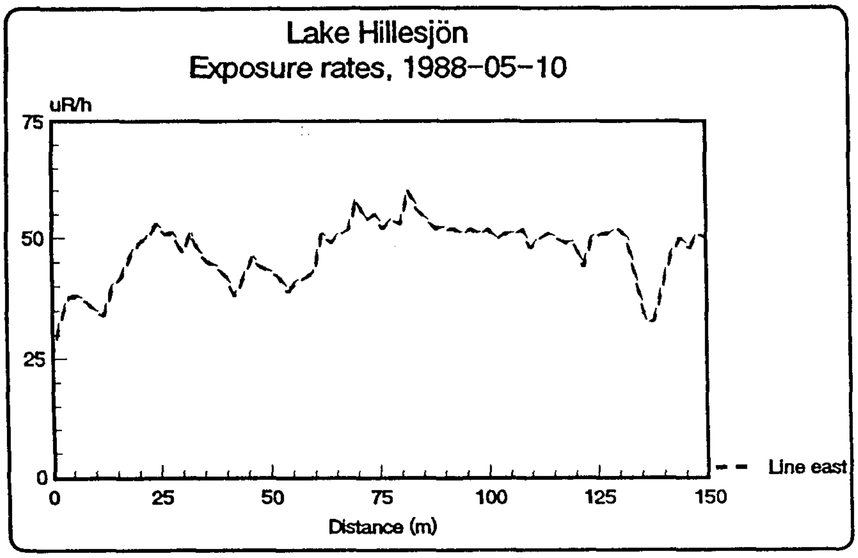


Fig. 5.1.3
Exposure rate (μR/h) along a transect from the shore of Lake Hillesjön, across a forested area with different degrees of cover. (From Sundblad et al., 1989.)

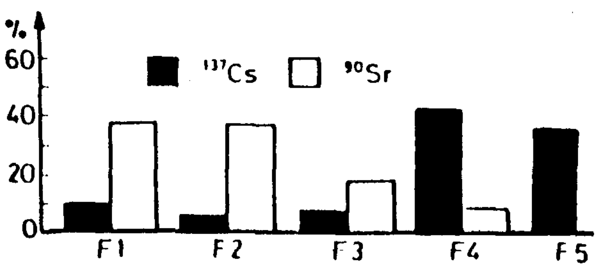
Certain parts of the catchment will be discharge areas in terms of radioactivity, while others will be recharge areas. This will be a function of vegetation, topography and soil type.

Chemical considerations

Radionuclide transport within the catchment will depend on the chemistry of individual nuclides. Their chemical and physical form will vary with fallout characteristics as well as processes occurring during transport through the catchment. For example, the soil's ion exchange capacity will be important. Cs^+ has a relatively large ion radius (1.69 Å) and a low hydration energy and is easily fixed by entrapment in the lattice structure of clay minerals (Squire and Middelton 1966). However, organic matter will apparently reduce the ion exchange capacity by blocking the active sites or by reacting with the Cs-ions and then preventing diffusion and entrapment in the lattice (Barber, 1964). In contrast, Sr^{2+}, with an ion radius of 1.13 Å, will remain in predominantly exchangeable forms (Squire, 1966). It should be mentioned that Sr^{2+} does not follow percolating water, but moves in the soil by diffusion. ^{90}Sr should therefore be given consideration, especially in the Nordic countries because of the high frequency of low pH and low soil calcium levels.

The degree of association of radionuclides with organic and mineral materials in the litter and upper soil layers can be seen in the results of sequential extraction (Riise et al., 1990, Fig. 5.1.4). These indicate that a major fraction of the radiocesium is strongly associated with litter and soil; less than 10 % is easily leachable. In contrast, ^{90}Sr has a relatively large leachable fraction.

Fig. 5.1.4 A typical relative distribution of radiocesium (^{134}Cs+^{137}Cs) and ^{90}Sr in different extractions in a soil sample (0-2cm), Vestre Slidre, Norway.



F1: Exchangeable fraction (1M NH_4Ac, pH7)
F2: Easily reducible fraction (0.04M NH_2OH HCl in 25% (v/v) HAc pH 2
F3: Oxidizable fraction (30% H_2O_2 adjusted to pH 2 with HNO_3
F4: Acid - digestable fraction(7M HNO_3)
F5: Residue (Total activity - (F1+F2+F3+F4)
(From Riise et al., 1990)

Runoff

The following factors are considered important in determining runoff characteristics:

1. Seasonal pattern of precipitation
2. Extent and nature of snow cover
3. Pattern of deposition
4. Topography
5. Soil type and water content (% saturation)
6. Frozen ground/permafrost - this will affect the inputs between the surface, subsurface and groundwater
7. Distribution of discharge and recharge areas within the catchment

Magnitude of runoff

Data on the magnitude of runoff are available from several studies. Radionuclide activity contents in surface runoff have been measured directly in Øvre Heimdalen, Norway, during spring snowmelt, giving a value of 0.007-0.1 % for annual runoff (Haugen et al., 1990). Calculations of surface runoff in the catchment of Hillesjön, Sweden, based on deposition and activity contents in tributary streams gave a minimum value of 0.65 % in 1986 declining to an annual value of about 0.01 % in 1990 (Sundblad et al., in prep.). A value of 8 % for 1986 runoff as a percentage of deposition was recorded for a forest catchment area in northern Sweden (Bergman et al., 1988).

Within 30 km of the Chernobyl reactor, surface runoff has been estimated to be 0.001-0.1 % during the growing season in 1986 and during snowmelt in 1987, with a tendency for lower values as time progressed (Borzilow et al., 1988). The Russian values are somewhat lower than values cited in a review paper (Bonnett, 1990) where values of 0.1 - 0.5 % were quoted for larger catchments.

Runoff composition

The chemical and physical form of isotopes in runoff will largely determine their significance for aquatic systems. Generally, one expects particle size to increase with increased runoff (erosion of soil, litter, etc.). Preliminary results from Øvre Heimdalen, Norway (Haugen et al., 1990) indicate that 55-74 % of radiocesium in snowmelt is in the fraction >2nm, interpreted as being bound to particles. These values agree with Russian studies (Borzilov et al., 1988) in which 50 % or more of radiocesium in pasture runoff was associated with particles.

The flux of radionuclides from land and from the watershed can be termed the secondary load, in contrast to the primary load which is the direct deposition on the lake surface. The secondary load has two main components, stream inflows and groundwater inputs.

Stream inflows

Lake radionuclide inputs from tributary streams and rivers are a function of tributary discharge and the activity contents of their waters and transported particles. Studies of stream sediments in tributaries to Øvre Heimdalsvatn have shown similar radiocesium levels to those in lake sediments (Hongve et al., 1991).

As far as Chernobyl radionuclide transport to aquatic systems is concerned there appear to be three phases. Firstly a rapid rise to peak inputs immediately following fallout, secondly a fairly rapid decline and finally a slow steady decline (Figs. 5.1.5, 5.1.6 and 5.1.7).

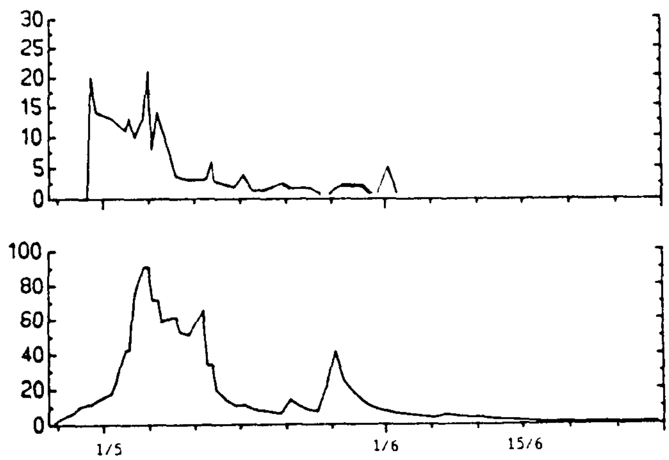


Fig. 5.1.5
Discharge (l/s) (upper graph) and ^{137}Cs concentration (Bq/l) (lower graph) in a catchment in northern Sweden (Svartberget) during the first two months after Chernobyl fallout. (From Bergman et al., 1988.)

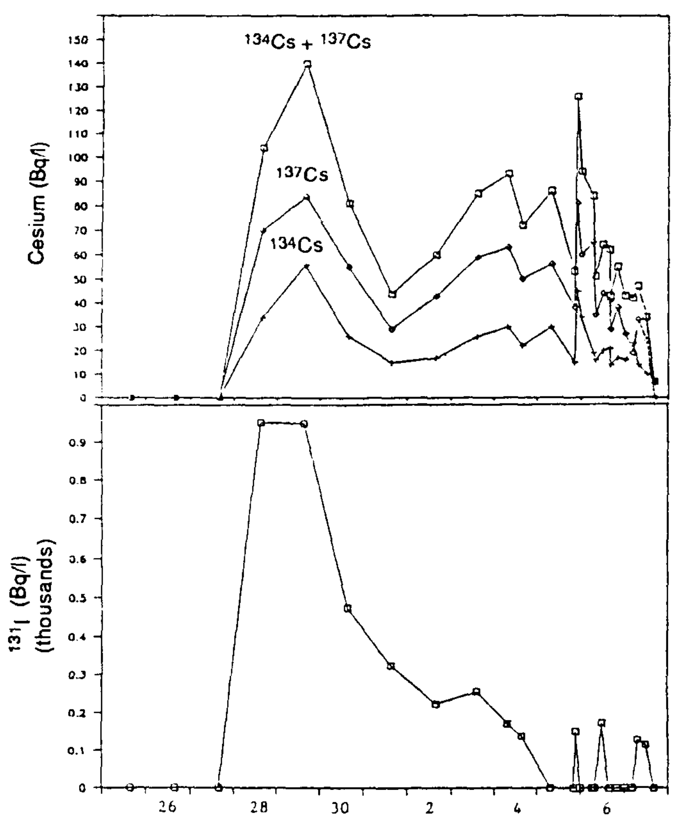


Fig. 5.1.6
Concentration of ^{131}I and Cs isotopes in stream waters in Atna, Norway during late April and early May 1986. (From Saltveit et al., 1989.)

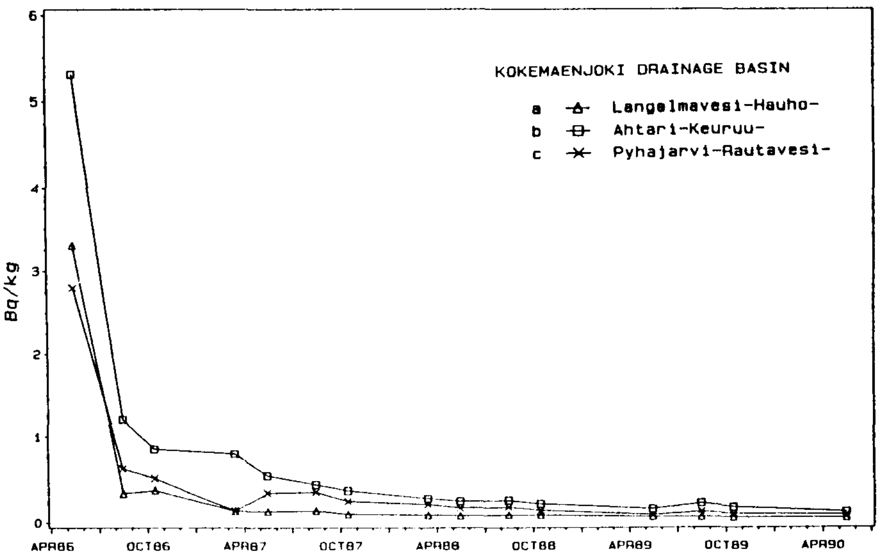


Fig. 5.1.7 Activity concentrations of ^{137}Cs in total surface water samples in three watercourses a,b and c of the Kokemäenjoki drainage area, Finland, 1986-1989. The Kokemäenjoki drainage area is located in the area of highest deposition in Finland (cf. Fig. 5.1.1). (From Saxén, 1990.)

The character of lake nuclide inputs will affect their accumulation in lake food chains. In lakes such as the Norwegian subalpine Lake Øvre Heimdalsvatn, particulate organic material from the catchment is a major food source of primary produced material for zooplankton and benthos (Fig. 5.1.8, Salbu et al., in press).

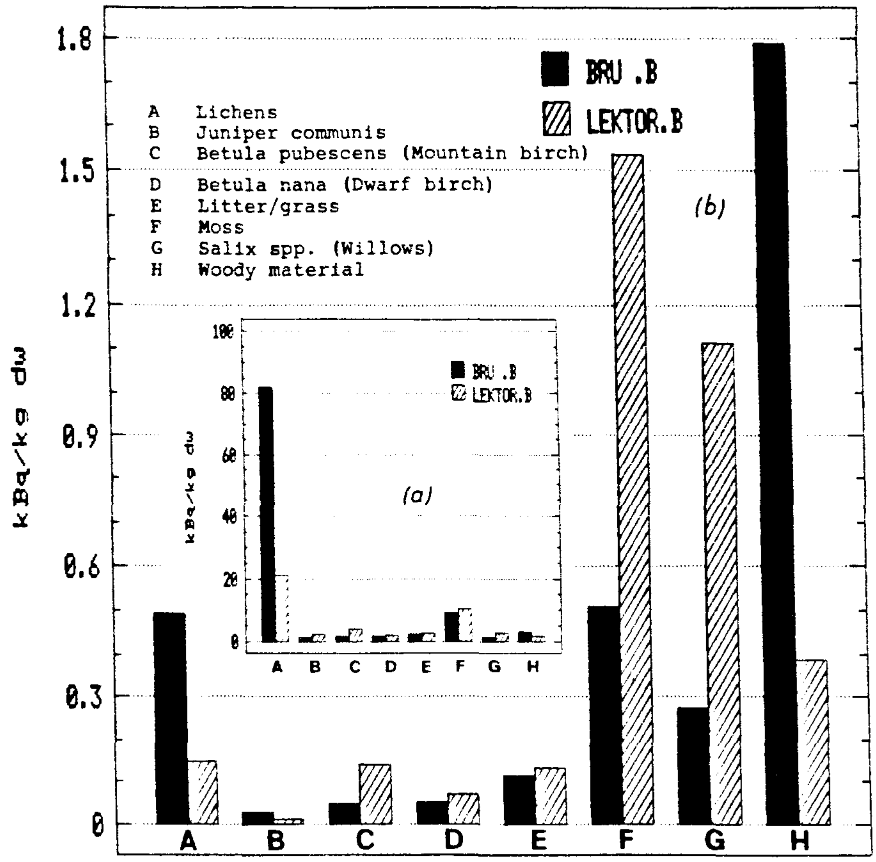


Fig. 5.1.8 Concentration of radiocesium in different plant material (Bq/kg dw) in streams Bruskardbekken (BRUD.B.) and Lektorbekken (LEKTOR.B.)) flowing into Øvre Heimdalsvatn (a). In (b) the concentration is corrected for the relative weight distribution of the particular plant materials. (From Salbu et al., in press.)

The amounts and activity contents of radiocesium and ^{90}Sr have been measured in four different fractions in inflowing streams (Table 5.1.1):

1. Water phase - low molecular wt. fraction (Mw < 10^4 Dalton or < 2 nm)
2. Water phase - colloidal/particulate fraction (Mw >10^4 Dalton or > 2 nm)
3. Fine particulate organic matter -FPOM- (0.063-1 mm)
4. Coarse particulate organic matter -CPOM- (> 1mm).

Groundwater inputs

Radionuclide transport from the subsurface levels down to groundwater levels will depend on soil characteristics. The radionuclides transported by groundwaters can enter the surface aquatic system either in discharge areas close to streams and lakes or through the lake sediments.

On the basis of the chemical considerations mentioned earlier, ^{90}Sr is expected to penetrate groundwater reservoirs to a greater extent than radiocesium. Calcium (Ca) will affect the movement of ^{90}Sr in the soil apparently by displacing bound Sr^{2+}. Although Sr^{2+} is an easily exchangeable cation, it moves through the soil by diffusion and not just by simple mass transport (Squire 1966). Soil type will therefore be a major determinant for the amounts of radionuclides reaching groundwaters.

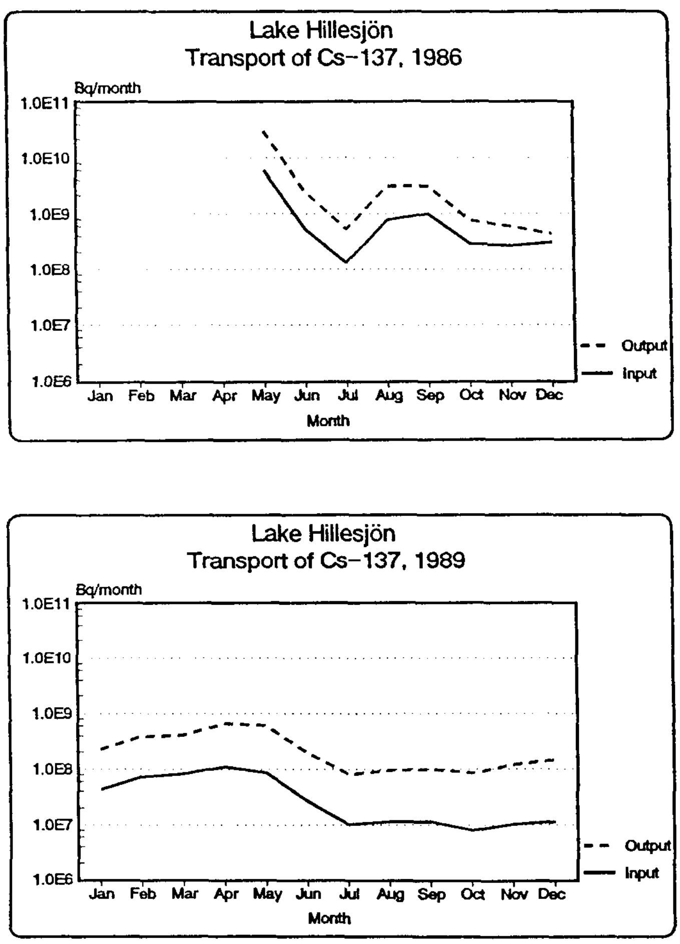


Fig. 5.1.9 ^{137}Cs inputs during 1986 and 1989 and outputs for the Swedish lake, Hillesjön. (From Sundblad et al., in prep.)

Outflow

The extent of radionuclide lake outputs will depend on two main factors. Firstly, the discharge (m^3/s) in the outflowing river and secondly the radionuclide concentration (Bq/l). Losses through lake outflows have been measured in Lakes Hillesjön, Sweden and Øvre Heimdalsvatn, Norway. Monthly measurements since 1986 in Lake Hillesjön have shown a net deficit for ^{137}Cs, with higher levels in total samples from the outflow than in inflows (Fig. 5.1.9). The difference between inflows and outflows has tended to increase over time.

In Lake Øvre Heimdalsvatn the relationship is different. Based on lake budget calculations for the spring spate, more than half the ^{137}Cs is retained in the lake, either entering the food chain or the sediments (Fig. 5.1.10, Table 5.1.1, Fig. 5.1.11, Salbu et al. in press). In contrast, about 90 % of the ^{90}Sr is transported through the lake into the lower parts of the drainage area. The chemical speciation of ^{90}Sr and ^{137}Cs is markedly different in lake inputs, but in the outflow differences are generally only slight.

Nuclide loss from lake ecosystems can also take place through fishing, although this is usually of minor importance.

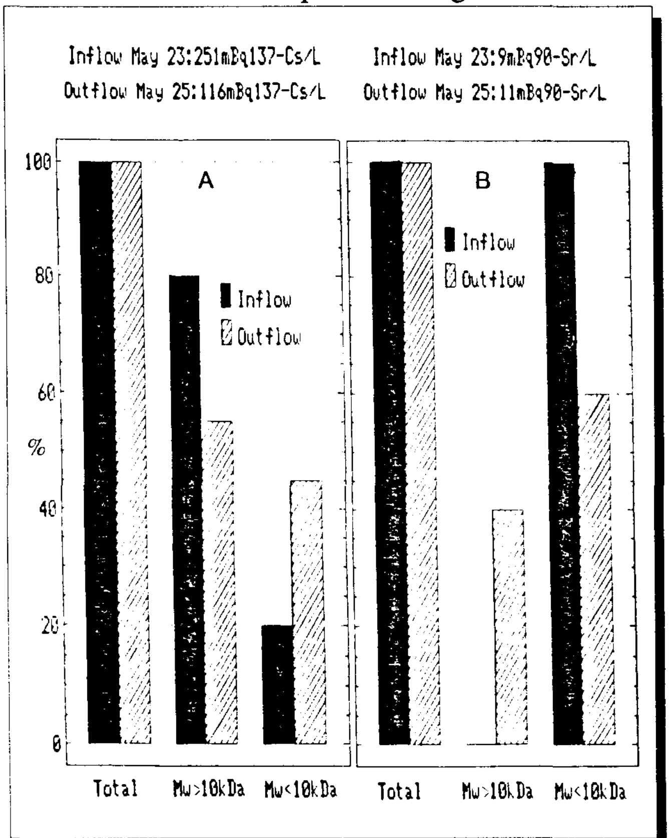


Fig. 5.1.10 Concentration and relative distribution (%) of radiocesium (A) and ^{90}Sr (B) associated with high ($Mw>10^4$ Dalton) and low molecular weight species ($Mw<10^4$ Dalton) in the main inlet and outlet streams to Lake Øvre Heimdalsvatn. (From Salbu et al., in press.)

^{137}Cs	Inflow	%	Outflow	%	Retention
$Mw<10^4$	11 365	18.0	14 453	43.9	- 3 088
$Mw>10^4$	48 066	76.2	18 421	56.0	+ 29 645
FPOM	3 475	5.5	37	0.1	+ 3 438
CPOM	145	0.2	2	< 0.1	+ 143
Total	63 051		32 913		+ 30 138

^{90}Sr	Inflow	%	Outflow	%	Retention
$Mw<10^4$	3 126	94.0	1 757	57.4	+ 1 369
$Mw>10^4$	71	2.1	1 304	42.6	- 1 233
FPOM	122	3.7	$2x10^{-2}$	< 0.1	+ 122
CPOM	5	0.2	$8x10^{-4}$	< 0.1	+ 5
Total	3 324		3 061		+ 263

Table 5.1.1 ^{137}Cs and ^{90}Sr budget (kBq/24 hr) for the sub-alpine lake, Øvre Heimdalsvatn, 23-25 May 1989. (From Salbu et al., in press).

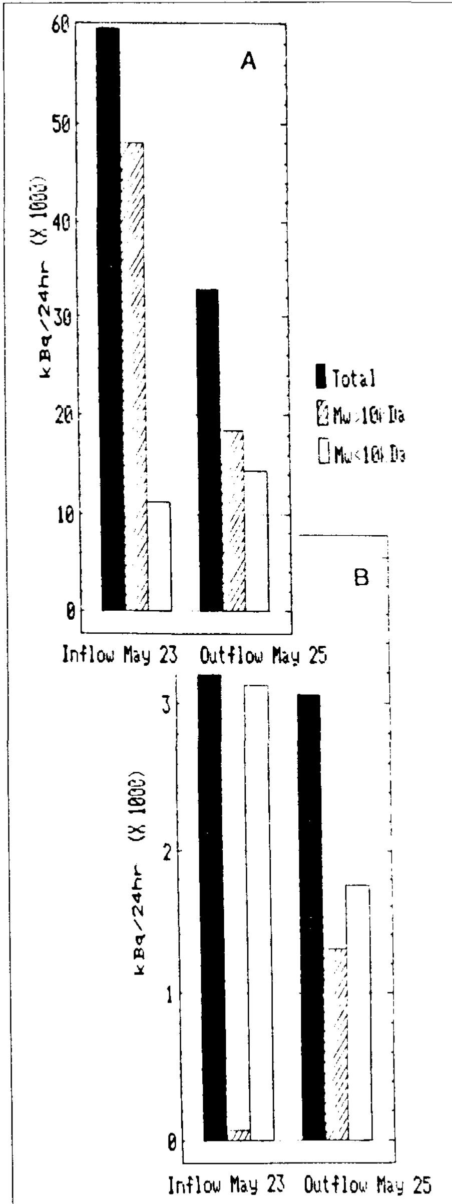


Fig. 5.1.11
Total inputs on May 23, total outputs on May 25 1989 under snowbelt into Lake Øvre Heimdalsvatn with corresponding partikel size distribution (%) for radiocesium (A) and ^{90}Sr (B). (From Salbu et al., in press).

5.2 Influence of lake specific characteristics on the distribution and biological uptake of ^{137}Cs

In this chapter we will try to define the lake typical characteristics of greatest importance for a/ the initial uptake in biota during the first year(s) after the fallout and b/ the temporal development regulated mainly by redistribution processes.

Fig. 5.2 gives a description of the most important factors and processes which will affect the fluxes and biological uptake of ^{137}Cs within a lake earlier described in Fig. 5.1. In Table 5.2.1 the parameters to consider in this context are summarized and divided in four main categories describing lake morphometry and chemical, physical and biological properties.

Lake ecosystems are very complex and many of these parameters are more or less intercorrelated, and the expected effect of one particular parameter on the biological uptake of ^{137}Cs may be either enhanced or decreased by other parameters.

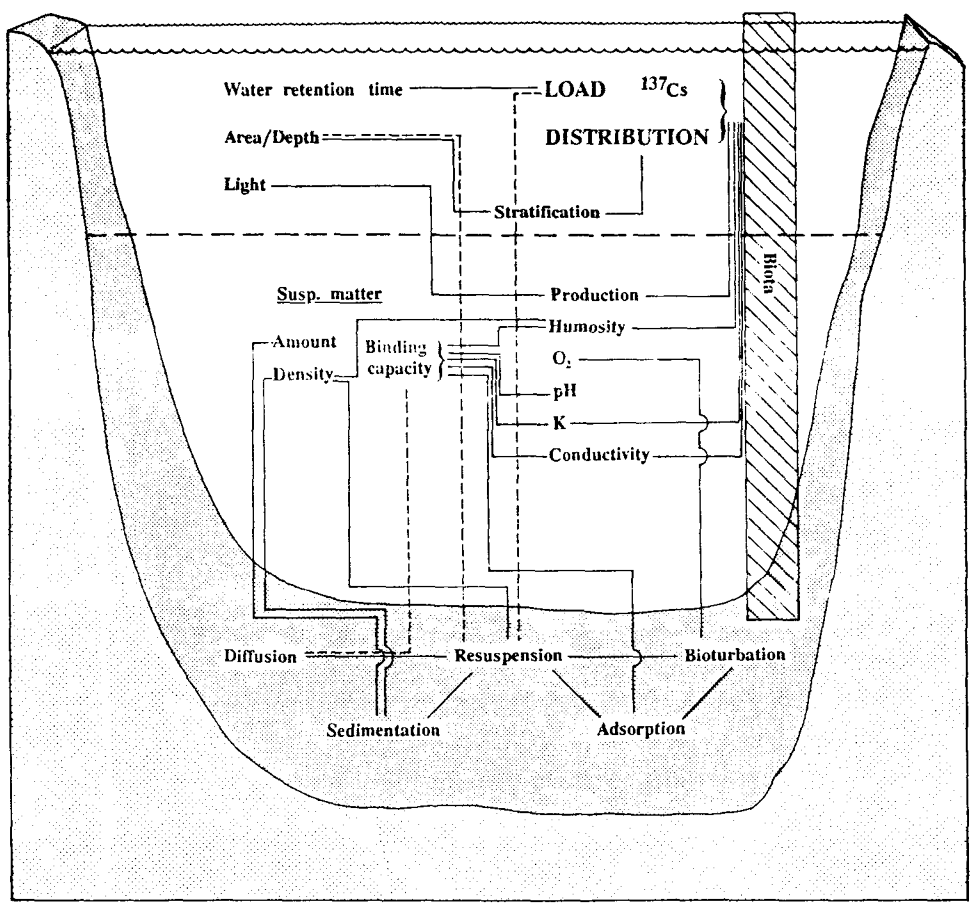


Fig. 5.2 Illustration of the main affecting factors of the processes which regulate the load and distribution of ^{137}Cs within a lake.

The first section will concentrate on the principal effect of lake specific factors on the initial removal processes from the water column. The second part will concentrate on the redistribution of ^{137}Cs within the lake and factors affecting internal loading.

There is a distinction between deposition on the lake surface (Primary Lake Load) and input from the drainage area (Figure 5.1). The time lag between primary deposition and the main part of the input from the lake catchments (Secondary Load) was very short in most Nordic countries and in this first part we will point out which factors regulated the magnitude and removal of this initial input.

Lake Morphometry	Chemical Properties	Physical Properties	Biological Factors
Lake area	pH	Light conditions	Littoral/profundal distribution
Depth	Conductivity	Turbidity	Biological activity
Volume	K	Stratification	Transport by biota (e.g.
Shape	Nutrients	Sediment structure	benthic fauna)
Water retention time	Organic content	Suspended matter	

Tabl 5.2.1 Lake specific characteristics.

As with most radionuclides, ^{137}Cs has a strong affinity for particles, and ^{137}Cs transfer from the water column to the sediments might be due to several possible mechanisms (from Kansanen et al., 1990);

- sedimentation of insoluble detrital particles from nuclear fuel (aerosols)
- adsorption or precipitation on inorganic compounds, e.g. carbonates, clays or oxyhydroxides
- sedimentation with humic matter
- sedimentation with autochthonous organic matter either after assimilation or adsorption onto cell surfaces
- direct uptake through assimilation by periphyton or other biota on surficial sediments
- direct adsorption on the surficial sediments.

The chemical properties of the lake waters and the sediments (Table 5.2.1) together with the physical state of the radionuclide itself will subsequently regulate the magnitude of each possible mechanism and the settling velocity of the particle will regulate the removal rate of the radionuclides from the water masses. Important factors in this context are the ratio between inorganic and organic content of the suspended matter, but of course the more specific nature of the suspended matter expressed by e.g. C/N ratio or chemical fractionation, may be important.

In southern Lake Päijänne (Asikkanselkä) the initial removal rate for ^{137}Cs during the first five months was 50 d and during later years about 300 d. The relative flux rates of different radionuclides to the sediments in this lake was $^{144}Ce > ^{125}Sb > ^{137}Cs > ^{110}Ag > ^{106}Ru$. A similar pattern with a rapid removal rate during the first year followed by a slower decrease was also found in small Swedish lakes (Fig 5.2.1).

Even in lakes with short water retention time or during situations with high runoff, lake internal processes seem to trap a considerable amount of the input of ^{137}Cs. Salbu et al. (in press) report a retention of about 50 % during spring flow conditions when the lake water retention time is in the order of a few days.

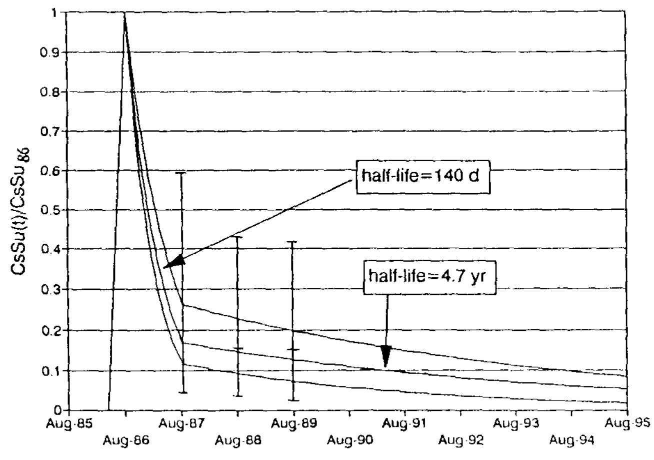


Fig. 5.2.1 Minimum, maximum and median values for the yearly ratios of ^{137}Cs activity in material from sediment traps during 1986 to 1989 vs. 1986, and extrapolated curves giving quartiles for the best fitting curve to an exponential decrease with corresponding "half-lives", n=15 lakes.

Lake morphometry

Lake water retention time is an important factor for how much of the initial input of the radionuclide will be retained within a lake. Lakes with a long retention time will retain a comparatively larger part of this initial input. This is supported by results from sediment inventories (Meili et al., 1989) and would also be a likely cause for the observed positive relationship between ^{137}Cs in fish and water retention time (Andersson et al., 1990).

Lake area would be important when related to catchment area (cf. retention time), or related to other lake morphometric characterics giving information about the basin shape which in turn affects sedimentation processes (e.g. areal distribution of accumulation bottoms), the distribution of littoral/profundal zones and water stratification.

Physical properties

Good light conditions would favour higher production both in the water column and on the bottom.This would give a comparatively faster biological uptake and in different types of biota compared to more humic lakes.

The amount of suspended matter and its density properties will affect the initial removal of ^{137}Cs from the water column. Lakes with high sedimentation rates will have a more effective removal of ^{137}Cs. Stratification and thermal regime will mainly affect the distribution of the initial load within the lake at a later stage as most of the input took place during spring overturn in the Nordic countries. Results from the Norwegian Lake Høysjøen and Swedish mountain lakes show the importance of these factors for the biological uptake and metabolism.

The structure and physical properties of the surficial sediments will affect the degree of adsorption on the sediment surfaces and the possibility of resuspension. However, there seems to be an effective binding to sediments of very different types (Kansanen et al., 1990), loose accumulation sediments as well as eroded clay sediments.

Chemical properties

At least for ^{137}Cs and in normal ranges for Nordic freshwaters of pH, conductivity, and [K], water chemical parameters are likely to be of less importance for the removal rate than the physical and chemical properties of the suspended matter. This is indicated by preliminary results from the 41 Swedish lakes in the project "Liming-Mercury-Cesium" where the inter-lake differences concerning ^{137}Cs in settling matter and water can be related to differences in humic content and C/N ratios rather than to pH, [K], conductivity or hardness due to liming and potash remedies.

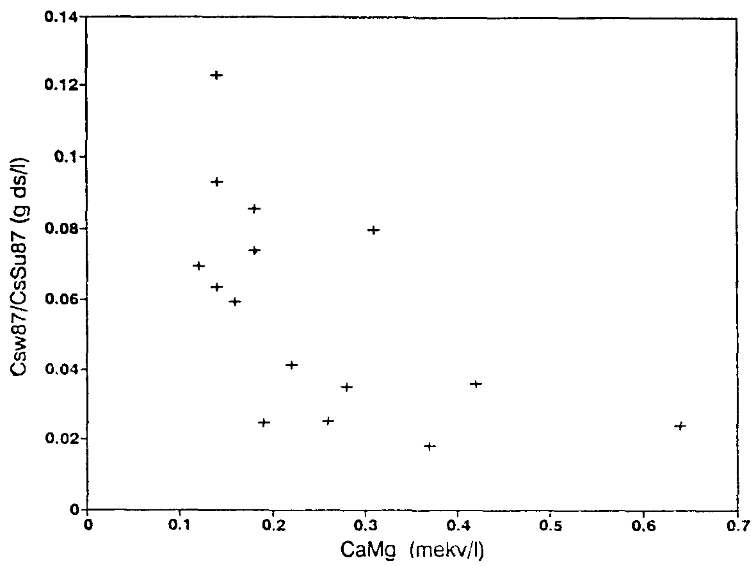


Fig. 5.2.2 The ratio between average ^{137}Cs activities in unfiltrated lake water (Csw) and settling matter (CsSu) during summer 1987 vs. lake mean values on hardness (CaMg), n=15 lakes.

The observed negative correlation between uptake of ^{137}Cs in small perch and, for example, hardness (Håkanson et al., 1988) might reflect differences between lakes concerning the nature of the suspended matter - higher hardness reflecting a larger part of inorganic material and lower C/N ratios. This is supported by Fig.5.2.2 which shows the ratio between the [^{137}Cs] in water (unfiltered), and in material from sediment traps (2m beneath water surface. This ratio is higher in lakes with low hardness. The gross sedimentation of ^{137}Cs (from sediment traps) in relation to the total amount of ^{137}Cs in the water body during the summer period is also very low in these low hardness lakes. The average (during the years 1987 to 1989) of the relative Cs-sedimentation is well correlated (r=0.90, n=15) to the initial hardness of the lakes and also, but to a lesser degree (r=-0.78), to the average carbon content in the settling matter. The increased hardness as a result of the introduced remedies has not influenced this relative Cs-sedimentation. Thus, it seems as if the amount of ^{137}C attached to humus colloids or low density organic matter, is indicated but not regulated by the hardness of the lake water.

Distribution of Cs within the sediments

The sedimentary distribution of deposited Cs is vital in determining the future effects of this Cs pool on the lake ecosystem. The term distribution encompasses both the spatial distribution (horizontal and vertical) and the association of Cs with different particulate fractions. The composition of the sediments influences the distribution of Cs, which in turn affects the further transport of Cs in the lake system.

The most important associations are Cs bound by adsorption to inorganic and organic material, combined with clay, carbonates, hydroxides/oxides (Fe/Mn), sulphides and bound to autochthonous or allochthonous organic matter. For example, a high content of clay results in a Cs-fraction which is tightly bound to the sediment, and environmental changes have only small effects on the transport of Cs (Heit & Miller, 1987). A moderate reduction of pH will mainly increase the transport of adsorbed and carbonate-bound Cs and decrease the fraction of Cs bound to organic complexes. In many stratified, productive lakes or in shallow lakes rich in organic matter there are periods with low concentrations of oxygen during summer and winter, respectively. These low levels of oxygen may increase the mobility of Cs associated to hydroxides/oxides. A total lack of oxygen can give positive effects on the binding of Cs because of a transfer of the element to less soluble sulphides and a lower rate of anaerobic mineralization.

If Cs has been transported to the sediment via organic material the binding or further transport is greatly affected by the microbial activity in the sediment. A large proportion of autochthonous material and a high oxygen concentration, results in high activity and fast mineralization of organic matter. The released Cs will normally be redistributed to another particulate fraction, but at high levels of ammonia the content of Cs in pore water can increase owing to ion exchange (Comans et al., 1989). The redistribution may have negative or positive effects on the release of Cs from the sediment depending on the composition of the sediment and available sites for association of Cs to various sediment fractions.

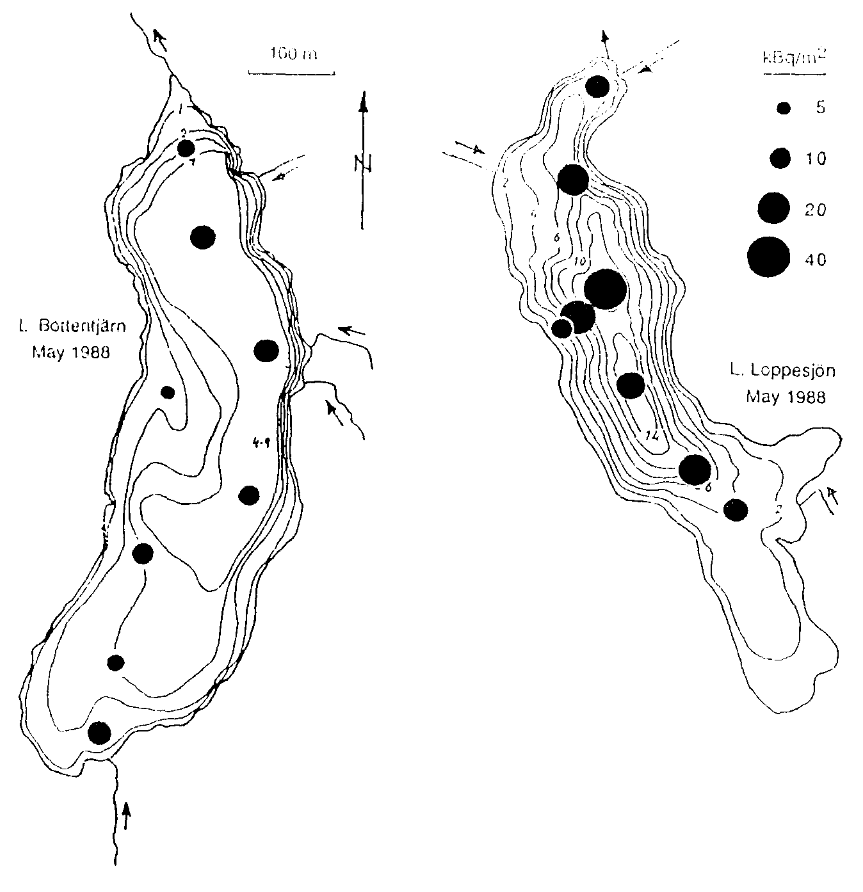


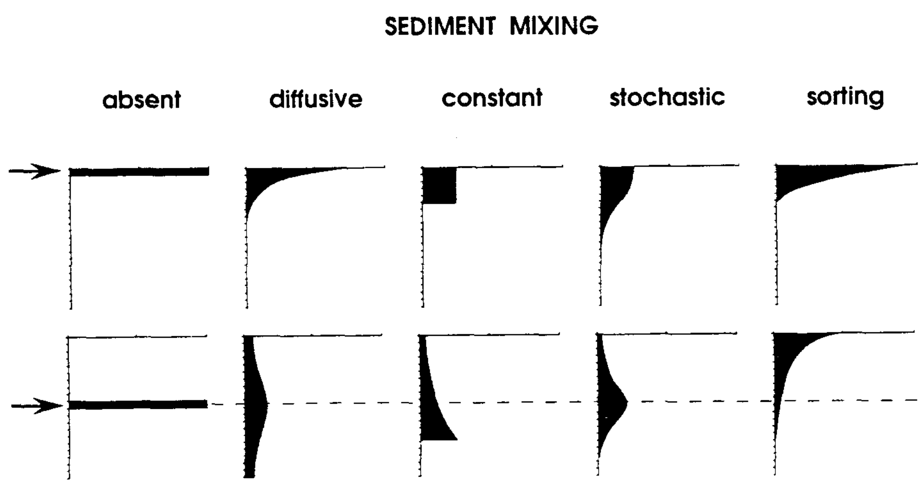
Fig. 5.2.3 Bathymetric maps of Lake Bottentjärn (left) and Lake Loppesjön (right) (Hudiksvall, central Sweden) showing the variation of area specific total activities of ^{137}Cs (kBq/m^2) in the sediment two years after the nuclear accident in Chernobyl. The values are corrected for radioactive decay to 1 May 1986. Contour depths in m. (From Meili et al., 1989)

In allochthonous organic matter the microbial activity and subsequently the rate of mineralization is often lower than in material produced within the lake. For this reason Cs associated to this fraction is quite stable. However, this type of sediment has a high content of dissolved organic material, capable of binding Cs, in pore water, which may result in a release of Cs from the sediment during disturbances of the sediment surface (e.g. resuspension).

The horizontal distribution of Cs in sediment is, among other things, affected by the shape of the lake basin. A steeply sloping bottom will result in a concentrating of Cs towards the deeper parts of the lake, whereas the horizontal distribution is more uniform in concave lakes (Figure 5.2.3). In lakes with large areas of shallow water, relatively large amounts of Cs can be bound to the sediment surface even at exposed sites (Kansanen et al., 1990), partly by physical/chemical adsorption and partly by binding to the benthic algal community or macrophytes. This portion of lake Cs is, to a greater degree than Cs in the deeper areas, exposed to the water, and is therefore very important for the circulation of Cs in the lake. In lakes with steep slopes this Cs may, for example through resuspension, be transported towards the deeper parts of the lake (Kansanen et al., 1990).

The conditions for sedimentation vary strongly in different parts of lakes, which results in large variations in Cs-content of the sediment but also variations in sediment profiles. In some lakes there is an increase in sediment radioactivity with increasing water depth (Blakar, 1987), while in lakes with complicated bottom topography there may not be any obvious pattern (Hongve et al., 1991). A pattern of horizontal (and vertical) divergence in Cs-concentration is seen in lakes with large inlets and/or strong seasonal fluctuations in water flow. For these reasons, the mechanisms which regulate the exchange of Cs between sediment and water are clearly different in different parts of such lakes. For example, Cs can be associated to different particulate fractions or the sediment structure results in strong variations in resuspension between the sub-areas.

The content of Cs in the uppermost sediment layer is crucial for the flux of Cs from the sediment to other parts of the ecosystem. Shortly after the Chernobyl accident Cs was deposited on the surface sediment, but after that period, there was a very extensive vertical redistribution of Cs in most lakes. Some possible mechanisms for this vertical distribution of a pulse of Cs are shown in Figure 5.2.4 (Meili and Broberg, in prep.). The initial stage as well as the situation after a certain



Fig, 5.2.4 Some possible mixing processes in lake sediments and resulting vertical profiles of radiocesium, months (upper) and years (lower) after a Cs addition to the lake. (From Meili & Broberg, in prep.)

time period is described. When mixing processes are missing, as in the deep areas of certain lakes, especially at low oxygen concentration and consequently little or no bioturbation, the pulse of Cs will be covered by new material without Cs. The rate of the covering process depends on the sedimentation rate and on the transport of material to the lake. Lack of mixing presupposes that Cs is very strongly bound to particles, which results in very slow diffusion or none at all.

If diffusion processes cause redistribution, Cs will be transported both to the water column and deeper down into the sediments, which can be illustrated by the situation in Lake Siggeforasjön in 1986 (Figure 5.2.5.A).

The sediments can also be mixed down to a certain, constant depth, which gives uniform distribution of Cs within this layer. As new sediment, containing less Cs, is mixed with the original, the content of Cs decreases continuously (Lake Siggeforasjön, 1987-1990, Figure 5.2.5.A).

The combined effect of diffusion, mechanical mixing and bioturbation give a stochastic depth distribution of Cs and the pulse of Cs will be mixed with a larger volume of sediment (Figure 5.2.5.B), whereby the concentration in the exposed surface layer will become lower.

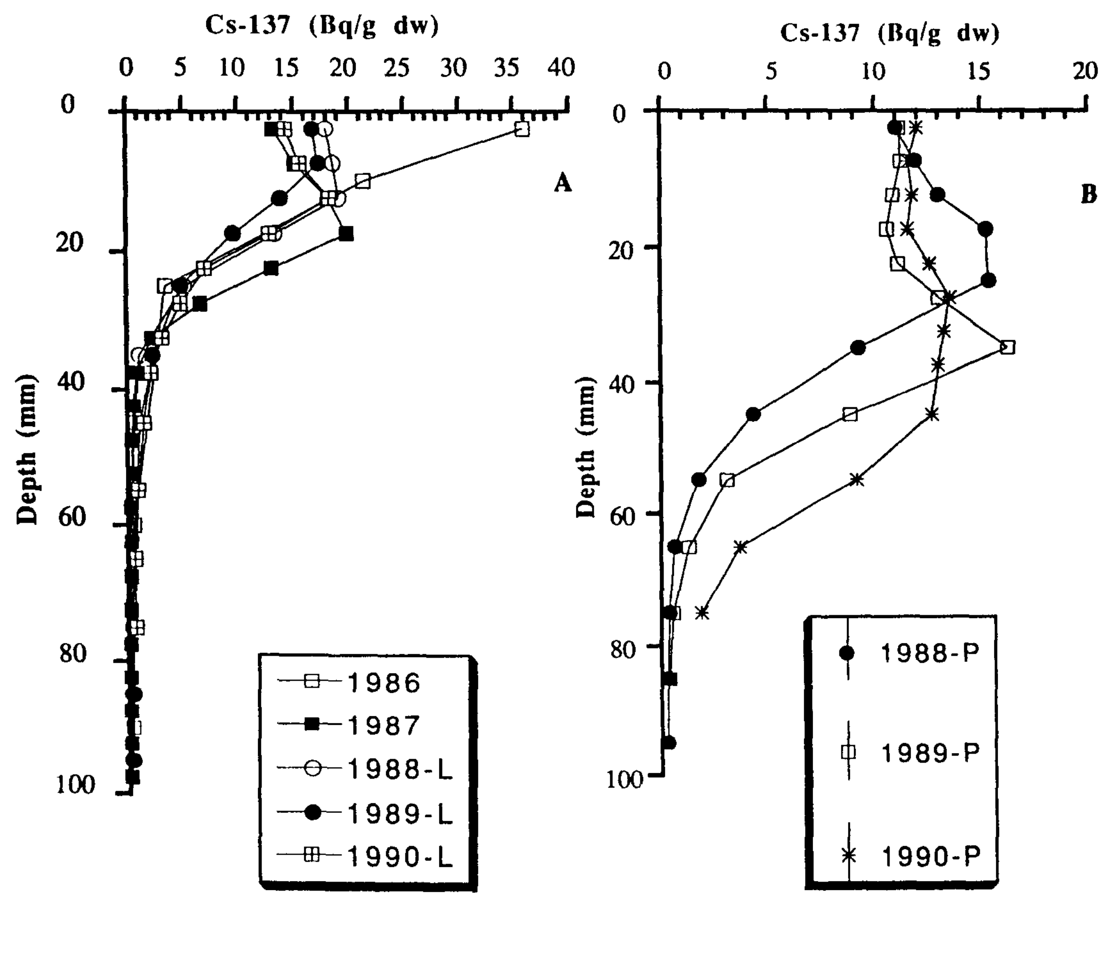


Fig. 5.2.5 A+B Vertical distribution of ^{137}Cs in Lake Siggeforasjön, Uppland, Sweden. A: Sediment cores from 4-5 m water depth, 1986-1990. B: Sediment cores from 10-11 m water depth, 1988-1990. (Broberg & Andersson, in prep.)

Transport of Cs from the sediment

The processes which can be important for the transport of ^{137}Cs from the sediments to the water column are:

1. diffusion
2. resuspension
3. bioturbation by benthic animals and fish
4. uptake by bacteria, benthic fauna, benthic algae and macrophytes

The diffusion rate is dependent on the concentration gradient between water and sediment. If this gradient is maintained at a high level by, for example, turbulent conditions in lake waters and a constant release of ^{137}Cs to the pore water, diffusion can remain at a high rate and will add ^{137}Cs to the water phase. High concentrations of Cs in pore water result from decreased pH, low oxygen content and/or high mineralization, which produces desorption or dissolution of particles or complexes.

The level of resuspension is dependent on lake specific properties such as depth, bottom configuration and wind exposure, but also on sediment structure and its physical properties (e. g. density). In shallow lakes like Lake Hillesjön (Sundblad et al., 1990) or Lake Flatsjön (Broberg, 1989) the resuspension is significant over the entire lake and ^{137}Cs is transported by this process out of the lakes. In deeper lakes, like Päijänne (Kansanen et al., 1990), resuspension results in a transport of a part of ^{137}Cs bound in shallow areas towards deeper areas. Resuspension also means that ^{137}Cs in fish is maintained at a high level in shallow lakes, partly owing to a direct uptake of resuspended Cs and partly owing to an increased supply of oxygen to the particles, which increases mineralization and the bioavailability of sediment-bound ^{137}Cs.

Bioturbation can have a similar effect. When the sediment is mixed by the activity of benthic fauna or fish, the magnitude of the transport to or from the sediment often increases. In most cases oxygen is added to the sediment, which gives increased mineralization and a redistribution or increased outflow of ^{137}Cs. The activity also results in a breakdown of the chemical or physical barrier towards transport which is often found at the sediment surface (Håkanson & Jansson, 1983) and the flow of ^{137}Cs from pore water may increase. Another very important effect of bioturbation is that ^{137}Cs deposited on the sediment surface is distributed in a much larger volume of sediment, which will lower the concentration of ^{137}Cs in the uppermost sediment layer.

The uptake of ^{137}Cs in biota has quite different effects on the transport from the sediment. There is, of course, the normal transport through different food chains but such processes will not be discussed further. As mentioned earlier, benthic algae and macrophytes in the littoral zone bound a fraction of the deposited ^{137}Cs during 1986 (Kansanen et al., 1990) and this binding gave a longer exposure of a large fraction of the pulse in shallow waters. This ^{137}Cs was transported in the food-chains by vegetation-feeders, but it was also released to the water by decomposition during autumn 1986. Another transport mechanism via the biota is the uptake of sediment bound ^{137}Cs by rooted vegetation and its excretion into the water or release in the water phase during decomposition.

5.3 Radioactivity in fish and turnover of radiocesium in lacustrine food webs.

In studies of Chernobyl fallout, cesium has been the major concern due to its long physical half-life, and because it is readily accumulated by organisms due to its chemical similarity to potassium which is a major component in cell metabolism. In freshwater fish, high levels of radiocesium occurred in muscle tissue.

Transfer factors

The effect of radioactive contamination can be described by means of transfer factors (e.g. Bq kg^{-1} wet weight in fish in relation to Bq m^{-2} deposited) (Fig. 5.3.1). In the case of a deposition of short duration, however, transfer factors become an intricate function of time, as they are determined by a large number of physical, chemical, physiological and ecological processes, which change in importance as cesium is redistributed within the ecosystem (see Ch. 5.2). Consequently, transfer factors need to be defined in relation to the time passed since contamination (Fig. 5.3.2). In addition, transfer factors vary considerably both with fish species and fish size.

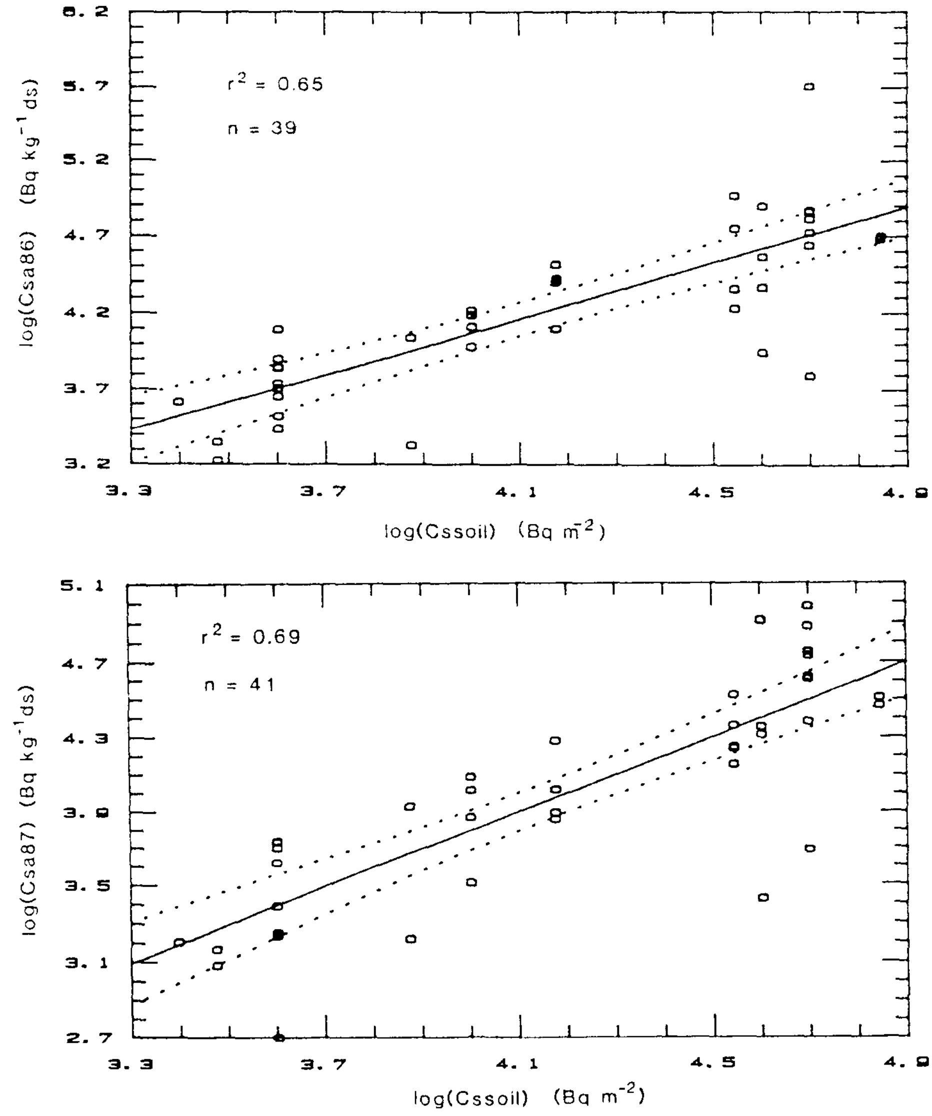


Fig. 5.3.1 Correlation between the concentration of cesium in perch (+1) and the primary load to the lake a) 1986, b) 1987. (From Håkanson et al., 1988.)

Many data are available today to estimate the radioactivity in freshwater fish as a function of the fallout, measured as the amount of radiocesium deposited (Forseth et al., 1991; Meili, 1991; Saxén, 1990; Saxén, 1989; Gaare et al., 1989; Sundblad, 1989; Andersson et al., 1990; Håkanson et al., 1990; Håkanson et al., 1988; Hammar et al., 1990; Brittain et al., in press). The results from different studies are in fairly good agreement with each other. Transfer factors are influenced by various environmental variables (cf. Chapter 5.2). Some important lake-specific variables which have been identified or confirmed as correlates, are water quality (e.g. ionic strength and lake productivity), and lake morphology and hydrology, resulting in different water residence times, flushing and resuspension of cesium (Håkanson et al., 1988; Håkanson et al., 1990; Andersson et al., 1990; Saxén,1987; Saxén et al.,1987; Andersson, 1989). A statistical evaluation of data from a wide range of Swedish lakes after the Chernobyl accident (Håkanson et al., 1988; Håkanson et al., 1990; Andersson et al., 1990) suggests that in softwater lakes, the transfer factor can be three times higher than in hardwater lakes (see also Andersson, 1989). In lakes with a long water residence time, the initial contamination of the fish, as well as the total lake inventory of cesium, was higher than in lakes with a rapid water exchange (see also Hammar et al., 1990; Meili et al., 1989). However, in the latter lakes, which are also more shallow, recovery was usually slower due to secondary contamination from the resuspension of contaminated sediments (Sundblad et al., 1989; Andersson et al., in prep., cf. section 5.2). In conclusion, a given type of transfer factor (at a given time and in a given type of fish, related to a given amount of cesium deposited) can vary up to 10-fold or more between lakes.

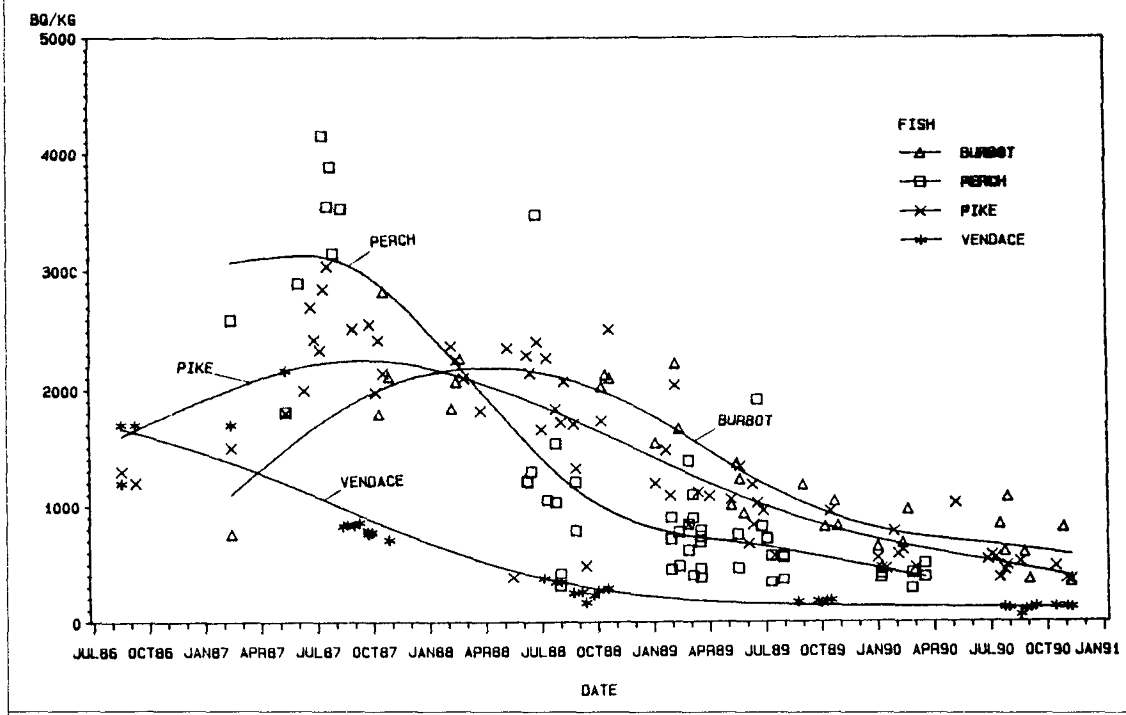


Fig. 5.3.2 Temporal changes of ^{137}Cs (Bqkg $^{-1}$ fresh weight) in pike, perch, burbot and vendace in a lake (area about 100 km^2) located in the area of highest deposition in Finland. (From Saxén et al., 1989.)

The maximum transfer factor was observed within four years after deposition in all types of fish (Fig. 5.3.2). The maximum transfer factor in any type of fish was observed during the first or the second growing season in rapidly growing invertebrate feeders such as brown trout and small perch (Forseth et al., 1990; Saxén et al., 1990; Gaare et al., 1989; Sundblad et al., 1989; Andersson and Broberg, 1990; Hammar et al., 1990; Andersson et al., 1990; Andersson, 1989). In softwater lakes, the maximum factor was typically in the order of 0.1 to 0.2 in perch (Saxén, 1990; Saxén et al., 1987; Håkanson et al., 1988; Andersson et al., 1990; Fig. 5.3.1) and 0.1 to 0.3 in brown trout (Forseth et al,. 1990; Gaare et al., 1989; Hammar et al., 1990).

The magnitude of the maximum transfer factor in a given species and size group appears to be a function of the diet of the fish, but also of the feeding rate (Forseth et al., 1991; Meili, 1991). In rapidly feeding and growing fish the maximum transfer factor was about twice as high as in slowly growing fish within the same lake, at the same cesium concentration in their diet (Fig. 5.3.3; 5.3.4). This implies that differences in growth rates also may contribute to the variation between lakes.

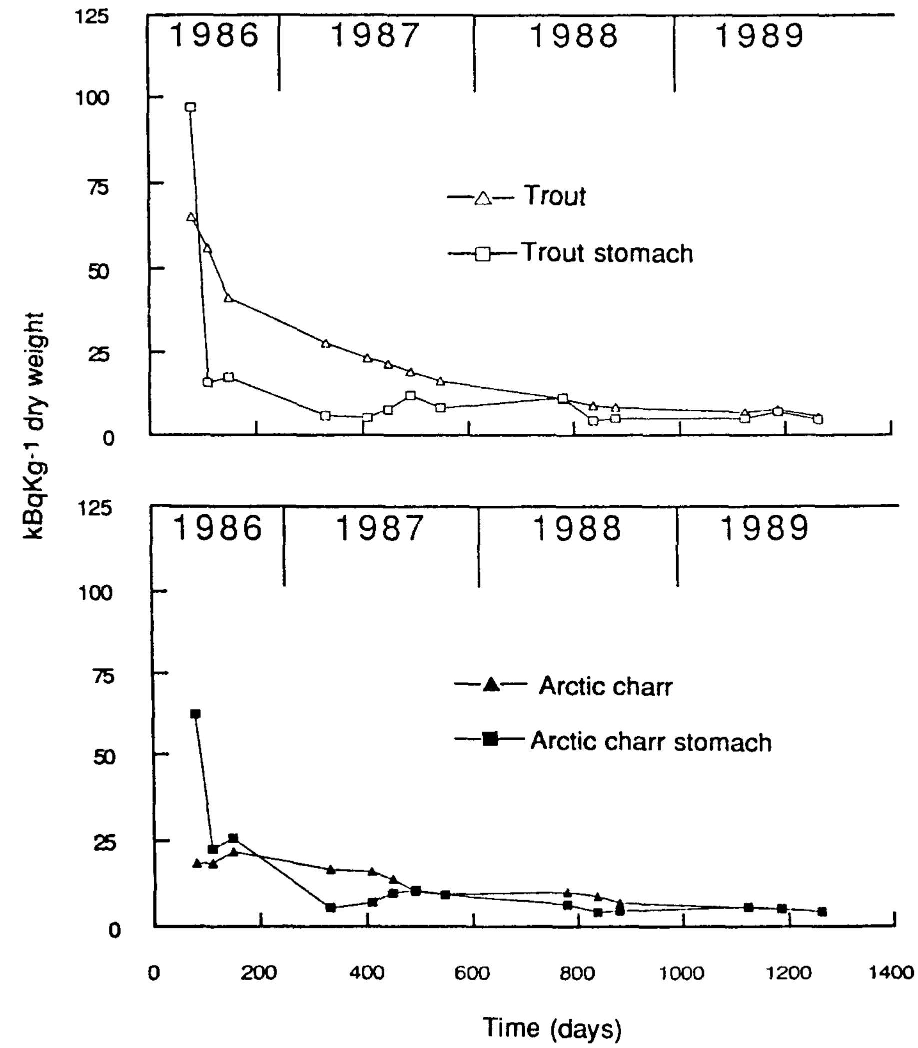


Fig. 5.3.3 a+b Radiocesium (kBqkg $^{-1}$ dry weight) in fish and stomach contents of trout and charr from Lake Høysjøen July 1986-1989; a): △ trout; □ trout stomach; b): ▲ charr; ■ charr stomach. (From Forseth et al. 1990.)

At "equilibrium" conditions (see below), biotic radioactivity can also be described with another widely used transfer factor for the bioconcentration from the water (Bq kg^{-1} wet / Bq l^{-1}). This factor appears to approach a value in the order of 1000 to 10000 in most fish, based on the fairly constant concentrations observed in lake waters during the period 1988-90 (Håkanson et al., 1990; Gaare et al., 1989; Sundblad et al., 1989; Broberg and Andersson, 1989).

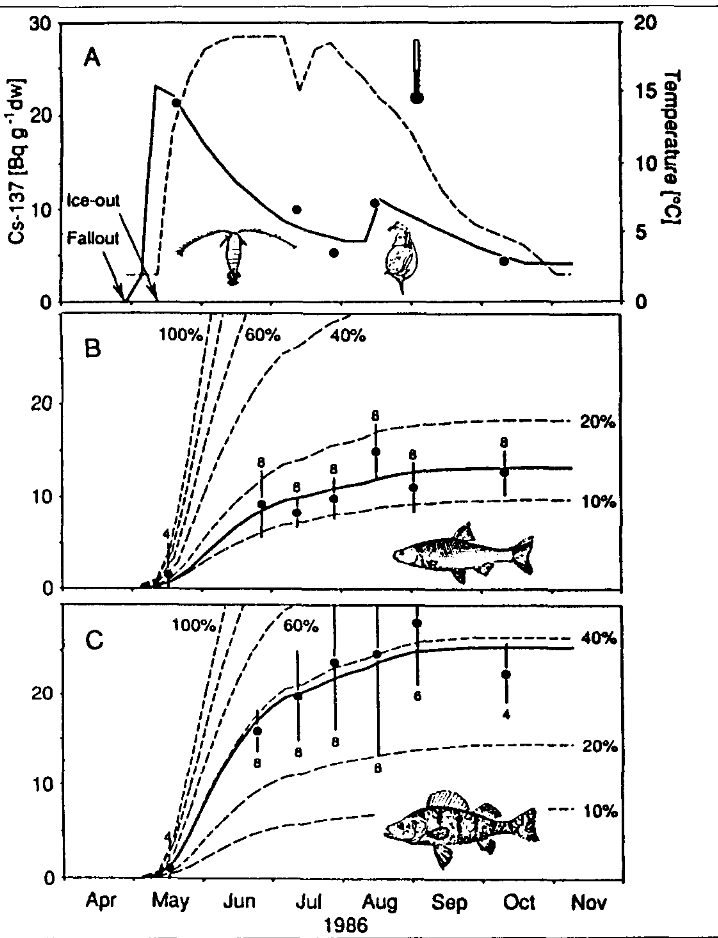


Fig. 5.3.4 A:
Observed (•) and interpolated (-) activities of ^{137}Cs (Bq/kg d.w.) in zooplankton (>250 µm) and the surface water temperature (^{0}C) (—) during the productive season of 1986.

B and C :
Observed activities of ^{137}Cs (Bq/kg d.w.) in the muscle tissue of roach (B) and perch (C) and predicted activities at different fractions of the maximum feeding rate (—). The actual mean feeding rate was estimated to be 14% of the maximum rate for roach and at 38% for perch. Vertical bars show ± 2 standard errors for observed activities, and the number of observations. Data from Blacksåstjärn, a small mesohumic forest lake in central Sweden with a primary deposition of 20 kBqm^{-2}. (From Meili, 1991.)

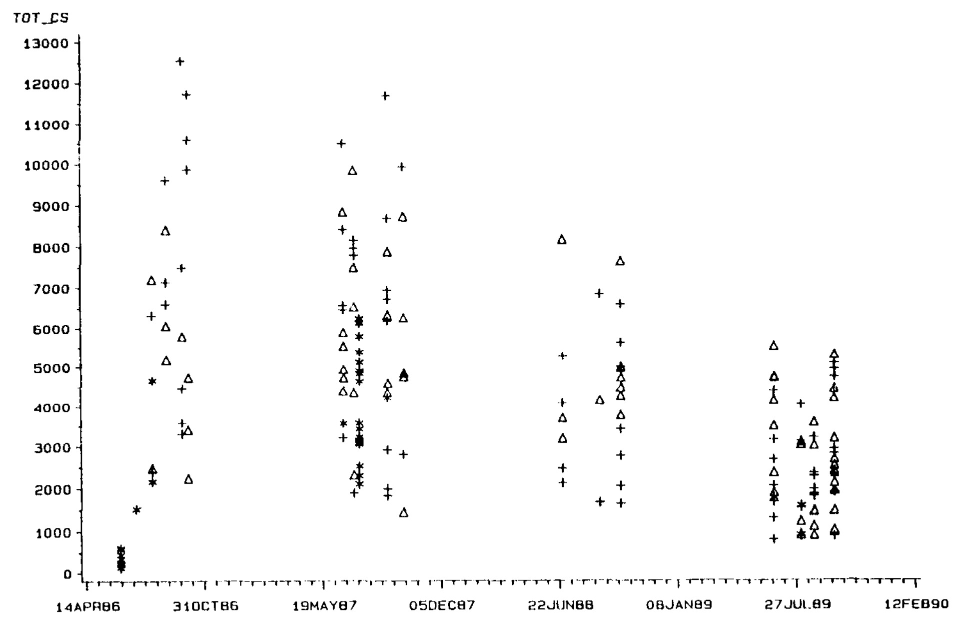


Fig. 5.3.5 Total radiocesium activity content ($^{134}Cs + ^{137}Cs$) (Bq/kg) in individual brown trout from Øvre Heimdalsvatn, 1986-89. +, female; Δ, male; *, not sexed. (From Brittain et al., in press.)

In a given fish population at any one time there is considerable variation in radiocesium activity between individual fish (Fig 5.3.5, Gaare & Ugedal 1989, Brittain et al. in press), largely reflecting differences in dietary intake (see following sections).

Temporal perspectives

During the first year, decreasing activities were reported in invertebrates and in the water within days or weeks after the deposition, whereas activities gradually increased in virtually all fish (Fig. 5.3.2; 5.3.4; Andersson, 1989). This apparent discrepancy is most probably due to trophic interactions and confirms that direct uptake of radiocesium from the water is of minor importance. As a result, maximum activities in fish occurred with a considerable time lag (Fig. 5.3.2). This time lag increases with increasing trophic level and reaches a maximum in piscivorous fish such as pike and large perch (Saxén et al., 1989; Andersson et al., 1990; Andersson and Broberg, 1990; Andersson, 1989).

During the first four years, an accumulation and subsequent gradual elimination of cesium was observed in all fish species, although at different rates. After the initial accumulation phase (A in Fig. 5.3.6), and a fairly rapid decline (B in Fig. 5.3.6), the radioactivity in fish gradually approaches a state where it will decrease only very slowly (see Fig. 5.3.3; 5.3.4; 5.3.6). An apparent "equilibrium" with a new transfer factor (TF_{new} in Fig. 5.3.6) is thus obtained, which is controlled by abiotic processes with a very long half life, such as the secondary dose of radiocesium from the catchment and from the resuspension of sediments (Carlsson, 1978; Carlsson & Lidén, 1978; Brittain, 1990).

The first fish species to reach this "equilibrium" are planktivores and herbivores, e.g. young and rapidly growing fish of most species, coarse fish such as roach and bream, and whitefish including vendace (Forseth et al., 1990; Saxén et al., 1989; Gaare et al., 1989; Andersson and Broberg, 1990; Håkanson et al., 1990; Andersson et al., 1990; Andersson, 1989). They will probably reach "equilibrium" about 5 to 10 years after deposition. At that time, the transfer factor (Bq kg^{-1} w.w./ Bq m^{-2} dep.) will probably be in the order of 0.01, or roughly 5 to 10 % of the maximum transfer factor (TF_{max}) observed in any type of fish. In piscivorous fish, the equilibrium will be reached many years later (Saxén et al., 1989; Andersson and Broberg, 1990; Håkanson et al., 1990; Andersson et al., 1990; Andersson, 1989). Their new final transfer factor (TF_{new}), will probably be somewhat higher; in the order of 0.02 (Carlsson & Lidén, 1978).

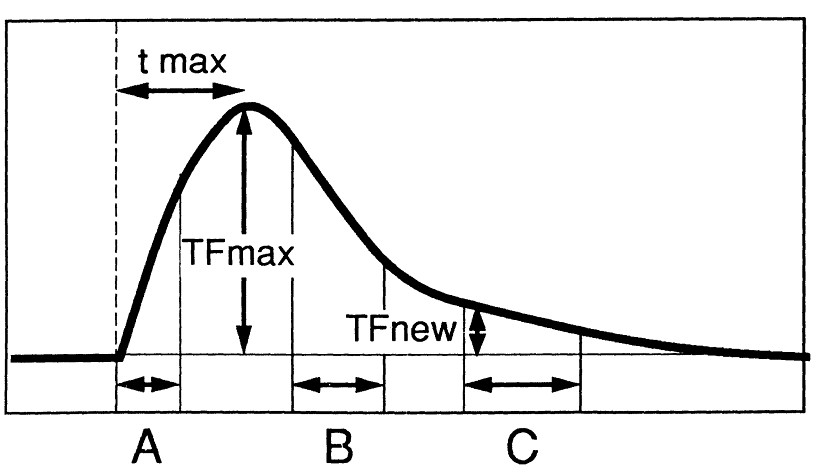


Fig. 5.3.6 Temporal development of radiocesium in fish (see text for explanations). (From Meili, in prep.)

It is important to point out that the observed activities and transfer factors of radiocesium and the patterns of its accumulation and elimination need not be representative but are highly dependent on the time or season of contamination. In the case of the Chernobyl accident, the deposition was at the very beginning of the growing season on a landscape which in most cases still was covered by snow and ice.

Distribution and redistribution of radiocesium within lakes

All studies on the distribution of Chernobyl radiocesium in freshwater ecosystems show that a large proportion of the radiocesium input entering lakes was rapidly deposited in the sediment. Only roughly 0.1 - 1% of the total pool of radiocesium in lakes is today found in the biota, including macrophytes, invertebrates and fish (Andersson, 1989; Andersson and Broberg, 1990; Meili et al., 1989; Gaare et al., 1989; Sundblad, 1989).

In different freshwater organisms, radiocesium concentrations varied widely during the initial phase after contamination, both within and between trophic levels. During the following years differences decreased, and several studies (Forseth et al., 1991; Saxén, 1989; Gaare et al., 1989; Carlsson et al., 1978) indicate that most organisms will eventually reach similar radioactivity concentrations.

Turnover of radiocesium in fish and aquatic invertebrates

Several important controlling factors for radiocesium turnover in fish were identified. Generally, both intake and excretion of radiocesium vary with season and with the life stage of the fish. The turnover is rapid in summer, with both high intake and rapid excretion, and slower during winter with lower intake and slower excretion (Forseth et al., 1991; Meili, 1991; Gunneröd & Garmo, 1988; Gaare et al., 1989). The dependence of uptake and elimination on temperature in a given type of organism may, however, differ significantly. Furthermore turnover is faster in smaller than larger fish, as small fish have a higher metabolism. Food selection may also vary with season and fish size, thus influencing the intake of radiocesium.

Uptake of cesium from contaminated food is the major source of radiocesium in fish, and intake from the water is of negligible significance to the body burden in natural freshwater systems. The radiocesium intake from the food is thus determined by the food selection, radiocesium levels in the prey, and the amount of food consumed (see above).

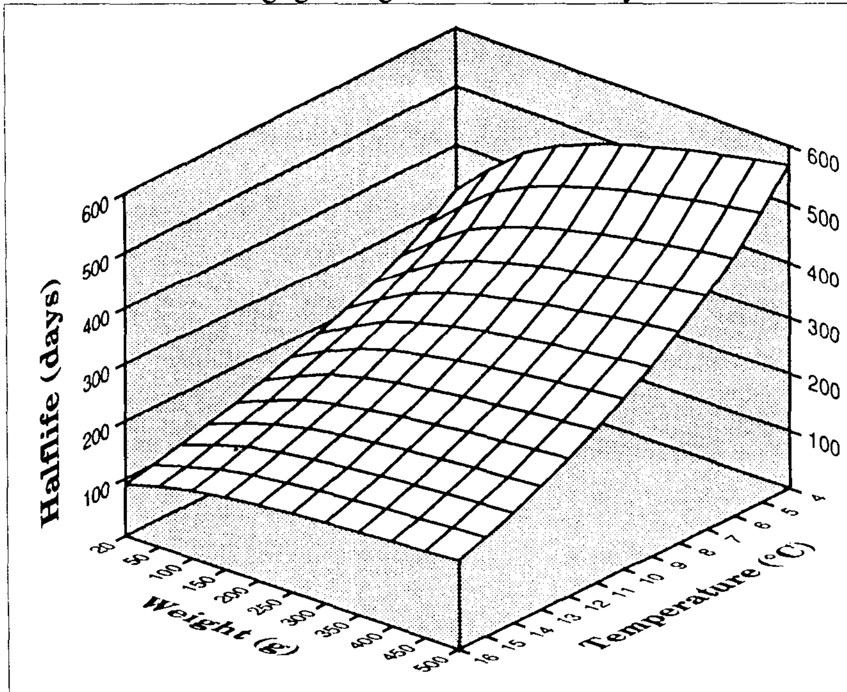


Fig. 5.3.7 Biological half-lives (days) of ^{137}Cs as a function of body weight (g) and water temperature (°C) in brown trout (*Salmo trutta*). (From Ugedal et al., 1990.)

On the other hand, excretion is probably determined by the metabolic rate (Carlsson, 1978; Evans, 1988) and may be species-specific. Several studies have shown that the elimination rate, similar to the metabolic rate, depends on both fish size and temperature (Fig. 5.3.7; Ugedal et al., 1991 and references therein, Evans, 1989). In Nordic lakes, temperature varies with depth and time, with maximum temperatures in epilimnetic waters during summer. Excretion may therefore be linked to the habitat of the fish which, in some species or size groups, varies with respect to temperature. The same applies to the feeding rate of fish, but not necessarily in the same manner (Forseth et al., 1991).

Radioactivity in polluted environments is determined by the physical, biological and ecological elimination half-lives of the isotopes. In a number of studies, the ecological half-life of radiocesium in natural fish populations was determined to be in the order of 1-3 years after passing maximum values (Forseth et al. 1991; Gaare et al., 1989; Håkanson et al., 1990; Andersson, 1989; Brittain et al., in press). However, this half-life may increase significantly after the first few years following deposition (Fig. 5.3.6).

The biological half-life of radiocesium was estimated experimentally in brown trout (Ugedal et al., 1991) and in one size class of roach (Evans, 1989). The former study confirmed the strong dependence on temperature. There is also an effect of fish size but to a lower degree than for temperature. The latter study showed no effects on fish of potassium addition to the water (but not to the food) on the cesium clearance rate after exposure. The rate of uptake of radiocesium from tap water by invertebrates was determined by Forseth et al. (unpubl.). The uptake was very rapid, with a 50% saturation time of about 40 hours at 8°C, and the bioaccumulation (transfer–) factor at equilibrium after one week was about 30. In snails *(Lymnaea)*, accumulation was much slower.

Modelling

Two main benefits of mathematical modelling can be distinguished. Firstly, models may be used for comparisons of ecosystems and for studies of specific processes in different parts of an ecosystem. Secondly, models may be used to predict future concentrations. The main types of models which have been used are statistical regression models (Andersson et al., 1990; Håkansson et al., 1988, 1990) and dynamic compartment models (Forseth et al., 1991; Sundblad et al., 1989; Håkansson et al., 1990; Meili, 1991; BIOMOVS, 1986).

Process-oriented models have been developed at different institutions with the use of the new data. In this type of model, different physical, chemical and biological factors are considered. Statistical models have been used to compare the fallout effects in different types of lakes (Andersson et al., 1990; Håkanson et al., 1988, 1990). Ecological compartment models, taking account of the trophic structure of food webs as well as the feeding rate and growth pattern of fish, allow good predictions of cesium activities where sufficient data are available (Fig. 5.3.4), at the same time as they provide information on processes (e.g. Meili, 1991; and in prep.). The understanding of such processes is crucial for the development and selection of appropriate remedial actions.

For long-term predictions of radioactivity in fish, both statistical regression models and dynamic compartment models have been used by Håkanson et al. (1990). Other compartment models and more simple models based on various transfer factors have been evaluated within the BIOMOVS project (Fig. 5.3.8; Biomovs,1986; Sundblad et al.,1989), in which Sweden and Finland contributed with models. As a result of the study the models have been extended and modified. Further validation studies will be performed within the VAMP project which hopefully will provide further developments.

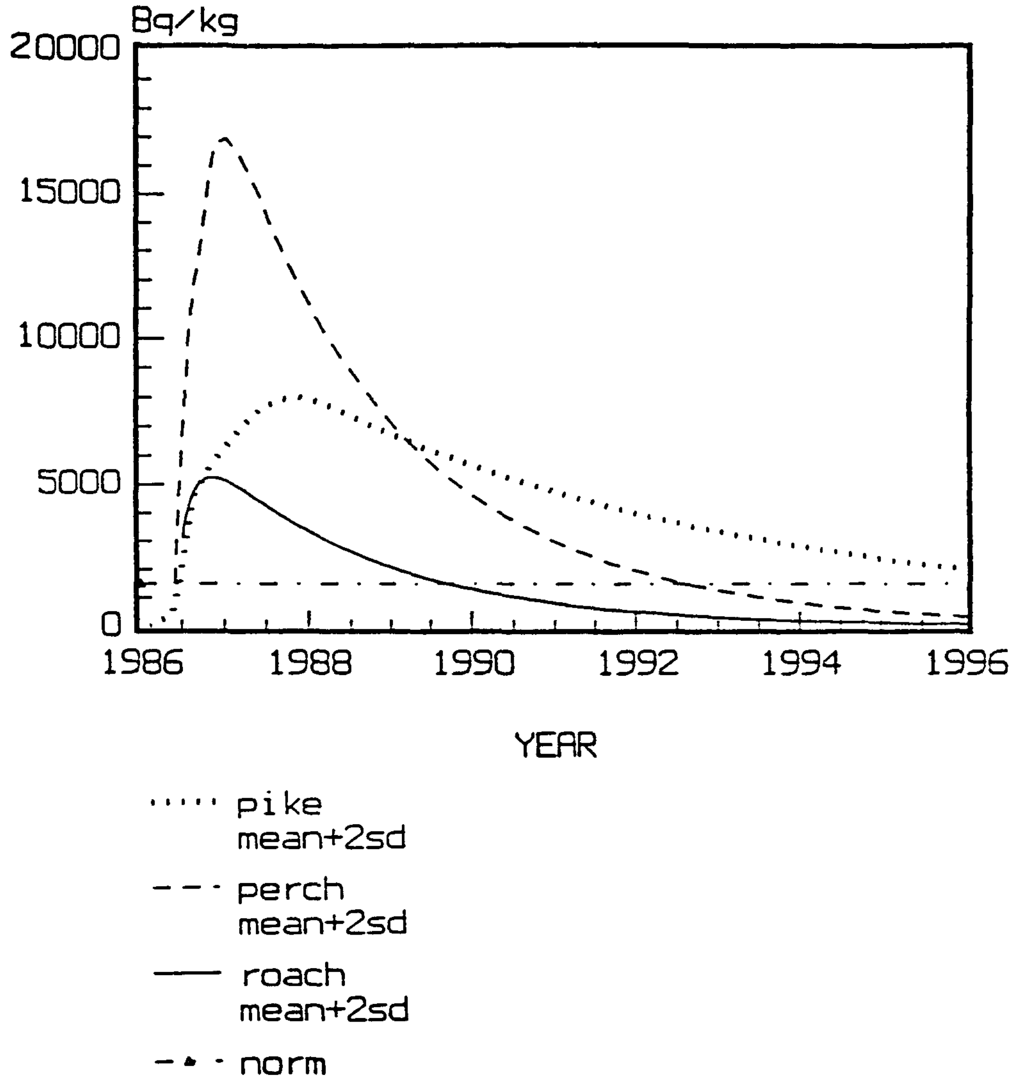


Fig. 5.3.8 Predicted year in which 95% of the different fish population in Lake Hillesjön reach 1500 Bq/kg. (From from Sundblad et al., 1989.)

The data used so far in prognostic modeling have been mainly from the first two or three years. During these years the redistribution of activity between different fish species and also to some extent in other ecosystem compartments is still important. This is one of the main reasons for the uncertainty and differences in the results of the predicted concentrations. In the future, the radioactivity in fish will be controlled by the turnover of cesium within the lakes and their catchment. With longer time series, model predictions can be more accurate.

The models used for long-term predictions of fish radioactivity are still built on rather rough assumptions. During their development it is often found that there is a lack of relevant data which requires further field or laboratory studies.

6. Recommendations for future research

The Chernobyl fallout encouraged many "new" scientists from different disciplines to take an interest in the behaviour of radioactive substances in lake ecosystems.

Today, a large body of field data is available. However, very little is understood about the mechanisms leading to the present situation. Co-operation between field scientists, experimentalists and modellers will be necessary to improve our understanding of the ecosystem transport mechanisms.

The data collected may be useful for the development of bioenergetic food web models by using ^{137}Cs as an ecological tracer (Meili, 1991b).

In most Nordic countries the financial support is declining and it is important that resources are concentrated in the same direction. The VAMP project within the IAEA is especially concerned with the validation and development of models. The meeting determined that the NKS aquatic group could support VAMP, for instance, by designing experiments and develop sampling methods to improve the quality of data, and thereby also support modelling approaches. More knowledge concerning the processes involved in the cycling of radioisotopes is of general interest, but may also provide possibilities for remedial action. For example, potassium treatment of lakes may only be efficient immediately after deposition of radiocesium, as potassium concentrations have been shown to be related to cesium activities under natural conditions but to have little effect on the elimination in fish after exposure (see section 5.3). The understanding of processes is also highly important for realistic predictions based on mathematical models.

The following list, which evolved during our discussions, includes the major gaps of knowledge:

- Bioavailability of cesium in natural waters, temporal changes (conditioning), interrelationships with the ionic strength as well as the concentration and type of particles.

- Improvement of dynamic models towards a more conceptual structure regarding the physiology and ecology of fish and invertebrates as well as the bioavailability of radiocesium in aquatic ecosystems.

- Cs retention (elimination half time) in the most important species of fish (pike, perch, roach, vendace, brown trout, Arctic charr) and its dependence on temperature, body size and feeding rate. Only a few data on brown trout (Ugedal et al., 1990) and roach (Evans, 1989) are available at present.

- Absorption efficiency of cesium from the food in the most important fish, and its dependence on the type of food and on the feeding rate.

- Accumulation and elimination rates in invertebrates as a function of temperature, body size, exposure route and species.

This helps to identify three different research areas for further support within the NKS aquatic group:

* Analyses of fractionated samples.

Knowledge of the extent and nature of the predominant radionuclide fractions is of prime importance in modelling radioactive fluxes in lake ecosystems. In Lake Øvre Heimdalsvatn, four fractions, two in the water phase (<2 nm, >2 nm) and two in the particulate phase (0.063-1 mm; >1 mm), have been measured in lake inflows and outflows as well as in lake waters. Similar fractionation studies are now planned in two other lakes, Hillesjön in Sweden and Valkjärvi in Finland. These two lakes will provide insight into the factors determining radionuclide transport in a range of lake ecosystems. All these lakes are part of the VAMP model validation exercise, and field data gained from these studies will provide important inputs to the model validation studies.

* Sediment processes.

The importance of different physical and chemical characteristics of a sediment for the binding of radionuclides. How, for example, will oxygen-conditions, stratification periods and mixing influence the redistribution of radionuclides within the sediment and their release from the sediment ?

* Joint development of a dynamic model for radiocesium concentration in fish.

Intensive studies of oligotrophic lakes have been performed both in Sweden and Norway. In these studies, different species at several trophic levels have been investigated. The fish species in these lakes are brown trout and Arctic charr. In Sweden, a cooperation project will be started where the turnover in Swedish lakes as well as in the fishes will be modelled.

A study in Norway in the same type of lake will yield results on the turn-over of activity in different trophic levels. It should improve the understanding of the processes if cooperation between these projects is undertaken. There are also other groups which have important data and information on the biological processes which could contribute to modelling of the turnover in fish.

This cooperation should mainly consider the biological process, turnover in plankton and other species consumed by the fishes, as well as in fish.

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Appendix 1.

Lectures given on November 12th 1990

The radioecology of a Norwegian subalpine lake and its catchment.

John Brittain

Abstract

The Norwegian subalpine lake, Øvre Heimdalsvatn, is situated at 1090 m a.s.l. in the Jotunheimen Mountains. The lake is an important reference site and has been the subject of extensive ecosystem studies since the 1950s. The lake is oligotrophic and ice covered from October to early June. The mean water retention period is 78 days, but varies considerably through the year, with a minimum during the spring spate and a maximum during winter. The input of terrestrial plant material is of major importance in lake production processes. The lake and its catchment received high levels of Chernobyl fallout. Multidisciplinary studies, involving scientists from the Norwegian Agricultural University and the University of Oslo, and partly financed by the Norwegian Agricultural Science Research Council (NLVF), are being carried out. Radionuclide (Cs-isotopes and ^{90}Sr fluxes have been estimated in tributary streams and the outflowing river. Special attention has been given to the different size fractions, both in the water phase (cross-flow ultrafiltration) and in particulate organic material (traps, filters). The different plant components in lake inputs have been separated, weighed and their activities measured. In the water phase, the Cs-isotopes are predominantly transported as colloids (>2 nm), while ^{90}Sr is present in the form of low molecular weight species (< 2 nm). Based on lake budget calculations during spring snowmelt, about 50 % of the cesium input is retained in the lake, while about 90 % of the ^{90}Sr is transported through the lake into the lower parts of the drainage area (Salbu et al., in press).

In connection with studies of radioactivity in mountain pastures, surface runoff has been measured from a small catchment during snowmelt. The total transport of ^{137}Cs during spring 1989 was estimated to be 0.007-0.1 % of deposition (Haugen et al., 1990). Within a small plot (c. 70 x70 m) deposition was mapped in detail. It showed an increased deposition in the lower parts of the plot, although there was often considerable variation between neighbouring points.

Deposition of ^{137}Cs in lake sediments is extremely variable with high values (>200 kBq/m^2) in both inlet and outlet areas (Hongve et al., 1990). There was no correlation between organic content or depth and ^{137}Cs deposition. Most activity was located in the upper cm of the sediments. Sediments in tributary streams showed similar ^{137}Cs levels to those in the lake.

Radiocesium activity contents have been monitored in brown trout since 1986 (Brittain et al., in press). After a rapid rise to an average of 7000 Bq/kg w.w. in the autumn of 1986, activities have fallen gradually and in 1990 were on average 2 200 Bq/kg. There is considerable variation in the radocesium activity content of individual fish. The estimated ecological half-life for ^{137}Cs in trout from 1986 to 1990 is 3.6 years, although there has been less reduction than expected between 1989 and 1990.

In addition to the above studies, investigations are being carried out into the radioecology of the lake food chain leading to trout. In the catchment, studies of radionuclide deposition and uptake

in pastures as well as various microbiological studies are in progress. The aim is to couple all these lake and catchment processes together to enable a better understanding of the major pathways and factors regulating radionuclide transport and accumulation in a montane catchment.

The importance of the discharge area in relation to the transport of ^{137}Cs, within the two catchments of Hillesjön and Sälgsjön, Sweden.

Björn Sundblad

Abstract

Measurement of the deposition of ^{137}Cs within the catchments of Hillesjön, the Gävle area, and Orrmyrbäcken, the Gideå area, has been carried out in different ways: soil samples were collected, in-situ gamma spectrometric measurements and exposure rates were made at different time points after the deposition event.

The different measurements of deposition show a variability of about one order of magnitude. Exposure rate measurements performed in 1988 covering different types of soil and vegetation indicate a lower amount of activity within the discharge areas. In addition, areas with dense forest exhibit the same pattern.

Attempts to model the concentration of ^{137}Cs in lake water as well as in streams were made. Compartment model technique was used in combination with catchment characteristics, water turnover, etc. The assumption used, that the discharge areas were contributing most to the leakage from the catchment, gives results similar to those observed. The importance of the resuspension was clearly demonstrated by the calculations.

The transport of ^{137}Cs from 1986 until June 1990 into Lake Hillesjön and out of the lake was calculated. A net loss of activity from the lake is observed during the whole period. This loss is about 30 % of the initial deposition. The leakage from the catchment is equal to about 1 % of the deposition on the whole area. The corresponding figure, considering the whole leakage originating from the discharge areas is about 8 % of the initial deposition of ^{137}Cs.

Measures to reduce high levels of radioactive cesium in fish.

Tord Andersson

Abstract

During the years 1986-1989 the uptake of ^{137}Cs and the effect of remedial measures were studied within the project "Liming-Mercury-Cesium". The studied lakes are 41 small, mainly oligotrophic Swedish lakes in an area with high Chernobyl fallout (4-70 kBqm^{-2}).

The first year was used as a reference year and the remedial measures; lake liming, wet land liming, fertilisation, extensive fishing and in 13 lakes combined with potash treatment, was

initiated in 1987. A broad set of data describing limnological characteristics and load of ^{137}Cs to the lakes was collected.

The decrease in small perch (1+, <10 g) was on average around 85 % from 1986 to 1989. In pike the concentration of ^{137}Cs increased from the spring 1987 (before remedial measures) to 1989 by, on average, >80 %. The maximum values in pike up to 1989 correspond to more than 80 % of the initial values (the highest) in small perch. The decrease in small perch in terms of "ecological half-lives" is between 0.6-2.1 yr with a mean of 1.1 yr. The size of this decrease cannot be related to the remedial measures but rather to factors regulating the degree of resuspension (a faster decrease in deep lakes) and type of "carrier particles" (e.g. humic content).

Even if any significant effect in terms of shorter "ecological half-lives" cannot yet be seen, a future reduction due to the remedial measures cannot be excluded, as the initial input of 137Cs and its distribution within the lake is still a dominating factor for the levels of ^{137}Cs in fish.

Distribution of ^{137}cesium in lake sediments.

Anders Broberg

Abstract

This study on ^{137}Cs from the Chernobyl accident was conducted in three lakes, L. Ekholmsjön, L. Flatsjön and L. Siggeforasjön, in central Sweden during 1986-1990. The purpose was to measure the depth distribution of cesium-137 in lake sediments during different time periods and to compare the fate of deposited ^{137}Cs in the investigated lakes.

Sediment cores were sliced in 5-10 mm increments to a maximun sediment depth of 150 mm. Standard physical-chemical parameters were analysed on the increments together with a measure of ^{137}Cs concentrations using a sodium iodine detector.

^{137}Cs concentration in the sediment in L. Flatsjön was 75-80 kBq/m^2 and in L. Ekholmssjön about 25 kBq/m^2, which is the same as the amount deposited on the different lakes. Sediment from L. Siggeforasjön contained higher amounts (about 50 kBq/m^2) than the deposition (30-40 kBq/m^2) because of a transport of Cs from the catchment area. Since 1986, there has been a vertical redistribution of ^{137}Cs and the maximum values are now found at greater depths (2-3 cm) in the sediment. The more homogeneous vertical distribution of ^{137}Cs in the sediment is due to water movements causing resuspension and redeposition of contaminated particles, together with bioturbation and sedimentation of new organic matter. This lowering and equalization of ^{137}Cs in the sediment was more pronounced at greater depth in the lakes.

Radiocesium in brown trout and Arctic charr.

Torbjørn Forseth

Abstract

The radioactivity of brown trout (*Salmo trutta* (L.)) and Arctic charr (*Salvelinus alpinus* (L.)) was monitored in Lake Høysjøen, central Norway from 1986 to 1989. A distinct difference between brown trout and Arctic charr in the accumulation of radiocesium (^{134}Cs and ^{137}Cs)

from the Chernobyl fallout was observed, and the study focused on the understanding of this difference.
Brown trout had a large food consumption and a corresponding high intake of radiocesium. Due to its temperature dependence, their excretion of cesium was rapid as brown trout lived at higher temperatures in epilimnic water. Arctic charr had a lower food consumption and lived in colder meta- and hypolimnic water. Arctic charr therefore had a lower intake and slower excretion of radiocesium. Brown trout and Arctic charr also had different diets. Zoobenthos was the dominating food item for brown trout, whereas Arctic charr mainly fed on zooplankton. The radioactivity in the stomach contents of the two species was different in 1986, but similar for the rest of the period. Higher levels of radiocesium in brown trout than Arctic charr in 1986 was caused by brown trout having a higher food consumption and more radioactive food items than Arctic charr. The parallel development in accumulated radiocesium through summer 1987 was probably caused by brown trout balancing a higher intake with a faster excretion.

The ecological half-lives of ^{137}Cs in brown trout (357 days) and Arctic charr were estimated to be 1.2 and 1.8 years, respectively.

Lake sediments are the major pool of radiocesium in the ecosystem, and less than 0.1 % is stored in the biota. The availability of sediment radiocesium has apparently not decreased throughout the study period.

A laboratory study was performed to examine the relationship between radiocesium retention, ambient temperature and body size. The retention is strongly dependent upon temperature, and weakly dependent upon fish weight.

Cycling of ^{137}cesium in Swedish forest lake ecosystems.

Markus Meili

Abstract

To study the cycling and bioavailability of ^{137}Cs and its bioaccumulation in aquatic food webs during the first months after the fallout, a large number of samples were collected in four different lakes at intervals of 2-5 weeks. The samples included most trophic levels (zooplankton, zoobenthos, fish of different species and size, including young of the year) as well as background data from water and sediment samples. In several hundred individuals of pike, perch and roach, different tissues were analysed separately. Analyses of gut contents provided information about the structure of the food webs and the biomass fluxes. The importance of abiotic versus biotic factors for the activities of radiocesium in food chains was compared.

The sample collection is unique as it systematically covers the whole growing season of 1986, starting from the ice-out a few days after the fallout. The large number of replicate samples also allows the comparison of different lake types and the construction of quantitative dynamic models despite the large variation in contamination typically encountered in animals of the same type.

The activities in different species and size groups of fish appear to be largely controlled by their

trophic level, feeding rate and habitat, which explains the widely varying accumulation patterns. In order to validate hypotheses and models, experimental studies have been recently initiated on the turnover of radiocesium in a controlled food web consisting of five trophic levels.

As the sediment compartment accounts for 99% or more of the ^{137}Cs, pool in the lakes, resuspension may be crucial for the recovery time of lake ecosystems. In 1988-1990 further studies were undertaken to assess the distribution and redistribution of ^{137}Cs, and the impact of lake morphology, hydrology and sediment characteristics.

As a spin-off result, the data and models on the turnover of ^{137}Cs have also proved to be very useful to study both trophic dynamic in lacustrine food webs and sediment movements in lakes.

Comparison of predicted and measured ^{137}Cs in a lake ecosystem.

Sture Nordlinder

Abstract

To make reliable predictions of the transfer of radionuclides in the biosphere, model results need to be tested against independent data sets. To a certain extent such data are now available due to the Chernobyl fallout. In this paper comparison is made between calculated and measured data of concentrations of ^{137}Cs in water, sediment and fish for the Swedish Lake Hillesjön situated in the most contaminated area in Sweden. This investigation is a part of a scenario in the international BIOMOVS study. Two approaches were used to model the uptake to fish. The differential equations of the models were solved using the BIOPATH code. The uncertainties of the results due to the uncertainties of the model parameters were calculated using the PRISM code.

Reasons for discrepancies between calculated and measured values are identified and discussed. The question of the validity of applying data for steady state conditions to dynamic systems is addressed. Some general problems concerning the testing of model results against independent data sets are also considered.

Transport of radiocesium to freshwater fish from Chernobyl fallout in Finland.

Ritva Saxén

Abstract

The Finnish Centre for Radiation and Nuclear Safety has monitored the amounts of radiocesium in freshwater fish with extended programmes since 1986. The main aim of monitoring has been to estimate the importance of freshwater fish as a source of radiocesium to consumers. Both large lakes most important for fishing and small oligotrophic lakes, where the highest activity concentrations were expected to be found, were included in the study.

Temporal changes in activity concentrations of different fish species and fish groups (predators, partly predators and non-predators) differ from each other. Predatory (piscivores) fishes reached

maximum in 1988, partly predators (omnivores) already in 1987 and ^{137}Cs in non-predators started to decrease already in the year of the accident, 1986.

In large lakes transfer of radiocesium from deposition to perch and pike was about 0.05 m^2/ kg on the average. In small lakes (<1 km^2) transfer factors were higher, about 0.20 m^2/kg on the average, with large range.

Water from some of the lakes was also analysed regularly. Activity concentrations of ^{137}Cs in water decreased quickly after the spring of 1986. Lake Päijänne was one of the lakes most intensively studied. It is one of the largest lakes in Finland and it is important for freshwater fishing as well as for drinking water for about one million inhabitants in southern Finland. The southern parts of the Lake Päijänne are located on the area of highest deposition of ^{137}Cs in Finland (45-67 kBq/m^2). The transfer factor from water to whitefish seemed to be time independent and was about 1000 in Lake Päijänne. For other fish species the steady state situation was not yet achieved and transfer factors seemed to depend on time.

Areal differences in transport of radiocesium to aetable fish were also detected. On the eight large drainage basins in Finland transfer factors of ^{137}Cs from deposition to aetable fish varied from 0.02 to 0.05 m^2/kg and from 0.01 to 0.20 m^2/kg in 1986 and 1989, respectively.

Cesium in Arctic charr lakes

Manuela Notter

Abstract

High levels of ^{137}Cs originating from the Chernobyl-accident in 1986 have been recorded in high altitude lakes in the upper River Ångerman-älven. The fish fauna of these headwater systems is dominated by Arctic charr (*Salvelinus alpinus*) and brown trout (*Salmo trutta*), two salmonid species of importance to recreational as well as commercial fisheries in the area. However, many of the lakes are exploited as reservoirs for hydroelectric purposes. The amplitude of the water level regulation may range up to 25 m. In order to compensate for the loss of littoral invertebrates and the subsequent damage to fish production, new fish food organisms such as *Mysis relicta* and *Pallasea guadrispinosa*, were introduced into several lakes and reservoirs in the upper parts of Rivers Faxälven and Fjällsjöälven during the 1960s. The large-scale impact of *Mysis* has affected the ecosystems in many ways. Due to its diurnal migration between deep waters in day time and surface layers at night, combined with feeding habits dominated by zooplankton and detritus, *Mysis* has previously been regarded as a living elevator of energy as well as heavy metals. The present cesium study suggests that the mechanisms involved with the transport of ^{137}Cs to brown trout and Arctic charr in natural and impounded lakes also include *Mysis* as an elevator for sedimented radionuclides.

Seven mountain lakes in the northwest part of the province of Jämtland have been sampled and analysed for ^{137}Cs levels in water, sediment, phyto- and zooplankton, macroinvertebrates, and fish on 7-8 occasions during the period August 1986 to September 1989. The preliminary results show that levels in surface sediment doubled during the period of study, and that the increase in reservoirs is both larger and faster than in natural lakes. An estimate

of the total cesium budget supports the findings that more cesium was deposited in reservoirs than in natural lakes during 1986. The initially very high levels of ^{137}Cs in water, phytoplankton and zooplankton decreased to a more stable level during 1987-88. The levels in *Mysis* were considerably higher than in zooplankton on subsequent sampling occasions, and decreased significantly during the winter 1986/87.

Radioactivity increased rapidly in the biota. In brown trout and Arctic charr during 1986 levels of 13 500 dry weight (d.w.) were recorded in both species. During early 1987 a decline in Arctic charr was recorded. In brown trout, however, the levels continued to increase until August 1987 after which there was a slow decrease. Analyses of the results indicate that the concentration of ^{137}Cs in fish muscle was higher for males and non-spawners than for females and spawners. Fish populations feeding on benthic invertebrates, especially *Mysis* and *Gammarus*, demonstrated higher relative levels than zooplankton feeders in 1986. Thus the brown trout had generally higher levels than the Arctic charr. In 1988 fish populations feeding on zooplankton were associated with low levels of ^{137}Cs. Brown trout in lakes with introduced *Mysis* had the highest cesium levels in this study, and in August 1989 levels around 1 500 Bq/kg wet weight (w.w.) were still recorded in fish from most of these lakes.

National Swedish Environmental Protection Board REPORT

This report was compiled during a meeting within the aquatic group in the Nordic Nuclear Safety Research Programme, in November 1990. It is a joint effort to summarize the results from post-Chernobyl research in Nordic limnic ecosystems. The most important pathways, processes and factors determining the ^{137}Cs concentration in fish are identified and discussed.

ISBN 91-620-3949-0
ISSN 0282-7298