Radiological consequence model for regional lake environments (REGLAKE)

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Radiological consequence model for regional lake environments (REGLAKE)

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Management Summary

This report descripes the developed regional consequence model REGLAKE for aquatic environments. Principles of radionuclides transport modelling in lake ecosystems and regional consequence assessment are presented.

Contents

1 Introduction

The aim of the work is to develope an areal lake consequence model, based on reliable concept of modelling the main existing features of lake ecosystems. Lake size, topography and nutrient level classification method is utilized in the areal model.

The evaluation of lake class specific consequences after an areal deposition of radionuclides is considered by certain “kernel” module. The kernel module consists of detailed sub parts: the model for catchment, the lake model and the dynamic fish chain model. The catchment model consideres radionuclides transfer from the catchment to the lake. The lake model takes care of sedimentation processes and water turnover effects. The fish chain model estimates the temporal concentrations in different fish types.

Special characteristic of the model is the possibility to consider systematically various sizes of lakes, topographies of catchments and nutrient contents of lakes for the deposition area. After certain specification of the aquatic deposition environment in every square of an areal grid, the model is planned to estimate aquatic consequences over the whole deposition area. Graphical presentation of concentration levels eg. in water or in fish illustrates the potential radiological consequences for human. The model has been started to affiliate in RODOS. At first the model will exists as a stand alone version under the RODOS user interface system.

2 Kernel module

2.1 Conceptual model

The goal of the model under development is the possibility to predict radiological consequences for lake ecosystems in case of local or areal depositions. The developed model concept is based on binding realistically the catchment (drainage) model, the lake model and the fish chain model (Fig. 1). The presented model concept forms a certain model “kernel” which can be utilized for single lake ecosystem types and further in areal deposition modelling approach.

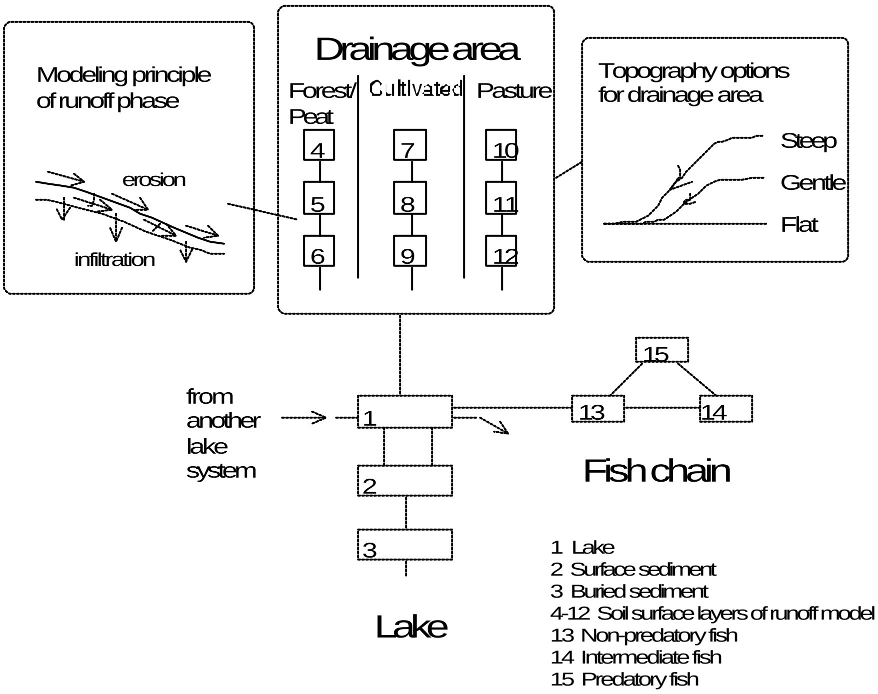

Fig 1. *Conceptual lake ecosystem model.*

2.2 Radionuclides transport modelling

2.2.1 Catchment area

The catchment area model is build up so that it realistically corresponds to the existing situation around a lake recipient. Normally, the land use of lake catchment consists of forest/peat, pasture or cultivated land types. The model therefore describes the land use distribution by these main components. Relative fractions of catchment types are usually proportional to the local topography: in relatively flat areas the fraction of cultivated land is greater than in case of steep topography of the catchment. The model therefore applies higher fraction of cultivated land for flat topography compared to steep topography option.

Erosion process causes radionuclides transport from the catchment to the lake recipient. The erosion intensities varies between different surface soil types. For cultivated soil erosion intensity is higher than for forest/peat soil type. The erosion term takes into account the flow of solid material from the catchment into the lake by water convection and also resuspension of solids from the catchment on the lake surface via atmosphere. In the model erosion intensity values are controlled by the catchment type and by the topography factor. Topography of the catchment area affects e.g. the expected amount of runoff water and also the intensity of resuspension. The characteristic wind field around a lake affects the airborne erosion rate from the catchment and therefore the erosion rate is considered as a function of typical vertical wind profile (Fig 2.). Three characteristic topography options are available in the model: flat, gentle and steep.

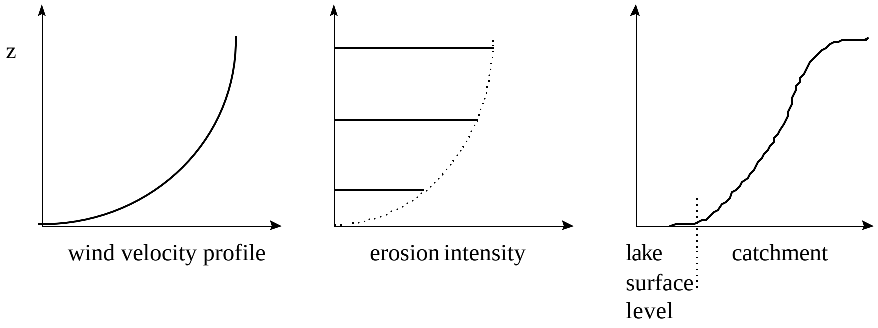

Fig 2. *Vertical wind profile and erosion rate as a function of topography.*

Effective runoff is assumed to take place in a relatively thin surface layer of the catchment. The amount of runoff water depends on area, topography and soil type of the catchment. Sorption and retardation of radionuclides in the catchment surface layer are modelled by utilizing element specific K_d-values (1) in the calculation formulas. The element specific activity distributed in water and solid phases are estimated by equations (2) and (3). The total erosion rate from the catchment to lake recipient is evaluated based on eq. (4).

$$K_d = \frac{A_S / m_S}{A_W / m_W} \qquad (1)$$

where

K_d	is distribution coefficient of element $(Bq/kg_s)/(Bq/litre_{water})$
A_s	is activity adsorbed in solid material (Bq/kg_s)
A_w	is activity adsorbed in water (Bq/litre)
m_s	is mass of solid material (kg_s)
m_w	is mass of water (kg_w)

$$f_w = 1 / (1 + K_d \cdot s) \tag{2}$$

$$f_s = 1 - f_w \tag{3}$$

$$\dot{m}_{erosion} = \sum_i I_{erosion,i} \cdot a_i \tag{4}$$

where

f_s	is fraction of activity in solid material (-)
f_w	is fraction of activity in water phase (-)
s	is amount of solid material $(kg_s/litre_{water})$
$\dot{m}_{erosion}$	is erosion mass rate $(kg_s/year)$
$I_{erosion,i}$	is erosion intensity $(kg_s/m^2/year)$
a_i	is area of catchment sub-block i (m^2)

The total activity flow from the catchment to lake is caused by activity carried over with convection of water and solids and with airborne solids. As mentioned earlier, the topography and soil type of catchment affect the activity rates. Therefore, the calculated reference level of erosion and water flow rates are weighted with corresponding functional dependence of topography and soil type in order to describe the activity flow rates with sufficient accuracy (5). This prodecure accounts for every sub-block of the considered catchment area.

$$\dot{A}_n = f(T) \cdot f(ST) \cdot \dot{A}_{ref,n} \tag{5}$$

where

$\dot{A}_n$	is activity flow rate of nuclide n from the catchment to lake (Bq/s)
$\dot{A}_{ref,n}$	is the calculated reference activity flow rate of nuclide n (Bq/s)
$f(T)$	is weighting factor caused by topography (-)
$f(ST)$	is weighting factor caused by soil type (-)

Catchment area might be remarkable activity source especially in the later phase of the release i.e. the secondary source component which occurs about after one or two years after the initial deposition on lake and catchment. Certain main parameters of the catchment model are listed below (Table I). Representative range of these parameter values are also suggested.

Table I *Catchment area model parameters.*

Parameter	**Representative range of values**	**Default**	**Unit**
Precipitation rate	0.2 – 0.9	0.6	[m/year]
Evaporation rate			
• forest/peat type catchment	0.1 – 0.6	0.3	[m/year]
• pasture type catchment	0.2 – 0.7	0.35	[m/year]
• cultivated type catchment	0.2 – 0.7	0.35	[m/year]
Infiltration rate			
• forest/peat type catchment	0.1 – 0.7	0.35	[m/year]
• pasture type catchment	0.1 – 0.6	0.3	[m/year]
• cultivated type catchment	0.1 – 0.6	0.3	[m/year]
Erosion rate			
• forest/peat type catchment	0.1 – 0.5	0.3	$[kg_s/m^2/year]$
• pasture type catchment	0.1 – 0.6	0.33	$[kg_s/m^2/year]$
• cultivated type catchment	0.2 – 0.7	0.4	$[kg_s/m^2/year]$
Sorption data for Cs nuclides (K_d-values)			
• forest/peat type catchment	50 – 80000	1000	$[Bq/kg_s]/[Bq/litre_w]$
• pasture type catchment	50 – 80000	1000	$[Bq/kg_s]/[Bq/litre_w]$
• cultivated type catchment	50 – 80000	1000	$[Bq/kg_s]/[Bq/litre_w]$
Density of solid material			
• forest/peat type catchment		2600	$[kg_s/m^3_s]$
• pasture type catchment		2600	$[kg_s/m^3_s]$
• cultivated type catchment		2600	$[kg_s/m^3_s]$
Porosity			
• forest/peat type catchment	25 – 40	35	[%]
• pasture type catchment	25 – 40	30	[%]
• cultivated type catchment	30 – 50	45	[%]

2.2.2 Lake recipient

The lake model is composed of lake water, surface sediment and buried sediment boxes. The key parameters, which are believed to affect mostly when considering the carry-over and transfer of radionuclides in a lake ecosystem, are accounted for. These parameters are: water exchange rate vs. water volume, sedimentation and resuspension rates. Suspended sediment load in water affects sedimentation rate values. The lake model parameters and representative range of values are given in Table II.

The lake environment in a broader deposition area can be described by three lake size classes: e.g. 1 km^2, 100 km^2 and 1000 km^2 lakes. Additionally, the nutrient content between various lakes changes and this can be taken into account in the model by applying different nutrient levels: low of nutrients, “normal” and high of nutrients. As a result, the model forms a family of lakes with various dilution factors and nutrient levels.

Table II *Lake model parameters.*

Parameter	Representative range of values	Default	Unit
Area Default classes: • 1 km^2 • 100 km^2 • 1000 km^2	Fraction specified by user [%] “ “		
Depth (mean)	1 – 100	2.5	[m]
Volume	$1\cdot 10^6 - 1\cdot 10^{11}$		[m^3]
Water exchange rate	0.1 – 10	2	[1/year]
Suspended sediment load	$5\cdot 10^{-4} - 1\cdot 10^{-2}$	$1.5\cdot 10^{-3}$	[$kg_s/m^3{}_w$]
Sedimentation rate	0.01 – 1	0.5	[kg_s/m^2/year]
Resuspension rate	0.001 – 0.1	0.05	[kg_s/m^2/year]
Density of solid material in sediments		2600	[$kg_s/m^3{}_s$]
Porosity of sediments	70 – 95	75 and 90	[%]

2.2.3 Fish chain

The fish chain model describes plankton – non-predatory fish – intermediate fish – predatory fish food chain. Plankton, non-predatory fish and predatory fish populations sizes in a lake recipient depend on each other. In the model these population components are harmonized so that the consumption rates corresponds to the real situation in lake. The concentration factor values between different components depend on the nutrient content of the lake ecosystem. In case that content of nutrients of lake system decreases the concentrations in fish seem to increase. The biological half-live ($T_{½,b}$) characterizes decrease or increase rate of radionuclide concentration in certain fish spices. From the point of view of modelling, application of seasonality weighted and averaged biological half-lives give relatively good predictions for temporal concentrations in non-predatory fish, intermediate fish and in predatory fish. Important parameters of the fish chain model are presented below (Table III).

Table III *Fish chain model parameters.*

Parameter	**Representative range**	**Default**	**Unit**
Plankton eaten by non-predatory fish	$1 \cdot 10^{-4} – 1 \cdot 10^{-2}$	$1 \cdot 10^{-3}$	$[kg_{d.w.\ plankton}/d]/[kg_{f.w.\ fish}]$
Non-predatory fish eaten by			
• intermediate fish	0.2 – 3	1.0	[kg/year]/[kg]
• predatory fish	0.5 – 5	2.0	[kg/year]/[kg]
Intermediate fish eaten by			
• predatory fish	0.1 – 1.0	0.5	[kg/year]/[kg]
Biological half-lives of nuclides in			
• non-predatory fish	50 – 200	150	[d]
• intermediate fish	150 – 400	250	[d]
• predatory fish	250 – 800	300	[d]
Fish population in lake	Lake specific value [kg]		
Nutrient content classification of lake water			
• low (oligotrophic)	Fraction specified by user [%]		
• “normal” (mesotrophic)	“		
• high (eutrophic)	“		

2.3 A sample outcome of the kernel module

The kernel module forms the basis for the areal calculation model. In order to show the relevant input data (Table IV) and main results, an example case calculation was carried through. Typical outcome of the kernel module are the temporal concentrations of various calculated components (Fig 3.) of the simulated environment.

Table IV *Some key parameters of the transport model.*

Parameter	**Default example value**[1)]
Catchment area submodel	
Sorption data of nuclides (K_d-value, Cs)	1000 $(Bq/kg_s)/(Bq/litre)$
Erosion rate	0.3 $kg_s/m^2/year$
Porosity	35 %
Infiltration rate	35 mm/year
Lake submodel	
Area	1 km^2
Depth	2.5 m
Exchange rate of water	2 1/year
Sedimentation rate	1 $kg_s/m^2/year$
Porosity of sediment	75 %
Fish chain submodel	
Biological half-lives ($T_{½,b}$) of nuclides in	
• non-predatory fish	150 d
• intermediate fish	250 d
• predatory fish	300 d
Nutrient content of lake water	
• low	
• normal	
• high	

1) Presented for illustrative purposes only in this connection.

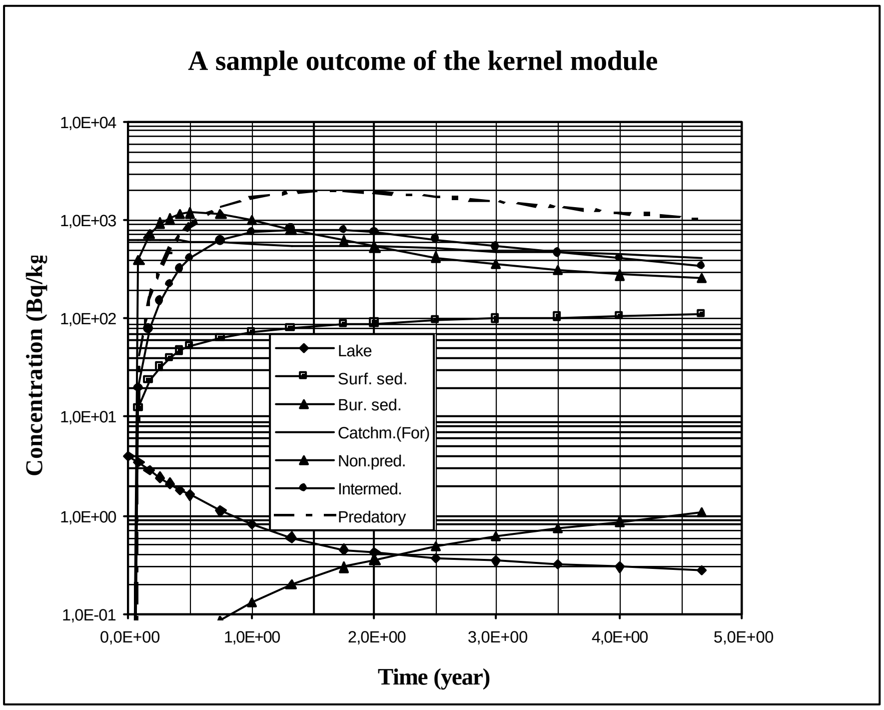

Fig 3. *Concentration results for a calculation case.*

[Specific data of this case: $A_{LAKE}/A_{CATCHMENT AREA}$ =1/3
Deposition 10 kBq(Cs-137)/m^2
Water exchange rate 2 times per year]

3 Areal consequence model

3.1 Combination strategy of various lakes in areally specified grid

The areal consequence model utilizes the unit model structures of the earlier specified three lake size classes. The basic precondition is that in a certain areal square (e.g. 40 km*40 km) the deposition intensity of radionuclides can assumed to be homogenized with sufficient accuracy. In consideration of the radioactive plume trajectory the general principle of the presentation of the occurence density of lakes is given in Fig 4.

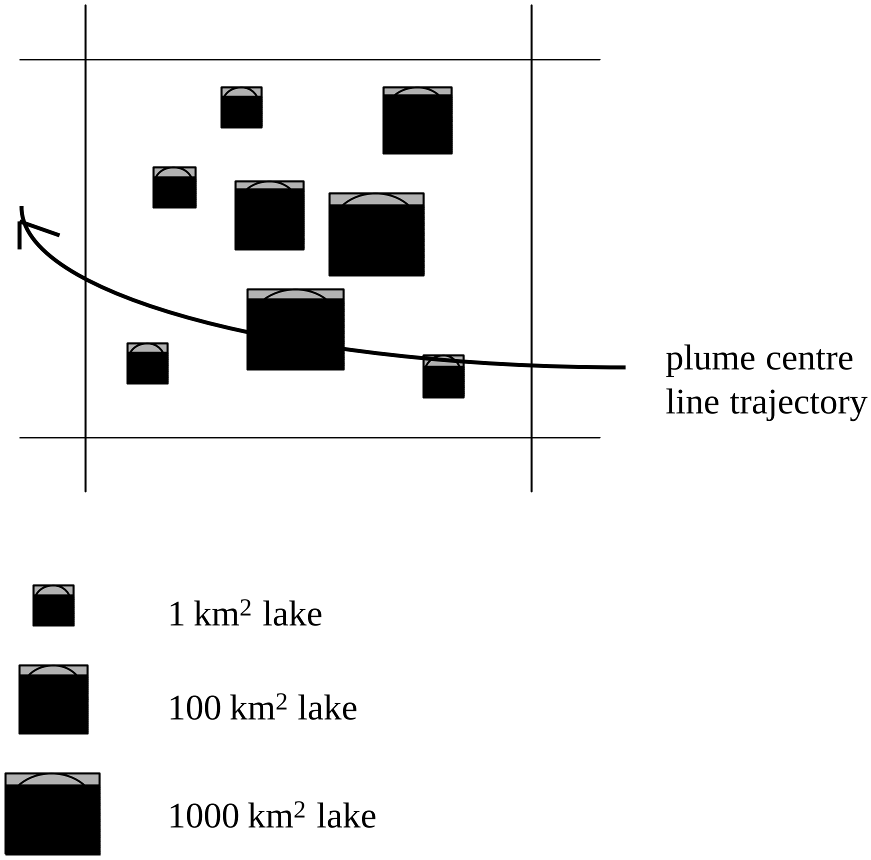

Fig 4. *Principle of occurence density formation of lakes in an areal grid.*

The occurence density of different lake size classes in a certain grid square can be specified by the model user or it could be read directly from a data base of RODOS if necessary data is available.

For a more detailed specification of the areal aquatic consequence assessment the user have to give some additional data of characteristic features of the lakes considered. Fig. 5 presents an “event tree” where the user gives relative fractions of different features for the lakes.

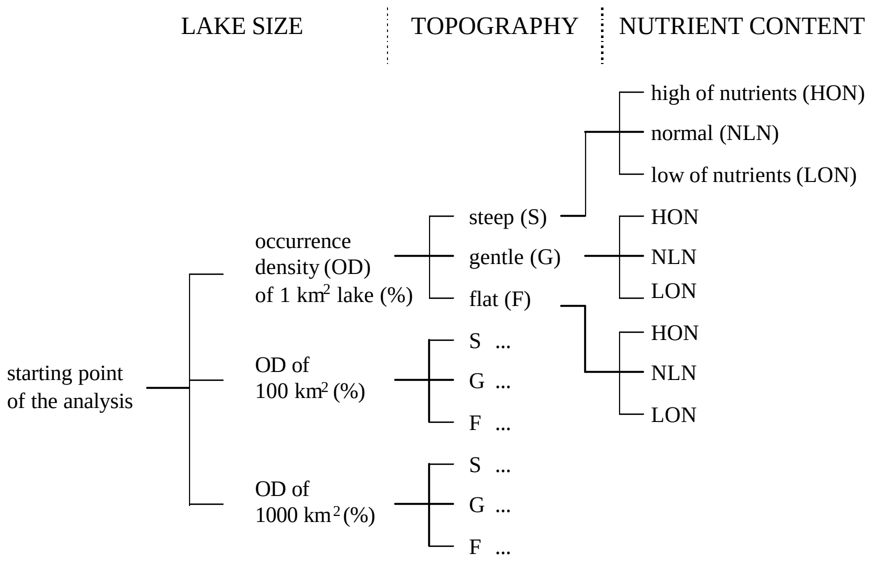

Fig 5. *Principle of the user interface system of areal model input data initialization.*

Altogether there exist many possible combinations for a single grid square specification: lake area (3 classes) * topography of catchment (3 classes) * nutrient content of lake (3 classes). This type of modelling approach should predict the arising aquatic consequences by a quite reliable way, and gives at least a good estimation of the early effects.

3.2 Consequence assessment methodology

The primary results of the model are radionuclide concentrations in water, in sediments, in catchment and in fish. A general formula to calculate these results for a specified time point is given in eq. (6).

$$\overline{C}(t)_{areal} = \frac{\sum_{si}\sum_{to}\sum_{nc} n_{si,to,nc} \cdot C(t)_{si,to,nc}}{n_{tot}} \qquad (6)$$

where

$C(t)_{si,to,nc}$ is temporal concentration of a specific component (Bq/kg)

$\overline{C}(t)_{areal}$ is areal averaged concentration of a specific component in a grid square (Bq/kg)

$n_{si,to,nc}$	is number of a specific component of different options of the event tree
n_{tot}	is total number of a specific component in a grid square.

The time-integrated consequences can be calculated by the following way

$$\bar{I}_c = \int \overline{C}(t)dt \tag{7}$$

where

$\bar{I}_c$	is the time-integrated averaged concentration of a component in a grid square (Bq·a/kg).

From the time-integrated values the doses can be calculated by applying consumption rates and radionuclide specific dose factors.

The areal consequence results can then be presented on map background. One possibility is to shade the grid squares by illustrative way. Certain color in a square refers to a specified concentration bounds of lake water or fish. Fig. 6 shows the principle of such presentation method.

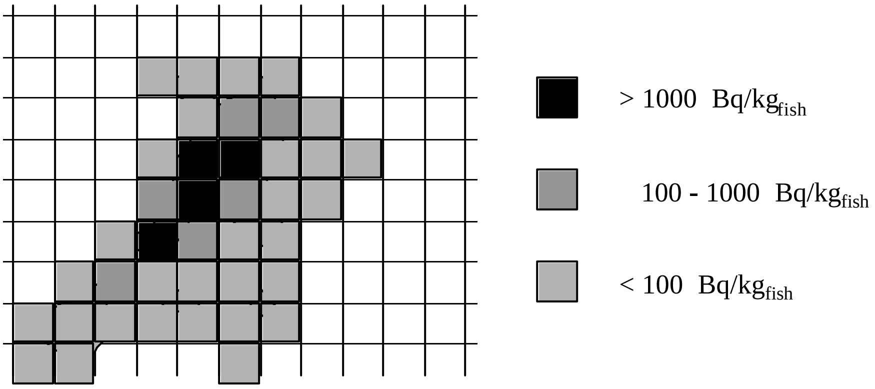

Fig 6. *Areal consequence results: activity concentration of Cs-137 in fish at certain time point after deposition (example).*

3.3 Principle of the user interface under RODOS-system

Implementation of the prototype module of the areal consequence model under RODOS user interface system needs certain operations to be performed. The input data initialization procedure and the output values have to be defined. As considering an areal deposition event and the consequence model, there are some vital input data which should be available for the calculation model. This data can be produced by the user, or it could be automatically taken from data base. The data is needed when specifying eg. the areal lake size distribution, catchments, mean depths of lakes, nutrient contents of lakes and local topographies. In the first version of the developed module the input data will not be fully available automatically from the data bases. Looking at the future, automatic input data pick up procedure could be possible.

A successful simulation of the areal consequence model needs at least next important specifications: lake size classification, topography and nutrient level, as indicated earlier in the “event tree” of Fig. 5. A more detailed list of relevant input data is gathered in Table V.

After definition of input parameters, the module is able to start simulation. Consequences of all combinations of lakes are calculated through. This calculation procedure is then repeated for every single considered square of the grid. After, or during simulation, the output data can be demonstrated by applying eg. presentation tools which are available in the RODOS system.

Table V *List of specified parameters of the areal lake model in RODOS user interface system.*

Parameters to be defined in every square of grid
• total deposition of nuclide i [Bq/m^2]
• lake size classification (3 classes) [%]
• catchment areas for lakes (3 classes) [m^2]
• water exchange rates of lakes (3 classes) [1/year]
• sedimentation rates of lakes (3 classes) [kg$_s$/m^2/year]
• topography (3 classes) [%]
• nutrient contents level classes (3 classes: low, “normal”, high) [%]
• biological half-lives of fish types (half-lives for 3 fish types) [d]

4 Data acquisition and model validation

The model validation work will be done in collaboration with Radiation and Nuclear Safety Authority (STUK) in Finland. STUK has gathered a representative set of lake data *(Saxén et.al., 1997)* to be utilized in the validation work of the areal lake model. The model validation will consists of calculation cases by applying different types of lake data which have been collected after the Chernobyl reactor accident.

The validation will confirm the applied modelling methodology and parameter value selections. This is important, because of the relative broad spectrum of different type lake ecosystems. The selected set of lakes sufficiently covers the expected changes in lake size, topography or nutrient content.

5 Summary

The report gives the outline and principle of the developed areal lake consequence model. The main parameters to be considered in forming the consequence environment are: occurence density of lakes, topography of catchments and nutrient contents of lakes.

Various lakes under the deposition area are classified in size classes in order to realistically describe the dilution environment. The steepness of catchment affect the runoff rate and erosion rate from the catchment to lake recipient. Therefore, different topography options are available in input specifications of the model. The nutrient contents of lake water affect the concentrations which will be obtained in different fish types in short and long term after deposition. This nutrient dependent concentration mechanism is controlled in the model by classification of lakes for low, “normal” or high levels of nutrients. By combination of all relevant input data, the model forms a family of lakes which are utilised in simulation of areal consequences.

Data aquisition and model validation work is also a necessary and important part of the work. A set of representative lake data is available and model comparison against this data can be performed. Affiliation of the model to RODOS user interface will clarify the final characteristics of the areal consequence model.

References

Saxén R., Alatalo M. and Koskelainen U., Description of lakes and their catchments selected for model development and model validation, 1997, RODOS(WG4)-TN(99).

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