The real-time on-line modelling of the dispersion of radionuclides in the aquatic environment after accidental releases

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Abstract: - The Hydrological Dispersion Module (HDM) of the RODOS (real-time on-line decision support) system for nuclear emergency management in Europe has been is developed at IMMSP, Kiev, Ukraine; NRG, The Netherlands; FZK, Karlsruhe, Germany; SPA "TYPHOON", Obninsk, Russia; IPEP, Minsk, Belorussia, and NCSR "Demokritos", Athens, Greece. Initial testing and customisation work was performed by NPPRI, Slovakia. The hydrological model chain of RODOS was outlined covering processes, such as runoff of radionuclides from watersheds following deposition from the atmosphere (RETRACE), transport of radionuclides in river systems (1-D model RIVTOX) and the radionuclide behaviour in lakes, reservoirs and estuaries (the radioecological box model LAKECO, the 2-D model COASTOX, and the 3-D model THREETOX). The main results of the HDM are simulated concentrations of radionuclides in water following the atmospheric fallout. HDM provides also the supplementary possibility to simulate radionuclides transport in aquatic systems following a direct release of radioactive material into water. The output from the HDM is transferred into the aquatic food chain and dose model FDMA (part of RODOS) to assess the main exposure pathways. The various hydrological models of HDM have to be adapted during the RODOS implementation phase taking into account the specific properties of the hydrological network in the area of implementation.

Key-Words: - Hydrological dispersion models, radionuclides, lakes, reservoirs, estuaries, runoff, Chernobyl

1 Introduction

The evaluation of the radiological consequences of accidental releases of radionuclides from various sites demonstrated a significant contribution from contaminated waterbodies to the dose of the population. This was clearly shown, e.g., for the Clinch River-Tennessee River basin - releases from Oak Ridge, for the Techa River / Ob River watershed - releases from "Mayak", and for the Dnieper River basin, and for the population in the vicinity of Scandinavian lakes - Chernobyl accident. The remobilisation of dry and wet deposited material by long term floods and heavy rain events, and the resuspension of sediments during storm events resulted in the migration of radionuclides and affected also uncontaminated agricultural areas together with drinking water supplies downstream from the source of the initial contamination. Additionally, the remobilisation of radionuclides stored in the bottom sediments of lakes and reservoirs caused a delayed transfer of activity to the aquatic environment.

Following the Chernobyl accident, the development of the Hydrological Dispersion Module (HDM) inside the RODOS –(real-time on-line decision support) system for nuclear emergency management in Europe [1] has been started [2-6]. The work on model development and customisation is sponsored by the Commission of the European Communities within its Radiation Protection Research Programme. The HDM was developed within the Working Group 4 of the RODOS project by NRG, The Netherlands; FZK, Karlsruhe, Germany; IMMSP, Kiev, Ukraine; SPA "TYPHOON", Obninsk, Russia; IPEP, Minsk, Belarus; and NCSR "Demokritos", Athens, Greece. Initial testing and customisation work was performed by NPPRI, Slovakia. The software framework of the whole RODOS system is being developed at the Forschungszentrum Karlsruhe (FZK/IKET), which acts as the coordinator in the CEC research programme. Since 2001 the RODOS implementation in East- and West-European countries has started as part of national programs of nuclear emergency preparedness and response.

2 THE HYDROLOGICAL MODELS OF RODOS HDM

In this section the important processes are briefly described, and an overview of the hydrological models as been used in the decision support RODOS are outlined.

2.1 Characterisation of the key transport, dispersion and exchange processes

Transport, diffusion and exchange processes are different in different waterbodies. Therefore, one has to consider separately three areas: surface runoff, transport in rivers, and behaviour of radionuclides in lakes or reservoirs. Furthermore it is reasonable to subdivide the physical dependencies into a pure hydrological part, e.g. water - and particulate transport, and into a radio-chemical part (e.g. exchange processes between the individual phases such as radionuclides bound on particles against radionuclides in solution). The basic approach of the RODOS model development is to present to the users the possibility to simulate both water and sediment transport and radionuclide transport for different water bodies and in different temporal and spatial scale of resolution.

Specific for radionuclide transport models - in comparison with other water contamination models - are the physical- chemical exchange processes in the system "water - suspended sediments - bottom depositions"[7, 8].

Mathematical models describing sorption of metals on homogeneous solid surfaces, which are primarily metal hydroxides and reference clay minerals, are based on surface complexation and ion-exchange theories. However, the traditional approach in describing and predicting the fate of radionuclides on heterogeneous solids such as soil, suspended and bottom sediments is mainly empirical and is still based on the use of the parametrisation of simplified adsorption- sorption kinetics and the use of the equilibrium distribution coefficients $Kd = Cs/C$, - where Cs is the amount of contaminant sorbed by sediments in equilibrium, and C is the amount of contaminant left in solution in equilibrium.

The distribution coefficient Kd, which is dependent on liquid and solid phase characteristics, is the integrated result of various physical-chemical processes controlling the retention of the radionuclides. This approach assumes complete sorption equilibrium, which is seldom the case under natural condition. The data from laboratory experiments and field measurements indicate that sorption of radionuclides by clay minerals, soil and sediments depends on the nature of the clay minerals and is a kinetically controlled process, which may continue over time scales up to several years. A kinetic approach of the sorption phenomena is therefore necessary for various reasons. Thus for realistic modelling of the vertical transport of radionuclides and heavy metals in soil, bottom deposition and in the aquatic environment, knowledge is needed not only about the sorption equilibrium, but also about the sorption kinetics. There is no unified mathematical description of the sorption process governing the behaviour of metals and particulate radionuclides. Further detailed study of the sorption kinetics of radionuclides will allow examining the existing concepts in terms of a more fundamental description of the underlying processes.

In general, models of radionuclide transport in rivers/reservoirs do not include the above-mentioned kinetics in their complete details. However, a reasonable level of model complexity which may reflect the main features of the exchange processes (radionuclides transfer in the system "water - suspended sediments - bottom depositions" - transition from a non-equilibrium to an equilibrium state, different Kd values for bottom deposition and suspended sediments, different rates of sorption and desorption) seems to be represented by a "Kd - exchange rates" approach which is used in many contemporary models, as can be found in [7, 8]. This approach could be also expanded to a more complicated two-step kinetics model, describing the ^{137}Cs transfer between exchangeable and non-exchangeable forms (e.g., [9]). Therefore, the "Kd - exchange rates" approach was used in most of the hydrological models of RODOS-HDM.

2.2 Model chain of HDM

RODOS-HDM consists of a number of state-of-the-art hydrological dispersion models for the various types of aquatic systems for predicting both the short- and the long-term dispersion of radionuclides in the aquatic environment.

The watershed model RETRACE [2,5] provides in different temporal and spatial scales the rates of water, sediment and radionuclide inflow into a river channel network, lakes and reservoirs within the considered watershed. The calculations are based on information of the deposited radionuclides and meteorological data (precipitation rate, temperature) provided by the atmospherical dispersion module ADM of the RODOS system. The temporally distributed data on lateral water inflow and radionuclide concentration are calculated for the nodes of grids created on the graphs of the river network, coastlines of large lakes and reservoirs or in the separate nodes representing small lakes.

The one-dimensional river model RIVTOX [2, 3, 10] simulates the cross-sectionally-averaged radionuclide concentration in water, suspended sediments and bottom deposition in the nodes of a river channel network. Two distinct variants of the hydraulics module are available: one model variant to calculate the water discharge and elevation in a simplified river net (RIVTOX-HD), and a variant for the enhanced modelling of the hydrology taking into account sluices and dams in the river system (RIVTOX-HSV). RIVTOX uses either output of RETRACE to simulate the transport of radionuclides after wash-off from watersheds or can consider direct releases to the water for the simulation of radionuclide transport from point sources. A specific procedure is used for the interpolation of the RIVTOX results – which are on a river grid - to the input grid of the RODOS dose module FDMA. The coupled subsystem RETRACE-RIVTOX has been validated for the Rhine River basin (Fig.1) and the Iliya River – Chernobyl zone [2,5]. RIVTOX was validated also on the basis of the data for Dnieper River, Clinch River- Tennessee River and the Vah –Dudvah river system in Slovakia [3, 10].

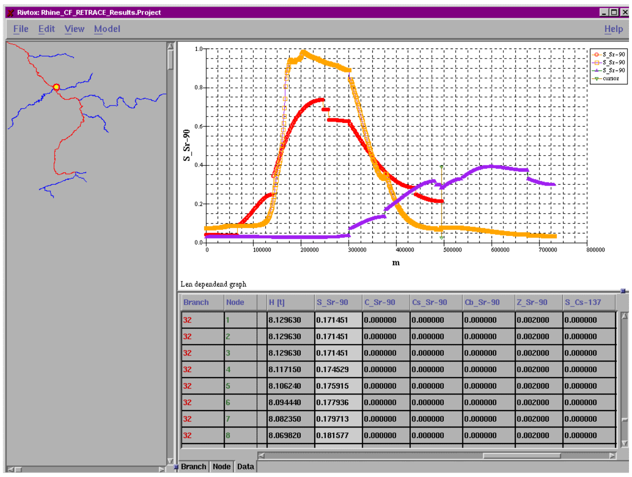

Fig. 1: RIVTOX implementation for the Rhine River basin

The two-dimensional model COASTOX [2, 4, 10] simulates the depth-averaged concentration of radionuclides in the nodes of a rectangular grid that covers waterbodies, which can be a part of a river in the vicinity of the point source, or a large shallow lake or reservoir. Simulated time-dependent concentrations can be interpolated to the nodes of the RODOS dose grid or used after a cross-sectional integration as input for RIVTOX for further propagation in the downstream river flow. COASTOX was applied to simulate the efficiency of hydrological countermeasures on the floodplain of the Pripyat River and for the simulation of radionuclide transport in the Kiev Reservoir [2, 4, 10].

One important step in the validation of COASTOX was the simulation of the dispersion of ^{137}Cs in the Kralova Reservoir, and in the Vah River, Slovakia, following an accidental release in June 1989 from the Bohunice NPP into the Dudvah River, a small tributary of the Vah River [10]. The simulation performed by COASTOX demonstrates that the dominant process in contamination of the reservoir bottom is the settling of contaminated sediments. The calculations revealed, that the highest concentration of ^{137}Cs should be expected in the central part of the reservoir, in a location where intensive sedimentation, downstream of a steep bottom slope, takes place (Fig.2). This prediction was later confirmed by field monitoring [10]. The maximum ^{137}Cs concentrations in the reservoir - about 35-45 Bq/kg in the top sediment layer and about 60-80 Bq/kg in the deeper sediment layer- were measured in the same location as predicted by the COASTOX model, which gave a value of about 76 Bq/kg (Fig.2).

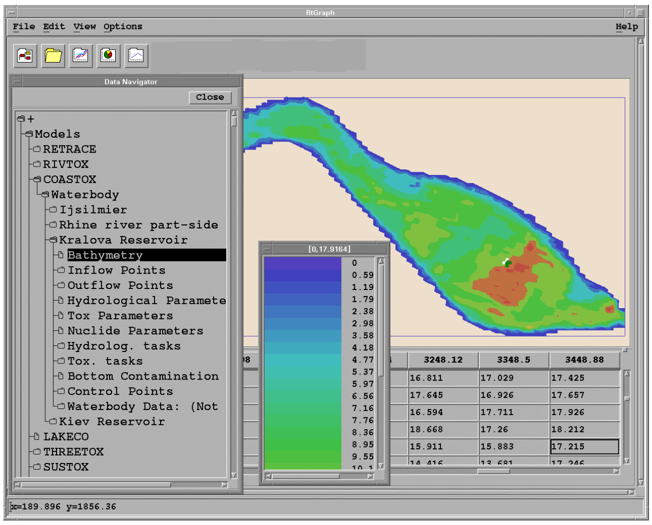

Fig.2: COASTOX implementation for the Kralova Reservoir, (part of the Vah River): simulated concentration of ^{137}Cs in upper layer of the bottom sediments (Bq/kg) after the dispersion of radioactivity after the accidental release in June 1989.

The three dimensional model THREETOX [2,7] simulates the radionuclide concentration in the nodes of a 3-D grid constructed within deep lakes and other stratified water bodies – estuaries, cooling ponds of nuclear power plants, and marine or coastal areas. The time-dependent 3-D results are either used to be interpolated to the grid of the dose module FDMA, or can be - in the case of a river outflow from a lake/reservoir - the basis for a boundary condition for RIVTOX. The model has been validated within studies of radionuclide dispersion in Lake Bodensee (Rhine River Basin, Fig.3), Dnieper-Bug Estuary (Ukraine) and Cooling Pond of the Chernobyl Nuclear Power Plant [11]. THREETOX is used in combination with the marine box-model of RODOS – POSEIDON [12] to improve the transfer coefficients between the coastal boxes of POSEIDON.

A further lake model in the HDM, the radioecological box model LAKECO calculates the radionuclide concentration in the biotic and abiotic compartments of the water body [6]. Temporal dynamic of the lake-averaged concentrations of radionuclide in waters, suspended sediment, phytoplankton, fishes and other components of the aquatic foodchain is simulated and data are transferred into the nearest node of the grid of the dose module FDMA. LAKECO was tested and validated within various international working groups. Within the IAEA/CEC VAMP-project the lake model was successfully applied to a wide range of lake ecosystems in Europe, different in terms of trophic status, climatology, deposition of radionuclides, and morphology. LAKECO participated in a blind test within the model validation benchmark “BIOMOVS II”, where a Chernobyl Cooling Pond Scenario was outlined as blind test. As tuning of the model was impossible, this study could be considered as a quality test. It showed that the original LAKECO model, with a relatively great number of parameters, most of them assessed on the basis of expert judgement, was not able to predict the concentration in the aquatic system with the required accuracy. The enhanced model LAKECO-B showed better results, which proved the increase of predictive power after the implementation of the new sub-models.

The models RETRACE, RIVTOX, COASTOX, THREETOX and LAKECO establish the main model set of the RODOS HDM. These models are integrated in the HDM interface and cover the main part of required functionality of HDM. However within the 4th Framework Project another set of the modelling tools were developed for special applications [2]. These models were not integrated in the HDM interface, however they can be used as “stand-alone” versions for specific cases of the HDM implantation

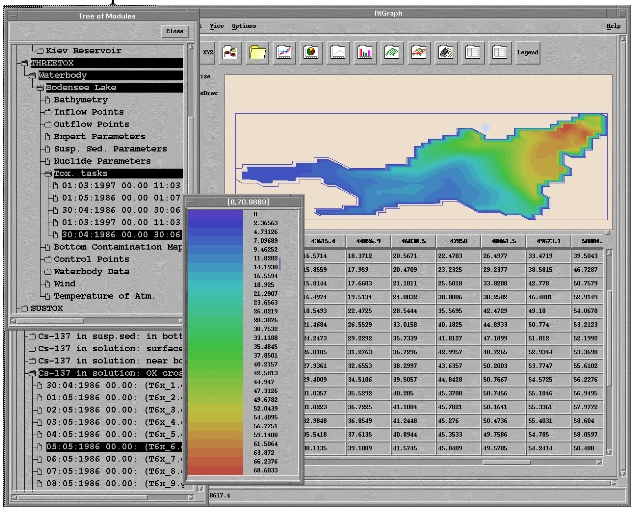

Fig.3: Implementation of THREETOX: simulation of ^{137}Cs dispersion in the lake Bodensee after the Chernobyl accident, overview of the THREETOX interface

The one-and-a-half dimension model LATOX simulates the radionuclide concentration averaged over vertical cross-sections of deep stratified lakes in a 1-D temporally variable grid. A special module of LATOX, parametrising the hydrodynamical processes in the lake provides a simulation of stratified lakes only on the basis of standard meteorological information without involvement of special input data on lake hydro-thermodynamics. The SUSTOX code, including 1D-, 2D-, and 3D-models, is used to calculate the radionuclide concentration from the unsaturated root zone up to the groundwater. Taking into account the rather low dose significance of groundwater pathways but the high interest of the public, the model results might be useful to estimate the efficiency of special late protective countermeasures for groundwater and to simulate the radionuclide flux from groundwater into the river net. Another model, GROWTOX, calculates 1-D or 2-D fields of cross-section- or layer-averaged concentrations of radionuclides in groundwater. GROWTOX is useful to estimate radionuclide transport in groundwater on a large scale. To allow a detailed view on the sedimentation and remobilisation processes within a smaller part of a river or reservoir, IPEP, Belarus had developed the RIVMORPH 2-D river model. This code can be also used for example to assess the efficiency of bottom traps in rivers. The infiltration model VADZONE, to describe the fast transfer of radionuclides in the initial phase after the accident from soil surface to the shallow groundwater, is under development by SPA "TYPHOON". This allows a first assessment if the shallow groundwater might be contaminated via transport through macropores (e.g. dead roots or rain worm holes) - a process which is much faster than the flux through the ordinary soil matrix.

3 HDM INTERFACE

As the hydrological chain will be an integrated part of the RODOS System, a user-friendly graphical interface has been developed to operate the individual models inside the hydrological module. The interface provides the possibility of easily accessing all the information necessary to run the individual models as well as displaying the results in a way decision makers can handle them. The interface allows:

- to input and to edit data and parameters through a system of user configured dialogues and input windows;
- to run models separately or simultaneously with the possibility of exchanging data between individual models via shared memory;
- to manage the database and to create predefined scenarios;
- to present data base information and on-line results of the simulations in graphs and maps (e.g. contamination);
- to receive data from and transfer data to other RODOS modules (e.g. read results of atmospheric dispersion, forward concentrations to the foodchain module).
- to operate individual models via the upper level HDM interface.

Some examples of the graphical user interfaces of main models are presented in Fig.1-3.

Further enhancement of the HDM will include the connection to the marine environment with the integration of the POSEIDON module [12]. In parallel, data assimilation tools will be integrated to allow for the correction of the calculated concentrations based on measurements. With the fully integrated hydrological model chain, it will be possible to describe radionuclide behaviour for releases all over Europe

4 Conclusion

A unique set of hydrological dispersion models (HDM) for real-time modelling of the consequences of accidental releases has been developed for the decision support system for nuclear emergencies RODOS. All possible transfers in the aquatic environment, from run-off to lakes and coastal areas were taken into account by the models of RODOS-HDM. The coupling of the different state-of-the-art hydrological models to the other modules of the RODOS system, such as the dose models and atmospherical dispersion models, and the application of user-friendly interface for data handling and presentation of the results, enables the user to evaluate the consequences of accidents with nuclear installations in a complete and enhanced matter.

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