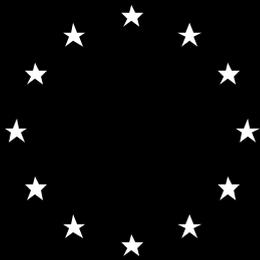


---

**RIVTOX - one dimensional model for the  
simulation of the transport of radionuclides  
in a network of river channels**

---



**RODOS**  
REPORT

DECISION SUPPORT FOR NUCLEAR EMERGENCIES

RODOS-WG4-TN(97)05

# **RIVTOX - one dimensional model for the simulation of the transport of radionuclides in a network of river channels**

RODOS-WG4-TN(97)05

---

**M.Zheleznyak, G.Donchytz, V.Hygynyak, A.Marinetz,  
G.Lyashenko, P.Tkalich**

Institute of Mathematical Machines and System Problems (IMMSP)

Prospect Glushkova 42, Kiev, 03187, Ukraine

Email: mark@immsp.kiev.ua

first draft version – June, 1998, revised – July, 2000

## **Management Summary**

The one-dimensional model RIVTOX, developed at IMMSP, Cybernetics Centre, Kiev, simulates the radionuclide transport in networks of river channels. The sources of radionuclide can be a direct release into a river or the runoff from a catchment. In the latter case, the output from RETRACE-2 is used as the input of RIVTOX. The stream functions, the concentrations of suspended sediment and radionuclide are averaged over a cross-section of a river. A 'diffusion wave' model, derived from the one-dimensional Saint-Venant's equation, describes the water discharge. An advection-diffusion equation simulates the transport of the suspended sediments in the river channel. Its sink/source terms describe the rate of sedimentation and resuspension as a function of the difference between the actual and equilibrium concentration of suspended matter with respect to the transport capacity of the flow. The latter is calculated on the basis of semi-empirical relations. The dynamics of the upper contaminated river bed is driven by the equation for the erosion of the bottom layer.

The radionuclide transport submodel of RIVTOX describes the dynamics of the cross-sectionally averaged concentrations of activity in solution, in suspended sediments and in bottom depositions.

The report presents the model, numerical methods and some of the validation studies results.

---

## Contents

<b>1</b>	<b>Overview of the modelling approaches.....</b>	<b>3</b>
1.1	<i>Modelling of radionuclide transport in rivers.....</i>	3
1.2	<i>Modelling of 1-D river hydrodynamics and sediment transport.....</i>	7
<b>2</b>	<b>Submodels .....</b>	<b>10</b>
2.1	<i>Submodel of river hydraulics .....</i>	10
2.2	<i>Sediment transport submodel.....</i>	13
2.3	<i>Submodel of radionuclide transport .....</i>	18
<b>3</b>	<b>Boundary and initial conditions in river network .....</b>	<b>20</b>
3.1	<i>River network .....</i>	20
3.2	<i>Boundary condition and initial conditions .....</i>	20
<b>4</b>	<b>Numerical solution.....</b>	<b>22</b>
<b>5</b>	<b>RIVTOX Input and Output Data.....</b>	<b>23</b>
<b>6</b>	<b>Model testing and validation studies .....</b>	<b>25</b>
6.1	<i>Numerical methods testing on the basis of the analytical solutions .....</i>	25
6.2	<i>Validation studies for the Rhine River watershed.....</i>	26
6.2.1	<i>High flood at Christmas 1993.....</i>	26
6.2.2	<i>Chernobyl radionuclides in the Rhine tributaries .....</i>	28
6.3	<i>VAMP validation study (Clinch-Tennessee and Dnieper).....</i>	29
6.4	<i>RETRACE - RIVTOX chain validation on the base of Ilya River case study .....</i>	34
6.5	<i>RIVTOX implementation for the simulation of consequences of an accidental release from the Kharkov sewage system (summer 1995) .....</i>	37
6.6	<i>Accidental releases from Bohunice NPP to Dudvakh River-Vakh River .....</i>	38
	<b>Document History .....</b>	<b>48</b>

## List of Figures

Figure 1: Flow diagram of the key-processes of the radionuclide transport in rivers	5
Figure 3: River stream parameters	11
Figure 4: River stream scheme	20
Figure 5: Comparison of numeric and analytic solutions for diffusive wave. (1 - Initial conditions; 2- Analytic solution, $t=9600$ sec; 3- Numeric solution, $Cr=1$ ; 4- Numeric solution, $Cr=0.5$ )	26
Figure 7: Simulation results of the combined RIVTOX and RETRACE model for the flood event of the River Rhine in 1993. Comparison of predicted and measured discharge data for Andemach and Maxau.	27
Figure 8: Comparison of the simulated by RIVTOX and measured discharges for 4 sites at the River Rhine for December 1993 flood.	27
Figure 9: Simulation of Cs-137 concentration in the Mosel River	28
Figure 11: Simulation of $^{137}\text{Cs}$ concentration in the Neckar River.	29
Figure 13: Simulation for the Clinch river	29
Figure 15: Concentration of Cs-137 in Kiev reservoir	30
Figure 11: Concentration of Sr-90 in Kiev reservoir	31
Figure 12: Concentration of Cs-137 in Kremenchug reservoir	31
Figure 13: Concentration of Sr-90 in Kremenchug reservoir	32
Figure 14: Concentration of Cs-137 in Dnieper reservoir	32
Figure 21: Concentration of Sr-90 in Dnieper reservoir	33
Figure 16: Ilya river basin	34
Figure 18: Meteorological and hydrological data for the Ilya river basin	35
Figure 20: Measured (2) and simulated (1) hydrograph in outlet of Ilya river.	36
Figure 22: Cs-137 in surface runoff; daily averaged concentration in runoff from the Ilya River catchment (simulation by RETRACE)	36
Figure 24: RIVTOX Simulation of $^{137}\text{Cs}$ concentration on suspended sediment at the outflow from the Ilya River	37
Figure 26: RIVTOX implementation for prognosis and decision support on the case of accident at Kharkiv sewerage	38

# 1 Overview of the modelling approaches

## 1.1 Modelling of radionuclide transport in rivers

The one-dimensional model RIVTOX was developed at IPMMS, Cybernetics Centre, Kiev, Ukraine to solve water contamination/use problems of Ukrainian rivers after the Chernobyl accident (Zheleznyk et al., 1992, Tkalich et al. 1994). The radionuclide transport part of the model is similar to the TODAM model (Onishi, 1982), however simplifications have been done to receive practically applicable model with not too much set of the input data. On the other hand, nowadays RIVTOX includes the more detailed description of the adsorption-desorption processes (e.g. non equal rates of the desorption and adsorption, different  $K_d$  for bottom sediments and suspended sediments) that was included into the model on the basis of validation on Chernobyl data. RIVTOX was validated for the Clinch River the Tennessee river in the frame of IAEA VAMP program (Zheleznyak et al. 1995) and for the Dudvah River-the Vah River that is the Danube tributary (Slavik et al., 1997). During last study the possibility of the use in the RIVTOX two-step kinetics has been analysed.

The studies of the environmental impact of radionuclide releases demonstrate that after the initial atmospheric fallout, the large river systems are the main pathways for radionuclide transport from the point of deposition to places which are hundreds of kilometres far away.

The modelling of the radionuclide dispersion in rivers has some peculiarities compared to the modelling of lakes. The radionuclide dispersion in rivers is affected by different flow velocities, short retention times, large variability in water discharge during the year and, as a result, strong temporal variations in sedimentation-resuspension rates. There are also channel and floodplain interactions during floods, strong impacts of the hydraulic structures on flow parameters, as well as rapid water level changes due to reservoir management. The simulation of these processes requires certain special approaches in radionuclide modelling. Some of these modelling methods have been reviewed in the early eighties (see e.g. IAEA Safety Series No.50-SG-S6, 1985; Codell et al., 1982; Onishi et al., 1981, Santschi and Honeyman 1989). The further development of the computer technology during the last decade and the urgent need to increase the predictability of models in order to provide adequate information for making decision concerning the remedial measures in the most contaminated water bodies after the Chernobyl accident has led to the intensive development of river modelling.

Mathematical models describing the radionuclide transport and dispersion in rivers and reservoirs can be classified according to two different approaches - (1) spatial averaging of the variables and (2) the

individual treatment of variables describing radionuclides in different physical-chemical forms.

Variables averaged over compartments represent the highest level of averaging and, as a result, are used in models of the lowest spatial dimension. These box-type (zero dimension) models treat the entire body of water (including the sediment layer, etc.) or a part of the entire body (e.g. one box for water and one for sediments) as a homogeneous compartment.

Cross-sectionally averaged variables are often used in the channel models and in the models for narrow reservoirs. This 1-D approach is used to simulate pollutant transport from the distances larger than tenths of river width downstream the point-source term ( i.e. after full mixing o contaminant over crossection) up to the hundreds of kilometres. The time scale for river 1-D models is from minutes up to tens of years (e.g. for long term sedimentation studies).

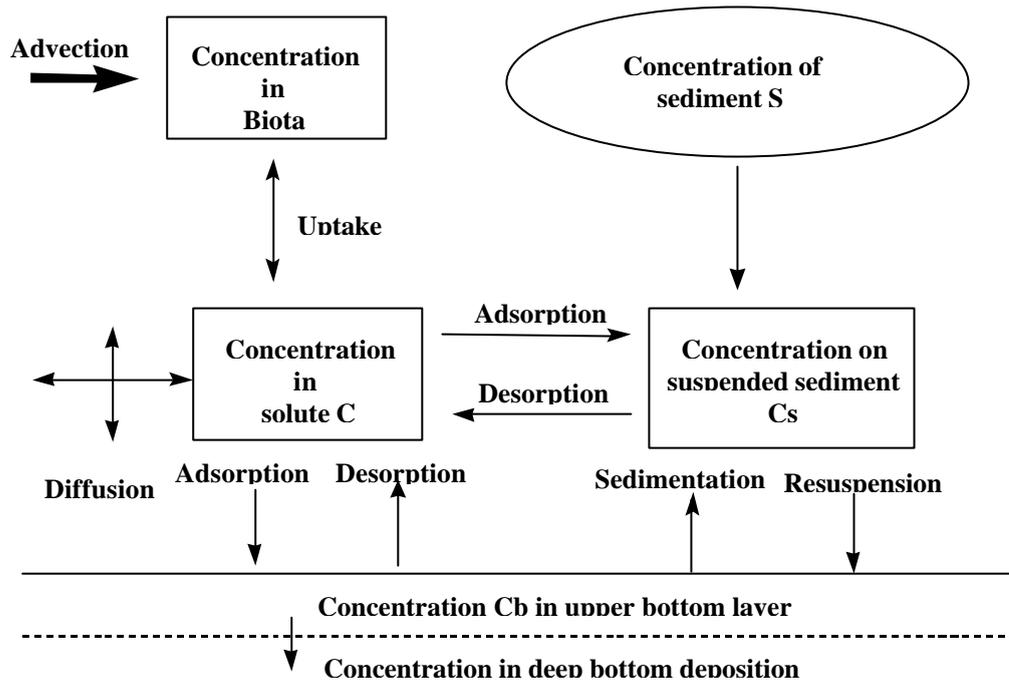
The Two dimensional (2-D) vertical models operate with width averaged variables. These models are used to describe a current, a suspended sediment and a radionuclide transport in case of a significant variability with respect to the channel depth.

Depth averaged variables are used in the lateral-longitudinal 2-D models which describe flow pattern and radionuclide dispersion in shallow reservoirs, parts of the river channels and flood plains.

The lowest level of averaging takes place in the 3-D models solving primitive or basic governing equations. The real spatial averaging scale of these models is based on the width of the computational grid but not on the a certain parameterization or averaging procedure.

The 1-D model (RIVTOX) was taken as the basic model in HDM to provide the radionuclide transport simulation in the river net in the short-term and the middle- term post accidental phase. The main processes governing the radionuclide transport in river systems are presented on the scheme of Figure 1. The pollutants in rivers are transported by the water flow (advection processes) with the simultaneous influence of the turbulent diffusion processes. The radionuclides can interact with the suspended sediments and bottom depositions. A pollutant transfer between the river water and the suspended sediment is described by the adsorption-desorption processes. The transfer between the river water and the upper layer of the bottom deposition is under the influence of adsorption-desorption and diffusion processes. The sedimentation of contaminated suspended sediments and the bottom erosion are also important pathway of the “water column-bottom” radionuclides exchange. Different types of river models describe these processes at different levels of parametrisation.

River models, independently of their spatial resolution, include two main submodels: hydraulic ones, describing water, suspended sediment and bottom dynamics and submodels concerning the fate of radionuclides in the different phases driven by these hydraulic processes.



**Figure 1: Flow diagram of the key-processes of the radionuclide transport in rivers**

The main physical exchange mechanisms are the sedimentation of the contaminated suspended matter into the river bed and the resuspension of the sediments into water. They are controlled by hydraulic factors (e.g., river flow, sediment transport), and strongly depend on the sediment size fractionation (e.g., clay, silt, sand and gravel). The Radionuclide diffusion through interstitial water is a process which accounts for migration phenomena not related to the sediment transport. Adsorption and desorption of a radionuclide by the surface bed sediment are the main chemical exchange processes. These processes are not always completely reversible and controlled by geochemical reactions of the dissolved radionuclides with the sediment. Uptake and subsequent excretion of radionuclides by aquatic biota and, in general, perturbation of sediments due to the action of living organisms represent biological processes which are responsible for the exchange of radionuclides between water and the bed sediment.

Modelling the fate of the radionuclides in all three different phases - radionuclides in solution, in suspension and deposited on sediments is very important. Such an approach of the simulation of radionuclide dispersion has been considered by Onishi et al. (1977, 1979, 1981, 1982) and Zheleznyak et al. (1990-1999) for one-, two- and three-dimensional models and by Booth (1975), Schückler et al. (1976), Monte (1992), Benes and Cernic (1990), and Hofer and Bayer (1993) for full-mixed box models.

The simplified approach of radionuclides-sediments interaction was used in models of White and Gloyna (1969), Shih and Gloyna (1970), CHNSED (Fields, 1976), HOTSSED (Fields, 1977).

For the simulation of radionuclide transport in several United States rivers, the one-dimensional channel model TODAM has been used (Onishi et al., 1982). The model describes radionuclide transport attached on three typical fractions of the suspended sediments - sand, silt and clay with the specific  $K_d$  values for each of them. The Radionuclide transport module is supported by the comprehensive suspended sediment transport module, that describes the transport of cohesive and non-cohesive sediments. TODAM does not include the river hydrodynamic module. It was used on the base of river hydrodynamics calculated by specific codes (DKWAV or HEC-2 or CHARIMA). TODAM was used to simulate PU-239 transport during flush-flood events in the Mortandad Canyon, New Mexico, USA (Whelan and Onishi, 1983), to reconstruct bottom contamination of the Clinch-River- Tennessee River System due to releases from the Oak Ridge National Laboratory (Onishi, private communication), to simulate Sr-90 and Cs-137 transport in Dnieper Reservoir after the Chernobyl accident (Zheleznyak, Blaylock and al., 1995).

The 1-D model of SPA "TYPHOON" State Hydrometeorological Committee of USSR (Borzilov et al., 1989) used empirical data on the sediment transport rate and flow. The model includes more detailed descriptions of the transfer between different forms of radionuclides. Model parameters have been identified on the basis of experimental data of the Pripyat River spring floods.

The 1-D model by Smitz and Everbecq (1986,) considers kinetics of radionuclide interaction with two size fractions of suspended solids. The model was verified for migration of radionuclides in the Meuse River, and subsequently was extensively applied elsewhere (Smitz, private communication).

Several 1-D numerical models have been developed to simulate non-radioactive pollutant transport in the rivers. These models do not take into consideration the specification of the radionuclide transport and radionuclide interaction with sediments, however some of them could be, in principal, modified for such purposes. One of the most well known European 1-D modelling system of the pollutant transport in the

river net is MIKE11, developed by the Danish Hydraulic Institute (Havno et al., 1995). MIKE-11 is a modelling system for the simulation of flows, sediment transport and water quality in estuaries, rivers, irrigation systems and other water bodies. MIKE11 has been designed for an integrated modular structure with basic computational modules for hydrology, hydrodynamics, advection -dispersion, water quality and cohesive and non-cohesive sediment transport. It also includes modules for the surface runoff. MIKE-11 has a well-developed graphical user interface integrated with the pre- and post-processors that support the system interaction with the GIS (Sorensen et al., 1996a).

One-dimensional model RIVTOX was developed to simulate the radionuclide transport in the solute, on the suspended sediments and in the bottom depositions. After the Chernobyl accident it has been applied for the prediction of the radionuclide transport in the river systems (Zheleznyak et al., 1992, Tkalich et al., 1993, Slavik, Zheleznyak et al. 1997). The model includes a submodel of the radionuclide transport and two submodels of the “driving forces” – a hydrodynamic (hydraulics) submodel and a sediment transport submodel.

## **1.2 Modelling of 1-D river hydrodynamics and sediment transport**

To simulate the radionuclide transport in rivers, it is necessary to estimate beforehand the river flow and the suspended sediment transport driven by the river hydrodynamic processes. There are a lot of models to simulate river hydraulics and hydrodynamics. The Overviews of the methods are presented in M. Abott, 1979; Cunge J., Holly F. and Verwey A., 1986; Orlob, 1983 and others. The contemporary “state-of-the-art” in the field is presented by Rutherford, 1994 and demonstrated by Jobson, 1989, Zheleznyak and Marinets, 1993.

The one-dimensional models based on cross-sectionally averaged variables seem to be the most important for the determination of the river flow. Well known are computer codes such as HEC-6 and HEC-2SR (Hydrological Engineering Center, 1977, 1982), REDSED (Chen, 1988), FLUVIAL 11 (Chang, 1988), IALLUVIAL (Karim et al., 1981, 1987) and CHARIMA (Holly et al., 1990) which expands the IALLUVIAL approaches, as well as MIKE-11 (Danish Hydraulics Institute), and TELMAC (Laboratory of Hydraulics, EDF, France). The two last ones are commercially distributed modelling systems which include models of different dimensions. HEC-2SR, FLUVIAL 11, CHARIMA, MIKE-11, and TELMAC contain river hydraulic modules based on a numerical solution of the Saint-Venant equation. The possibility of an efficient estimation of river hydraulics on the base of the numerical solution of the “diffusive wave” equation and the simplified version of the Saint-Venant equation were

Suspended sediments act as a carrier of radionuclides in the river/reservoir flow. The amount of radionuclides transported by the sediments depends on the suspended sediment concentration in the river flow and the  $K_d$  value. After the Chernobyl accident, for example, up to the half of CS-137 transported by the Pripyat River from the vicinity of the Chernobyl NPP was bound on suspended sediments (Voitsekhovitch et al., 1992). The sedimentation and bottom erosion processes play a key role in the flow self-purification and in the secondary contamination.

The mathematical modelling of the sediment and the transport is a large branch of hydraulics where overviews could be found in Ackers and White (1973), Grishanin (1976), Cunge, Holly and Verwey (1986), Engelund and Fredsoe (1976), Holly et al. (1990), Karim et al. (1981,1987), Mehta et al. (1989), Onishi (1993), Raudkivi (1967), van Rijn (1984). For the steady state conditions, the sediment discharges are calculated by the empirical and semi-empirical formulae which connect the sediment discharge with the sediment parameters, the flow velocities and the river cross-section characteristics or shear stress acting on the bed. In case of the cohesive sediments (finest silt and clay) andhesive bonds between the particles it has to be taken into account (Mehta et al. 1989). The variability of the streams and sediment parameters lead to the situation that up to nowadays several different formulae are used for the practical applications. It was demonstrated within validation studies (Onishi, 1993) that the approaches of Ackers -White, Engelund-Hansen, Rijn and Toffaleti show the most acceptable results for non-cohesive sediments over a wide range of flow and sediment conditions. However, for an individual river, the best result can be also obtained by the empirical formulae especially tuned for this river.

The sediment transport models are based on the suspended sediment-mass conservation equation (advection-diffusion equation with the sink-source term describing sedimentation resuspension rate) and the equation of bottom deformation (Exner equation). The most important problem for modelling is the parametrisation of the sedimentation and resuspension rates. A physically based approach calculates these rates as a function of the difference between the actual and the equilibrium concentration of the suspended sediments. This is often titled "suspended sediment capacity" and can be derived on the base of the above mentioned formulae.

The Suspended sediments models include different formulae for calculating the equilibrium sediment concentration. The most comprehensive models (e.g. CHARIMA) contain modules of the river hydraulic computation and methods to simulate the bottom erosion dependent on the sediment grain distribution in the upper bottom layer (bottom armouring calculation) and to calculate the bottom friction dependent on the simulated dynamics of the bottom forms.

The sediment transport models are also a part of the radionuclide transport models described in Onishi et al. (TODAM, SERATRA, FETRA, FLESQOT) and RIVTOX, COASTOX and THREEETOX models included into the RODOS –HDM. .

The 1-D models describe the cross-sectionally averaged flow and contamination parameters in channels. This kind of models is more widely used to simulate dynamics of the radionuclide transport in the network of river channels.

## 2 Submodels

### 2.1 Submodel of river hydraulics

RIVTOX includes two submodels for simulation crosssectional averaged flow velocity and water elevation in a network of river canals. The First one is based on the full set of the Saint-Venant equations. The Second one is “diffusive wave” simplified form of the Saint-Venant equations. The latter one as it was demonstrated (e.g. Jobson, 1989; Marinets, Zheleznyak 1993) could give a good accuracy in the results for the flood routing in the river net that does not include structures (dams, gates) which could have significant upstream influence on the flow parameters. Full Saint-Venant equations should be used in the situation with significant upstream influence of the river structure, including e.g. pumping to the water intakes of the irrigation channels and so on.

The hydraulic parameters of a stream (depth, sectional area, velocity) could be calculated using the full dynamic model or the diffusive wave model. The Full dynamic model is used for rivers with dams other obstacles in the channel and for accelerated flows. The Diffusive wave approximation of full dynamic model could be used in case of the insignificant upstream influence of peculiarities in a channel.

The next assumptions should be valid to use the Saint-Venant equations for water flow modelling:

- flow is mainly one-dimensional (velocity is constant in the cross section), fluid which is incompressible and homogeneous;
- curvature of current-flow lines is small, and vertical acceleration is insignificant;
- bottom slope is small, and parameters change slightly along a stream;
- turbulence and friction influence could be taken into account in accordance with resistance laws for constant flows;

The system of Saint-Venant equations include continuity equation (mass conservation law) (1) and momentum equation (2)

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_t \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{Q^2}{A} \right) + gA \left( \frac{\partial h}{\partial x} + S_f \right) = 0 \quad (2)$$

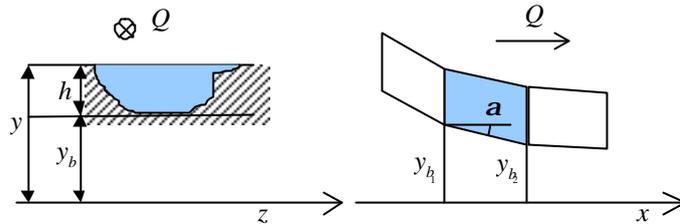
The glossary of terms used in the models is presented at the end of the subsection.

The components of the equation (2) mean: local acceleration, hydrostatic gradient, gravity, and friction.

The total water depth and bed slope are defined as follows:

$$h = y - y_b \quad (3)$$

$$S_0 = -\frac{\partial y_b}{\partial x} = \text{tga} \quad (4)$$



**Figure 2: River stream parameters**

The momentum equation (2) could be rewritten on the basis of above notation as follows

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{Q^2}{A} \right) + gA \left( \frac{\partial y}{\partial x} + S_f - S_0 \right) = 0 \quad (5)$$

The friction slope  $S_f$  is calculated using one of the empirical resistance laws, such as Chezy's or Manning's, for example:

$$S_f = \frac{Q|Q|}{K^2} \quad (6)$$

here  $K$  is a stream metering characteristics.

The usual approach in river hydraulics is to use empirical Chezy's friction coefficient  $C_{cz}$ .

$$K = C_{cz} A \sqrt{R} \quad (7)$$

The hydraulic radius of the flow  $R$  is defined as  $A/P$ , where  $P$  is "wetted perimeter" of the stream. For a wide river channel  $P$  value is close to a river width  $b$  ( $P \approx b$ ) and then  $R \approx h$ .

On the basis of the Mannings's empirical "friction parameter"  $n$  (average value is  $0,02 \div 0,03$  for the plain rivers)  $C_{cz}$  is determined as

$$C_{cz} = \frac{1}{n} R^{\frac{1}{6}} \quad (8)$$

In the kinematic wave approximation only two lass terms are considered in the equation (5), i.e.  $S_f = S_0$ ., that leads to formula

$$K = \frac{Q}{\sqrt{S_0}} \quad (9)$$

In this approximation using (6) -(8), could be obtained Chezy's formula for steady state flow

$$Q/A = C_{cz} \sqrt{RS_0} . \quad (10)$$

The substitution of (11) into the mass balance equation (1) using the assumptions  $A = bR, R \approx h$  and Manning's formula (8) will lead to kinematic wave equation

$$\frac{\mathcal{I}(bh)}{\mathcal{I}t} + S_0^{\frac{1}{2}} n^{-1} \frac{\mathcal{I}(bh^{\frac{10}{6}})}{\mathcal{I}x} = q_l \quad (12)$$

The diffusive wave approximation of Saint-Venant equations (1),(5) could be derived by the neglecting the first two terms in the momentum equation (5). In this case after differentiation (1) on  $x$  and (5) on  $t$  and assuming

$$\frac{\partial K}{\partial t} = \frac{dK}{dh} \frac{\partial h}{\partial t} = \frac{dK}{dh} \left( -\frac{1}{b} \frac{\partial Q}{\partial x} - \frac{1}{b} q_l \right) \quad (13)$$

we obtain:

$$\frac{\partial Q}{\partial t} + V_w \frac{\partial Q}{\partial x} - E_{wd} \frac{\partial^2 Q}{\partial x^2} - V_w q_l = 0 \quad (14)$$

here  $V_w$  is the wave propagation velocity (wave celerity), and  $E_{wd}$  is the diffusion coefficient

$$V_w = \frac{Q}{bK} \frac{\partial K}{\partial h}, \quad E_{wd} = \frac{K^2}{2bQ} \quad (15)$$

As a result it is received one parabolic equation instead of the system of two hyperbolic equations.

The formulas (15) could be simplified on the basis of assumption (9) that leads to

$$V_w = \frac{1}{b} \frac{dQ}{dh}, \quad E_{wd} = \frac{Q}{2bS_0} \quad (16)$$

On the basis of formula (10) and approximations  $A = bR, R \approx h$  the formula for the wave propagation velocity could be further simplified :

$$V_w = \frac{3}{2} \frac{Q}{bh}, \quad E_{wd} = \frac{Q}{2bS_0} \quad (17)$$

The functional relation between water discharge and water elevation (depth) is established on the basis of Chezy formulae.

The numerical solver for diffusive wave equation (14), (17) is included into the main hydraulic module of the RIVTOX –HDM. The module of the numerical solution of the full Saint-Venant equations is included only as the option for rivers with dams and gates (without support via GUI).

### *Glossary of terms used in the section 2.1*

$Q$	$\text{m}^3/\text{sec}$	water discharge
$A$	$\text{m}^2$	water sectional area
$b$	M	water width
$h$	M	water depth
$y$	M	depth, (calculated from reference level)
$y_b$	M	river-bed level, (calculated from reference level)
$q_l$	$\text{m}^3/\text{sec}^2$	water discharge of lateral inflow, distributed along stream
$g$	$\text{m}^2/\text{sec}$	gravitational acceleration
$S_f$		Stream friction slope
$S_0$		Stream bed slope
$K$	$\text{m}^3/\text{sec}$	Metering characteristic
$V$	$\text{m}^2/\text{sec}$	Water velocity
$E_{wd}$	$\text{m}^2/\text{sec}$	Water longitudinal diffusion coefficient

## **2.2 Sediment transport submodel**

The suspended sediment transport in river channels is described by the 1-D advection -diffusion equation that includes a sink-source term describing sedimentation and resuspension rates and lateral distributed inflow of sediments

$$\frac{\partial(AS)}{\partial t} + \frac{\partial(QS)}{\partial x} - \frac{\partial}{\partial x} \left( E_s \frac{\partial(AS)}{\partial x} \right) = \Phi_b + \Phi_l, \quad (18)$$

where  $\Phi_b$  is a vertical sediment flux at the bottom, describing sedimentation or resuspension processes in the dependence on the flow dynamical parameters and size of bottom sediments.

$$\Phi_b = \frac{A}{h} \cdot (q_{res} - q_{sed}). \quad (19)$$

The fluxes are calculated as a difference between actual and equilibrium suspended sediment concentration multiplied on fall velocity of sediment grains:

$$\begin{aligned} q_{res} &= \mathbf{b} w_0 \cdot F(S_* - S) \\ q_{sed} &= w_0 \cdot F(S - S_*) \end{aligned} \quad (20)$$

where  $F(x)$  is a function defined as

$$F(x) = \frac{x + |x|}{2} \equiv \begin{cases} x, & x > 0 \\ 0, & x < 0 \end{cases} \quad (21)$$

The coefficient of the erodibility  $\mathbf{b}$  characterizes the bottom protection from erosion due to cohesion and natural armoring of the upper layer of river bed, vegetation. This empirical coefficient as usually has values of magnitude 0.1-0.01.

The equilibrium suspended sediment concentration (flow capacity)  $S_*^*$  can be calculated by different approaches. The first empirical formula used in RIVTOX ( Zheleznyak et al.1993) was taken from Bijker's method ( Bijker, 1998).

The equilibrium discharge of the suspended sediments  $p=QS_*$  is calculated as a function of the bed load  $p_b$ :

$$p = 1.83p_b \left( I_1 \ln \frac{h}{z_0} + I_2 \right) \quad (22)$$

where  $I_1$  and  $I_2$  are the functions of the undimensional fall velocity  $w_* = w_0 / (kU_*)$

and bottom roughness  $r_* = r / h$

$$I_1 = 0.216 \frac{r_*^{w_*-1}}{(1-r_*)^{w_*}} \int_{r_*}^1 \left[ \frac{1-z'}{z'} \right]^{w_*} dz' \quad (23)$$

$$I_2 = 0.216 \frac{r_*^{w_*-1}}{(1-r_*)^{w_*}} \int_{r_*}^1 \left[ \frac{1-z'}{z'} \right]^{w_*} \ln z' dz' \quad (24)$$

where

$z'=z/h$ ,  $r=30 r_0$  - typical size of the bottom inhomogeneity,  $k$  - von Karman parameter ( $k=0.4$ ),  $U_*$  - bottom shear stress velocity

$$U_* = \sqrt{T_c / r_w} = \sqrt{ghS_f} \quad (25)$$

The bottom sediment equilibrium flow is described as follows:

$$\bar{p}_b = 5D \frac{\bar{T}_c}{\sqrt{\bar{T}_{cw}}} \left( \frac{m}{r} \right)^{0.5} \exp \left( -0.27 \frac{rD}{|\bar{T}_{cw}|} \right) \quad (26)$$

where

$\bar{T}_c$  - current driven bottom shear stress,

$\bar{T}_{cw}$  - bottom shear stress driven by joint action of the currents and waves,

D - averaged size of sediments,

$\mu$  - the parameter of the bottom ripples.

The formula (26) was proposed for coastal areas and for rivers mainly used for the large reservoirs parts. In recent versions of RIVTOX van Rijn's methods of calculation of suspended sediment transport is included into the module library.

The lateral inflow of suspended sediments to the river net  $\Phi_l$  in the equation (18) could be presented as follows

$$\Phi_l = q_l S_l, \quad (27)$$

The distributed runoff inflow to the river net  $q_l$  and the suspended sediment concentration in the runoff  $S_l$  are simulated by the HDM RETRACE model.

Substitution of the (19) and (27) into (18) leads to the following equation:

$$\frac{\partial(AS)}{\partial t} + \frac{\partial(QS)}{\partial x} - \frac{\partial}{\partial x} \left( E_s \frac{\partial(AS)}{\partial x} \right) = \frac{A}{h} (q_{res} - q_{sed}) + q_l S_l, \quad (28)$$

which could be taken into account the water balance equation (1) presented in such a form

$$\frac{\partial S}{\partial t} + U \frac{\partial S}{\partial x} - \frac{1}{A} \frac{\partial}{\partial x} \left( A E_s \frac{\partial S}{\partial x} \right) = \frac{1}{h} (q_{res} - q_{sed}) + \frac{q_l}{A} (S_l - S) \quad (29)$$

where  $U = Q/A$  - cross-sectionally averaged flow velocity,  $E_s$  - dispersion coefficient for suspended sediments. It is assumed, that for suspended sediments could be used the same dispersion coefficient as for a soluble tracer in water flow. The overview of the methods of the calculation of the dispersion coefficient for 1-D channel flow has been presented by F.Holly (1985) and recently by Won Seo (1998).

The widely used formulas are as follows:

Elder (1958):

$$E_x = \mathbf{a}_E U_* h \quad (30)$$

The calibration constant  $\alpha_E$  has a constant value of 5.9.

Fischer (1973) (in presentation of van Majzik, 1992):

$$E_x = \mathbf{a}_F \frac{b^2 U^2}{h U_*} \quad (31)$$

The calibration constant  $\alpha_F$ , e.g. for the Rhine River has a value of 0.011.

Won Seo (1998):

$$E_x = \mathbf{a}_W \left( \frac{b}{h} \right)^{1.23} \left( \frac{U}{U_*} \right)^{1.25} \quad (32)$$

The calibration constant  $\alpha_W$  is given in the literature having a value of 0.64.

The simplest approach based on the Elder formula (30), shear stress velocity definition (25) and Chezy's and Manning's formula (3)-(6), is used in RIVTOX

$$E_s = E_x = \mathbf{a}_E U_* h = \mathbf{a}_E \sqrt{gn} U h^{-\frac{5}{6}} \quad (33)$$

The values of the parameter  $\mathbf{a}_E$  should be calibrated if trace experiment data are available for the river of the model implementation.

The Other longitudinal dispersion formulas could be used optionally.

The fluxes of the sedimentation and the resuspension (20) control the dynamics of the upper most contaminated layer of the bottom sediments. The thickness of this layer  $Z^*$  could be calculated from the mass balance equation

$$\mathbf{r}_s (1 - \mathbf{e}) \frac{dZ^*}{dt} = q_{sed} - q_{er} \quad (34)$$

After the simulation of stream hydrodynamics, the numerical solution of the equations (21), (24) is used with the appropriate empirical formulas for the modelling of the suspended sediment transport in the river flow.

*Glossary of terms used in section 2.2*

$S$	$\text{kg/m}^3$	Suspended sediment concentration
$S_*$	$\text{kg/m}^3$	Suspended sediment equilibrium concentration
$\Phi_b$	$\text{kg/m}\cdot\text{sec}$	total vertical flux of sediments at water-river bed interface per unit of river branch length
$q_{res}$	$\text{kg/m}^2\cdot\text{sec}$	Resuspension (erosion) rate per unit area of the bottom (upward directed flux)
$q_{sed}$	$\text{kg/m}^2\cdot\text{sec}$	Sedimentation rate per unit area of the bottom (downward directed flux)
$b$		Erodibility empirical coefficient
$w_0$	$\text{m}^2/\text{sec}$	Sediment fall velocity
$\Phi_l$	$\text{kg/m}\cdot\text{sec}$	Suspended sediment flux from lateral inflow per unit of river branch length
$S_l$	$\text{kg/m}^3$	suspended sediment concentration in the lateral water inflow
$E_s$	$\text{m}^2/\text{sec}$	longitudinal dispersion coefficient for sediments
$E_x$	$\text{m}^2/\text{sec}$	longitudinal dispersion coefficient for soluble tracer
$a_E$		parameter of the longitudinal dispersion for Elder's formula
$U$	$\text{m}/\text{sec}$	crosssectionally averaged flow velocity
$U_*$	$\text{m}/\text{sec}$	bottom shear stress velocity
$K$		von Karman parameter
$\bar{T}_c$	$\text{kg}/(\text{m sec}^2)$	current driven bottom shear stress
$D$	$\text{M}$	averaged size of sediments,
$Z^*$	$\text{M}$	thickness of the bottom sediment upper layer
$r_s$	$\text{Kg}/\text{m}^3$	density of the suspended sediments ( default value 2600 )
$r_s$	$\text{Kg}/\text{m}^3$	water density ( default value 1000 )
$e$		porosity of the bottom sediments

### 2.3 Submodel of radionuclide transport

This submodel of RIVTOX describes the advection diffusion transport of the cross-sectionally averaged concentrations of radionuclides in the solution  $C$ , the concentration of radionuclides on the suspended sediments  $C^s$  and the concentration  $C^b$  in the top layer of the bottom depositions. The adsorption/desorption and the diffusive contamination transport in the systems "solution - suspended sediments" and "solution - bottom deposition" is treated via the Kd approach for the equilibrium state, additionally taking into account the exchange rates  $a_{i,j}$  between solution and particles for the more realistic simulation of the kinetic processes.

The present version of RIVTOX uses different values of the sorption and desorption rates  $a_{1,2}$  and  $a_{2,1}$  for the system "water-suspended sediment" and  $a_{1,3}$  and  $a_{3,1}$  for the system "water-bottom deposits" because this fits better with the real physical-chemical behaviour of radionuclides in the water systems. Furthermore, the use of the different exchange rates gives a better fit in the simulations

$$\begin{aligned} \frac{\partial C}{\partial t} + \frac{Q}{A} \frac{\partial C}{\partial x} - \frac{1}{A} \frac{\partial}{\partial x} \left( AE_c \frac{\partial C}{\partial x} \right) &= f^C (S, C, C^s, C^b, Z, \bar{p}^C) + f^{C_i} (C, C_i) \\ \frac{\partial C^s}{\partial t} + \frac{Q}{A} \frac{\partial C^s}{\partial x} - \frac{1}{A} \frac{\partial}{\partial x} \left( AE_c \frac{\partial C^s}{\partial x} \right) &= f^{C^s} (S, C, C^s, C^b, Z, \bar{p}^{C^s}) + f^{C_i^s} (C, C^s, C_i, C_i^s) \\ \frac{\partial C^b}{\partial t} &= f^{C^b} (S, C, C^s, C^b, Z, \bar{p}^{C^b}) \\ \frac{\partial Z^*}{\partial t} &= f^{Z^*} (S, \bar{p}^{Z^*}) \end{aligned} \quad , \quad (35)$$

where

$$\begin{aligned} f^C &= -IC - a_{1,2} (K_{ds} SC - C^s) - a_{1,3} (K_{db} C - C^b) \frac{\mathbf{r}_s (1 - \mathbf{e}) Z^*}{h} \\ f^{C_i} &= \frac{Q}{A} (C_i - C) \\ f^{C^s} &= -IC^s + a_{1,2} (K_{ds} C - C^s) + \frac{q_{sed} (C^b - C^s)}{hS} \\ f^{C_i^s} &= \frac{QS_i (C_i^s - C^s)}{AS} \\ f^{C^b} &= a_{1,3} (K_{db} C - C^b) - \frac{q_{res} (C^b - C^s)}{\mathbf{r}_s (1 - \mathbf{e}) Z^*} - IC^b \end{aligned} \quad , \quad (36)$$

The numerical solver for the system of the equations (36) is included into the RIVTOX code.

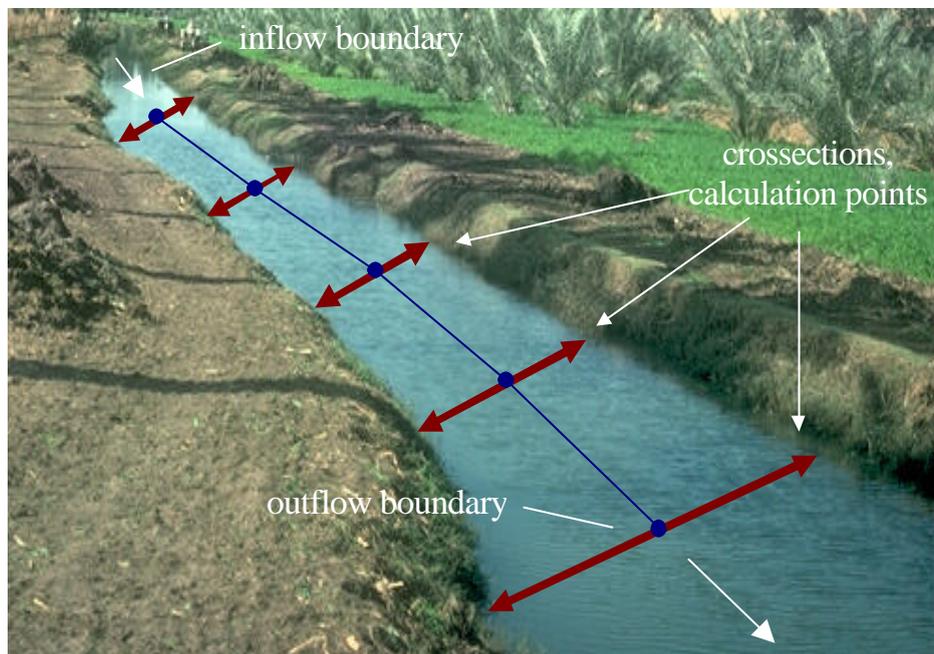
*Glossary of terms used in section 2.3*

$C$	Bq/m <sup>3</sup>	radionuclide concentration in solution
$C^s$	Bq/kg	radionuclide concentration on suspended sediments
$C^b$	Bq/kg	radionuclide concentration in bottom depositions
$C_l$	Bq/m <sup>3</sup>	radionuclide concentration in solution of lateral inflow
$C_l^s$	Bq/kg	radionuclide concentration on suspended sediments in lateral inflow
$E_c$	m <sup>2</sup> /sec	radionuclide longitudinal dispersion coefficient
$I$	sec <sup>-1</sup>	decay coefficient
$a_{1,2}$	sec <sup>-1</sup>	sorption rate in “water-suspended sediments” system
$a_{2,1}$	sec <sup>-1</sup>	desorption rate in “water-suspended sediments” system
$a_{1,3}$	sec <sup>-1</sup>	sorption rate in “water-bottom deposition” system
$a_{3,1}$	sec <sup>-1</sup>	desorption rate in “water-bottom deposition” system
$K_{as}$	m <sup>3</sup> /kg	distribution coefficient in “water-suspended sediments” system
$K_{db}$	m <sup>3</sup> /kg	distribution coefficient in “water-bottom deposition” system

### 3 Boundary and initial conditions in river network

#### 3.1 River network

For a complex river net the above models are applied to the river network graph. Each equation is solved for the respective "simple channel" (branch) with the relevant initial conditions on a branch and the appropriate boundary condition in a junction of the river net. Each branch is considered as a river channel name "simple channel" means that inside this branch there are no junctions with 2 or more inflows or outflows, sharp changes in depth or width of the stream or water discharge. These points are named "special" points and define a scheme of the river net for the simulation purposes.



**Figure 3: River stream scheme**

For the numerical solution of the model equations each branch is covered by the set of the grid nodes (computational mesh) as presented on Figure 3. The configuration of the graph and the size of the branches could be taken from the GIS (e.g. MapInfo map) , The information about the river hydrographical characteristics (e.g. mean depth and width, typical discharge, the crosssection data -  $A=A(h)$  or  $b=b(h)$  tables) is prepared for some river crosssections to be interpolated into the computational nodes in the modelling system.

#### 3.2 Boundary condition and initial conditions

- a) In all models, for all influx points of the river net, the source term conditions should be set:

$$\begin{aligned}
Q(t)|_{x=0} &= \tilde{Q}(t) \\
S(t)|_{x=0} &= \tilde{S}(t) \\
C(t)|_{x=0} &= \tilde{C}(t) \quad , \\
C^S(t)|_{x=0} &= \tilde{C}^S(t)
\end{aligned} \tag{37}$$

where  $\tilde{Q}(t)$ ,  $\tilde{S}(t)$ ,  $\tilde{C}(t)$ ,  $\tilde{C}^S(t)$  are the source functions

b) At the outflow nodes the condition of the free propagation:

$$\begin{aligned}
\left( \frac{\partial Q}{\partial t} + \frac{Q}{A} \frac{\partial Q}{\partial x} \right)_{x=l} &= f^Q |_{x=l} \\
\left( \frac{\partial S}{\partial t} + \frac{Q}{A} \frac{\partial S}{\partial x} \right)_{x=l} &= f^S |_{x=l} \\
\left( \frac{\partial C}{\partial t} + \frac{Q}{A} \frac{\partial C}{\partial x} \right)_{x=l} &= f^C |_{x=l} \quad , \\
\left( \frac{\partial C^S}{\partial t} + \frac{Q}{A} \frac{\partial C^S}{\partial x} \right)_{x=l} &= f^{C^S} |_{x=l}
\end{aligned} \tag{38}$$

where  $l$  - a branch length.

c) The Conjunction node (inflow from more than one branch and outflow through one branch) conditions of the free propagation are imposed at the inflow branch.

The mass balance conditions:

$$\begin{aligned}
(Q)_{out}|_{x=0} &= \sum_i (Q)_i |_{x=l} \\
(QC)_{out}|_{x=0} &= \sum_i (QC)_i |_{x=l} \\
(QS)_{out}|_{x=0} &= \sum_i (QS)_i |_{x=l} \quad , \\
(QSC)_{out}|_{x=0} &= \sum_i (QSC)_i |_{x=l}
\end{aligned} \tag{39}$$

d) The fork nodes (inflow from one branch and outflow through two or more branches).

At the inflow branch the free propagation conditions (38) are imposed. At the outflow branches source term conditions (37) are imposed, where the source functions are equal to the output from the inflow branch.

The initial conditions should be also set for all parameters in all points of the numerical mesh at the start time.

## 4 Numerical solution

The implicit finite difference scheme (Fletcher, 1988) was used for the numerical solution of the parabolic advection-dispersion equations on the river network grid. The finite-difference scheme could be written in the next general form:

$$M_x \left( \frac{\Phi_{n,i}^{n+1} - \Phi_{n,i}^n}{\Delta t} \right) + (V_{n,i}^{n+1} \cdot L_x - E_{n,i}^{n+1} \cdot L_{xx}) \cdot 0.5 \cdot (\Phi_{n,i}^n + \Phi_{n,i}^{n+1}) = f_{n,i}^n, \quad (40)$$

Where  $n$  - is the number of the branch,  $i$  is—the number of the point on each branch,  $n$  - the time layer number;

the functions  $\Phi$ ,  $f$  presents the model variables  $Q$ ,  $S$ ,  $C$ ,  $C^S$  in the equations and the source term functions

The finite-difference operators  $M_x$ ,  $L_x$ , and  $L_{xx}$  are applied to three neighbour nodes of the spatial mesh  $\{i-1, i, i+1\}$  and could be formally written as

$$\begin{aligned} M_x &\equiv \{d, (1-2d), d\} \\ L_x &\equiv \frac{1}{2\Delta x} \{-1, 0, 1\} \quad , \\ L_{xx} &\equiv \frac{1}{\Delta x^2} \{1, -2, 1\} \end{aligned} \quad (41)$$

where  $0 < d < 1$ , formally this scheme assumes the second order and is stable when  $d \leq 0.25$ .

Assuming  $s = E_{n,i}^{n+1} \Delta t / \Delta x^2$  and  $C = V_{n,i}^{n+1} \Delta t / \Delta x$  (Courant number) (40) could be transferred into the next three diagonal form:

$$\begin{aligned} &[d - 0.25C - 0.5s] \cdot \Phi_{n,i-1}^{n+1} + [(1 - 2d) + s] \cdot \Phi_{n,i}^{n+1} + [d + 0.25C - 0.5s] \cdot \Phi_{n,i+1}^{n+1} = \\ &= [d + 0.25C + 0.5s] \cdot \Phi_{n,i-1}^n + [(1 - 2d) - s] \cdot \Phi_{n,i}^n + [d - 0.25C + 0.5s] \cdot \Phi_{n,i+1}^n + \Delta t \cdot f_{n,i}^n \quad , \end{aligned} \quad (42)$$

here  $n = 1, \dots, N$ ,  $i = 2, \dots, I_n - 1$

The solution of the system (42) with the finite-difference approximation of the boundary conditions (37)-(39) is obtained on the basis of the three-diagonal sweep procedure.

## 5 RIVTOX Input and Output Data

The input data of the model are as follows:

- The Parameters of the river channel network such as the length of the branches and the positions of the junctions, the dependence of the area of cross-section of the channel from the water surface elevation, the bottom roughness, typical scenarios of the river floods for the simulation of direct releases of radionuclides into the water.
- The Typical distribution of the grain size of the suspended sediments and grain sizes of the bottom deposits.
- Time dependent information about the point sources for the simulation of the direct release and the output from RETRACE as the lateral inflow of the contamination for the modelling of the fate of pollutants which were washed out from the watershed.

The radionuclide transport parameters are defined in RIVTOX –HDM 4.0 for 7 radionuclides. The presented values in table 3.3. could be considered as the default values, that could be supplementary calibrated on the basis of processing of measured data during the direct implementation of the model.

Table 3.1. Radionuclide transport parameters

<b>Nuclide</b>	<b>K<sub>db</sub></b> <b>(m<sup>3</sup>/kg)</b>	<b>K<sub>ds</sub></b> <b>(m<sup>3</sup>/kg)</b>	<b>a<sub>12</sub></b> <b>(1/day)</b>	<b>a<sub>21</sub></b> <b>(1/day)</b>	<b>a<sub>13</sub></b> <b>(1/day)</b>	<b>a<sub>31</sub></b> <b>(1/day)</b>
Cs-137	3	15	1	0.02	0.01	0.002778
Sr-90	0.25	0.8	1	0.02	0.04	0.002778
H-3	0	0	0	0	0	0
Co-60	5	20	1	0.02	0.01	0.002778
I-131	0.01	0.01	1	0.02	0.04	0.002778
Pu-239	200	800	1	0.02	0.01	0.002778
Ru-106	4	15	1	0.02	0.01	0.002778

The output data are as follows arrays that presents the value of variables in the nodes of the grid, constructed on river branches

- time variable crosssectionally averaged concentration of radonuclides in the solute;
- time variable crosssectionally averaged concentration of radonuclides on the suspended sediments;
- time variable crosssectionally averaged concentration of radonuclides in the upper layer of the botttom sediments.

The output data of the RIVTOX module is used by the special module "PREPARATION" to be transferred into the RODOS dose calculation module FDMA.

## 6 Model testing and validation studies

### 6.1 Numerical methods testing on the basis of the analytical solutions

The analytical solutions of the advection- diffusion equation could be obtained for the simplified cases. The diffusive wave equation could be presented as:

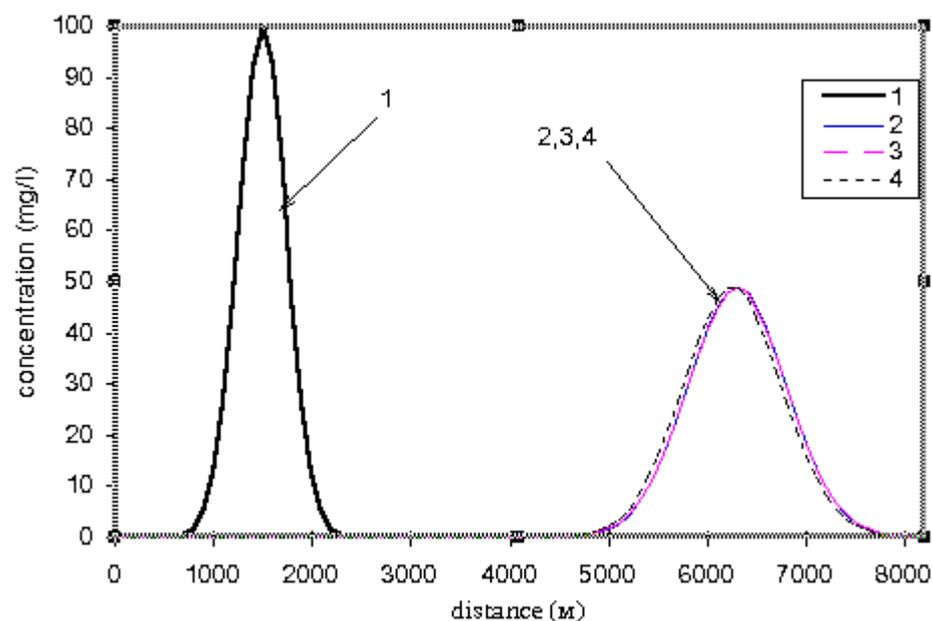
$$\frac{\partial Q}{\partial t} + V \frac{\partial Q}{\partial x} = E \frac{\partial^2 Q}{\partial x^2}, \quad (43)$$

$$\frac{\partial Q}{\partial t} + V \frac{\partial Q}{\partial x} = E \frac{\partial^2 Q}{\partial x^2} \quad (44)$$

Assuming the constant values of the wave propagation velocity and the diffusion coefficient the following analytical solution of the above equation could be obtained

$$Q(x, t) = \frac{M}{2B\sqrt{pEt}} \exp\left(-\frac{(x-Vt)^2}{4Et}\right) \quad (45)$$

The simulated results (Figure 4) are in good correspondence with the analytical solution.



**Figure 4: Comparison of numeric and analytic solutions for diffusive wave. (1 - Initial conditions; 2- Analytic solution,  $t=9600$  sec; 3- Numeric solution,  $Cr=1$ ; 4- Numeric solution,  $Cr=0.5$ )**

## 6.2 Validation studies for the Rhine River watershed

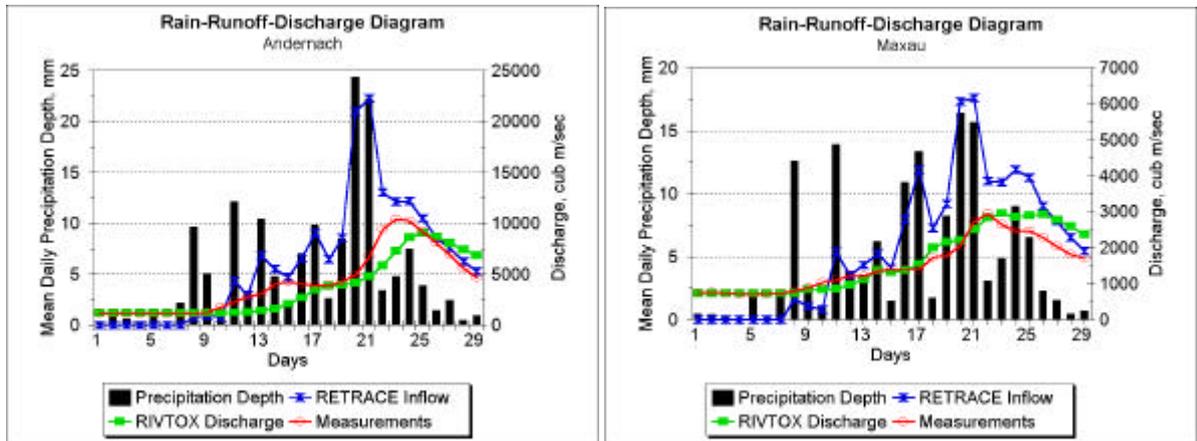
### 6.2.1 High flood at Christmas 1993

RIVTOX was tested coupled with RETRACE to simulate the extremely high flood event that took place in the Rhine River for a period of December 1993 - January 1994..

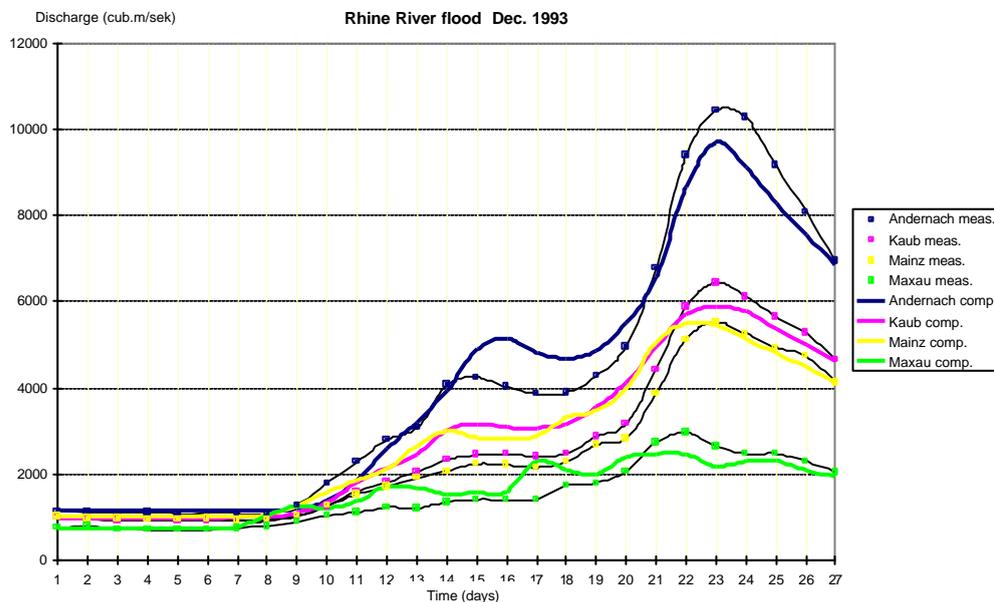
The main objective of the validation study was to compare the model chain results with the daily averaged measured discharges in four outlets of the Rhine river. It should be mentioned that elevation data for the Rhine watershed channel net (orographical) data used in validation have been obtained from the maps with the different spatial resolution. This discrepancy in data resolution resulted in problems with the definition of runoff directions based on relief. Therefore, due to input data resolution discrepancy of some misplacements of the lateral inflow has been inserted into the simulation. Unfortunately, it is impossible now to estimate the magnitude of the errors dealt with input data problem.

Another problem concerned the input meteorological data. Precipitation data were provided by the German Meteorological Service for about 70 meteorological stations but the air moisture data was not available for this validation. To correct this absence of data it was supposed that for the whole period of the validation when the

intensive rains took place, the air temperature was 5° C and the relative air humidity was 90% which gives the air moisture deficit 0.873 hPa. (Popov,1997).



**Figure 5: Simulation results of the combined RIVTOX and RETRACE model for the flood event of the River Rhine in 1993. Comparison of predicted and measured discharge data for Andernach and Maxau.**



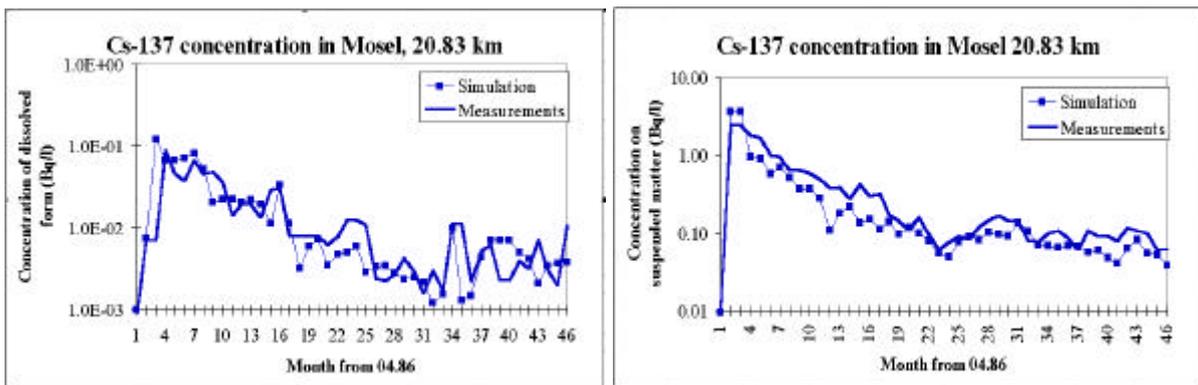
**Figure 6: Comparison of the simulated by RIVTOX and measured discharges for 4 sites at the River Rhine for December 1993 flood.**

In Figure 5 and Figure 6, the simulation results are compared with the measurements for four crosssections of the River Rhine. For two of

them – upper site the Andemach and the lower one the Maxau. On figure 7 here are presented . the input precipitation data and the result of the runoff simulation by RETRACE. The model agreement with the measured data for this extreme flood situation was reasonable. The Reasons for the disagreement are associated with the more diffusive character of the discharge hydrograph simulated by RIVTOX. More precisely, RIVTOX’s hydrographs demonstrate less steepness of the fronts, and less magnitudes than measured. This behaviour might be a result of the not enough detailed data about the river crosssections, used during the simulations.

### 6.2.2 Chernobyl radionuclides in the Rhine tributaries

Testing and tuning exercises RIVTOX was performed for two watersheds of the Mosel and the Neckar. In the first case the most complete set of data was available for water contamination which included monthly average values of  $^{137}\text{Cs}$  concentrations in the dissolved form and on the suspended particles [Mundschenk]. As the most contaminated region of the Mosel, catchment was situated upstream from the upper measured cross section and it was assumed, that the concentration of  $^{137}\text{Cs}$  in the lateral inflow was negligibly small compared to the one in the main stream. The upper cross-section was located about 222 km upstream from the junction of the Mosel with the Rhine river. The comparison with field data was performed for a cross-section located about 2 km from Koblenz. The results of the simulation for the years 1986-1988 are presented in Figure 7 and cover the Chernobyl ve fallout and runoff from the Mosel watershed.



**Figure 7: Simulation of Cs-137 concentration in the Mosel River**

The sub-module for modelling of the transport of the suspended matter was tested in the frame of the Neckar River study. Experimental data contained the daily suspended matter concentrations for two cross-sections at km 160 and 60.7 of the Neckar [RODOS data]. The simulation was done for the 30-day period and includes a period of 10

days with heavy rain events (Figure 8). The inflows of the lateral water and the suspended matter were estimated from available meteorological data and from runoff coefficients.

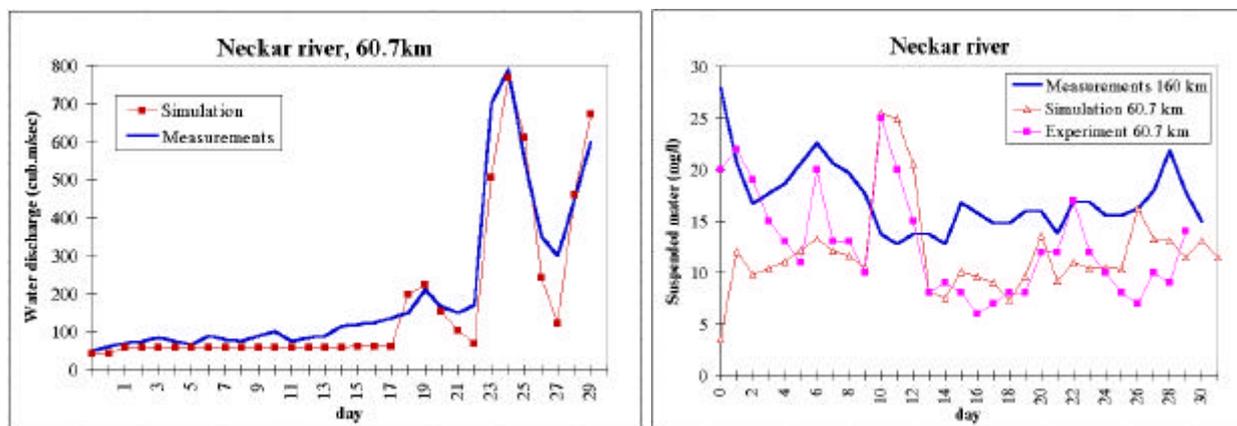


Figure 8: Simulation of <sup>137</sup>Cs concentration in the Neckar River.

### 6.3 VAMP validation study (Clinch-Tennessee and Dnieper).

The RODOS RIVTOX model was validated in the frame of the IAEA VAMP project. Two scenarios were prepared in the River and Reservoirs sub-group.

The first scenario described the long term release of, Cs<sup>137</sup>, Sr<sup>90</sup>, Ru<sup>106</sup> and Co<sup>60</sup> to the Clinch-Tennessee river system from Oak Ridge National Laboratory (ORNL). Experimental data include monthly averaged water concentration values near ORNL and the water discharge rates. The simulated period was expanded from 1964 to 1983. The result of the validation is shown in Figure 9.

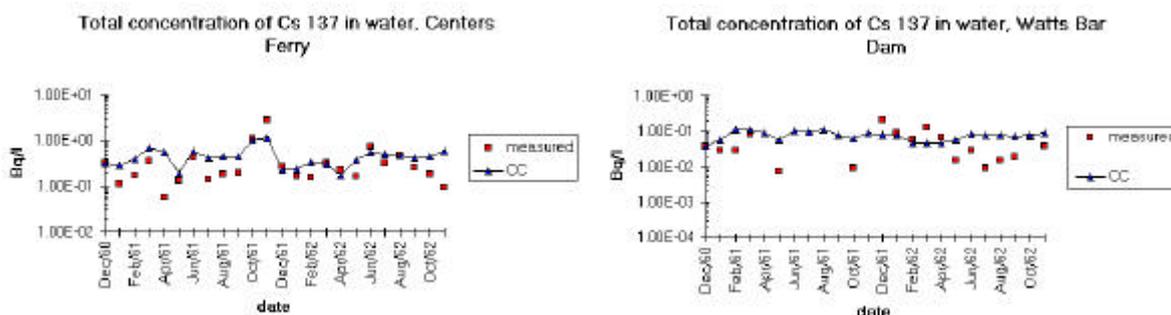
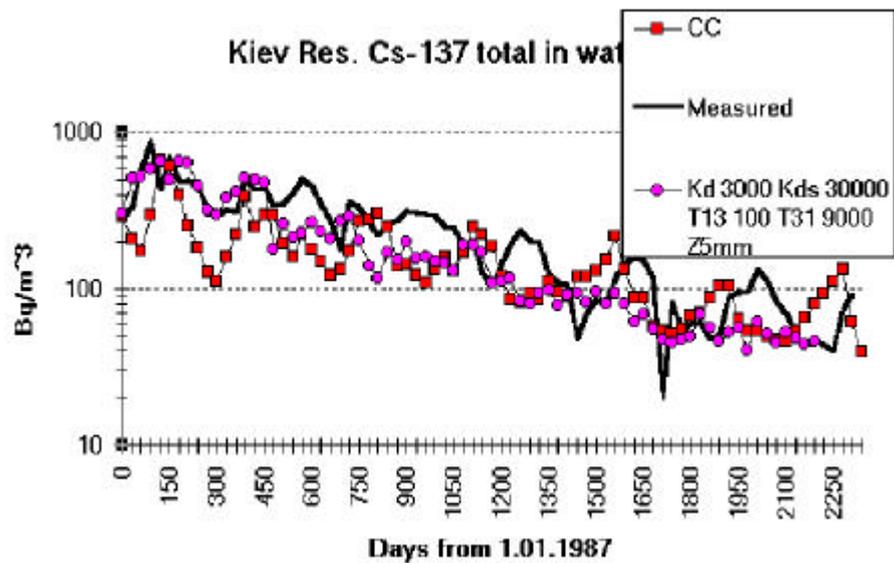


Figure 9: Simulation for the Clinch river

The second scenario covered the long term contamination of water and sediment by Cs<sup>137</sup> and Sr<sup>90</sup> for the set of the Dnieper reservoir cascade. The simulations were performed in two steps. In the first stage, model results were compared with unknown experimental data. The best estimate and confidence interval were obtained with the help of the uncertain analysis. In the second stage, the model parameters were tuned to reach a good agreement with the experimental data and the most sensitive parameters were defined which were the most important for the migration of radionuclides in the river systems. During the validation exercise, on the basis of the Dnieper river data the second version of RIVTOX model has been developed. Figure 10 - Figure 15. show the results of the second version of RIVTOX in comparison with the first version (curve CC) and measured data. This version differs from the previous first one by using different values for the sorption and the desorption rates  $a_{1,2}$  and  $a_{2,1}$  for the system "water-suspended sediment" and  $a_{1,3}$  and  $a_{3,1}$  for the system "water-bottom deposits". One can see that RIVTOX with those different exchange rates provides a better agreement with the measured data.



**Figure 10: Concentration of Cs-137 in Kiev reservoir**

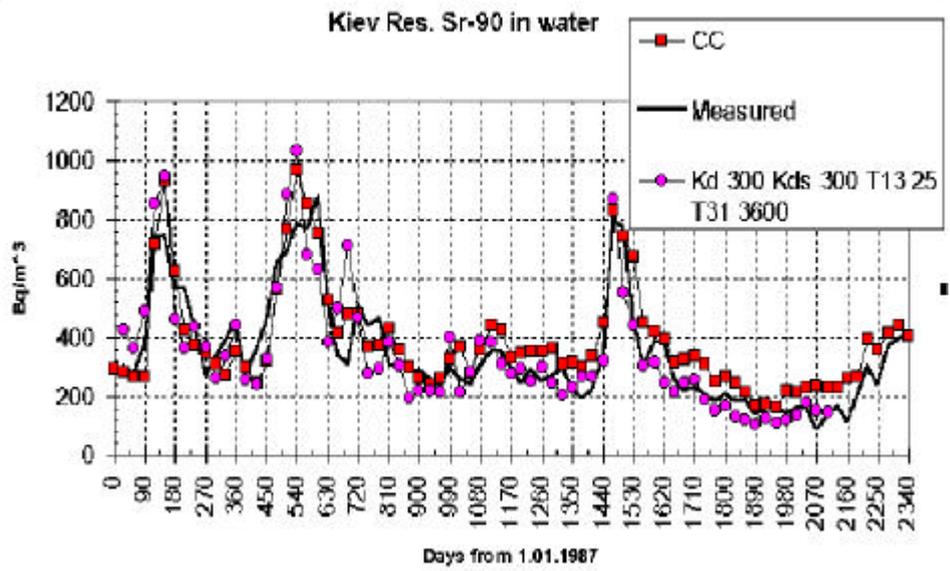


Figure 11: Concentration of Sr-90 in Kiev reservoir

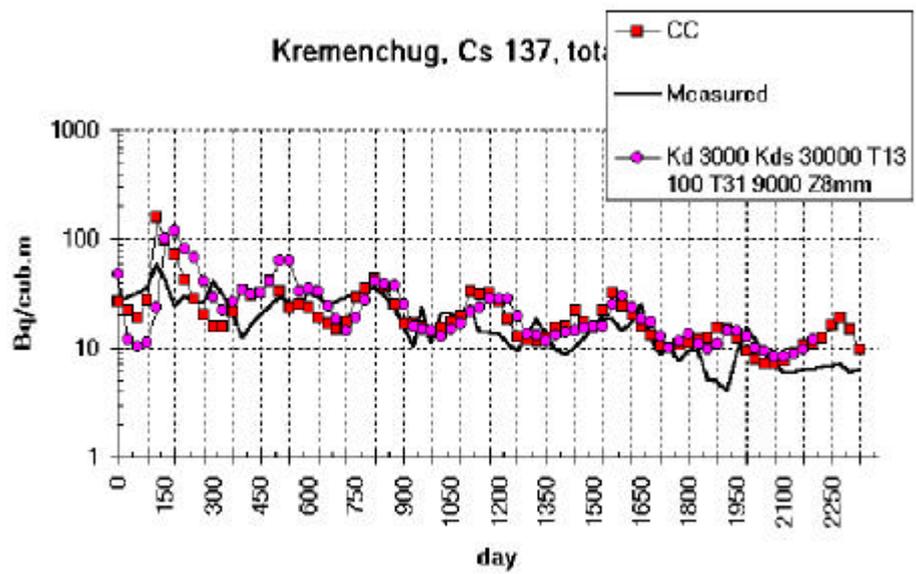


Figure 12: Concentration of Cs-137 in Kremenchug reservoir

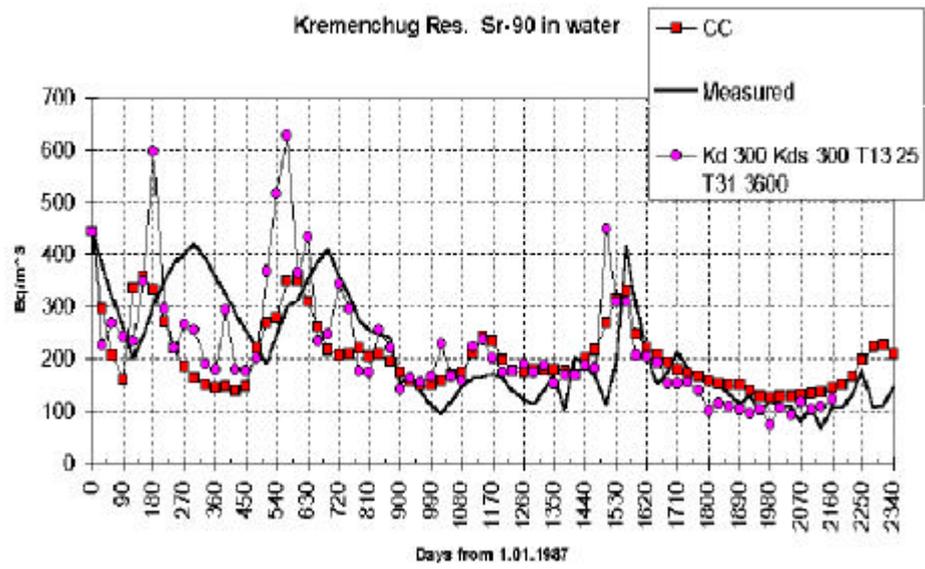


Figure 13: Concentration of Sr-90 in Kremenchug reservoir

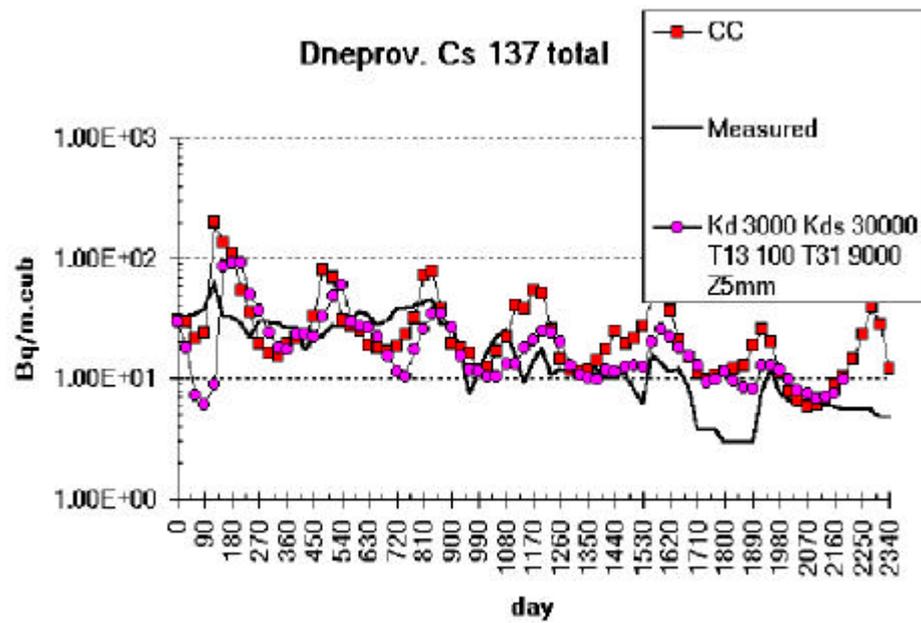


Figure 14: Concentration of Cs-137 in Dnieper reservoir

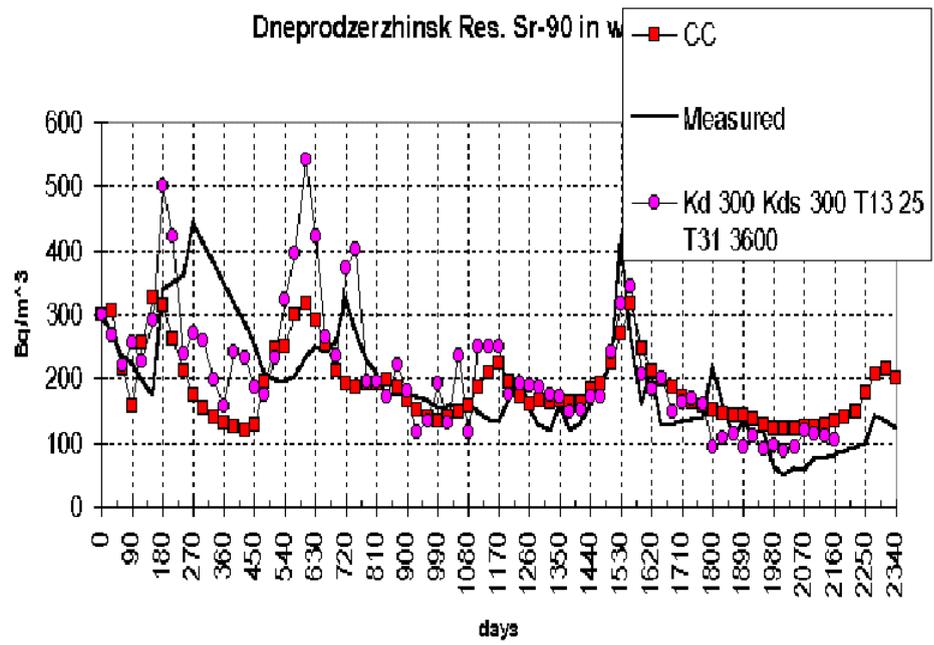


Figure 15: Concentration of Sr-90 in Dnieper reservoir

#### 6.4 RETRACE - RIVTOX chain validation on the base of Ilya River case study

The Ilya river watershed is the first object for a validation of the whole chain of the hydrological modelling starting from the precipitation – the infiltration the surface runoff the sub-surface runoff - and finally the channel flow. This exercise will also include the toxicological part with the surface runoff and wash-off and the migration in the river net. The catchment of the Ilya River, which is the tributary to the Uzh River (flowing into the Kiev Reservoir), is situated mainly in the 30-km Chernobyl zone (Figure 16) and has a sizes of about 20 km in longitudinal direction and of about 15 km in the lateral direction. The data measured in 1988 by the SPA Typhoon (Obninsk, Russia) and the Ukrainian Hydrometeorological Institute (Kiev, Ukraine) were used in this validation study (Figure 17). The following set of the data is taken into account:

- the map of soil contamination;
- the meteorological scenario (daily precipitation);
- the water discharge at the outlet;
- the concentration of soluble and sorbed forms of  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  at the outlet;
- the contamination of bottom sediments.

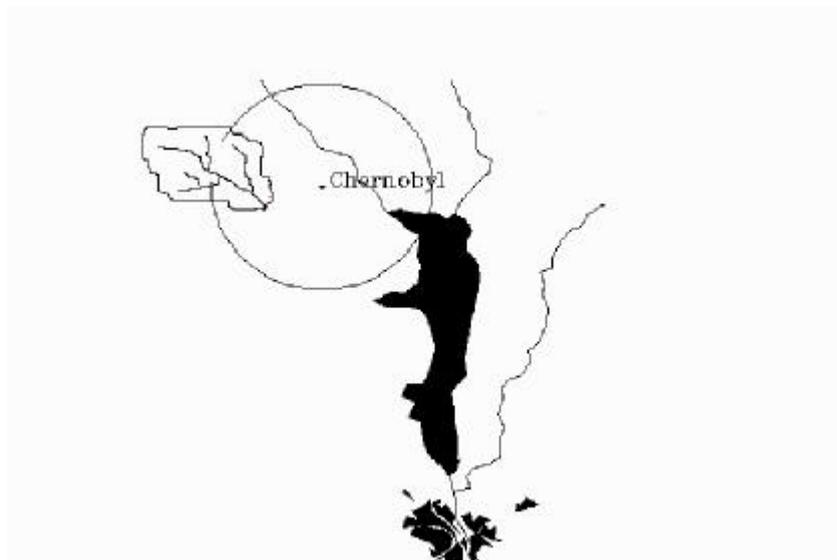
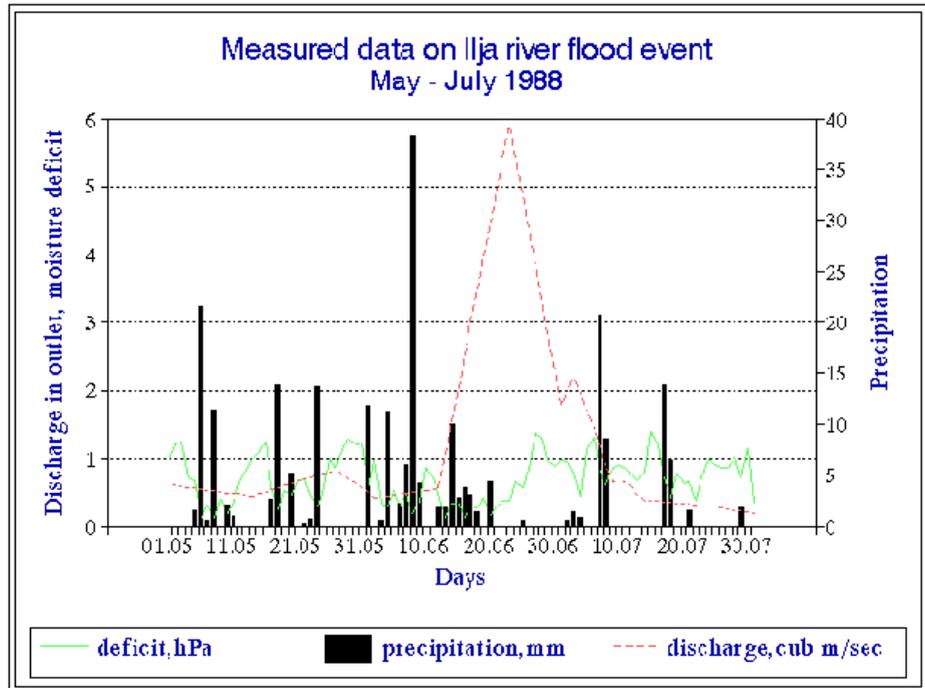
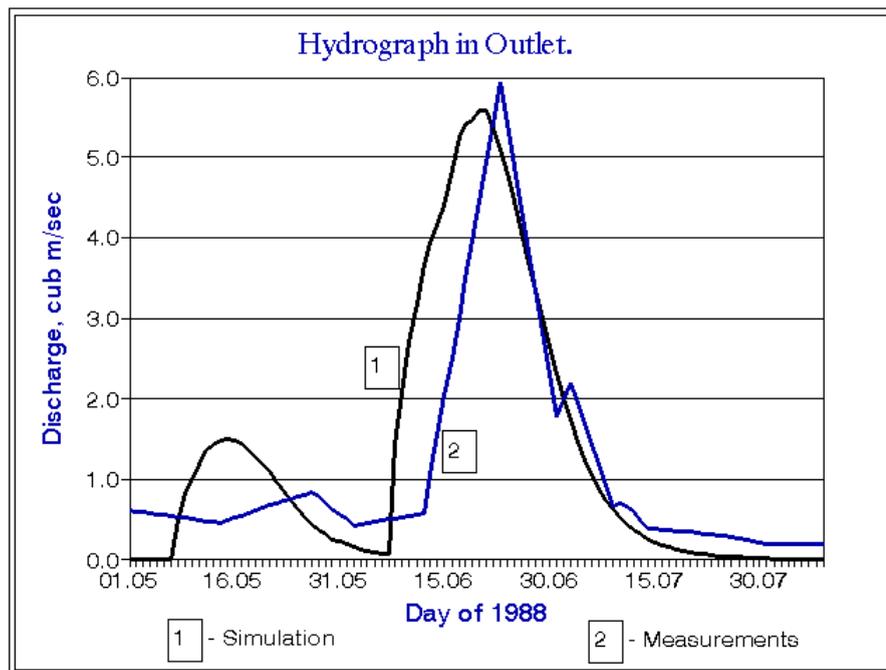


Figure 16: Ilya river basin

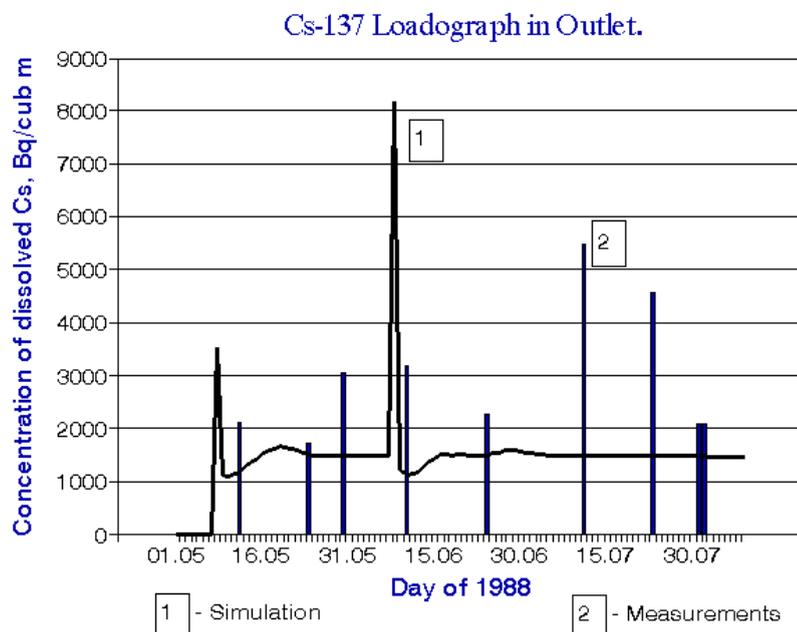


**Figure 17: Meteorological and hydrological data for the Ilya river basin**

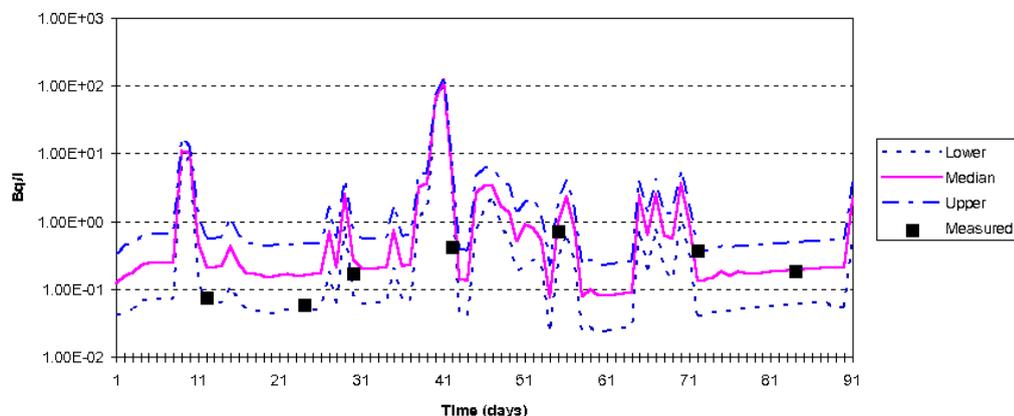
The lateral inflow into the river net is simulated by the RETRACE (Figure 18) and was then used by RIVTOX to simulate the transport in the river channels taking into account the interaction between radionuclides in the solution and on the suspended sediments (Figure 19). The limited measured data are not coincident with the exact moments of the short rainstorm floods at the river. Therefore, the comparison of the measured and calculated radionuclide concentrations should be done for averaged rather than for peak values. The uncertainties of the RIVTOX modelling were evaluated using the Monte-Carlo techniques for water-sediment exchange parameter variations. The measured data are within 90% confidence intervals of simulated  $^{137}\text{Cs}$  concentration on the sediments (Figure 20).



**Figure 18: Measured (2) and simulated (1) hydrograph in outlet of Ilya river.**



**Figure 19: Cs-137 in surface runoff; daily averaged concentration in runoff from the Ilya River catchment (simulation by RETRACE)**



**Figure 20: RIVTOX Simulation of  $^{137}\text{Cs}$  concentration on suspended sediment at the outflow from the Ilya River**

### **6.5 RIVTOX implementation for the simulation of consequences of an accidental release from the Kharkov sewage system (summer 1995)**

The RIVTOX was used in Ukraine in summer 1995 to evaluate the consequences of the extended accidental release of the Kharkov municipal waste water to the rivers. Within several days, the model as the part of the RODOS hydrological chain was customized and adopted by IMMSP to simulate the chemical and bacteriological contamination of the Udy River the Siversky Donets River aquatic system. Based on the request from the State Emergency Commission, several calculations have been provided to evaluate the amount of water that should be pumped to the Siversky Donets trough the channel from the Dnieper River to improve the water quality to permissible levels. This countermeasure on the basis of the RODOS' hydromodule calculations was successfully implemented by the Ukrainian State Committee on the Water Resources (Figure 21).

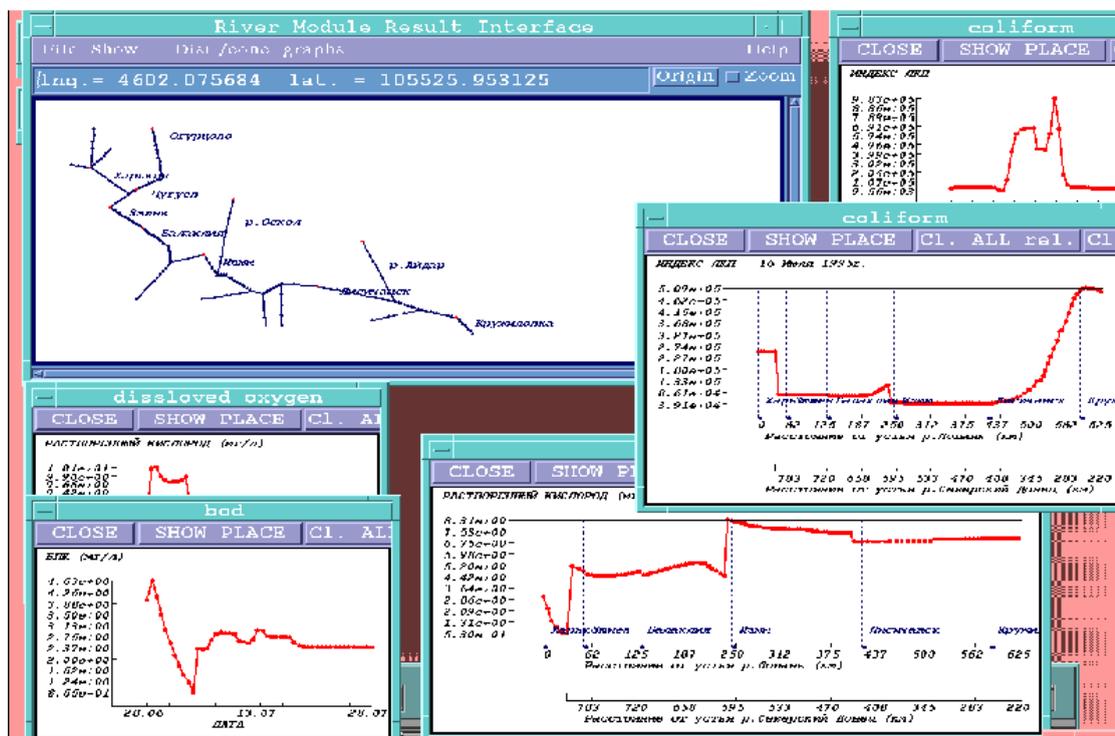


Figure 21: RIVTOX implementation for prognosis and decision support on the case of accident at Kharkiv sewerage

## 6.6 Accidental releases from Bohunice NPP to Dudvakh River-Vakh River

RIVTOX was implemented in collaboration with VUJE, Trnava, Slovakia to simulate the radionuclide transport in the river system of the Dudvakh River-the Vakh River and the Bohunice NPP.

The waste water from the NPP “Bohunice” at Jaskovske Bohunice, Slovakia is released through the technological 15 km long pipeline into the Vah River. Another pathway for radionuclides released from the NPPs during the accident (or regularly during switch off the technological pipeline) is the 5.2 km long Manivier canal with the concrete paved bed that transports water from the NPP units cooling towers to the Dudvah River, that is right tributary of the Vah River. The last accidental release of  $^{137}\text{Cs}$  from the Unit A-1 occurred by this way in January 1989 that highly contaminated the bottom sediments of the canal and of the Dudvah River.

The data collected in VUJE for this accident provides a unique possibility to test the model of the direct release of radionuclide into the river system and its propagation in the river net from first hours after the accident. The implementation of the RIVTOX for this situation (Slavik et al., 1997) has demonstrated the needs to use two –step radionuclide exchange kinetic

submodels to simulate radionuclide dynamics in the first post-accidental hours.

The detailed description of these results are presented in the publication of Slavik et al., 1997.

## Conclusion

The report presents the modules, the numerical algorithms and the results of the case validation studies of the the one-dimensional model RIVTOX, developed at IMMSP, Cybernetics Centre, Kiev to simulates the radionuclide transport in the networks of the river channels. The Sources can be a direct release into a river or a runoff from the catchment.

The model is implemented into the Hydrological Dispersion Module (HDM) of the RODOS coupled with the watershed radionuclide runoff model RETRACE-2.

As the part of the RODOS HDM the RIVTOX code was implemented and tested for the case studies of the River Rhine, the Dudvakh River-the Vakh River (Slovakia), the Iljya River (the Pripjat River Basin, Ukraine).

The model was tested and verified in different case studies (the Dniper River, the Clinch River-the Tennessee River and others). Some of these results are also presented in the Report.

The graphical user interface of the RIVTOX and User Manual are presented in the separate reports.

## REFERENCES

- Ackers P., White R. Sediment transport: new approach and analyses. J.Hydr.Div. ASCE, v99, No.11, 2041-2060 (1973).
- ANONYMOUS, Methodology for evaluating the radiological consequences of radioactive effluents released in normal operations, National Radiological Protection Board, Chilton, United Kingdom (1994).
- ANONYMOUS, Guidelines for calculating derived release limits for radioactive material in airborne and liquid effluents for normal operation of nuclear facilities, CAN/CSA-N288.1-M87, Canadian Standards Association Ed., Toronto, Ontario, Canada, 69p (1987).
- Benes P., Cernik M., Slavik, O., Modelling of Migration of  $^{137}\text{Cs}$  Accidentally Released into a Small River. J. Environ. Radioactivity **22**, 279-293 (1994).
- Benes P., Cernik, M., Model Calculations and Experimental Analysis of Transport of Radiocesium in the System Wastewater Channel - Dudvah (in Czech Republic). Report of the Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Prague 1990.
- Bijker E.W, Some considerations about scales for coastal models with movable bed, Delft Hydr. Lab., Publ. No 50, 1968.
- Booth R.S, A system analysis model for calculating radionuclide transport between receiving water and bottom sediments, Oak Ridge National Lab., ORNL-TM-4751, 1975, 37p.
- Borzilov, V.A., Sedunov, Yu.S., Novittsky, M.A., et al., Forecasting of secondary radioactive contamination of the rivers in 30-th kilometers zone of the Chernobyl NPP, Meteorologia i Gidrologia, 2, 5-13 (1989) (In Russian).
- Burkov A., Gerasimenko A., Jobson H., Novitsky M., Voszhennikov O., Zheleznyak M. Methods of calculating and forecastng pollutant transport in water bodies. - Hydrological aspects of accidental pollution of water bodies. Ch.6, Operational Hydrological Report No.37, WMO -No 754, Geneva, Switzerland, pp.65-92., 1992.
- Callendar E., Robbins J. Transport and acumulation of radionuclides and stable elements in a Missouri River Reservoir. - Water Resources Research, v. , No. 1992
- Chang H.H. Fluvial processes in river engineering. - New York: Wilcy, 1988. - 105 p.
- Chapman B.M. Numerical simulation of the transport and speciation of nonconservative chemical reactions in rivers. //Water Resources Research, Vol. 18, No.1, 1982, p. 155-167.
- Chen, Y.H. Development of a quasi-nonequilibrium reservoir sedimentation model: REDSED. //In: Twelve Selected Computer Stream Sedimentation Models Developed in the United States, edited by S-S. Fan, Federal Energy Regulatory Commition, Washington, D.C., 1988, p. 491-510.
- CHR/KHR (1978), "Das Rheingebiet, Hydrologische Monographie / Lebassin du Rhin, Monographie hydrologique", Staatsuitgeverij Den Haag, ISBN 90-12-775-0.
- Codell R.B., Key K.T., Whelan G. Collection of mathematical models for radionuclide dispersion in surface water and ground water. //NUREG - 0868, 1982. - 271 p.

- Colon R., McMahon G.F. BRASS model: application to savannah river system reservoirs. //J. Water Resour. Plann. Manage., 1987, vol. 113, no. 2, p. 177-190.
- Coppe, P., Estimated models of impact used by Electricité de France within the framework of the french and european regulations, Radioprotection, Special issue, Proc. of the joint seminary from September 15th to 18th 1992, Fribourg, Switzerland, 185-189 (1993).
- Cunge J.A., Holly F.M. and Verwey A. (1980) Practical Aspects of Computational River Hydraulics, Pitman Publishing Ltd., London.
- Cunge J.A., Holly F.M., Verwey A., Practical Aspects of Computational River Hydraulics, Pitman Publ., London, 250p., 1986.
- Deutsches Gewässerkundliches Jahrbuch des Rheingebiets, Teil 1, 2, 3. 1989.
- Ehrhardt, J. The RODOS system: decision support for off-site emergency management in Europe. -Radiation Protection Dosimetry, 1997, v.73, No.1-4, pp.35-40
- Elder J.W, 1958, *The dispersion of marked fluid in turbulent shear flow*, Cavendish laboratory, University of Cambridge, Fluid mechanics 5
- Engelund F., Fredsoe J., A sediment transport model for straight alluvial channels. - Nordic Hydrology, 7, (1976), pp.293-306
- Eraslan A.H., Akin E.J., Barton J.M., Bledsoe J.L., Cross K.E., Diament H., Fields D.E., Fisher S.K., Harris J.L., Hetrick D.M., Holdeman J.T., Kim K.K., Lietzke M.H., Park J.E., Patterson M.R., Sharp R.D., Thomas B. Development of a unified transport approach for the assessment of power-plant impact. //ORNL/NUREG/TM-89, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1977. - 409 p.
- Fields D.E. CHNSED: simulation of sediment and trace contaminant transport with sediment/contaminant interaction. //ORNL/NSF/EATC-19, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1976. - 170 p.
- Fields D.E. HOTSET: a one dimensional, tidal-transient, discrete element model for simulating hydrodynamic conditions and absorbed and dissolved radioisotope concentration in controlled rivers and estuaries. //ORNL/CSD-16, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1977. - 227 p.
- Fischer H.B, 1973, *Longitudinal dispersion and turbulent mixing in open-channel flow, annual review fluid mechanics*, University of California
- Fletcher C.A.J., 1988, *Computation Techniques for Fluid Dynamics: Fundamental and General Techniques*, Springer-Verlag, Berlin-Heidelberg-London. Ch.1,2
- Gofman D., Lyashenko G., Marinets A., Mezhueva I., Shepeleva T., Tklich P., Zheleznyak M. Implementation of the Aquatic Radionuclide Transport Models RIVTOX and COASTOX into the RODOS System. //The radiological consequences of Chernobyl accident. Proceedings of the first international conference. Minsk, Belarus 18 to 22 March 1996. Editors A.Karaoglou, G.Desmet, G.N.Kelly and H.G.Menzel. European Commission. Luxembourg, 1996, p.1181-1184.
- Handbook of parameter values for the prediction of radionuclide transfer in environments. //IAEA Technical Report No. 364, Vienna, 1994. - 284 p.
- Havno K., Madsen M.N., Dorge J. MIKE 11 -a generalized river modelling package.- *Computer Models of Watershed Hydrology* (Ed. V.P. Singh), Water Resources Publications, USA, 1995.- p.p.733-782 .
- Heling R., Zheleznyak M., Raskob W., Popov A., Borodin R., Gofman D., Lyashenko G., Marinets A., Pokhil A., Shepeleva T., Tklich P. Overview of

- modelling of hydrological pathways in RODOS. - Radiation Protection Dosimetry, 1997, v.73, No.1-4, pp.67-70
- Hofer H., Bayer A. Calculation of radionuclide dispersion in flowing waters with a dynamic model., Kerntechnik, v.58, No3, (1993) 164-169
- Holly F.M, Dispersion in rivers and coastal waters. -1.Physical principles and dispersion equations. Developments in Hydraulic Engineering., 3(1987)1-37.
- Holly F.M., Yang J.C., Schwarz P., Schaefer J., Hsu S.H., Einhellig R. CHARIMA: numerical simulation on unsteady water and sediment movement in multiply connected networks of mobile-bed channels. //IIHR Report No. 343, Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa. 1990. - 327 p.
- Hubel K., Erstellung eines dynamischen Modells zur Berechnung der Strahlenexposition über den Wasserpfad bei stehenden und fließenden Gewässern. Jahresbericht Bayerische Landesanstalt für Wasserforschung (St.Sch.1071), München 1989
- Hydrologic Engineering Center. HEC-2 water-surface profiles users manual. //U.S. Army Corps of Engineering, Davis, California. 1982. - 402p.
- Hydrologic Engineering Center. HEC-6 scour and deposition in rivers and reservoirs. //U.S. Army Corps of Engineering, Davis, California. 1977. - 295 p.
- Hydrological Dispersion of Radioactive Material In: Relation to Nuclear Power Plant Siting, Safety Series N50-SG-S6, IAEA, Vienna, 1985, 116p.
- IAEA, Safety Series N 100, Evaluation the Reability of Predictions Made Using Environmental Transfer Models, IAEA, Vienna, 1989;
- IAEA, Safety Series N50-SG-S6, Hydrological Dispersion of Radioactive Material in Relation to Nuclear Power Plant Siting, Vienna, 116p (1985).
- Jannasch H.W., Honeyman B.D., Balistreri L.S. and Murray J.W. (1988) Kinetics of trace element uptake by marine particles. Geochim. Cosmochim. Acta 52, 567-577.
- Jobson H.E. Users manual for a flow model based on the diffusion analogi. //U.S. Geological Survey, Resfton; Virginia, 1989. - 56 p.
- Karim M.F., Holley F.M., Yang J.C. IALLUVIAL numerical simulation of mobile-bed rivers, part theoretical and numerical principles. //IIHR Report No. 309, Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa, 1987. - 198 p.
- Karim M.F., Kennedy J.F. Computer-based predictors for sediment discharge and friction factor of alluvial streams. //IIHR Report No. 242, Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, Iowa, 1981. - 273 p.
- Konoplev A.V., Bulgakov A.A., Popov V.E., Bobovnikova, Ts. I. Behaviour of Long-lived Chernobyl Radionuclides in a Soil-Water System. Analyst 117, 1041 (1992).
- Konoplev A.V., Bulgakov, A.A., Popov, V.E., Bobovnikova, Ts. I. Behaviour of Long-lived Chernobyl Radionuclides in a Soil-Water System. Analyst 117, 1041 (1992).
- Konoplev A.V., Golubenkov A.V. Modelling of the vertical migration in soil as result of a nuclear accident. Meteorologia i Hidrologia. v. 10, 62-68(1991)
- Liquid pathway generic study. Impact of accidental radioactivity releases to hydrosphere from floating and land-based nuclearpower plants. //United States Nuclear Regulatory Commission. USNRC, NUREG-0440, 1978. - 212 p.

- Marinets A., Gofman D., Zheleznyak M. Using GIS for modelling radionuclide transport in complex river-reservoir network. - HydroGIS 96: Application of Geographical Information Systems in Hydrology and Water Resources Management (Proc. of Vienna Conf. 1996) IAHS Publ. No. 235, 1996, 325- 330.
- Mazijk van A. One dimensional approach of transport phenomena of dissolved matter in rivers. – Communication on Hydraulic and Geotechnical Engineering. – Delft University of Technology, Faculty of Civil Engineering, Report No. 96-3, September 1996, -310 p.
- Mehta J., Hayter P., Parker W., Krone R., Teeter A., Cohesive sediment transport. I: Process description. J. Hydraul. Eng., 115 (1989) 1076-1093
- Modelling and study of the mechanisms of the transfer of radioactive material from terrestrial ecosystems to water bodies, (1996) Final report ECP-3 Project, CEC-Belarus, Russia, Ukraine Programme on the radiological consequences of the Chernobyl accident.
- Morozov A., Zheleznyak M., Aliev K., Bilotkach U., Votsekhovitch O. Prediction of radionuclide migration in the Pripjat River and Dnieper Reservoirs and decision support of water protection measures on the basis of mathematical modelling.- Book of Extended Synopsesc. International Conference “One Decade after Chernobyl: Summing up the Radiological Consequences of the Accident”, Vienna, Austria 8-12 April 1996
- Mundschenk H., Tolksdorf W. Methodische Untersuchungen zur Sedimentation mit Hilfe radioactiver Leitstoffe am Beispiel eines Kleinhafens am Mittelrhein. Deutsche Gewässerkundliche Mitteilungen 32 (1988) 110-119
- Mundschenk H, W.J. Krause, G. Dersch and P. Wengler, “Überwachung der Bundeswasserstrassen auf radioaktive Stoffe im Normal- und Ereignisfall. Konzept, Methoden und Ergebnisse.”, Bundesanstalt für Gewässerkunde, Koblenz, 1994, Bericht BfG-0783.
- Onishi Y., Wheelan, G., Skaggs, R.L., Development of a Multi-media Radionuclide Exposure Assessment Methodology for Low-Level Waste Management, PNL-3370, Pacific Northwest Laboratory, Richland, Washington D.C., (1982).
- Onishi Y. Sediment transport models and their testing. - In NATO Advanced Studies Institute Lecture Series, Pullman, WA, 1993
- Onishi Y., Mathematical simulation of sediment and radionuclide transport in the Columbia River, Battelle Pacific Northwest Lab., Richland, Washington D.C., Rep. BNWL-2228, (August 1977).
- Onishi Y., Serne J., Arnold E., Cowan C., Thompson F., Critical review: radionuclide transport, sediment transport, water quality, mathematical modeling and radionuclide adsorption/desorption mechanism, NUREG/CR-1322, Pacific Northwest Laboratory, Richland, 1981, 512p.
- Onishi, Y., Sediment and Contaminant Transport Model, Journal of Hydraulic Division, American Society of Civil Engineers, 107 (HY9) 1089-1107 (September 1981).
- Orlob G.T.(Ed.), Mathematical Modeling of Water Quality: Streams, Lakes, and Reservoirs, International Series. on Applied Systems Analysis, IASA, Pitman Press, 12 (1983) -518p..
- Raudkivi A. Loose boundary hydraulics, Pergamon Press, N.Y., (1967)
- Rijn, van L.C., Model for sedimentation predictions In: XIX Congr. International Association for Hydraulic Research, Congress Proceedigs, New Delhi, India, 3(1981) 321-328.

- Rijn van L.C., Sediment transport, Part I: Bed load transport. J. Hydraul.Engineering, 110(1984), pp 1431- 1456.
- Rijn van L.C., Sediment transport, Part II: Suspended load transport. J. Hydraul.Engineering, 110(1984) 1613- 1641.
- Santschi P.H., Honeyman B.D., Radionuclides in aquatic environments. Radiation Phys. and Chem., v.34, 2(1989) 213-240&
- Schnoor J.L., D.J.Mossman, V.A.Borzilov, M.A.Novitsky, O.I.Voszhennikov, A.K.Gerasimenko. (1992) Mathematical model for chemical spills and distributed source runoff to large rivers, In: Fate of Pesticides and Chemicals in the Environment, J.L.Schnoor, (Ed.) John Wiley&Sons,Inc.
- Schuckler M., Kalckbrenner R.,Bayer A, Zukunftige radiologische Belastung durch kerntechnische Anlagen im Einzugsgebiet des Oberrheins, T.2, Belastung uber denWasserweg, Conference Dusseldorf Proceedings, ZAED, Eggenstein-Leopoldshafen, 1976.
- Shin C.S., Gloyna E.F. Mathematical model for the transport of radionuclides in stream system. //Environmental surveillance in the vicinity of nuclear facility. /Reinig W.C., Charles C. ed., Thomas Publishing Co., Springfield, Illinois, 1970, p. 518-532.
- Slavik O., Zheleznyak M., Dzuba N., Marinets A., Lyashenko G., Papush L., Shepeleva T. Mihaly B. Implementation of the decision support system for the river-reservoir network affected by releases from the Bohunice NPP, Slovakia - *Radiation Protection Dosimetry*, 1997, v.73, No.1-4, pp.171-175
- Slavik O., Zheleznyak M., Dzuba N., Marinets A., Lyashenko G., Papush L., Shepeleva T. , Mihaly B. Implementation of the decision support system for the river-reservoir network affected by releases from the Bohunice NPP, Slovakia - *Radiation Protection Dosimetry*, 1997, v.73, No.1-4, pp.171-175
- Smitz, Y., Everbecq, E., Modeling the Behaviour of Radionuclides in Aquatic Ecosystems, Paper presented at CEC Seminar on Cycling of Long-Lived Radionuclides in the Biosphere: Observations and Models, Madrid, September 1986.
- Sørensen, H.R., Kjelds, J., Deckers, F., Waardenburg, F. (1996a): Application of GIS in hydrological and hydraulic modelling: DLIS and MIKE11-GIS. HydroGIS 96: Application of Geographic Information Systems in Hydrology and Water Resources Management. Proc. Vienna, April 1996, (IAHS Publ. no. 235, 1996).
- Tkalich P., Zheleznyak M., Lyashenko G., Marinets A. RIVTOX - Computer Code to Simulate Radionuclides Transport in Rivers, //A. Peters et al.( eds.) , Computational Methods in Water Resources X, vol. 2, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1994, pp. 1173-1180.
- Tkalich P., Zheleznyak M., Lyashenko G., Marinets A. RIVTOX - Computer Code to Simulate Radionuclides Transport in Rivers, //A. Peters et al.( eds.) , Computational Methods in Water Resources X, vol. 2, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1994, pp. 1173-1180.
- USNRC, Liquid pathway generic study, United States Regulatory Commission, Rep. NUREG-0440, Washington D.C., (February 1978).
- Voitsekhovitch O., Sansone U., Zheleznyak M., Bugai D. Water quality management of contaminated areas and its effect on doses from aquatic pathways . //The radiological consequences of Chernobyl accident. Proceedings of the first international conference. Minsk, Belarus 18 - 22 March 1996. Editors A.Karaoglou, G.Desmet, G.N.Kelly and H.G.Menzel, European Commission. Luxembourg,1996, p.p. 401-410.

- Voitsekhovitch O.V., Zheleznyak M.J., Onishi Y. Chernobyl nuclear accident hydrological analyses and emergency evaluation of radionuclide distribution in the Dnieper River, Ukraine during the 1993 summer flood. - Pacific Northwest Laboratories, Battelle, PNL-9980, Richland, Washington, June 1994, - 96 p.
- Westall I.C., Zachary J.L., Morel F.M. MINEQL: a computer program for the calculation of chemical equilibrium composition of aqueous systems. //Tech. Note 18, Dept. Civil Eng., Massachusetts Institute of Technology, Cambridge, Massachusetts, 1976. - 102 p.
- White A., Gloyna E.F. Radioactivity transport in water-mathematical simulation. //EHE-70-04, Technical report No. 19, prepared for the U.S. Atomic Energy Commission by the University of Texas, Austin, Texas, 1969. - 231 p.
- Won Seo I, Sung Cheong T, 1998, Predicting longitudinal dispersion coefficient in natural streams, J.Hydraulic Eng., Proc.ASCE. g
- Zheleznyak M. Multiple scale analyses of radioactive contamination for rivers and reservoirs after the Chernobyl accident. - Multiple Scale Analyses and Coupled Physical Systems. Proc. Saint-Venant Symposium, August 28-29, 1997, Presses de l'ecole nationale des ponts et chaussees, Paris, 1997, p.p. 45-52.
- Zheleznyak M., Mathematical models of radionuclide dispersion in a reservoir set In: System Analysis and Methods of Mathematical Modelling in Ecology, V.Glushkov Institute of Cybernetics, Kiev, 1990, 48-58 (in Russian).
- Zheleznyak M., Blaylock G., Gontier G., Konoplev A. et al. Modeling of radionuclide transfer in rivers and reservoirs: validation study within the IAEA\CEC VAMP Programme. International Symposium on Environmental Impact of Radioactive Releases, IAEA, Vienna, 8-12 May 1995, IAEA-SM-339, IAEA, 1995, p.330-331
- Zheleznyak M., Demchenko R., Khursin S., Kuzmenko Yu., Tkalich P., Vitjuk N. Mathematical modeling of radionuclide dispersion in the Pripyat-Dnieper aquatic system after the Chernobyl accident. -The Science of the Total Environment. 1992, v.112, p.89-114.
- Zheleznyak M., Demtchenko R., Kuzmenko Yu., Tkalich P., Dzuba N., Mezhueva I. Mathe-matical modelling of radionuclide dispersion in the water bodies of the Chernobyl NPP zone and in the Dnieper Reservoirs.- Hydrological Impact of Nuclear Power Plants. Proc. UNESCO Workshop-92, UNESCO Press, Paris,1993, pp.173-185
- Zheleznyak M., Heling R., Raskob W., Popov A., Borodin R., Gofman D., Lyashenko G., Marinets A., Pokhil A., Shepeleva T., Tkalich P. Modelling of Hydrological Pathways in RODOS. //The radiological consequences of Chernobyl accident. Proceedings of the first international conference. Minsk, Belarus 18 - 22 March 1996. Editors A.Karaoglou, G.Desmet, G.N.Kelly and H.G.Menzel. European Commission. Luxembourg, 1996, p.p.1139-1148.
- Zheleznyak M., Kuzmenko Yu., Tkalich P., Dzuba N., Gofman D., Golovanov I., Marinets A., Mezhueva I. Modelling of Radionuclides Transport in the Set of River Reservoirs.//A. Peters et al.( eds.) , Computational Methods in Water Resources X, vol. 2, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1994, pp. 1189 - 1196
- Zheleznyak M., Marinets A. Modelling of long wave propagation in river channels on the base of "diffusion wave" equation, In book: Copmputational Technologies, v.2, N 6, 1993, Novosibirsk, Institute of Computational Technologies of Russian Academy of Sciences, p.147-154 (In Russian)
- Zheleznyak M., Tkalich P.V., Lyashenko G.B., Marinets A.V. Radionuclide aquatic dispersion model-first approach to integration into the АÑ decision support

system on a basis of Post-Chernobyl experience. - Radiation Protection Dosimetry, N6, 1993, pp.37-43.

Zheleznyak M., Vojtcekhovich O., Demchenko R., Kuzmenko Yu., Tkalich P., Khursin S., Simulating the effectiveness of measures to reduce the transport of radionuclides in the Pripyat-Dnieper - Proc. International Seminar on Intervention Levels and Countermeasures for Nuclear Accidents. Cadarashe, France, 7-11 October 1991.-Commission of the European Communities, Radiation Protection-54, EUR 14469, 1992, p.336-362.

## Document History

Document Title: RIVTOX - one dimensional model for the simulation of the transport of radionuclides in a network of river channels  
RODOS number: RODOS-WG4-TN(97)05  
Authors/Editors: M.Zheleznyak, G.Donchytz, V.Hygynyak, A.Marinetz, G.Lyashenko, P.Tkalich  
Affiliation: Institute of Mathematical Machines and System Problems (IMMSP)  
Address: Prospect Glushkova 42, Kiev, 03187, Ukraine  
E-Mail: mark@immsp.kiev.ua  
Date of Issue: first draft version – June, 1998, revised – July, 2000  
File Name: RIVTOX-WG4 -97(05).doc