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JAEA – 2nd Caesium Workshop: meeting challenges for Fukushima recovery, 6-9 October,2014

Mathematical Modeling of Radiocesium Transport through the Subsurface Environment, Rivers, Reservoirs, and Watersheds for Justification of Post-Accident Countermeasures: Experience of Post Chernobyl Studies and Testing of the Applicability to Fukushima Conditions

Sergii Kivva, Mark Zheleznyak, Kenji Nanba

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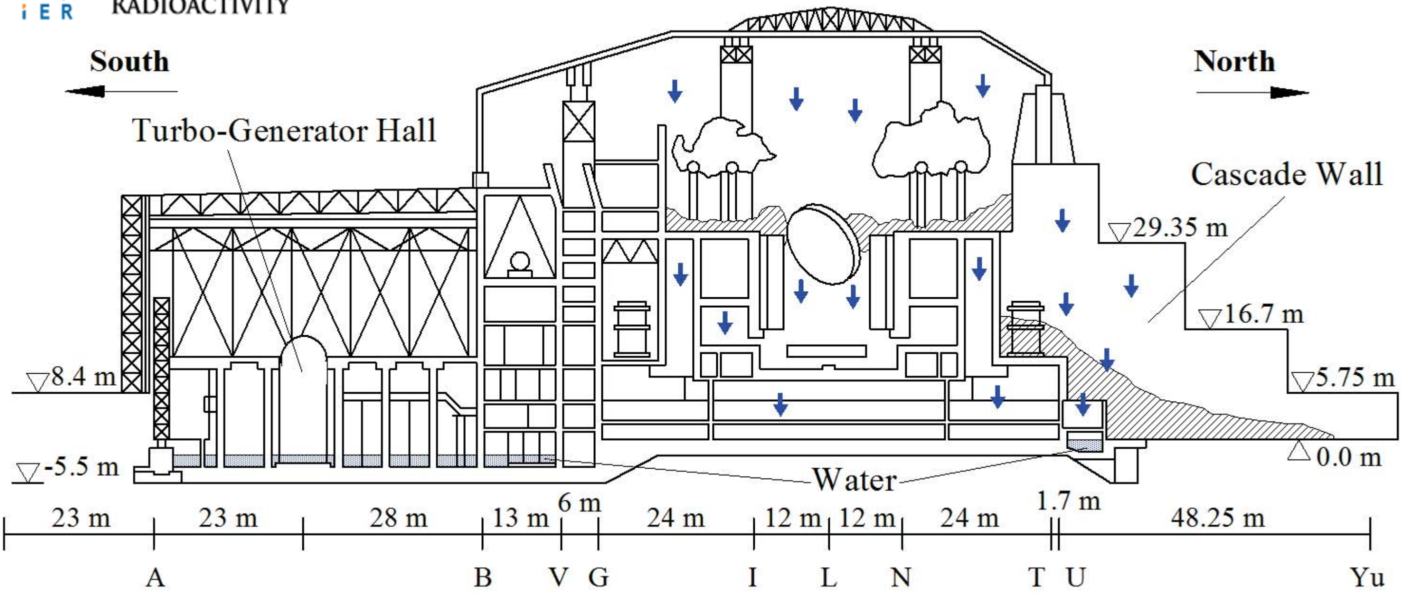
Environmental Impact Assessment of the Chernobyl NPP Unit-4 Shelter

Primary Objectives:

- To evaluate impact assessment of the Shelter on contamination of the subsurface environment;
- To evaluate impact assessment of the Shelter on contamination of the Pripyat river.



Schematic of the Chernobyl Unit-4 Shelter, water pathways and water locations within the Shelter. North-South Cross-Section along Axis 47.

Area of breaks and openings in the roof and the walls of the Shelter was ~1200 m^2

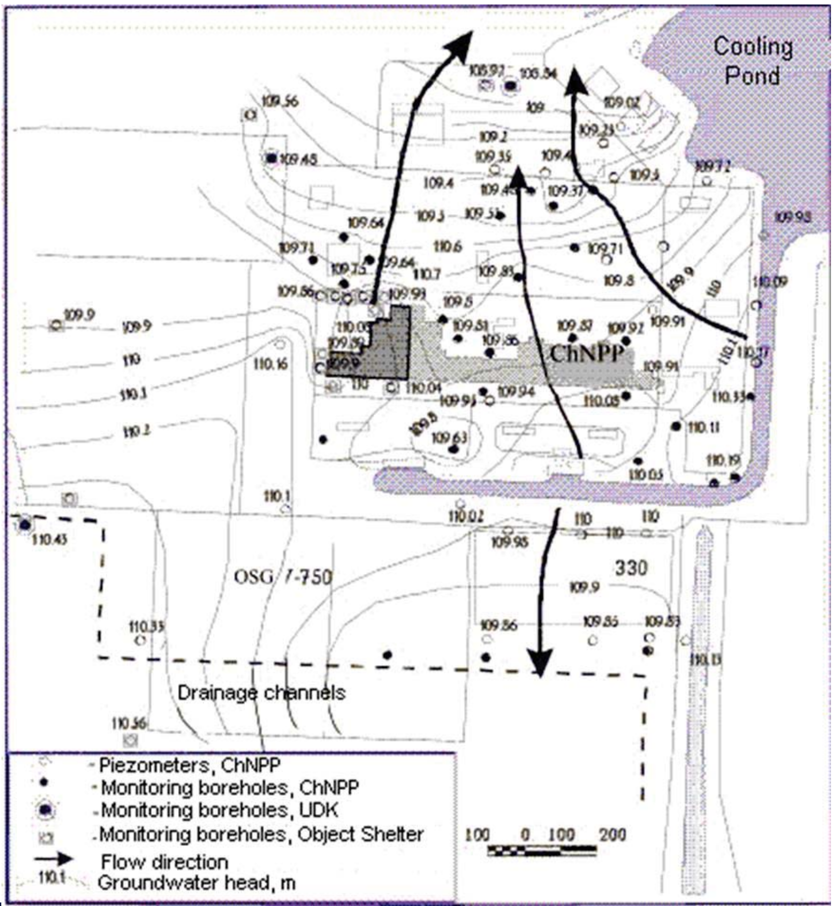
Main water sources inside the Shelter:

- **Rain ~ 1000 m^3 per year;**
- **For dust suppression ~ 30 m^3 per month**

Activity of contaminated water inside the Shelter:

Cs-137: $1.6 \times 10^2 \div 5.5 \times 10^4$ **kBq/L**

Sr-90: $3.6 \div 1.1 \times 10^3$ **kBq/L**



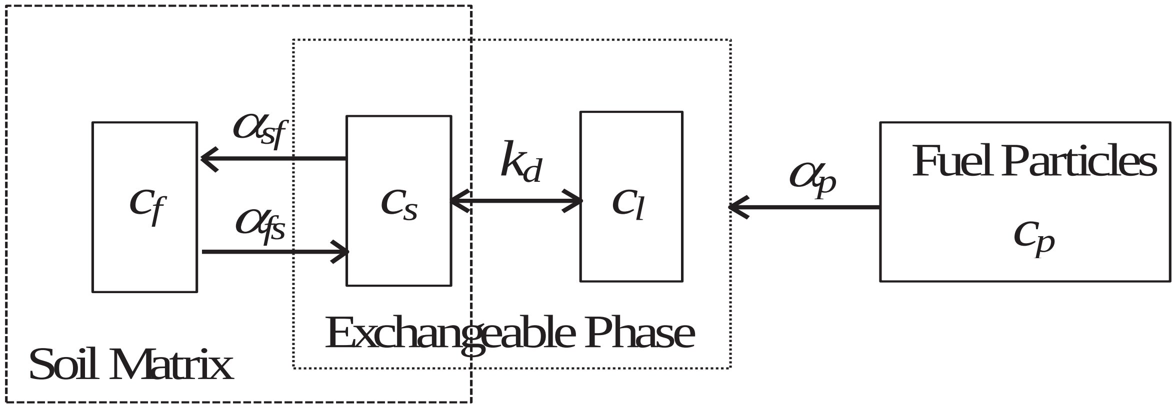
Groundwater levels of unconfined aquifer and groundwater stream lines in the ChNPP Near Zone

Model assumptions:

- Liquid flow through the subsurface environment occurs in response to gradients in liquid pressures and gravitational body forces according to Darcy’s flow law;
- Species transport through the variably saturated porous media occurs by molecular diffusion, hydrodynamic dispersion, and advection;
- Interphase species mass transfer between exchangeable sorbed solid and aqueous phases is assumed being under thermodynamic and geo-chemical equilibrium conditions;
- Slow sorption/desorption processes between exchangeable sorbed solid and fixed solid phases are considered as non-equilibrium exchangeable processes

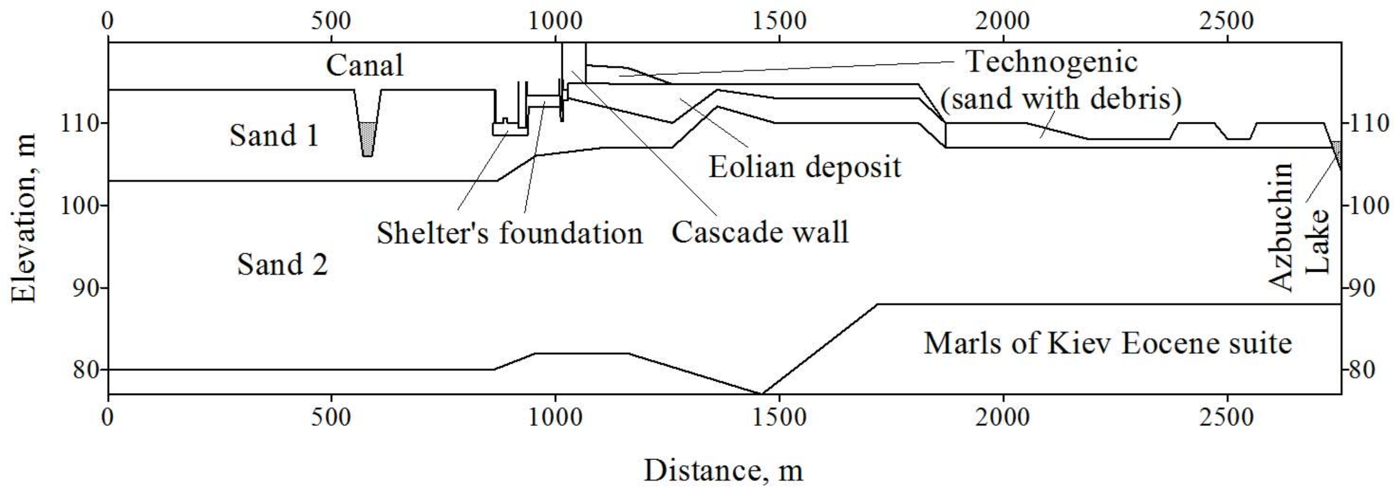
Radionuclide phases:

- Aqueous phase;
- Exchangeable sorbed in solid phase;
- Fixed in the mineral lattice;
- Fuel particles.

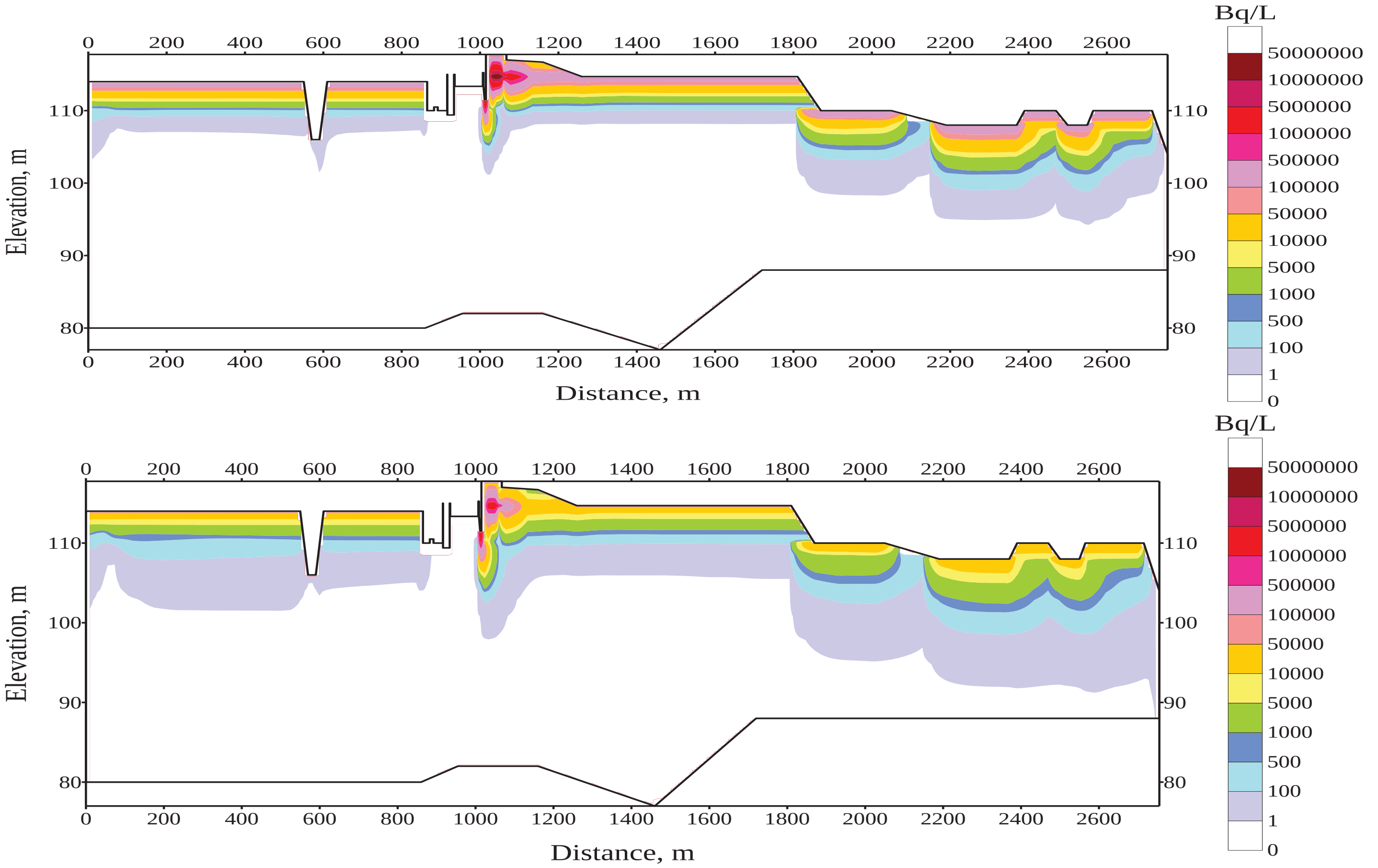


Schematic representation of the kinetic sorption model

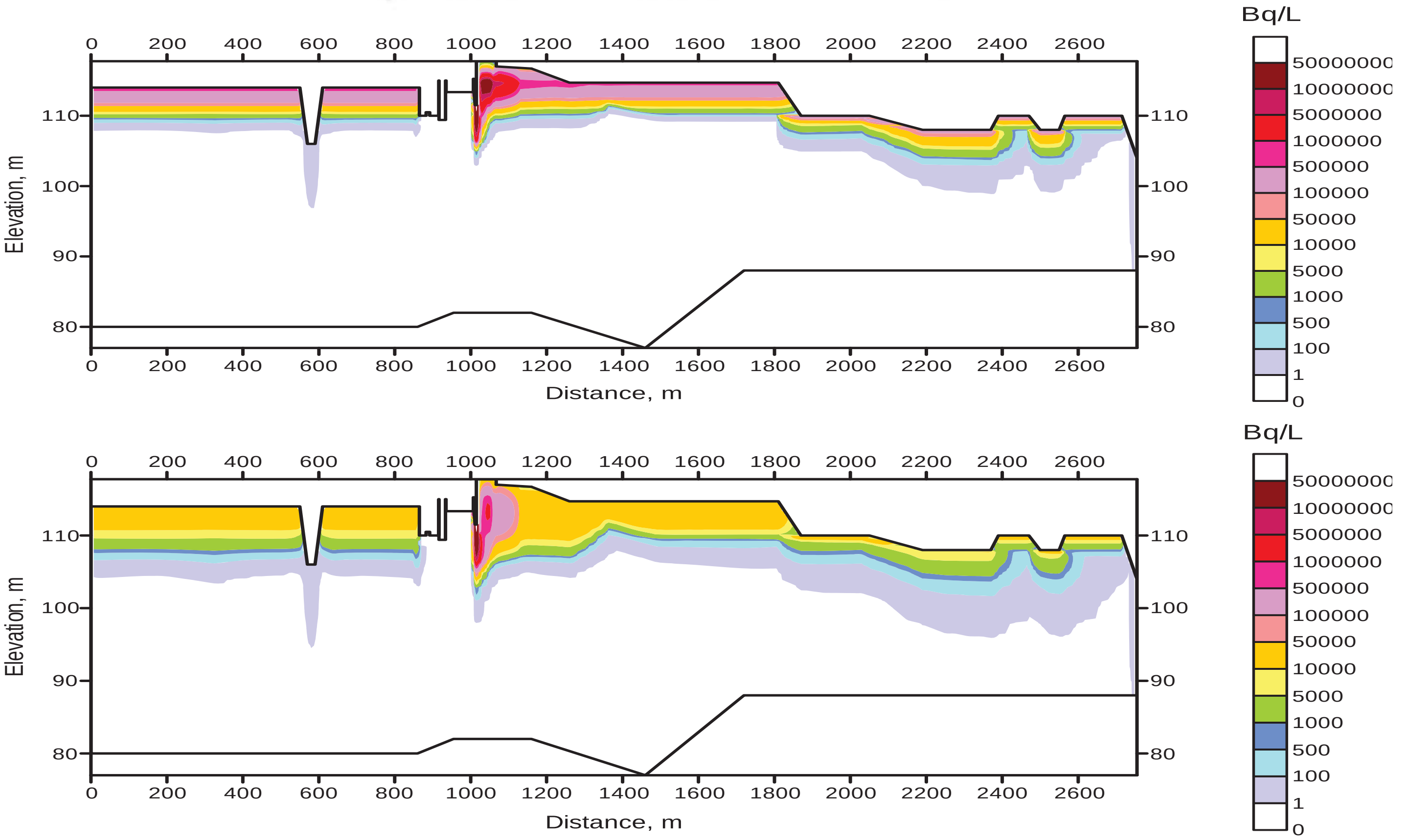
Schematic representation of the geologic section



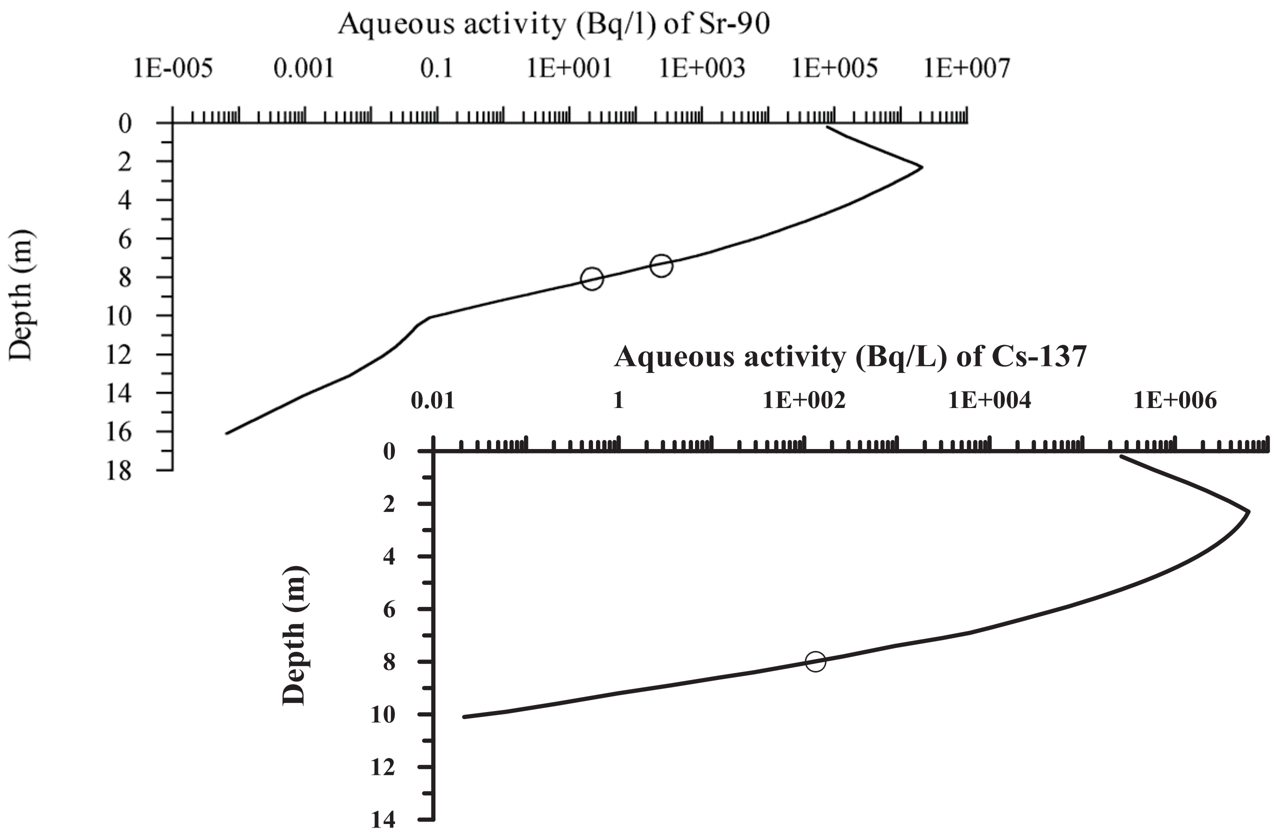
Predicted activity of 90Sr (Bq/L) in the aqueous phase in 1995 (upper) and 2045 (lower)



Predicted activity of 137Cs (Bq/L) in the aqueous phase in 1995 and 2045



Comparison of predicted and measured activity-depth profiles of radionuclides in the aqueous phase in 1995



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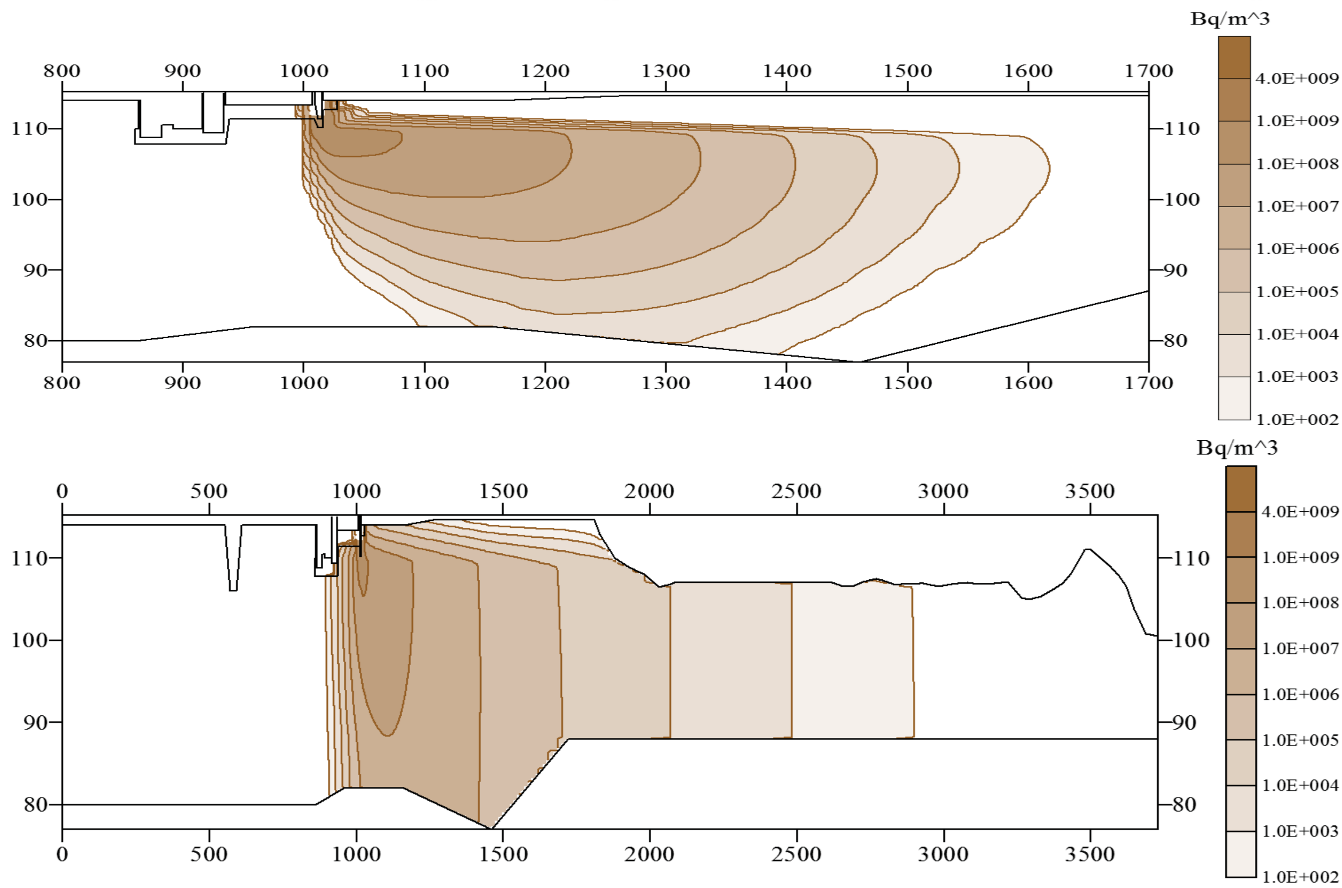
Predicted 90Sr concentrations in the aqueous phase after 100 and 1000 yrs



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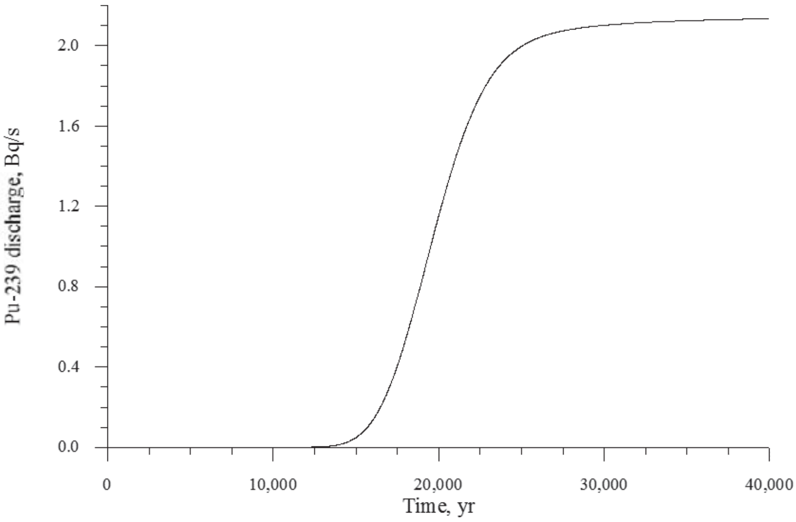
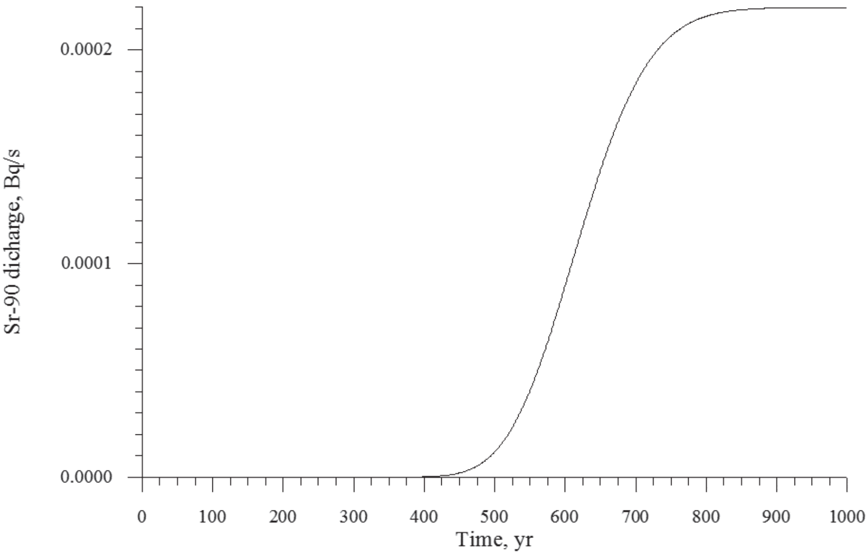
Predicted 239Pu-discharge in the Pripyat river from the Shelter





90Sr-discharge in the Pripyat river from the Shelter

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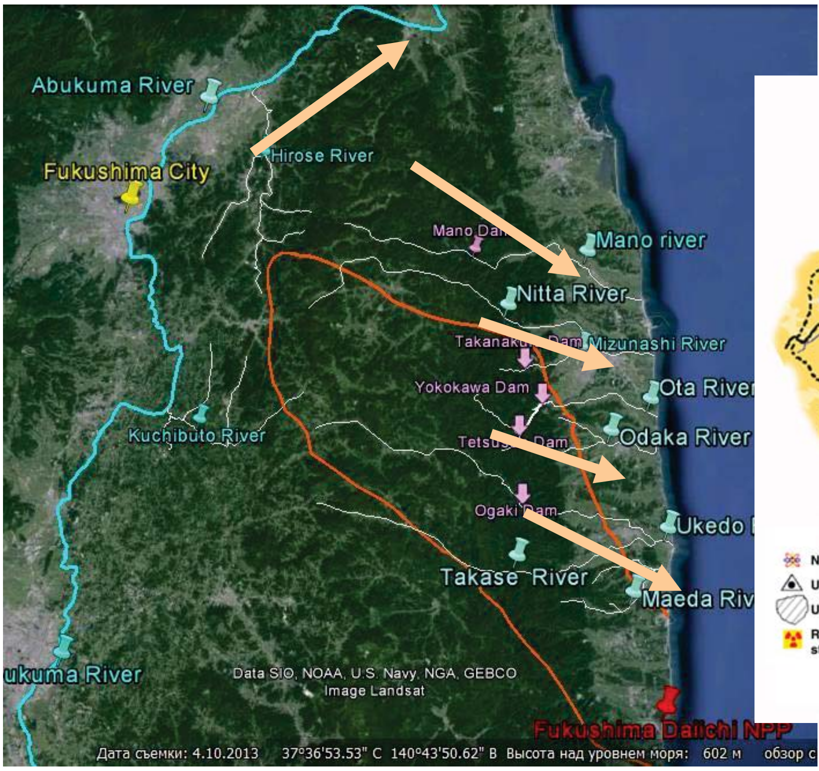
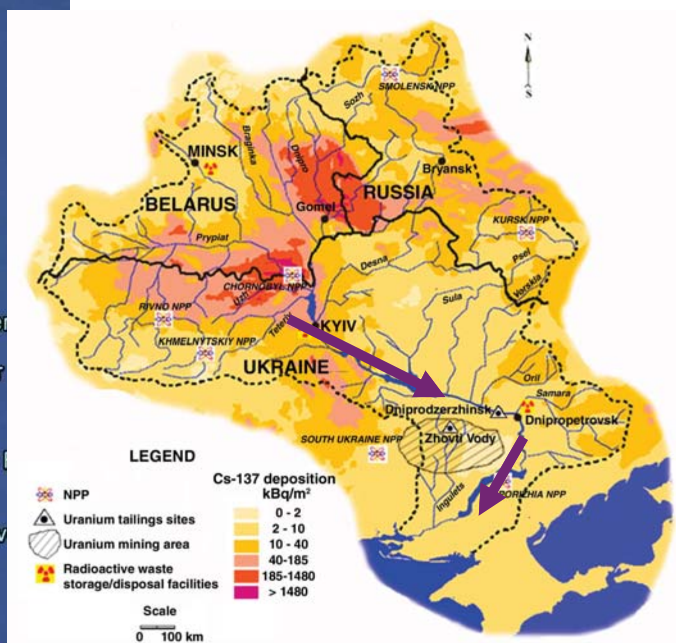
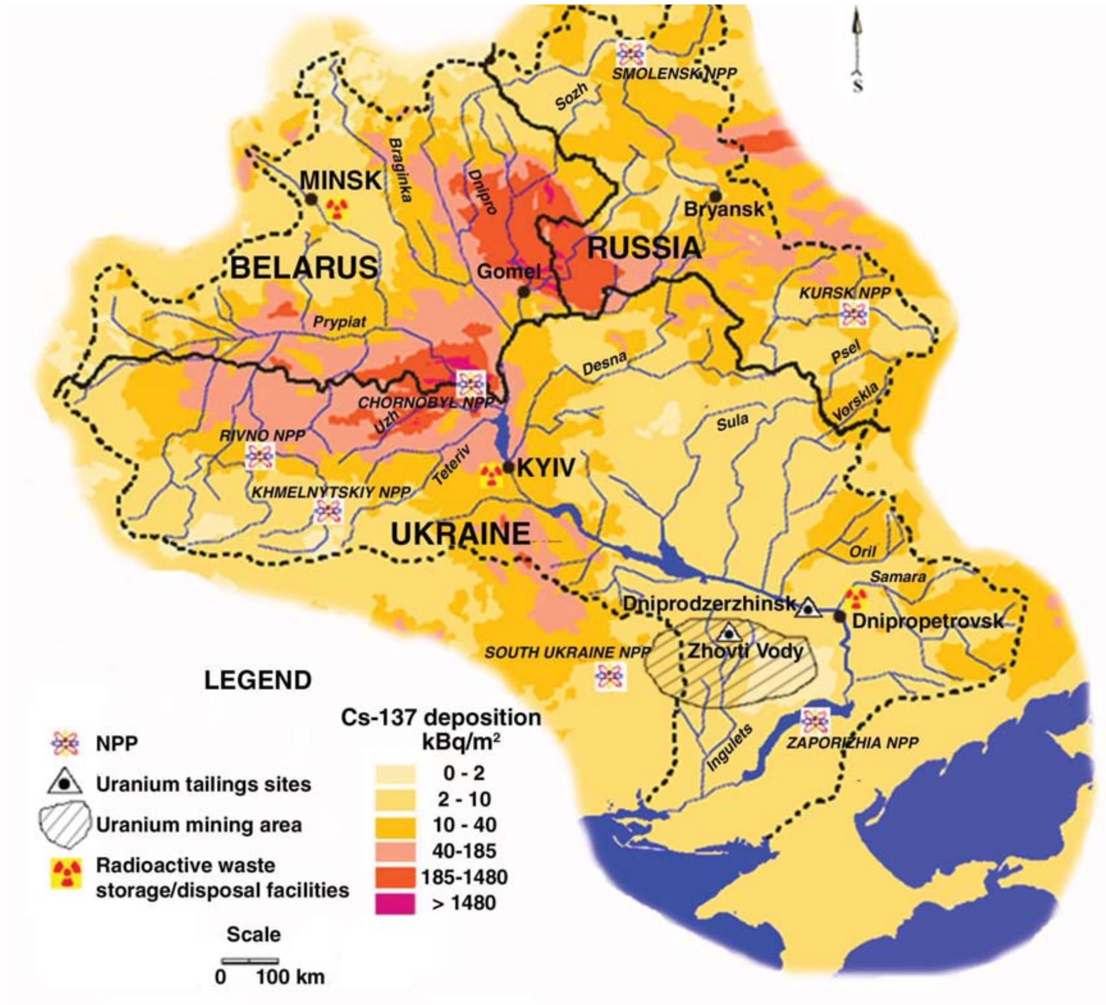
Water systems of Chernobyl and Fukushima regions:

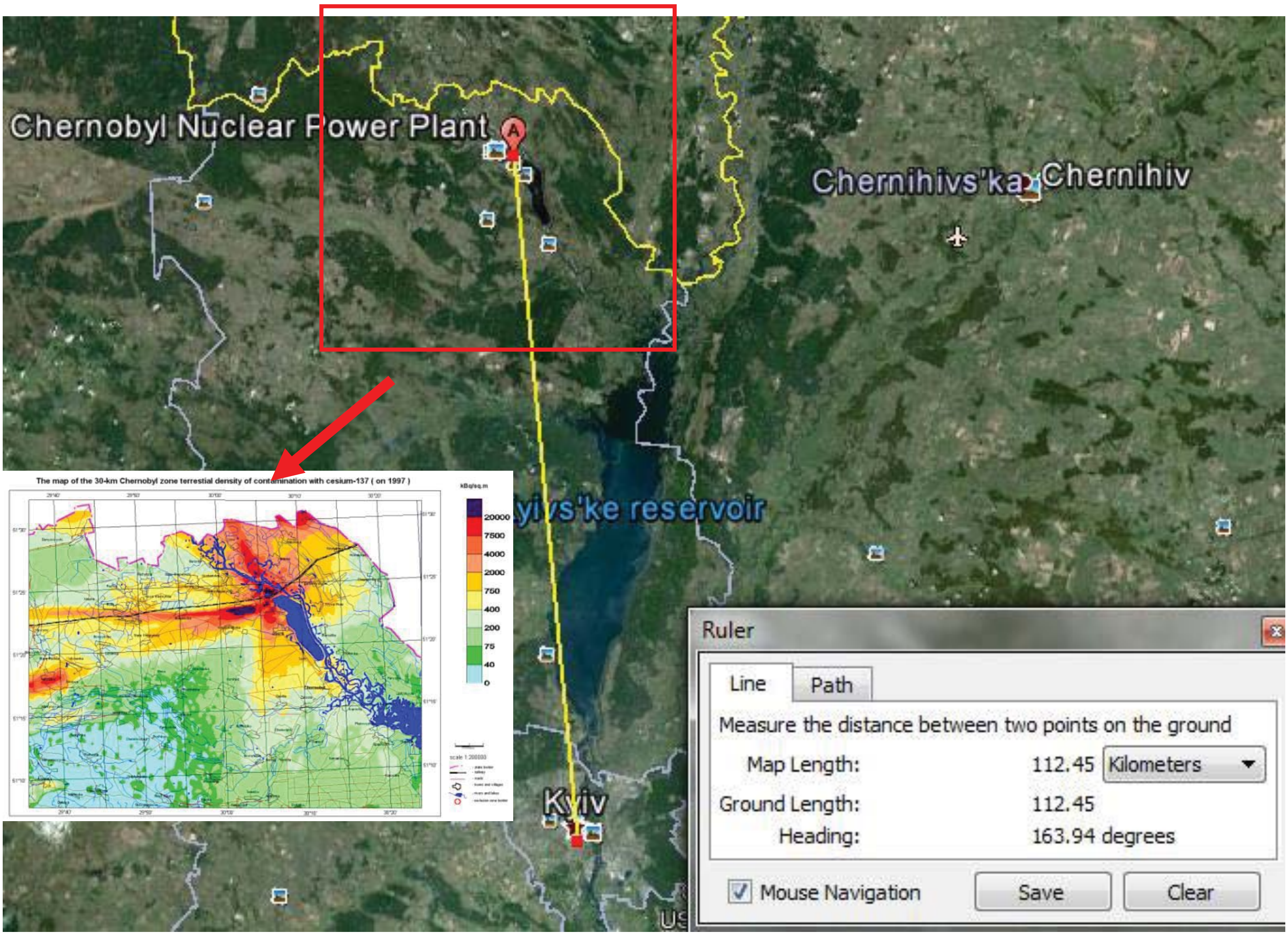
Common problems = rivers/reservoirs as pathways of radionuclide transport from the most contaminated zones to the populated areas:

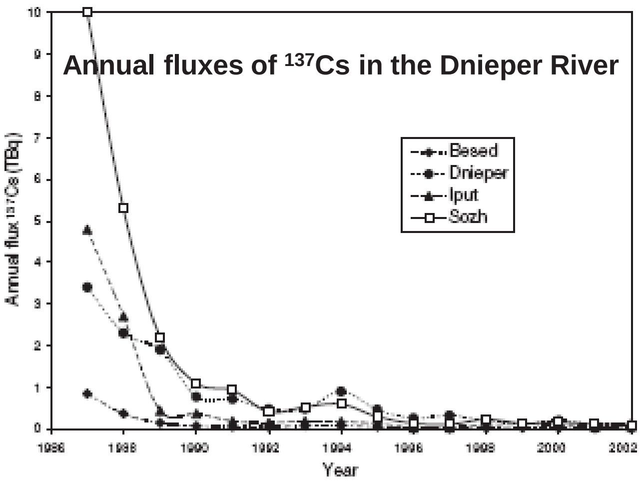


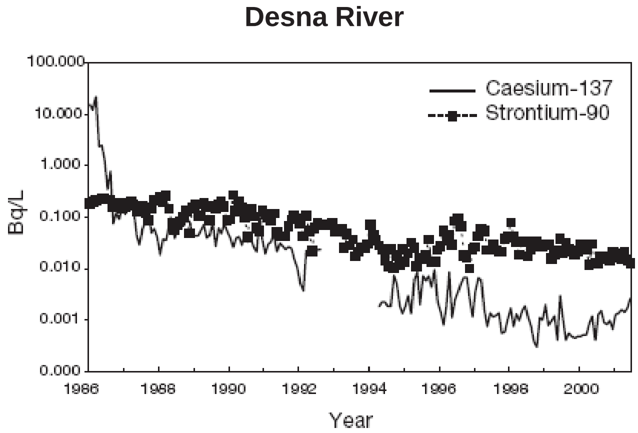


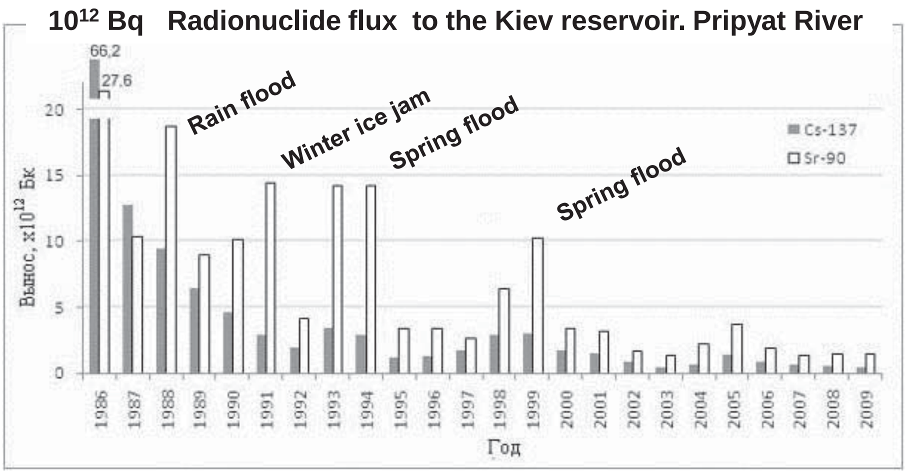
Density of Cs-137 deposition in Dnieper Basin











Data of Ukr. Hydromet. Institute

Voitsekhovic et al.

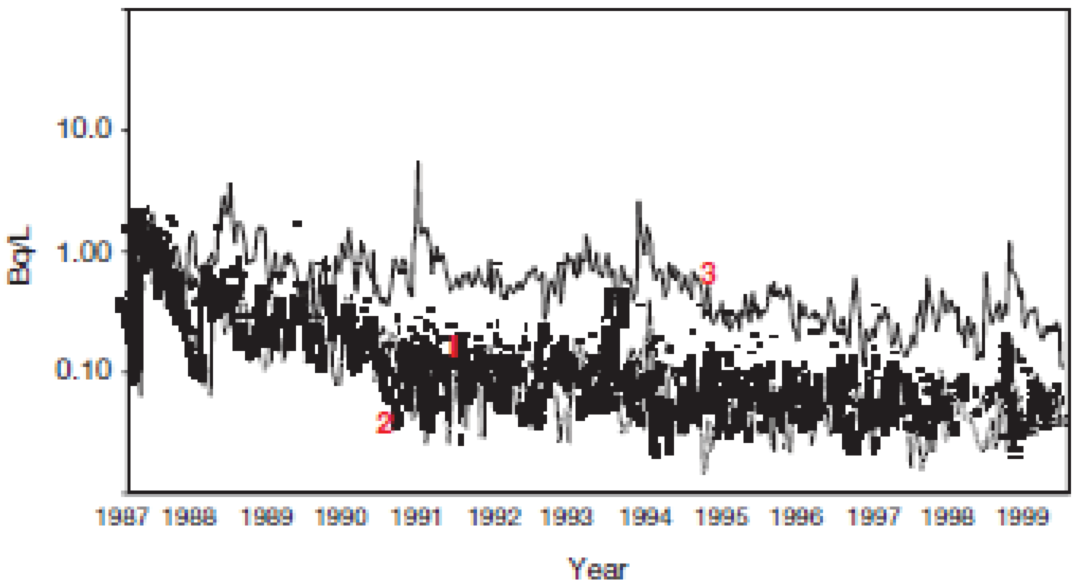
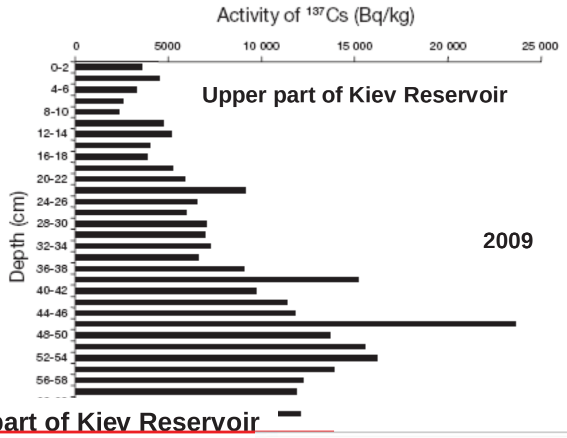


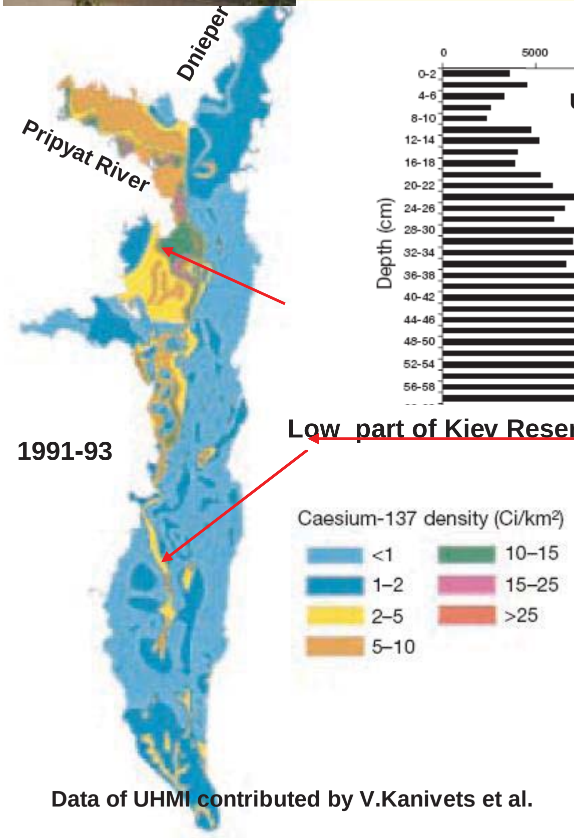
FIG. 4.18. Radionuclide concentration (10 day averages) in the Pripyat River. 1: ^{137}Cs, dissolved; 2: ^{137}Cs, particulate phase; 3: ^{90}Sr.

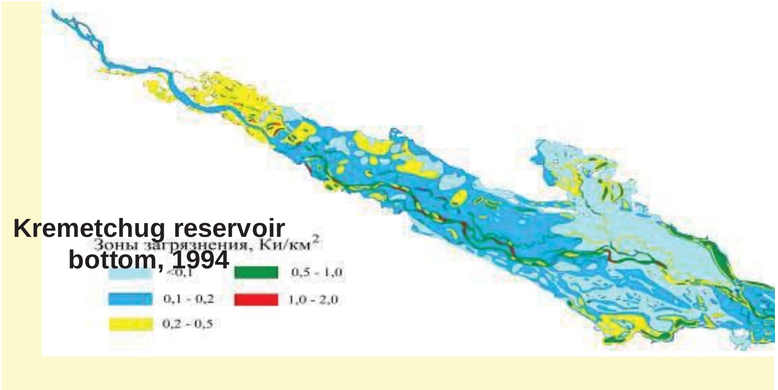
O,Voitsejkhovich , 2000

At equal amount of Cs-137 in solute and on sediments first years after the accident

^{137}Cs in the bottom sediments of Reservoirs





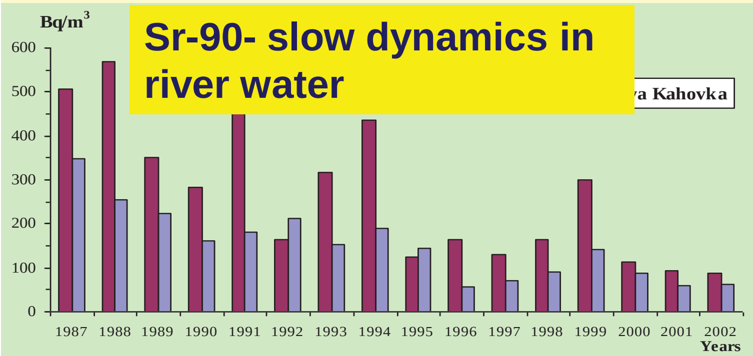


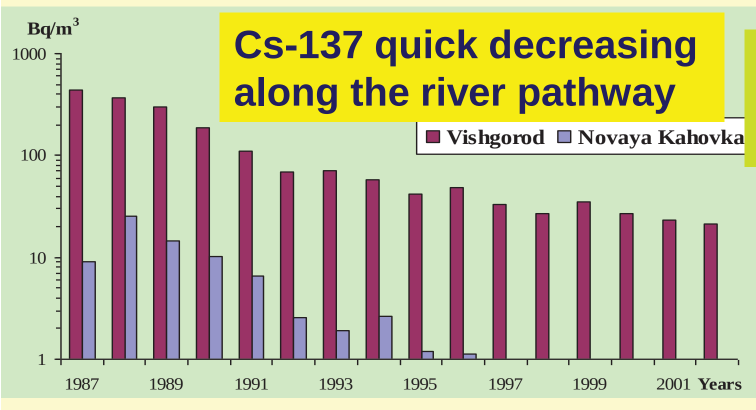
Slide presented by Oleg Voistekhovich (UHMI)

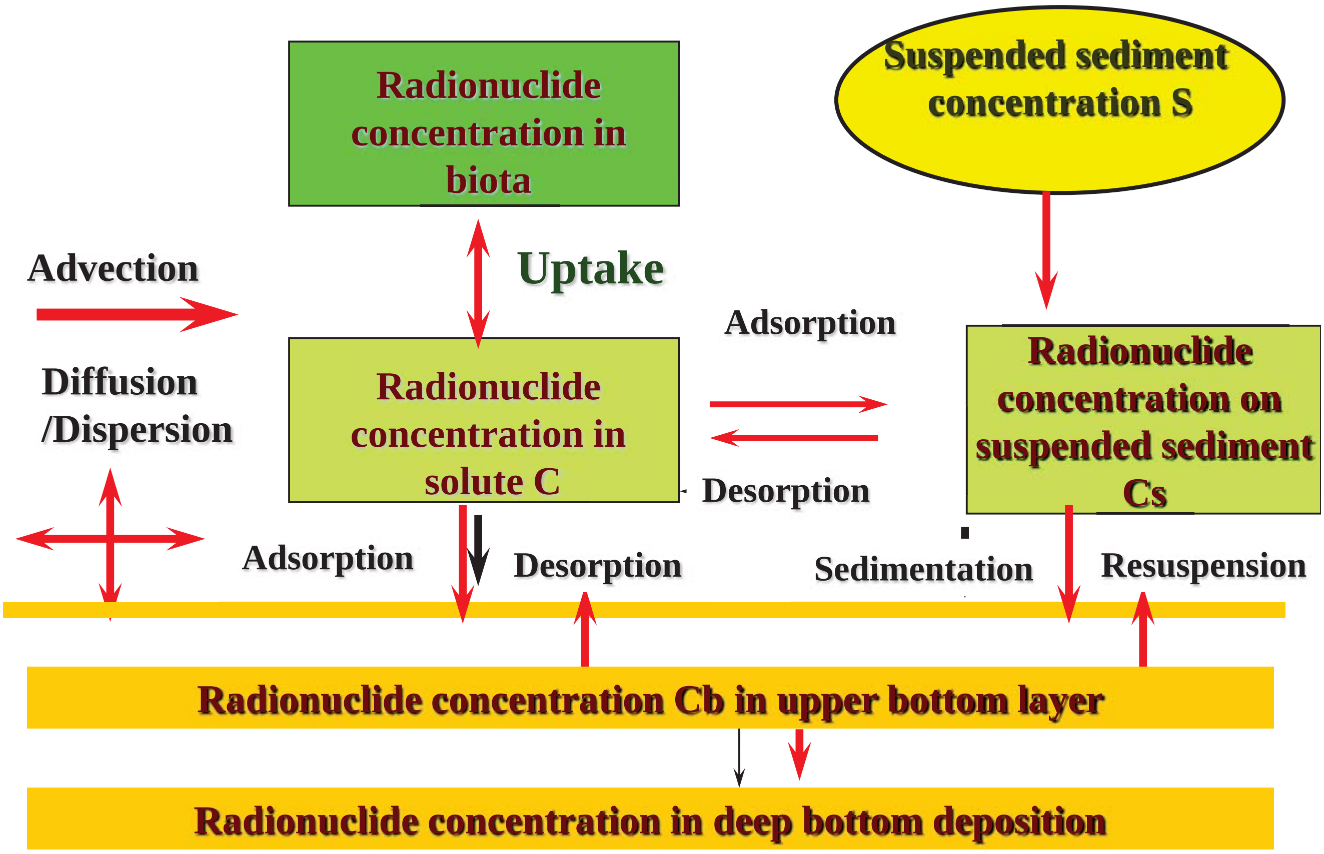
^{90}Sr and ^{137}Cs in the waters of the Dnieper's reservoirs

^{90}Sr in the reservoirs of the Dnieper cascade is still above of its pre-accidental levels

^{137}Cs activity concentration in the water at the lowest reservoir returned to its pre-accidental level in 1996-1998.







Processes to be modeled for simulation radionuclide fate in surface water

Radionuclide Transport

$$\frac{\partial(hC)}{\partial t}+\frac{\partial}{\partial x_i}(u_i hC)=\frac{\partial}{\partial x_i}\left(hD_i\frac{\partial C}{\partial x_i}\right)-\lambda hC-a_s hS\left(\frac{k_d^s}{\rho}C-C_s\right)-$$

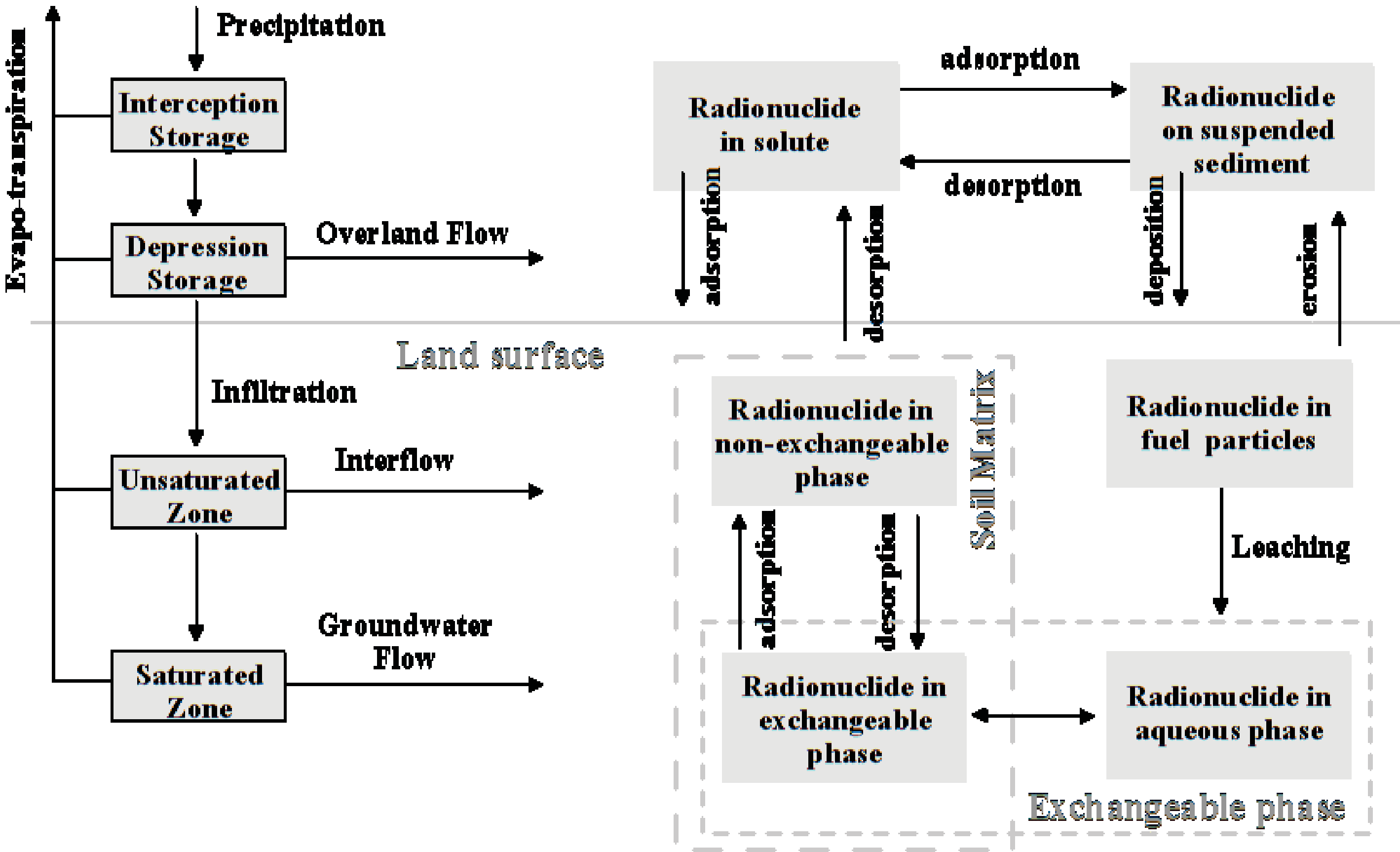
$$-(1-\phi)Z_* a_b\left(k_d^b\frac{\rho_b}{\rho}C-C_b\right)$$

$$\frac{\partial(hSC_s)}{\partial t}+\frac{\partial}{\partial x_i}(u_i hSC_s)=\frac{\partial}{\partial x_i}\left(hD_i\frac{\partial SC_s}{\partial x_i}\right)-\lambda hSC_s+a_s hS\left(\frac{k_d^s}{\rho}C-C_s\right)+$$

$$+\frac{1}{\rho_b}q_b C_b-q_s C_s$$

Contamination of Upper Bottom Layer

$$\frac{\partial}{\partial t}(Z_* C_b)=a_b Z_*\left(k_d^b\frac{\rho_b}{\rho}C-C_b\right)-\lambda Z_* C_b-\frac{1}{1-\phi}\left\{\frac{1}{\rho_b}q_b C_b-q_s C_s\right\}_b$$



The developed set of the hydrodynamics – sediment transport- radionuclide transport models includes:

- Watershed models RETRACE-R and RUNTOX
- 3D Model- THREETOX (hydrodynamics hydrostatic model similar to POM)
- 2D Model – COASTOX (hydrodynamics – shallow water equations)
- 1D Model – RIVTOX (hydraulics – Saint Venant Equations)

Radionuclide transport in solute and on suspended sediment modules :
advection diffusion equations including the exchange rates between liquid and solid phases on the basis of adsorption-desorption kinetic equations based on “distribution coefficient” – Kd and exchange rate coefficients parameterizations (similar to Prof. Yasuo Onishi’s models, TODAM, FETRA, SERATRA)

Since 1991 these **models were validated within IAEA's Programs** on assessment of efficiency of the models of radionuclide transfer in the environment, including the aquatic transport: VAMP, BIOMOVS-1, EMRAS-I, II; MODARIA (2012- now)

1996

IAEA-SM-339/175

MODELLING OF RADIONUCLIDE TRANSFER IN RIVERS AND RESERVOIRS
Validation study performed within the IAEA/CEC VAMP programme

M. ZHELEZNYAK[1], G. BLAYLOCK[2], J. GARNIER-LAPLACE[3], G. GONTIER[3], A.V. KONOPLEV[4], A. MARINETS[1,5], L. MONTE[6], Y. ONISHI[7], K.-L. SJOEBLOM[8], M. TSCHURLOVITS[5], O. VOJTSEKHOVICH[9], V. BERKOVSKY[10], A. BULGAKOV[4], P. TKALICH[1,7], N. TKACHENKO[11], G. WINKLER[5]

[1] Institute of Mathematical Machines and Systems, Cybernetics Centre (CC), Ukrainian Academy of Sciences, Kiev, Ukraine

[2] SENES Oak Ridge Inc., Oak Ridge, Tennessee, United States of America

[3] Institut de protection et de sûreté nucléaire (IPSN-CEA), Commissariat à l'énergie atomique, Centre d'études de Cadarache, Saint-Paul-lez-Durance, France

Environmental Modelling for Radiation Safety (EMRAS) — A Summary Report of the Results of the EMRAS Programme (2003–2007)

IAEA-TECDOC-1678

Testing of Models for Predicting the Behaviour of Radionuclides in Freshwater Systems and Coastal Areas

Report of the Aquatic Working Group of EMRAS Theme 1

Environmental Modelling for RAdiation Safety (EMRAS) Programme

Modeling system for watersheds- rivers –reservoirs has been developed after the Chernobyl accident.

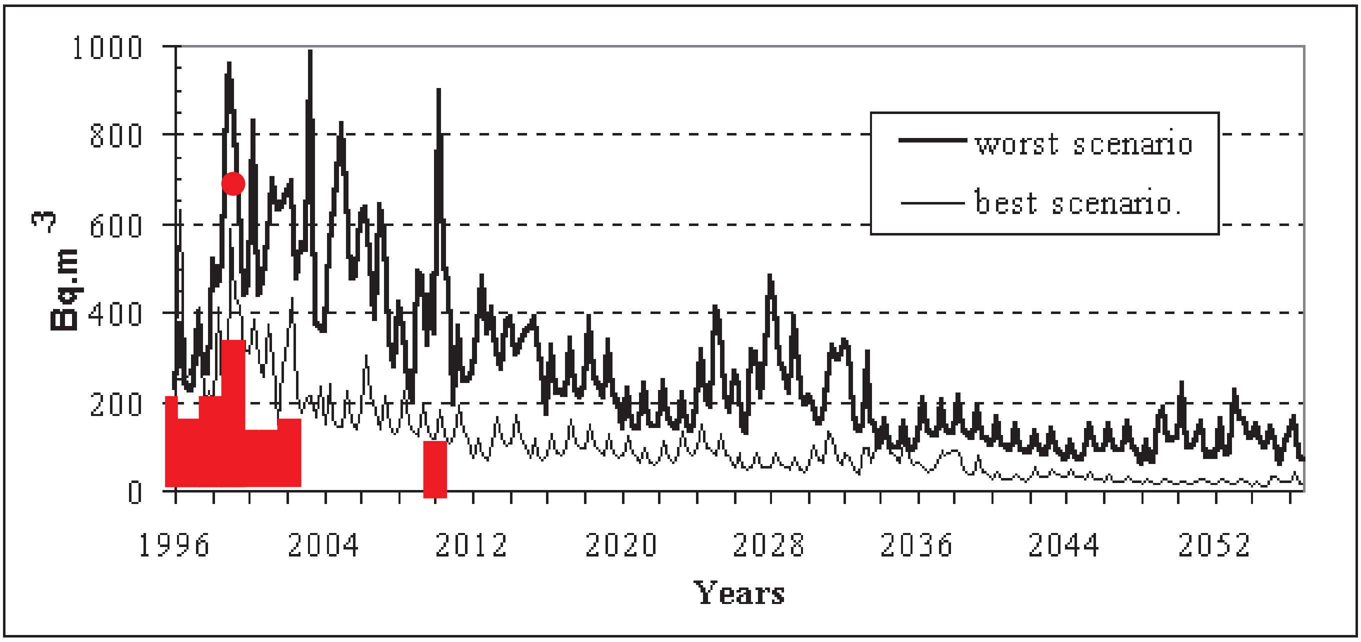
Useful implementations:

- **Prediction and long term assessment of the temporal dynamics of the radionuclide concentration in water bodies;**

- **Risk assessment for the potential emergency (extreme floods, dam breaks);**

- **Analyses of the efficiency and justification of the measures preventing transfer of radionuclides;**

- **Supporting of the post accidental communications with the population and mass media.**



Simulation of long-term fate of ^{90}Sr in Kiev Reservoir

Input scenarios of low- and high- water hydrological years in assumptions of absence of emergency situations in Chernobyl zone .Simulation has been done in 1995. The measured data 1996-2012 are close to the averaging of the "best" scenario

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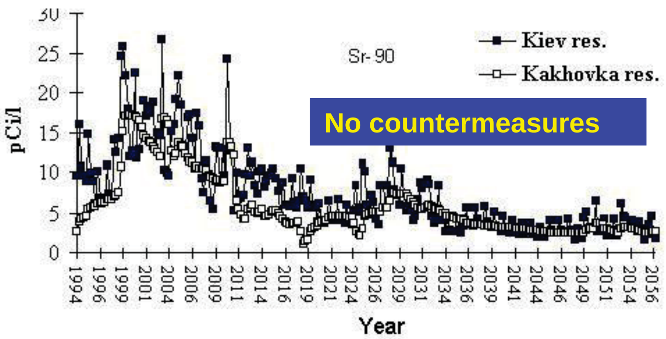
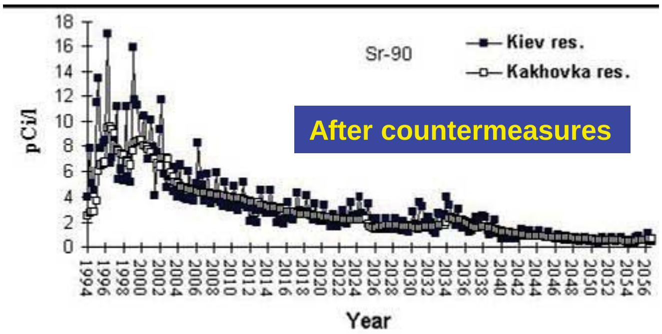
Chernobyl water modeling

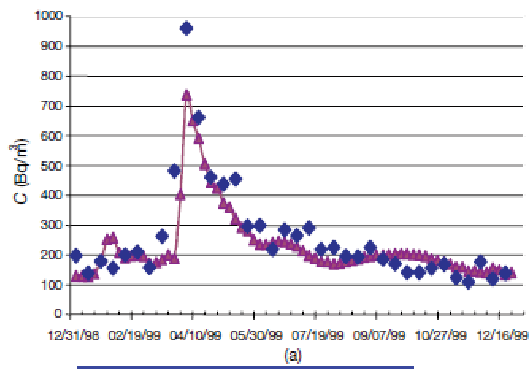
Model based forecasting of radionuclides fate in water systems

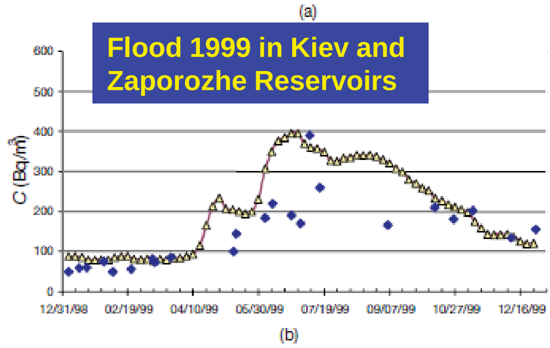
Long term (scenario based) forecasting for dose assessment





Seasonal (flood events) forecasting





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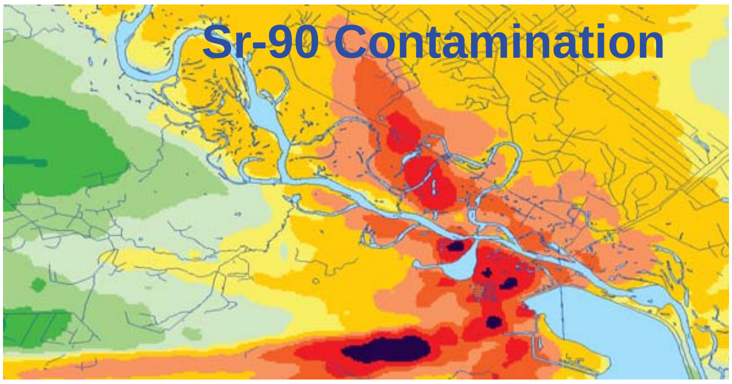
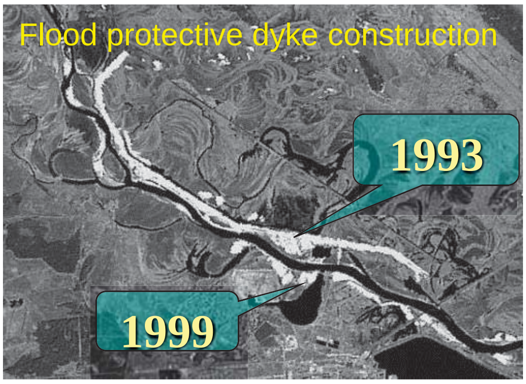
Pripyat River Floodplain around Chernobyl NPP was heavy contaminated after the accident.

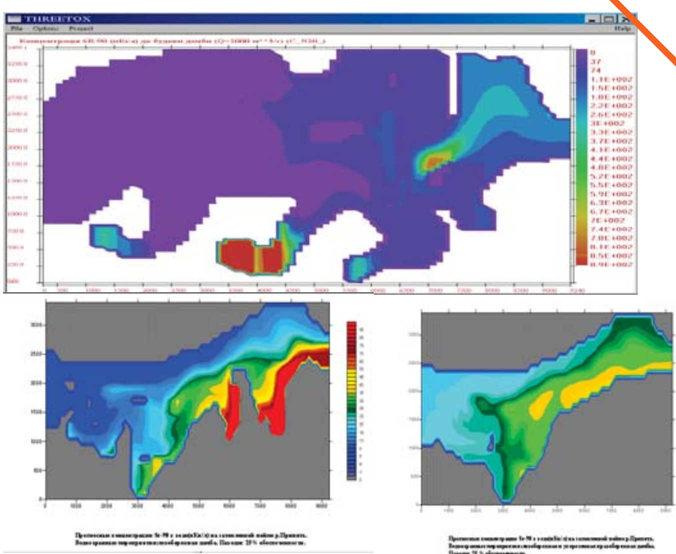
Pripyat river floodplain was the most significant source of ^{90}Sr secondary contamination in Dnieper system. No significant impact of ^{137}Cs, because of its fixation in soils

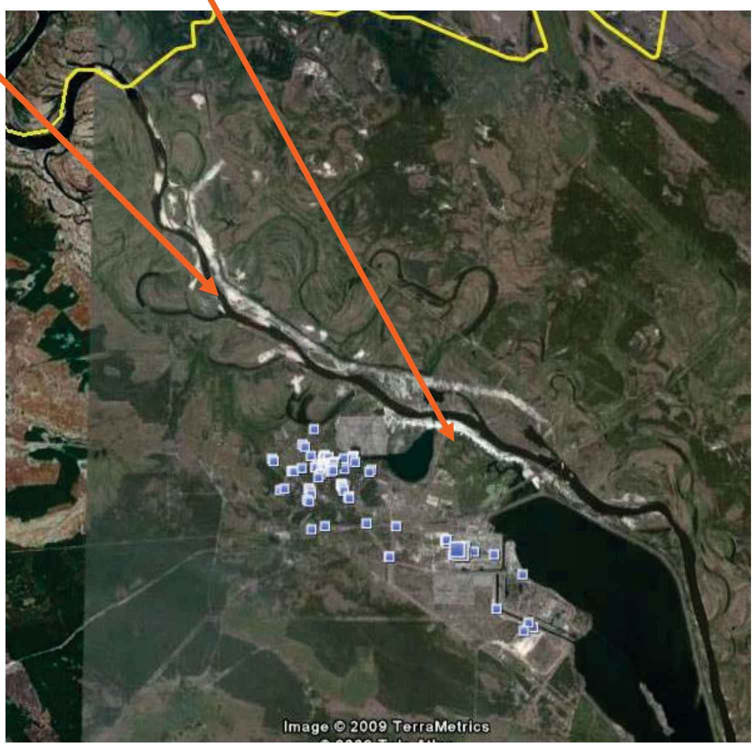


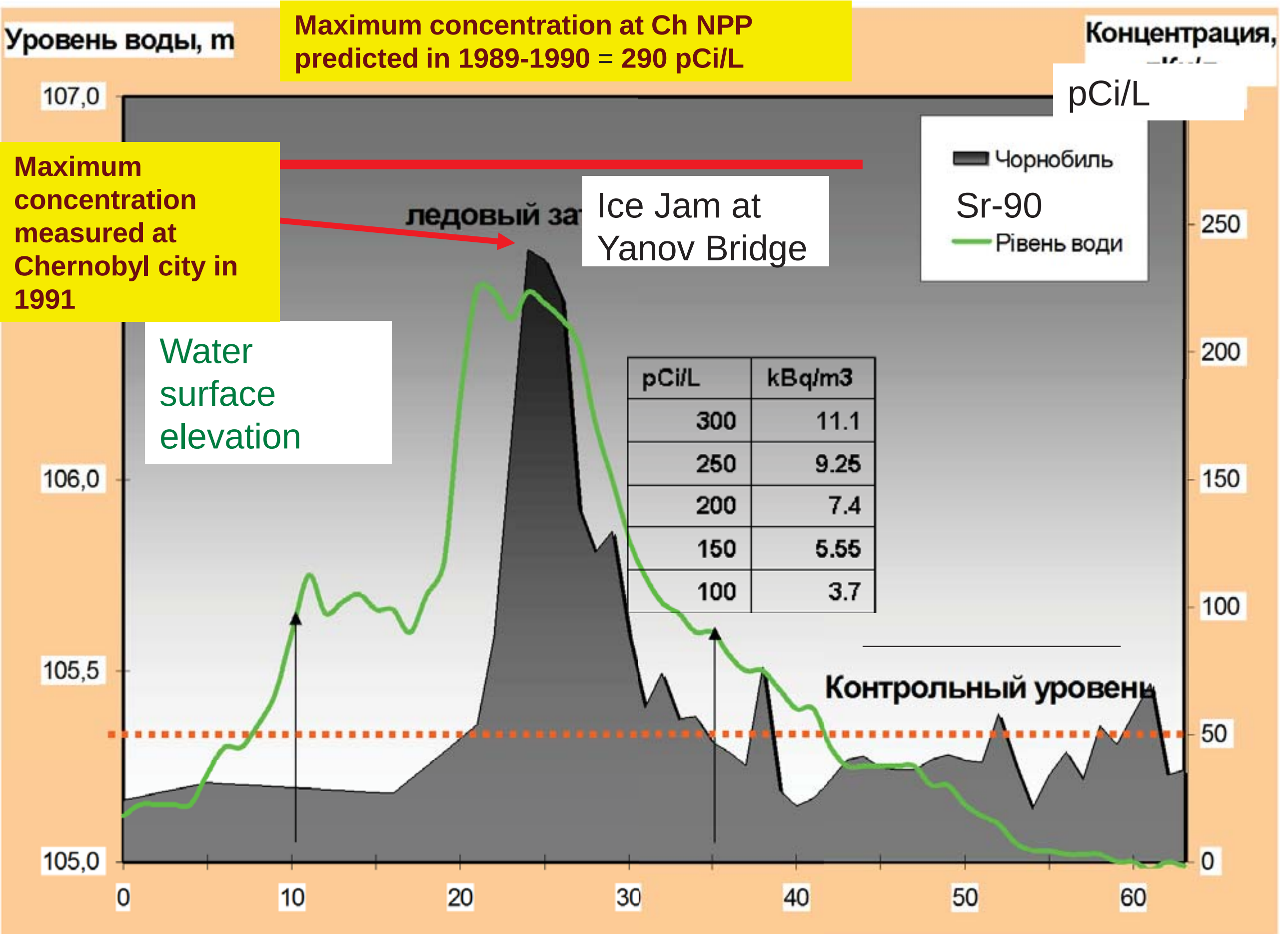


The most efficient water protection was to prevent the inundation of the most contaminated floodplains **by the flood protection sandy dikes** constructed at left and right banks of the Pripyat river

2D modeling predicted the efficiency of special dikes for the reducing of radionuclide wash-off from the heavy contaminated floodplain of the Pripyat River at the city of Pripyat



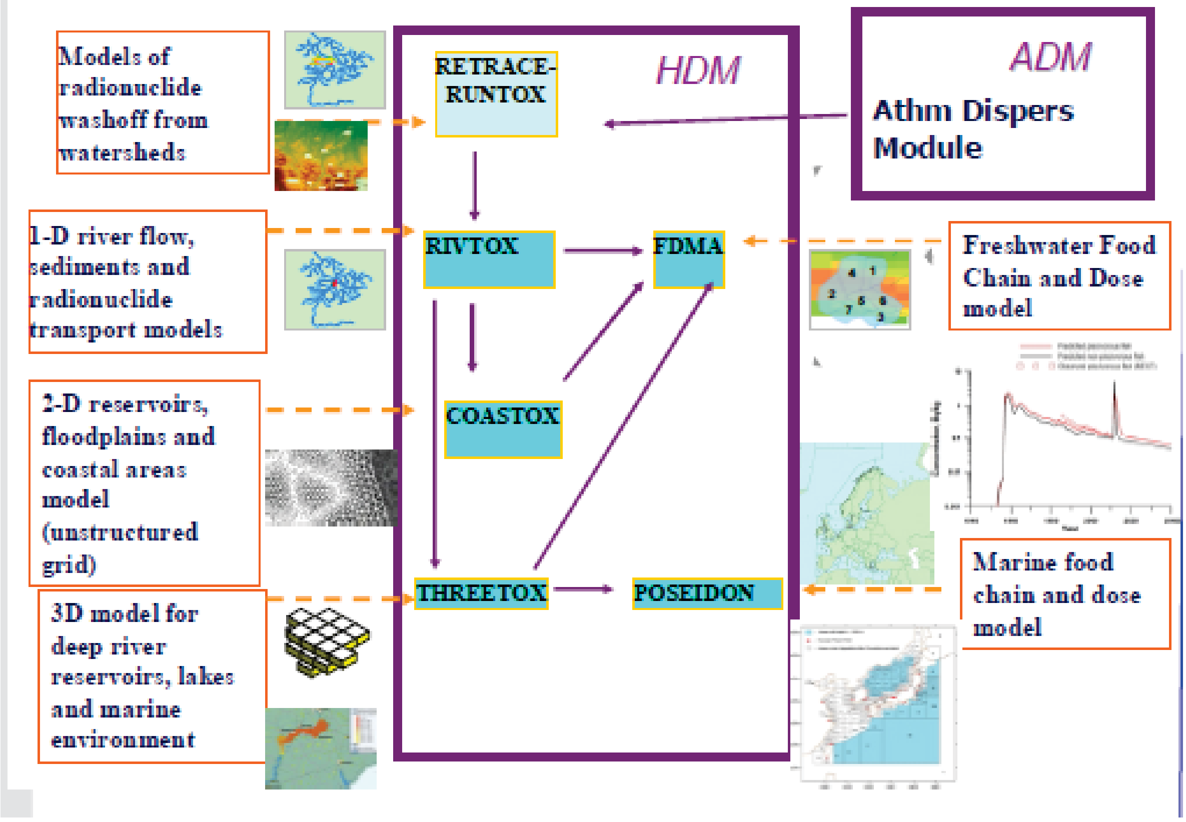




Measured Sr-90 concentration and water elevation in Pripyat River in January 1991 at Chernobyl ! The forecast of 1990 was confirmed by the monitoring data of 1991 !!!

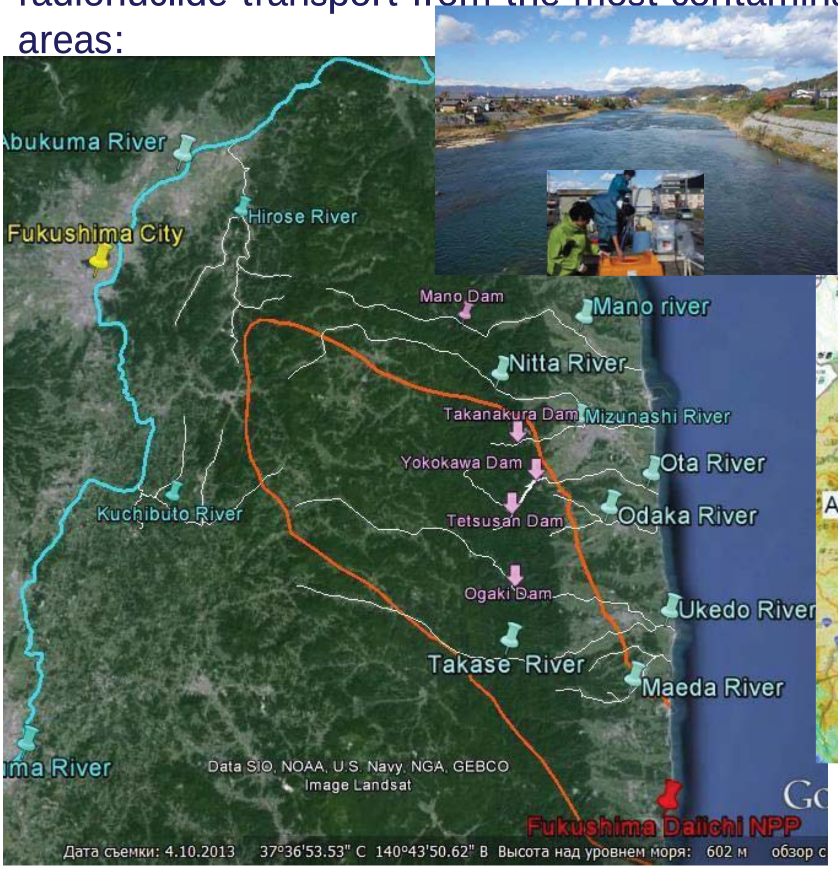
The models were included into the Hydrological Dispersion Module of EU decision support system for nuclear emergency management- RODOS

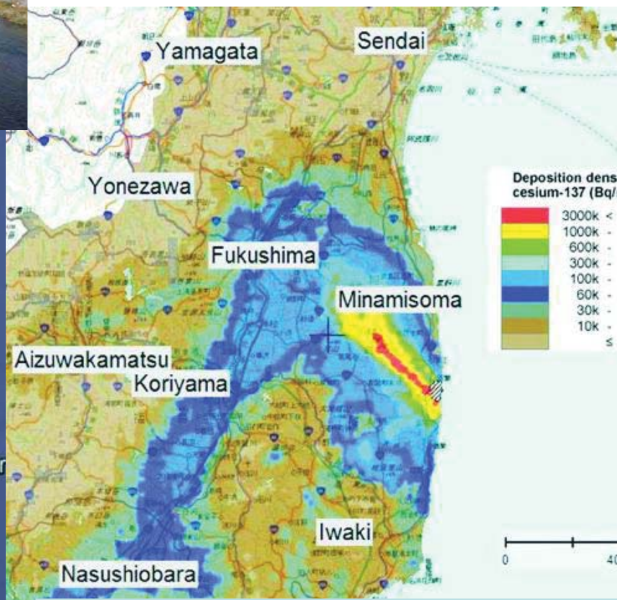
Hydrological Dispersion Models (HDM) of EC Decision Support System for Nuclear Emergency- JRODOS



Water systems of Fukushima regions:

Common with Chernobyl problems = rivers/reservoirs as pathways of radionuclide transport from the most contaminated zones to the populated areas:





Falllout density December 2012

http://ramap.jmc.or.jp/map/eng/

Water systems in Chernobyl and Fukushima regions. Differences:

Fukushima Region: Mountainous watersheds - steep slopes, high erosion

High amount of precipitations, rain seasons, typhoons

Volcanic soils

Chernobyl Region:

Plain watersheds- mild slopes, small erosion

Mild amount of precipitations, no rain season

Monitoring radioactive cesium in Abukuma River in Fukushima Prefecture

Kenji NANBA

Date	Sediment Concentration g/L	Dissolved Cs-137 (Bq/L)	Cs-137 on Suspended Sediment (Bq/L)	Total Cs-137 in River Water (Bq/L)	Dissolved/Total (%)
5/8/2012	0.0268	5.42E-02	2.00E-01	2.54E-01	21.31
6/5/2012	0.021035	1.19E-02	1.24E-01	1.36E-01	8.75
6/26/2012	0.008126	1.26E-02	5.49E-02	6.75E-02	18.67
7/10/2012	0.011275	1.61E-02	1.26E-01	1.42E-01	11.33
7/30/2012	0.013214	1.84E-02	5.99E-02	7.83E-02	23.50
9/4/2012	0.00991	1.73E-02	1.46E-01	1.63E-01	10.62
9/11/2012	0.007573	2.12E-02	8.69E-02	1.08E-01	19.60
9/25/2012	0.017388	2.73E-02	2.92E-01	3.19E-01	8.56
10/9/2012	0.008278	1.58E-02	7.90E-02	9.48E-02	16.67
10/29/2012	0.01169	1.36E-02	1.68E-01	1.81E-01	7.50
11/13/2012	0.006408	1.27E-02	6.81E-02	8.08E-02	15.73
12/5/2012	0.020319	2.27E-02	6.10E-01	6.33E-01	3.58
12/11/2012	0.002451	1.37E-02	5.58E-02	6.96E-02	19.74
12/18/2012	0.003274	9.78E-03	3.42E-02	4.40E-02	22.22
12/25/2012	0.002347	1.22E-02	2.67E-02	3.89E-02	31.36

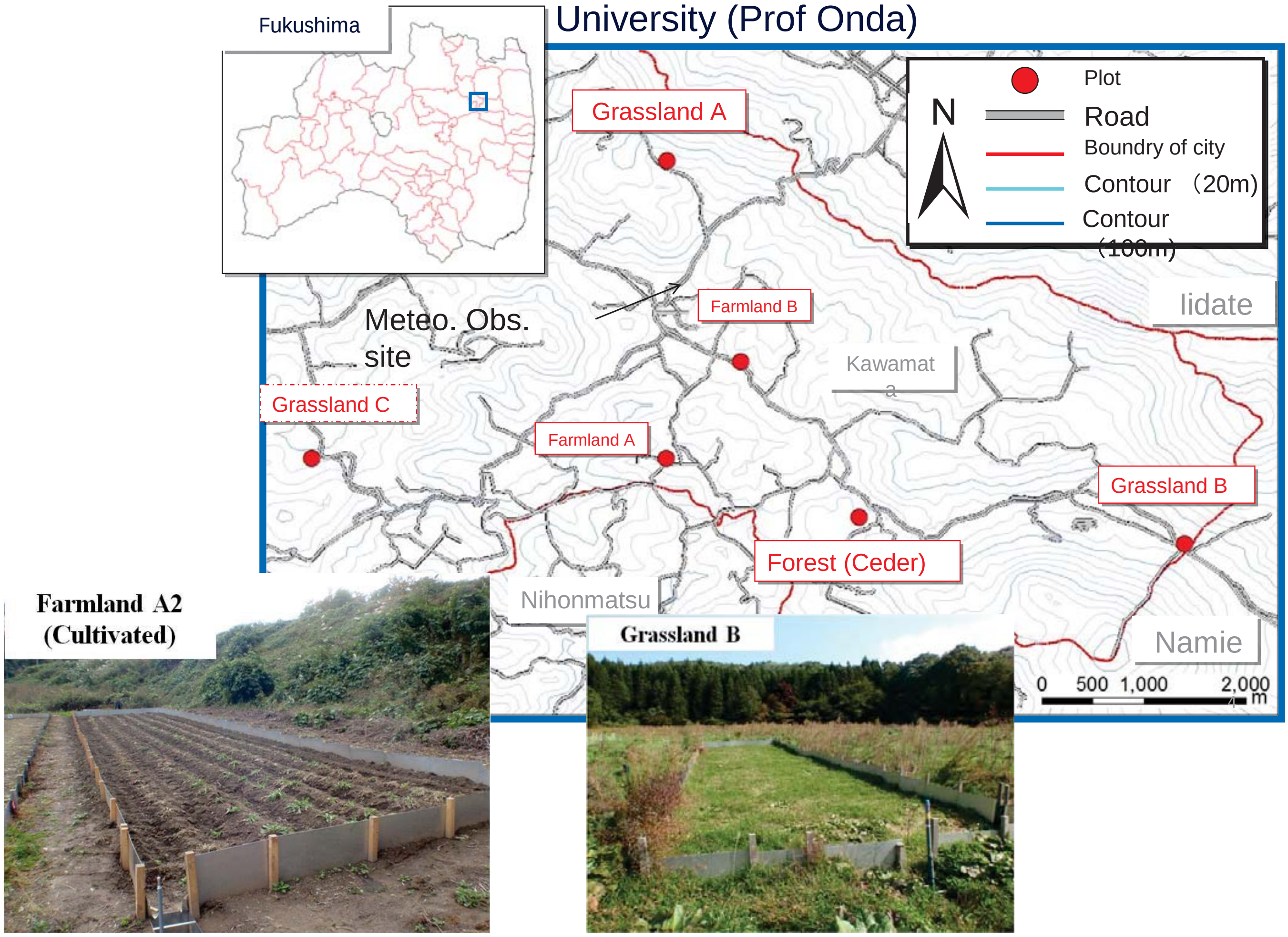
5-35% of Cs-137 in solute, up to 95% on sediments

At 90%-95% of Cs-137 at Fukushima is transported by sediments in river water.

At Chernobyl – only up to 50% in initial period, than less, why?? Who is “guilty” and in which scale for such difference??

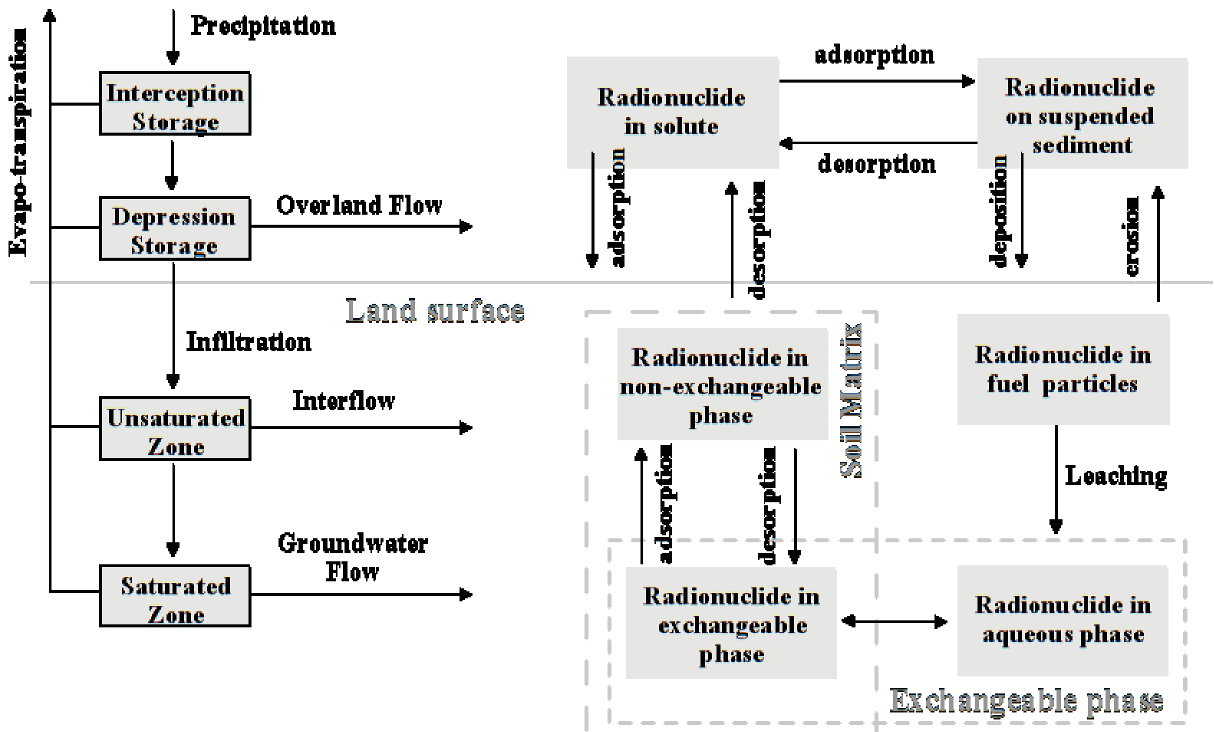
1) Steep mountain slopes vs mild or small plain slopes ???
2) Volcanic Fukushima soils vs soils of the Ukrainian- Byelorussian Poles’ye , i.e difference in Kd?
3) Typhoon generated higher amount of precipitations?

Experimental watershed plots of Tsukuba University (Prof Onda)

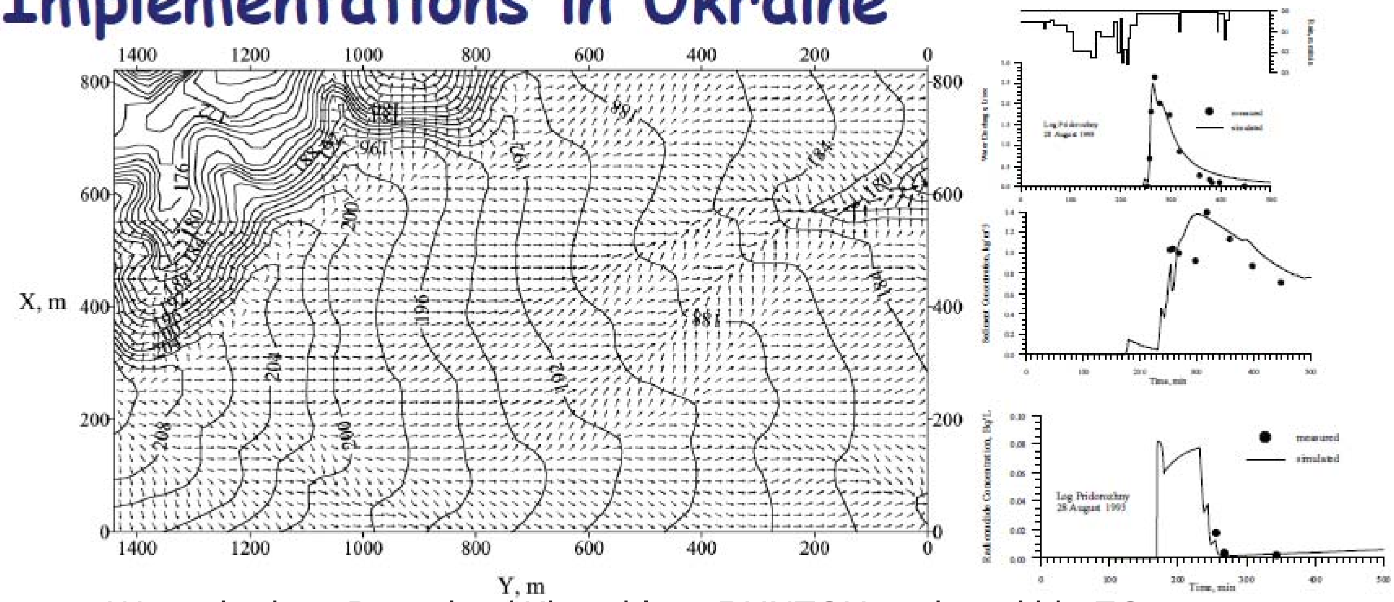


Since November 2013 the model implementation for the water bodies of the Fukushima fallout zone has started in IER Fukushima university:

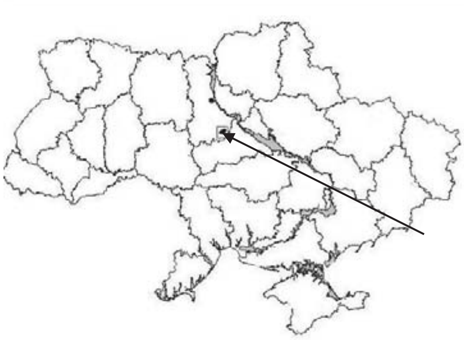
Watershed modeling: distributed models RUNTOX and DHSVM-R



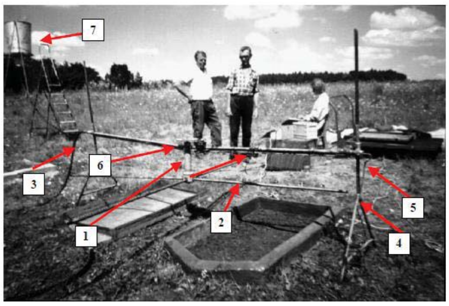
Implementations in Ukraine



Watersheds at Boguslav / Kiev oblast, RUNTOX testing within EC SPARATCUS Project (M. van der Perk, Kivva, Korobova et al.)



Butenya River watershed



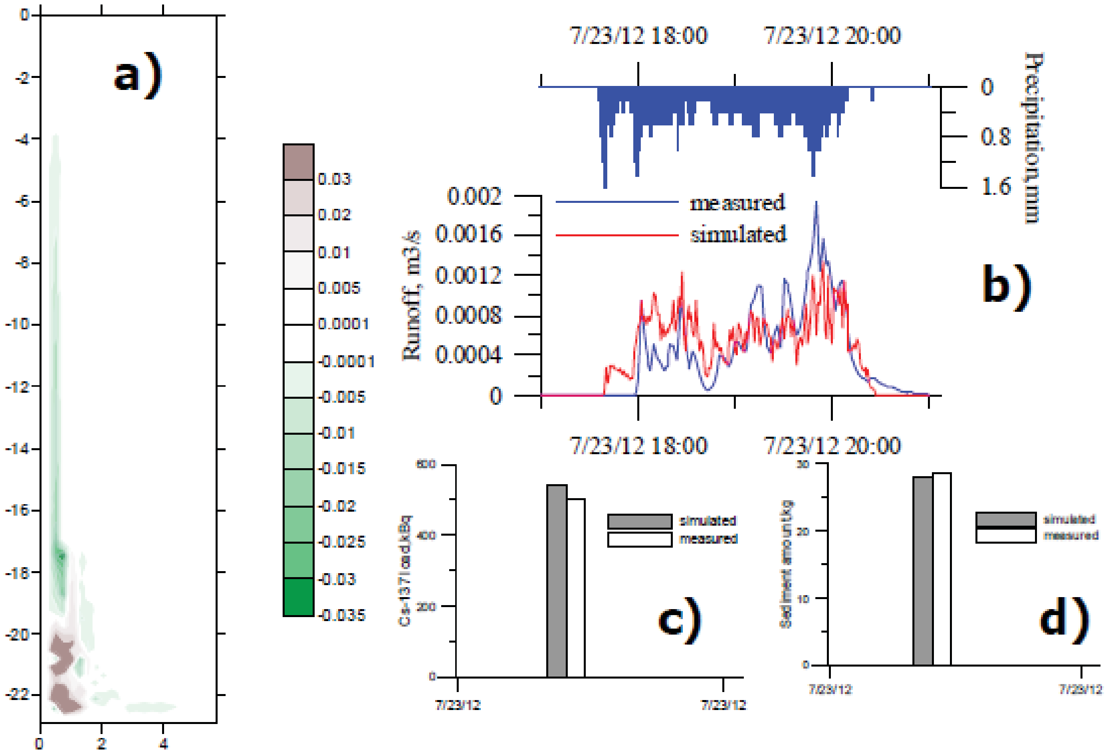
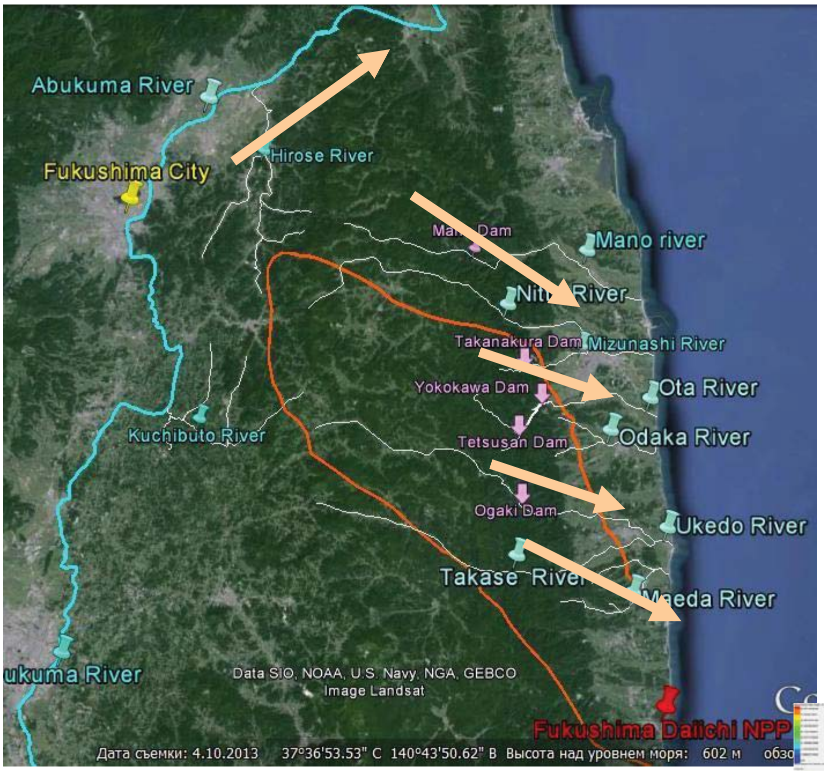
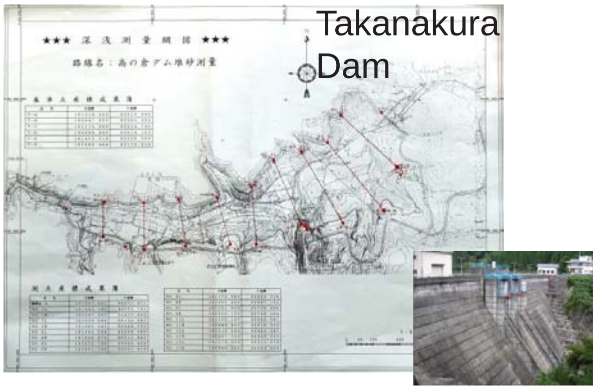
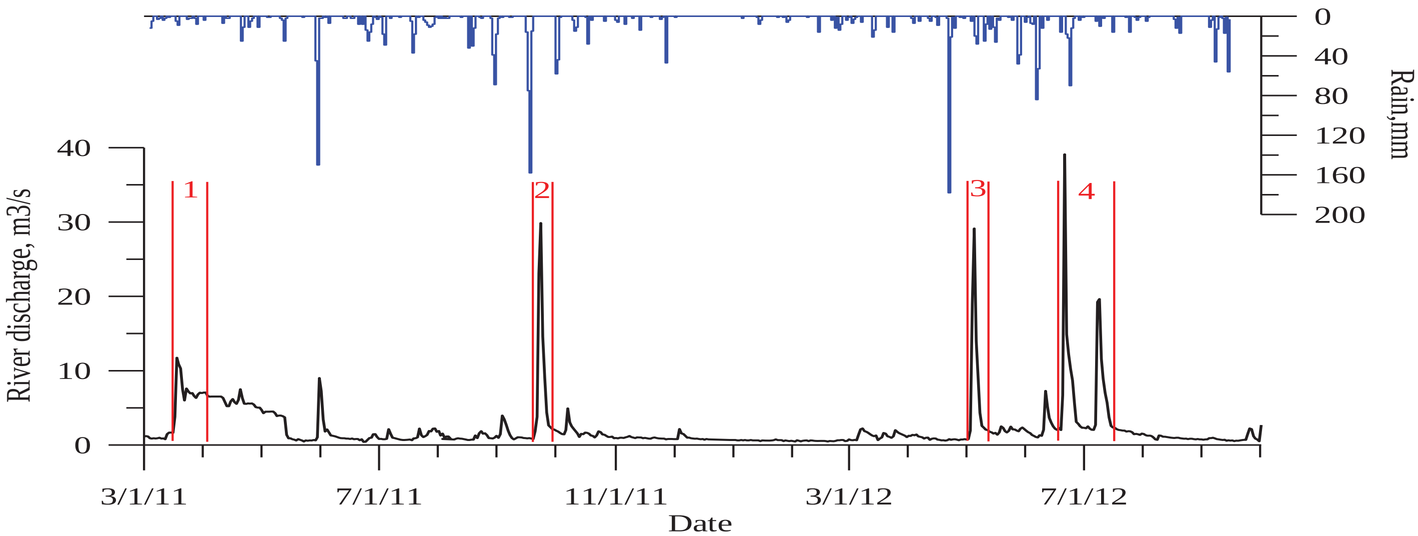


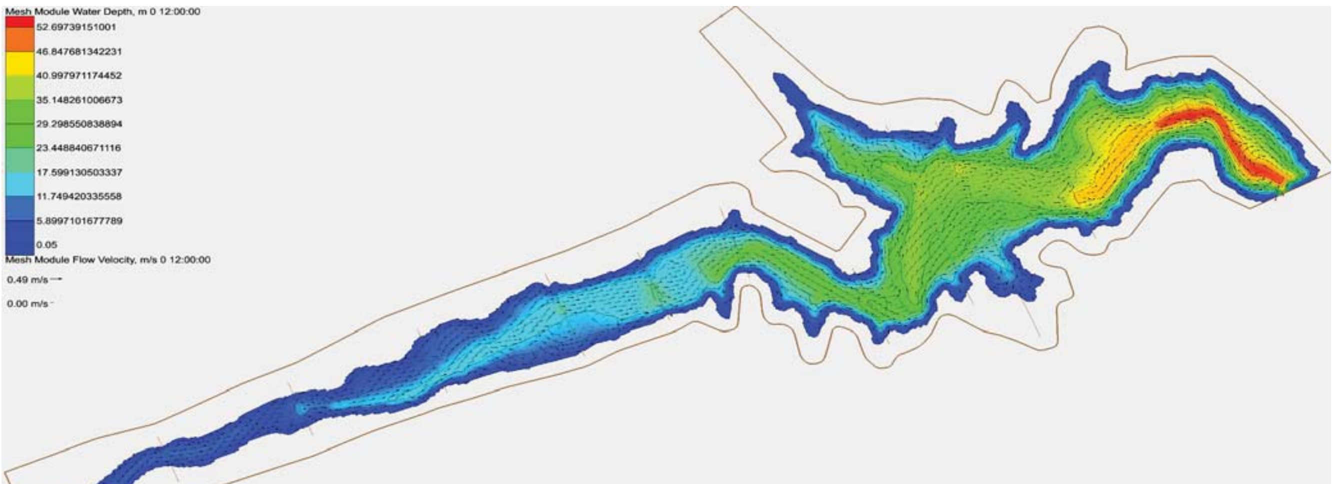
Fig.5 DHSVM-R testing versus the data from the "Farmland A1" plot measured during heavy rainstorm 23.07.2012: a) simulated zones of erosion and accretion, b) precipitation and simulated water discharge; c) total weight of the eroded sediments; d) total amount of ^{137}Cs washed out on sediments,

2D COASTOX model implementation for simulation of Cs-137 transport in the reservoirs of Fukushima fallout Zone





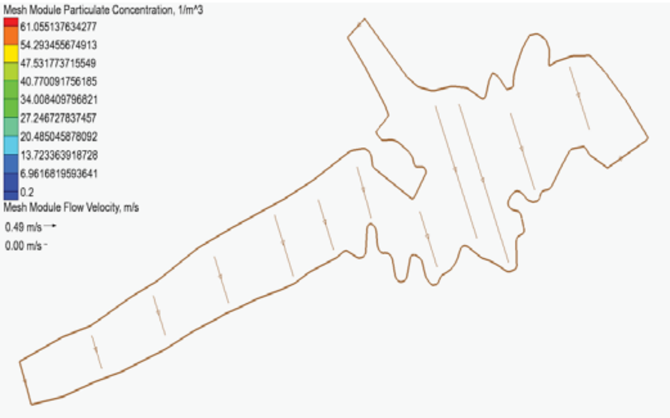


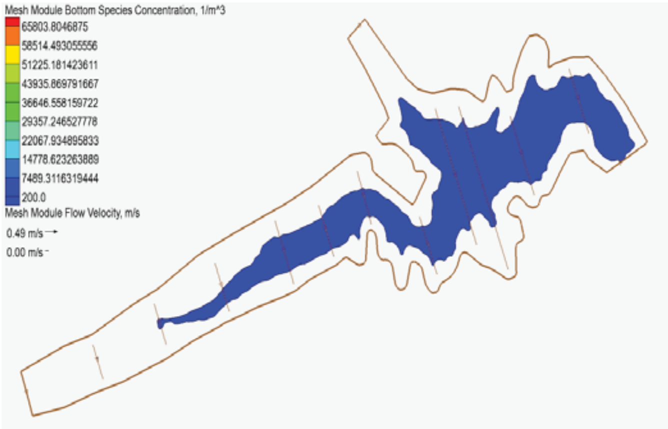


Water depth and water velocity field

Fukushima University
INSTITUTE OF ENVIRONMENTAL RADIOACTIVITY

COASTOX model is customized and preliminary tested for three reservoirs





Cs -137 concentration on the suspended sediments (left) and in the bottom deposition of the Yokokawa Dam during the high flood in the reservoir

Conclusions:

1 The modeling system that was implemented for Chernobyl site, validated within IAEA programs and integrated into the EC decision support system RODOS, start to be implemented for the watersheds, rivers, reservoirs of Fukushima Prefecture

2 Reliable short term and long term forecasting of the future dynamics of Cs-137 in water bodies in different hydro-meteorological scenarios and the quantization of the efficiency of the countermeasures can be provided using such modeling tools for Fukushima area