1. INTRODUCTION

Dnieper River watershed have been heavy contaminated by radionuclides under the influence of the Chernobyl accident. Significant part of radionuclides fallout took place on the watershed of Pripyat River. Chernobyl NPP stays near its bank approximately near 30 km from the Pripyat River outflow to the Kiev Reservoir of Dnieper river. The floodplain territory near Chernobyl NPP and surrounding watersheds are heavy contaminated by $^{137}\text{Cs}$ and $^{90}\text{Sr}$. The spots of $^{137}\text{Cs}$ are in the upper Dnieper watershed in Russian and Belorussian territory and on whole Pripyat watershed. This surface contamination leads to the permanent influx of $^{137}\text{Cs}$ and $^{90}\text{Sr}$ into the Kiev Reservoir and consequent radionuclide transport through the whole cascade of six Dnieper reservoirs. The magnitude of this distributed source increased during each spring floods generated by snow melting (1987-1996) and by high rainfall floods in Pripyat river (October 1987, July 1988, October 1990, July 1993). As result the Ukrainian population consuming Dnieper water down stream from Kiev up to the Black sea are under the impact of the Chernobyl radionuclides. More than 20 million people inhabited there consuming a drinking water (about 9 million people). Also the fishery and irrigation agriculture products are linked with water usage from the Dnieper's reservoirs. Therefore the population even nowadays 10 years after the accident are very sensitive for this problem.

Since May 1986 in Kiev in the Institute of Mathematical Machines and System Problems, Cybernetics Center of the National Academy of Sciences of Ukraine has been started the development of the computerised system for processing of Dnieper basin radiological monitoring data and modelling of radionuclide dispersion in rivers and reservoirs. For this work it was established the Interdisciplinary Working Group that joints the specialists from the State Committee of Water Resources, State Committee of Hydrometeorology, National Academy of Sciences and other Ukrainian institutions. The objectives of the computerized system development were formulated by the State Emergency Commission and later by the Ukrainian Minchernobyl as follows:

- reliable evaluation of the surface water contamination at Pripyat River and Dnieper River on the basis of monitoring data from the different institutions;
- seasonal and long-term prediction of the surface water radioactive contamination;
- decision support for the aquatic post-accidental countermeasures, directed to diminish the radionuclides fluxes from the Chernobyl area through the Pripyat River and Dnieper Reservoirs;
- decision support for the countermeasures directed on changes in the water assumption.
The first operational version of the computerized system was running since September 1986. It has been used for the forecasting of radionuclides dynamics in the Dnieper Reservoirs during the period of the Autumn heavy rainstorms, as also for the operative evaluation of the efficiency of several aquatic countermeasures. In 1987 the system was first time used for prediction the Dnieper reservoirs contamination during the spring flood. Within the decade after the accident the system was used, permanently improving and refining, for the radionuclide concentration prediction in water bodies as also for the water protection decision support [1-5]. The main results of this work are overviewed in the paper.

2. ACCIDENTAL CONTAMINATION AND WATER PROTECTION COUNTERMEASURES

The monitoring system for water contamination measurements have been established on the Dnieper-Pripyat aquatic system after the Chernobyl accident [6,7]. The highest level of radioactivity in the water of Pripyat river was observed during the initial period after the accident. Over the time from 1986 to 1994 radionuclides contents in the river flows are permanently decreased in general, but during each high water period its concentration in the water temporary increased under the wash-off and erosion phenomena, creating a secondary contamination of the water masses. Therefore, the ratio between Sr-90 and Cs-137 in water flow have been changed significantly as well as the ration between its suspended and soluble part in the water (Table I.)

Table. I. Annual total influx of \(^{137}\text{Cs}\) and \(^{90}\text{Sr}\) (Ci\(^1\)) to Kiev Reservoir from Pripyat River and Dnieper River.

<table>
<thead>
<tr>
<th>Years</th>
<th>(^{137}\text{Cs}) in solute</th>
<th>(^{137}\text{Cs}) on sediments</th>
<th>(^{90}\text{Sr}) total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>2261</td>
<td>359</td>
<td>1034</td>
</tr>
<tr>
<td>1987</td>
<td>505</td>
<td>213</td>
<td>496</td>
</tr>
<tr>
<td>1989</td>
<td>255</td>
<td>110</td>
<td>338</td>
</tr>
<tr>
<td>1991</td>
<td>68</td>
<td>65</td>
<td>511</td>
</tr>
<tr>
<td>1993</td>
<td>69</td>
<td>47</td>
<td>425</td>
</tr>
</tbody>
</table>

\(^1\) 1 Ci= 37 GBq

The main feature of the radionuclide release from the contaminated watersheds to the Kiev reservoir within 10 years after the accident is the significant diminishing of the \(^{137}\text{Cs}\) influx to the reservoir, however \(^{90}\text{Sr}\) washing out to river net continue to be on practically the same level. Since 1992 the rate of \(^{90}\text{Sr}\) release to Pripyat River was diminished due water protection measures (dam construction) on floodplain near Chernobyl NPP.

The difference in the behaviour of the radionuclides appears also in the phenomenon that large part of \(^{137}\text{Cs}\), as well as some other radionuclides, are associated in water with suspended particles. The average size of suspended particles of the river's flow varied from 0.02 mm in low water period and to 0.25 mm during the floods. The total amount of suspended sediments in the river flow with size particles less than 0.05 mm was presented approximately in range 55-60 % of total. On the contrast, the bed sediments of the Pripyat river consist almost exclusively of the sands with very small amount of silt and practically without clay size sediments. The ratio of \(^{137}\text{Cs}\) amounts transported with suspended sediments to ones in solute has the tendency to increasing (Tabl.I) due to decreasing of Cs-137 contents in mobile forms in upper surface layer of the catchment because of its fixation and vertical migration in soils.
The specific of radionuclide transport defines the strategies of aquatic countermeasures. A lot of remedial strategies that has been proposed may be classified as follows.

A. Measures in drainage area
a) Removal of contaminated soil;
b) Alternations in the catchment area to minimize the run-off of radionuclides from land to water, e.g., planting of trees, digging of channels/ditches, or adding the chemicals to bind the radioisotopes (e.g., lime, potash or dolomite);
c) Prevention of flooding most contaminated territories attached to a water body (e.g., floodplain dams);
d) Construction to prevent radionuclide transport to surface water bodies by ground water flow (e.g. contra-seepage wall in soil).

B. Measures in water bodies
a) Constructions to increase the sedimentation of contaminated suspended materials in rivers (e.g. a quarry - a bottom trap for contaminated sediments, dams, ditches and spurs).
b) Construction to separate most contaminated parts of the water bodies from a main stream (e.g., dikes and dams dividing the water bodies);
c) Dredging of contaminated deposits;
d) Change in mode of the Dnieper reservoir management to optimize it on radionuclide concentration criteria.
e) Change in drinking water intakes, e.g. recommendation to switch on other water supply sources.

The efficiency of the countermeasures depends from the taking into the account the above described specific of radionuclides transport in dilute and with suspended sediments for different kinds of radionuclides. A lot of non efficient measures were provided in first emergency phase of water protection activities. The description of the different phases of countermeasures activities and examples of non-efficient countermeasures are presented in [8]. Since September 1986 when first version of modelling system have started to work in the Cybernetics Center the evaluations of countermeasures efficiency were provided there to support the Emergency Commission decisions. The positive results of the system implementation was not only recomendation for efficient countermeasures, however also the recomendation to stop non-efficient projects.

3. MATHEMATICAL MODELS

Due to the objectives of the computerized system to support the water protection measures the radionuclides dispersion in the Pripyat River and Dnieper Reservoirs should be simulated within the wide range of temporal and spatial scales—from tenth of meters to thousand kilometers and from second to tenth of years. To simulate processes in such wide range of scales the set of mathematical models have been formulated [1-4] which equations have been derived from the equations of the basic three-dimensional model by their averaging over the different scales.

Each model includes submodel of hydrodynamics (hydraulics), suspended sediments transport submodel and radionuclides transport submodel. In the suspended sediment transport submodel the rate of sedimentation and the resuspension rate are calculated as the function of the difference between actual suspended sediment concentration and equilibrium concentration relevant to the transport capacity of the flow. The later is calculated on the base of semi-empirical relations.

The radionuclides transport submodels describe the dynamics of concentrations of radionuclides in solution, in suspended sediments and in bottom depositions. For describing the adsorption/desorption and diffusion contamination transfer in the systems "solution - suspended sediments" and "solution - bottom deposition" the Kd approach has been used. For a more realistic simulation of the kinetics of the processes the exchange rates between solution and particles was taken into account by additionally taking the exchange rates between solution and particles into account for
simulation kinetics processes. The adsorption and desorption rates assumes not to be equal. The contamination exchange between bottom deposition and suspended sediment is describing taking into account sedimentation and resuspension processes.

The modelling system nowadays includes following models.

WATOX - box model, which variables are averaged over compartments that as usual represent whole reservoir or it's large section. The resulting set of the ordinary differential equations describes the dynamics of the water volume in a box and the compartmentally averaged value of the suspended sediment concentration, the concentration of the radionuclide in solution, on suspended sediments and in bottom deposition. The results of the prediction of the radionuclide concentration within flood period depend on the operation mode of the reservoirs, i.e. from the changes in the water levels at the Hydropower Plants dams. The optimization methods are used to provide choices of the reservoir system operation mode under the water quality criteria.

RTVTOX-one dimensional river model, is used to simulate radionuclides transport in networks of river channels generated by the direct pollutant release into the river or by the washing out of radionuclides from the catchments. The variables in RTVTOX which describe flow, suspended sediments and radionuclide dynamics are averaged over the river channel crossections. A 'diffusion wave' model is used to describe water discharge and surface elevation dynamics, that has been derived from the one-dimensional Saint-Venant's equation. The advection-diffusion equation is used to describe suspended sediments transport in the river channel. The dynamics of the upper contaminated bottom layer is driven by the equation of bottom erosion. The high order accuracy finite-difference methods (FDM) are used to solve "diffusion wave" equation and advection-diffusion equations that describe transport of suspended sediments, radionuclides in dilute and radionuclides adherent to suspended sediments. The ordinary differential equation simulate the radionuclides dynamics in the upper contaminated bottom layer.

COASTOX is two-dimensional lateral-longitudinal model developed to simulate depth averaged concentration of radionuclides in solute, suspended sediments and in bottom depositions of reservoirs, floodplains and coastal areas. The model is used to analyze radionuclide dispersion in water bodies with significant spatial variations of the concentrations (vicinity of the releases, transport above inhomogeniously contaminated bottom, etc.). The model describes currents, sediment transport, advection-diffusion pollutant transport, radionuclide - sediment interaction. The FDM are used to solve the model's equations.

VERTOX is two-dimensional vertical -longitudinal model developed to simulate radionuclides transport in the vicinity of the abrupt depth changes- such as bottom traps for contaminated sediments and other engineering constructions. The model equations have been derived by the averaging of the equations of basic 3-D model over the river channel width. The numerical solution of the models equations are obtained by FDM.

THREETOX is three dimensional model developed to simulate radionuclide transport with large vertical and lateral variability of flow parameters ( deep lakes and reservoirs, cooling ponds of nuclear power plants). The model implementation requires a lot of input data and computer resources, therefore it is used only in situations where spatial variability of parameters do not permit use more simple approaches.

WATOX and RIVTOX models were validated within IAEA/CEC VAMP programme [9]. COASTOX was verified within CEC JSP -1 project[10]. The sediment transport and bottom erosion modules of VERTOX were tested on the base of laboratory experiments data [3]. THREETOX is under testing studies now.

4. PREDICTION OF THE PRIPYAT RIVER-DNIEPER RESERVOIRS RADIONUCLIDE CONTAMINATION

The predictions of $^{137}\text{Cs}$ and $^{90}\text{Sr}$ concentration in the Dnieper reservoirs during spring flood were prepared in February-March each year since the accident by applying the WATOX code[1,4]. The predictions also was developed during the high rainstorm flood and other extremal events at Pripyat River watershed [11]. The data of the watersheds contamination density and the averaged values of the
radionuclide wash off coefficients were used to predict $^{137}$Cs and $^{90}$Sr concentrations in the tributaries released into the reservoirs. Since 1986 the level of $^{137}$Cs concentration in the Dnieper reservoirs decreases (close to the pre-accident values in the southern reservoirs) due to low magnitude of the spring floods and as a result of the diminishing of $^{137}$Cs wash-out coefficient. The coefficient of $^{90}$Sr wash out does not diminish in the same manner. Therefore the $^{90}$Sr contamination remains most significant problem for high spring floods in the Pripyat River - Dnieper River system. The simulation of processes on the floodplain at the Chernobyl NPP have been supplemented by forecasting of $^{90}$Sr dispersion in the Dnieper reservoirs. The seasonal and short term predictions are in reasonable agreement with the measured data for the spring floods, rainstorm floods, consequences of the radionuclide releases from the Pripyat floodplain as results of the ice jams in winter 1991 and 1993.

The computerized system is used for the prediction of Dnieper reservoirs contamination during 1996 spring flood. The unusual large amount of snow in the winter 1995-1996 at northern part of Ukraine put public attention to the problem of radionuclide contamination of Dnieper reservoirs. For the most probable estimation of the magnitude of hydrograph of the Pripyat River that have been done by the Ukrainian hydrometeorological service at middle of march - 1900-2100 cub.m /s the simulation gives $^{90}$Sr concentration at 80 pCi/l in the Pripyat river and its increasing from 2-4 pCi/l to 20 pCi/l near Kiev at the end of April. This upper estimation of the maximum of concentration is several times lower than Maimum Permissible Level - 100 pCi/l. The results of simulation was presented to State Emergency Comission and was used for public information.

To estimate the collective dose for population of Ukraine from the consumption of Dnieper water during 70 years after the accident (till 2057) WATOX code was used in the version based on three months averaged input data. The three month averaged discharge of the Dnieper River, Pripyat River and tributaries to the Dnieper Reservoirs since 1895 were used to create hydrological data base for a long term prediction. The scenario of the worst radiological conditions should be based on the sequences of high runoff years since 1994. The constructed set of the hydrological data used 1970-1992 (high runoff period) and then 1912-1950 (low runoff period) as a "hydrological forecast" for 1994-2057. For the prediction of radionuclides concentration in the tributaries to the Kiev Reservoir the regression relations between concentration and water discharge were constructed based on the experimental data and evaluation of the dynamics of washing -out coefficients governing by the leaching from fuel particles and by the decay and the percolation into the soil. The simulated results demonstrate that the large southern Kakhovka reservoir, damping the seasonal oscillations, will have after some years practically the same level of $^{90}$Sr concentration as the Kiev reservoir. In the last three month averaged concentration will change from 27 pCi/l in the initial period to the 3-5 pCi/l in 2056. These data and data of the better from radiological conditions hydrological scenarios was used to calculate dose for the development of the post-Chernobyl countermeasures in Ukraine [12].

5. MODELLING SUPPORT OF THE WATER PROTECTION MEASURES

5.1. Optimization of reservoir management

The box model WATOX includes the optimization module to provide choices of the reservoir operation mode on the base of water use and water contamination criteria. The optimization efficiency increases with the diminishing of the ratio of spring flood volume to total reservoirs volume. The results for the average spring flood demonstrate that maximum diminishing of the concentration in the reservoirs could be near 25% of the peak value within the hydropower production restrictions. The maximum diminishing (up to 50% of the peak value) could be achieved for low water flood (probability of exceeding PE=95%). The model is implemented in the State Committee on Water Resources for Dnieper Reservoirs management.

5.2. Countermesures to increase radionuclide sedimentation

The VERTOX and COASTOX models were used to evaluate the efficiency of the countermeasures proposed to diminish the radionuclide concentrations in the Dnieper reservoirs. The
demonstration of low efficiency of the large scale hydraulics projects for Kiev Reservoir - the construction of the new dam through the reservoir and submerged dike near Hydropower Plant, was background to stop this expensive projects.

The VERTOX model was applied used to simulate the efficiency of the bottom traps for contaminated sediments in the Pripyat River channel [3]. It was demonstrated that the selectivity of the traps for sedimentation in depend of radionuclides distribution through the size fractions of the sediments grains. \(^{137}\text{Cs}\) is transported by the finest suspended sediments that provides non-efficiency of such countermeasures.

5.3 Countermeasures on the Pripyat River floodplaine

One of the most powerful source of \(^{90}\text{Sr}\) contamination of the Pripyat water and as result in all down flow Dnieper reservoirs is the fuel particles fallout on the Pripyat river floodplain North-Eastward from the Chernobyl Plant. Near 10000 Ci of \(^{90}\text{Sr}\) were deposited here on the territory 4 km \(\times\) 10 km. The simulation of the potential flooding of this territory has been provided since 1989 on the base of COASTOX computer code [1,2,4]. This territory has not been flooded till 1991 because of low spring floods during this period.

The simulation of the floodplain flow has demonstrated that the most dangerous situation, causing large increases in radionuclides concentrations is a spring flood with a maximum discharge of 2000 m /sec. The probability of exceeding (PE) this flood magnitude for the area considered of the Pripyat river is 25\%. During such spring flood the water covers all parts of the contaminated floodplain, but water depth is less then one for floods with lower PE. It was demonstrated [1,2] that during such flooding the concentration of \(^{90}\text{Sr}\) would increase from 50 pCi/l at inlet crossection (10 km upflow Chernobyl NPP) to 250-270 pCi/l at outlet crossection (the Yanov Bridge near Chernobyl NPP) due to the interaction with the contamination in the bottom depositions. The construction of the special dam around the contaminated area on the left bank of the Pripyat river has been recommended in 1990 on the base of simulated results as the optimal countermeasure to prevent release from floodplain.

In January 1991 before starting of the dam construction ice-jam was formed in the Pripyat river channel between Yanov Bridge and the town of Chernobyl. As a result the Pripyat floodplain near the Chernobyl NPP was covered by water for the first time after the accident. Maximum concentration of \(^{90}\text{Sr}\) near the Yanov Bridge increased to the values 250-300 pCi/l. This way the results predicted during simulation of countermeasures effectiveness has been confirmed by a wide scale natural experiment. During the flooding the modelling system was use for real-time simulation of the situation on the floodplain on the base of COASTOX model and for prediction dynamic \(^{137}\text{Cs}\) of \(^{90}\text{Sr}\) concentration in the reservoirs and especially near Kiev on the base of WATOX model. Due to dilution and dispersion of contamination in the reservoir the maximum concentration on the way from River Pripyat mouth to Kiev HPP (more than 70 km) diminished from 200 to 30 pCi/l.

The forecasts (confirmed later by direct measurements) have been presented to the State Commission. It was used to make optimum change in February1991 to the municipal water supply arrangements without having to use water from the River Dnieper. The dam preventing future flooding of the considered part of the Pripyat floodplain has been constructed till 1992 spring flood. Recently small dam have been constructed on the right side of the floodplaine. The simulation demonstrates that in case without this dams constructions the concentration of \(^{90}\text{Sr}\) at Kiev Reservoir could be three time more (up to the 60 pCi/l) that it predicted now, after this countermeaasure fulfillment.

CONCLUSION

Within the decade after the accident the computerized system was improved and used for the radionuclide concentration prediction in water bodies as also for the water protection decision support. Main practical outputs of the system are as follows

- background of the dam construction at the Pripyat River floodplain at city of Pripyat;
- negative conclusions for the several non-efficient projects;
predictions of the seasonal variations of radionuclides concentration in Dnieper reservoirs as results of the follows hydrological events: spring floods generated by snow melting, and summer - autumn floods generated by rainstorms, flooding of the territories at Chernobyl NPP due to ice jams in the Pripyat river;

long-term forecasting of radionuclide concentration in Dnieper reservoirs for life-time dose calculation taking into account radionuclide dynamics on watersheds within different hydrological scenario;

The experience of the model application for prediction of rivers and reservoirs contamination and water protection decision support after the Chernobyl accident is used to develop the hydrological module of the European comprehensive decision support system for nuclear emergency - RODOS.

REFERENCES


