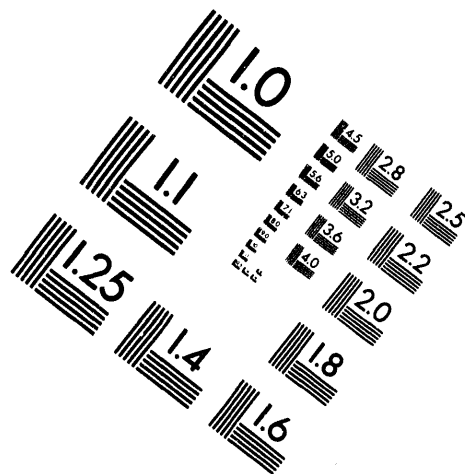# AIIM

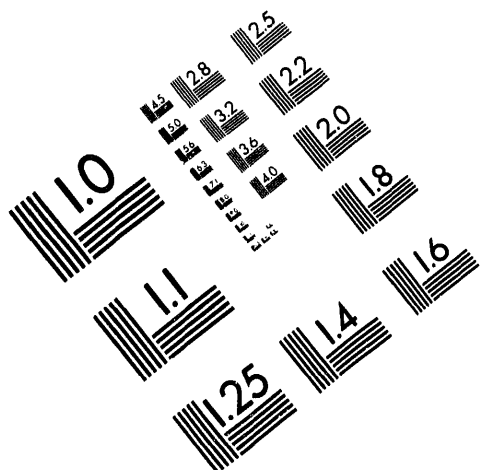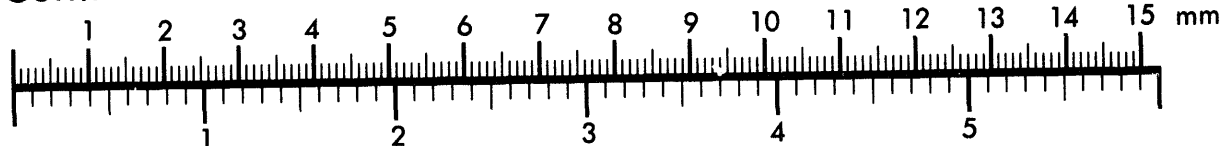**Association for Information and Image Management**
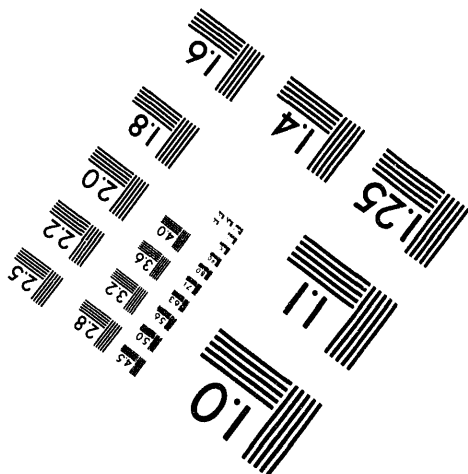
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Silver Spring, Maryland 20910

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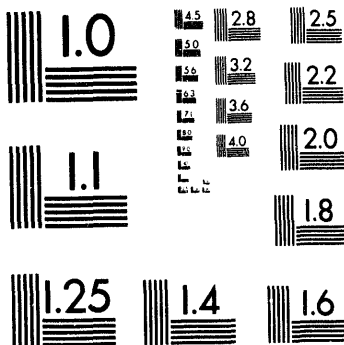
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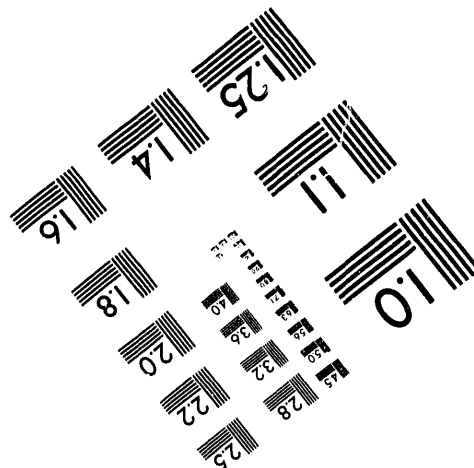
Chernobyl Nuclear Accident Hydrologic Analysis and Emergency Evaluation of Radionuclide Distributions in the Dnieper River, Ukraine, During the 1993 Summer Flood

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Summary

This report describes joint activities of Program 7.1.F, "Radionuclide Transport in Water and Soil Systems," of the USA/Commonwealth of Independent States (CIS) Joint Coordinating Committee of Civilian Nuclear Reactor Safety to study the hydrogeochemical behavior of radionuclides released to the Pripyat and Dnieper rivers from the Chernobyl Nuclear Power Plant in Ukraine. These joint activities included rapid evaluation of radionuclide distributions in the Pripyat and Dnieper river system and field data evaluation and modeling for the 1993 summer flood to assist the Ukrainian government in their emergency response during the flood.

About 19 million people in Ukraine consume water from the Dnieper River between Kiev and the Black Sea and thus are exposed to the impacts of the radionuclides in the river through drinking water, irrigation, and fishing; 8 million consume Dnieper River water as their drinking water. With the most current water use information available, a collective effective equivalent dose (EED) of internal exposure to the population and expected risks due to different water usage was calculated. We estimated that during 1986-1992, the collective dose (EED) for 19 million people resulting from 8 million people drinking the Dnieper River water and 19 million people consuming fish or irrigated food products are 216, 100, and 513 menSv, respectively, for a total of 829 menSv. The irrigation pathway is clearly the dominant pathway among these aquatic pathways. The total aquatic pathway contribution constitutes about 7.0% of the total collective EED of 11,832 menSv from all pathways. The equivalent radiation risks from the aquatic pathway for the 19 million people are 3.2×10^{-6}, as compared to 4.5×10^{-5} for all pathways. The expected human cancer effects from drinking the Dnieper River water and consuming radioactively contaminated fish and irrigated food products are estimated as 16, 7, and 38 people with cancers, for a total of 61 people in the total population of 19 million. The total number of people who will get cancers due to all pathways is expected to be 864.

Even though the aquatic pathway contributes only 7% of the total dose from all the pathways, radionuclide migration into and within the rivers is important for determining potential dose to people through aquatic pathways. This is mainly because most of the practical current and future remediation will be confined to within a 30-km zone around Chernobyl to control and reduce potential radionuclide

migration in the aquatic (surface and groundwater) pathways. The field data evaluation and modeling revealed that flooding is a critical factor that increases radionuclide concentrations in the rivers. The Pripyat River floodplain directly across from the Chernobyl Nuclear Power Plant is especially important because it received a significant amount of ^{137}Cs and ^{90}Sr deposition, with ^{90}Sr concentrations reaching 1000 μCi/m^2, accounting for approximately half of all ^{90}Sr entering the Pripyat River. During a January 1991 flood caused by an ice jam, the ^{90}Sr concentrations reached 250-300 pCi/L at Yanov Bridge (at the downstream end of the floodplain, exceeding the local drinking water limit of 100 pCi/L). The search for effective countermeasures led to the construction of an earthen dike in 1991. The construction of a 10-km dike in the floodplain across from the Chernobyl Nuclear Plant has proved to be effective for reducing ^{90}Sr concentrations in the Pripyat River. However, despite construction of the dike, radionuclide migration and interaction between the floodplain and the Pripyat River are a long-term problem. Surface and groundwater interaction must be assessed in the future.

Despite these remediation measures, the problem of increasing of 90Sr concentrations in the Pripyat and Dnieper rivers during high floods still remains. In July-August 1993, heavy rainfall over the Pripyat River catchment in Belarus and Ukraine caused severe flooding, significantly raising ^{90}Sr concentrations in the river. Because of heightened public concern about radionuclide levels in the river and the need of the Ukrainian government to make an emergency response, we conducted an emergency evaluation of radionuclide distributions in the Dnieper River, while the flooding was occurring. Near the Chernobyl area, the maximum ^{90}Sr concentration in the Pripyat River reached 20-25 pCi/L in early August; near the Pripyat River mouth, the concentration rose to 35 pCi/L. The peak ^{90}Sr concentration in the Kiev Reservoir (a major source of drinking water for Kiev) was 12 pCi/L. The evaluations showed that if the 10-km dike had not been constructed, ^{90}Sr concentrations in the Pripyat River, and thus also in the Dnieper River, would have been much higher. Based on these measured radionuclide levels, additional modeling results and the assumption of water purification in a water treatment station, ^{90}Sr concentrations in Kiev's drinking water were estimated to be less than 8 pCi/L. Unlike ^{90}Sr, ^{137}Cs concentrations in the Pripyat River during the flood did not rise significantly from the pre-flood levels. Estimated ^{137}Cs concentrations for the Kiev drinking water were two orders of magnitude lower than the drinking water standard of 500 pCi/L for ^{137}Cs. Thus the water was determined to be safe for Kiev's citizens to drink during the 1993 summer flood.

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1.0 Introduction

Within the framework of the activities of Program 7.1.F "Radionuclide Transport in Water and Soil Systems" of the USA/Commonwealth of Independent State (CIS) Joint Coordinating Committee on Civilian Nuclear Reactor Safety, a USA/CIS working group has been studying the behavior of radionuclides in soil and water contaminated by the 1986 Chernobyl Nuclear Power Plant accident (Onishi et al. 1993). This document has been prepared during the group members' joint work at the Pacific Northwest Laboratory (PNL).[a]

The Dnieper River watershed in Ukraine, Russia, and Belarus was heavily contaminated by radionuclides accidentally released from Reactor Unit No. 4 of the Chernobyl Nuclear Power Plant in Ukraine on April 26, 1986. During the accident, approximately 4% of the fission products and activates in Reactor Unit No. 4 were released to the atmosphere (Izrael et al. 1987; Izrael 1988). A significant portion of the radionuclides released fell onto the watershed of the Pripyat River in Ukraine and Belarus. The Chernobyl Nuclear Power Plant is located along the west bank of the Pripyat River approximately 30 km from its mouth at the Kiev Reservoir on the Dnieper River. Other areas that were heavily contaminated by ^{137}Cs are in the upper Dnieper watershed in Russia and Belarus (Figure 1 and Table 1). As a result of this surface contamination, there is a long-term influx of ^{137}Cs and ^{90}Sr into the Dnieper River, which passes through six reservoirs before discharging into the Black Sea. There has also been a significant increase in ^{90}Sr concentration in the Kiev Reservoir (reaching

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(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

The Dnieper River

Orsha

Borisov

MOGILEV

BOBRUYSK

Sozh

Besed

Iput

Grezla

Dnieper

Desna

PINSK

Styr

The Pripyat River

MOZYR

Goryn

Chernigov

NEDANCHICH

CHERNOBYL

Desna

Konotop

Nezhin

ROVNO

Teterev

KIEV

Trubezh

0   40   80   120 km

The range of surface ^{137}Cs contamination

1-5 Ci/km^2 15-40 Ci/km^2

5-15 Ci/km^2 > 40 Ci/km^2

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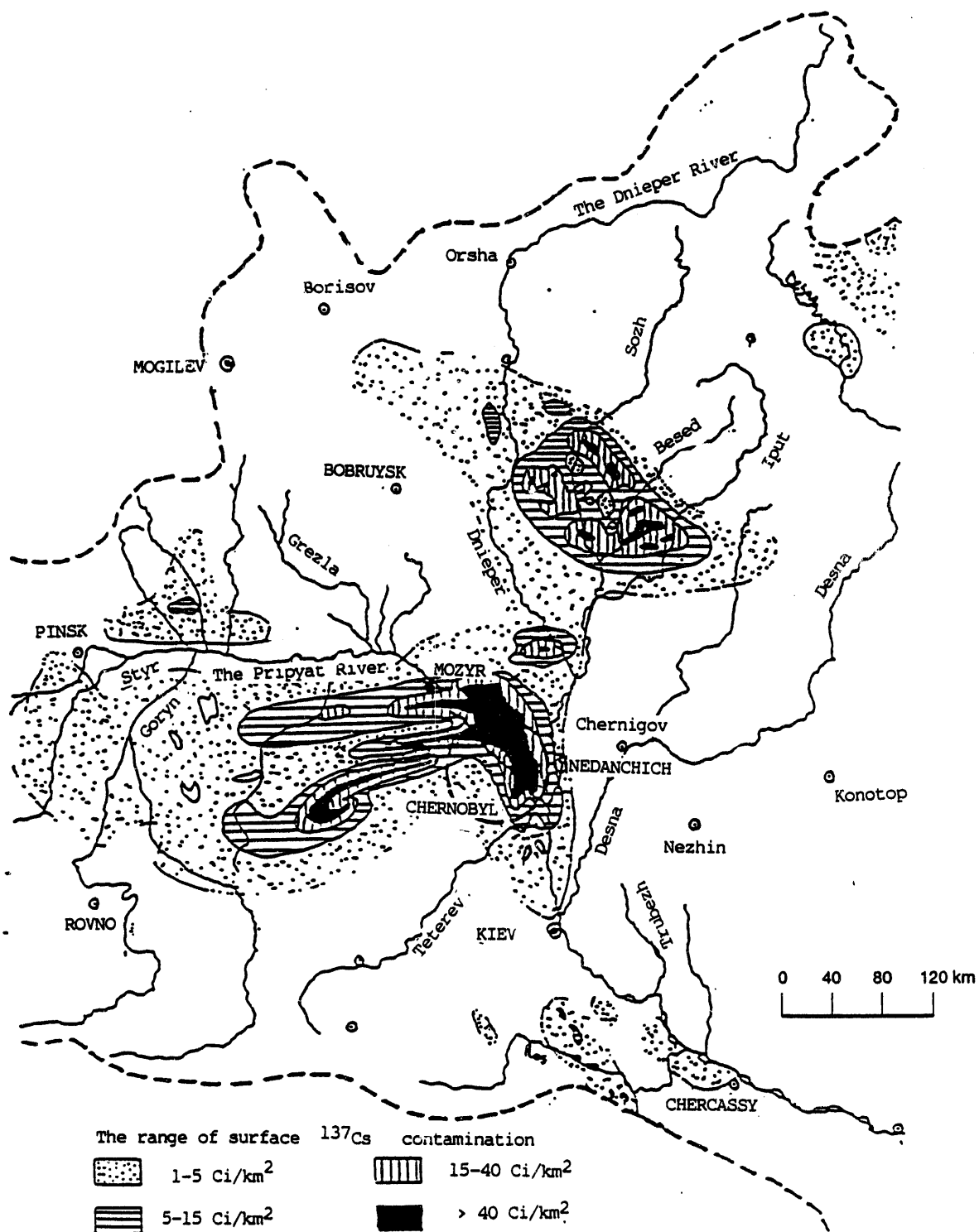
Figure 1. ^{137}Cs Contamination of the Catchment Areas of the Pripyat and the Upper Dnieper River Basins

Table 1. Amounts of ^{137}Cs and ^{90}Sr in the Catchment Areas of the Main Rivers and Tributaries Feeding the Kiev Reservoir[a]

Watershed	Catchment Area, 10^3 km²		Amounts of Radionuclides, 10^3 Ci	
	Basin	Area with Radionuclide Greater than 1 Ci/km²	^{137}Cs	^{90}Sr
Above Dnieper mouth	105	29	275	6
Above Pripyat mouth	115	27	180	42
Braginka and interfluve	2	2	55	12
Above Desna mouth	89	61	8	< 1

(a) The radioactive contamination of the Chernobyl Nuclear Power Plant site was not taken into account when evaluating the radionuclide contents.

more than 100 pCi/L in the northern part of the reservoir). The radionuclide influx from these distributed (non-point) source areas to the rivers has increased during each spring flood generated by snow melting (1987-1992) and during floods caused by high rainfall in the Pripyat River watershed (July 1988, October 1990). In addition, during the winter of 1991, the formation of a ice jam in the Pripyat River caused flooding of the Pripyat River floodplain near Chernobyl Nuclear Power Plant.

More than 20 million people in Ukraine consume water from the Dnieper River downstream from the Kiev Reservoir to the Black Sea, and thus are exposed to the impact of these radionuclides. The surface-water protection activities in this area have in effect been concentrated mainly on counter-flooding measures (Voitsekhovitch et al. 1989; Zheleznyak and Voitsekhovitch 1991). A 10-km dike was constructed along the Pripyat River in 1991 to prevent flooding of the heavily contaminated flood-plain just upstream of the Chernobyl Nuclear Power Plant.

Despite these measures, the problem of increasing of ^{90}Sr concentration in Dnieper water during high floods remains.

During July-August 1993, heavy rainstorms in the Belarus and Ukrainian districts of the Pripyat River catchment raised water levels in the upper tributaries and the main river unusually high for summer flooding. From the second week of July to late August, Pripyat River discharges increased from 250 m^3/s to 1200 m^3/s near Chernobyl, with an increase in ^{90}Sr concentrations in the river waters from 7-10 pCi/L to 25-30 pCi\L.

This report describes the USA/CIS working group members' joint work at PNL, emphasizing two main objectives:

1. Evaluation of radionuclide distributions in the Pripyat-Dnieper aquatic system, which was heavily contaminated by the 1986 Chernobyl nuclear accident, and associated radiation dose.

2. Emergency evaluation of the radionuclide distribution in the Dnieper River system during the 1993 summer flood to assist the Ukrainian government for their emergency response, based on group members' experience, in studies in Ukraine and the United States and based on simple mathematical modeling and available results of experimental studies.

2.0 Field Data

2.1 Data Collected Prior to the 1993 Summer Flood

Immediately after the 1986 accident, a main monitoring system around Chernobyl was organized by the USSR State Committee on Hydrometeorology with the scientific guidance of the committee's Scientific Production Association (SPA) Typhoon (Izrael 1987; Vakulovsky et al. 1991). During the years after the accident, the monitoring system was evaluated by various Ukrainian government agencies, including the Ministry of Chernobyl Affairs, the Hydrometeorological Service of Ukraine, the Committee of Water Supply, and the Geological Service of Ukraine. The Special Monitoring Environment Safety Department of SPA Pripyat and the Ministry of Chernobyl Affairs of Ukraine were responsible for surface and groundwater monitoring, water protection activities, and emergency control of radionuclide contamination of the river and groundwater in the 30-km area surrounding the Chernobyl Nuclear Power Plant.

The Ukrainian Hydrometeorological Institute provided the generalization of these data and the evaluation of the water monitoring system for surface-water contamination (Voitsekhovitch et al. 1990, 1991); for groundwater, the Institutes of Geological Science of the Ukrainian Academy of Sciences provided corresponding information.

2.1.1 Source/Watersheds Data

The radioactive cloud caused by the Chernobyl release and the subsequent aerosol fallout caused radioactive contamination in areas to the west and north of the Chernobyl Nuclear Power Plant subjected to the meteorological conditions for air mass transfer. From April 26 to May 8, 1986, the continuing release of gaseous, volatile, and aerosol products from the plant led to the formation of what are known as the near and distant zones of radioactive fallout (see Figure 1).

Data on the daily releases into the atmosphere make it possible to determine the composition of the release and the physical and chemical properties of the radionuclides, which changed during the time that radionuclide atmospheric transport and deposition took place. For this reason, the radionuclide composition of the fallout over the territory was heterogeneous, varying with direction and distance from the Chernobyl Nuclear Power Plant.

The shock wave of the Chernobyl explosion, the temperature gradient present, and oxidation of the nuclear fuel (uranium dioxide, or UO_2) led to the formation of "hot" fuel particles, over 90% of which had an activity on the order of 1 nCi per particle. These "hot" fuel particles had a radionuclide composition similar to that of spent fuel. The release of "hot" fuel particles into the environment is the unique feature of contamination from the Chernobyl accident. The destruction of the fuel elements and the "annealing" of the nuclear fuel also released a considerable quantity of volatile fission products into the atmosphere, some of them condensed on the inert carrier particles of the aerosols (e.g., mixtures of dust, and construction materials). The properties of the "hot" particles formed in the accident were similar to those formed in the last stage of a nuclear explosion (Demchuk et al. 1991).

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The condensed particles (with aerosols) that formed as a result of the Chernobyl accident are similar to radionuclides of the global fallout after nuclear weapons tests, and therefore it is possible to predict their behavior in water bod: ; to a reasonable degree. However, the behavior of the fuel particles, which are a unique feature of the Chernobyl accident and are concentrated primarily within approximately 60 km around the Chernobyl Nuclear Power Plant, presents major scientific problems.

Most of the radioactive fallout was deposited on the catchment areas of the Pripyat, Dnieper, and Desna Rivers, which are the main rivers feeding the reservoirs in the Dnieper cascade (Figures 1, 2, and 3; Tables 1 and 2). The radioactive trail has three distinct branches (northern, western and southern), which cover the southern districts of Belarus, the western part of the Bryansk region of Russia, and the northern and central regions of Ukraine. Measurements of ^{137}Cs and ^{90}Sr in the catchment areas of the main tributaries of the Pripyat and the Dnieper rivers were provided by Vakulovsky and Voitsekhovitch (1990) and Vakulovsky et al. (1991, 1993). The accident contaminated the water bodies in two stages: first via direct radioactive fallout from atmosphere during the first weeks after the explosion, and then via the aquatic pathway as a result of various secondary radionuclide migration processes. The important feature of the data on the Chernobyl fallout is the large difference in radionuclide distributions between ^{90}Sr (which is mainly localized around the Chernobyl Nuclear Power Plant) and ^{137}Cs (which is spread over large territories outside the 30-km zone but also localized in contaminated spots in the upper Dnieper catchment).

Study of the distribution of physical-chemical forms of the radionuclides and their transformations in the water-soil systems in the water catchments during the five years after initial fallout showed that the proportion of mobile (soluble and exchangeable) forms in aerosol fallout immediately after the accident was significantly higher for ^{137}Cs than for ^{90}Sr (Bobovnikova et al. 1990).

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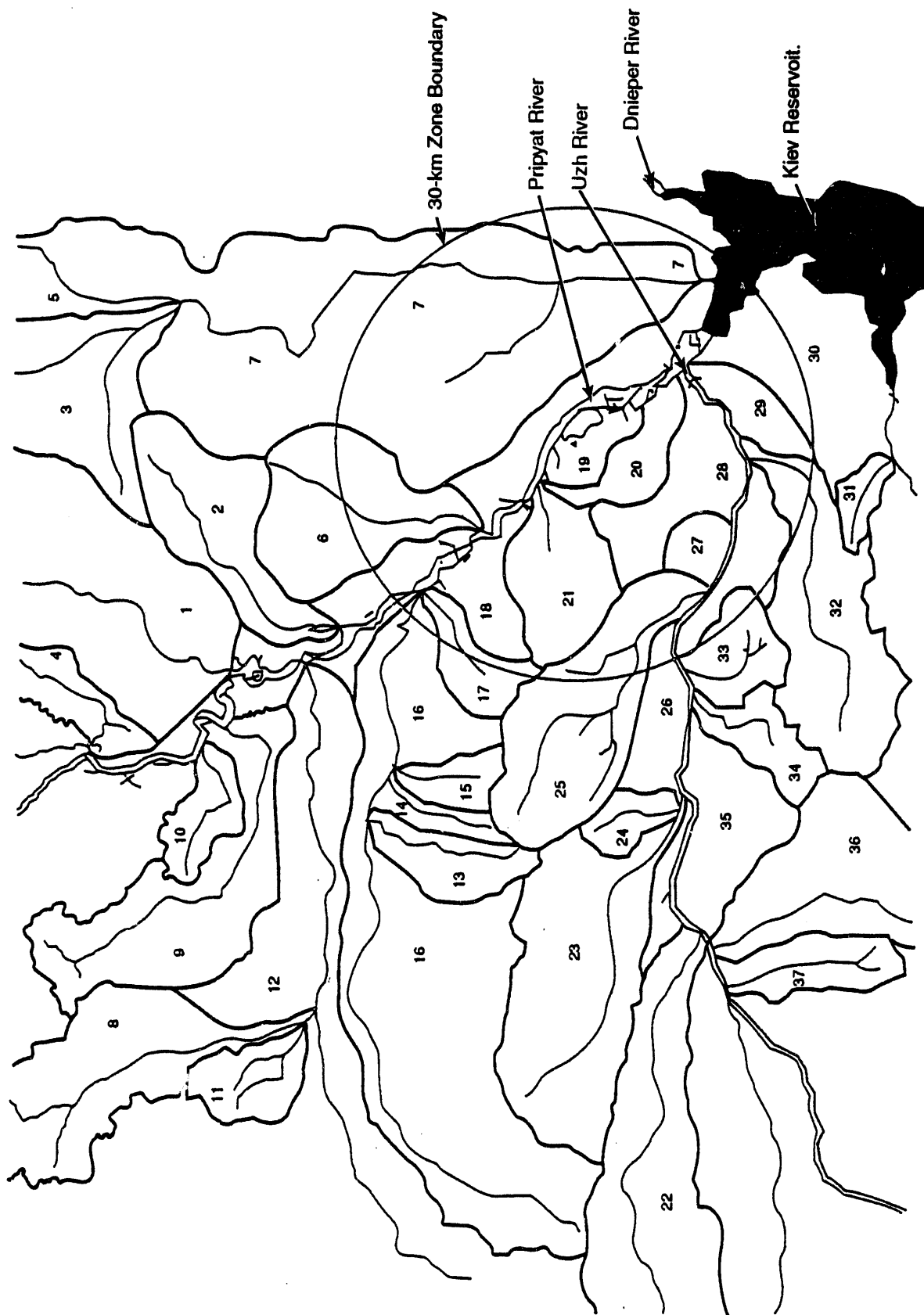
Figure 2. Watersheds of Small Rivers Inside the Chernobyl 30-km Zone and Nearby Area
(by Konoplev et al. 1993)
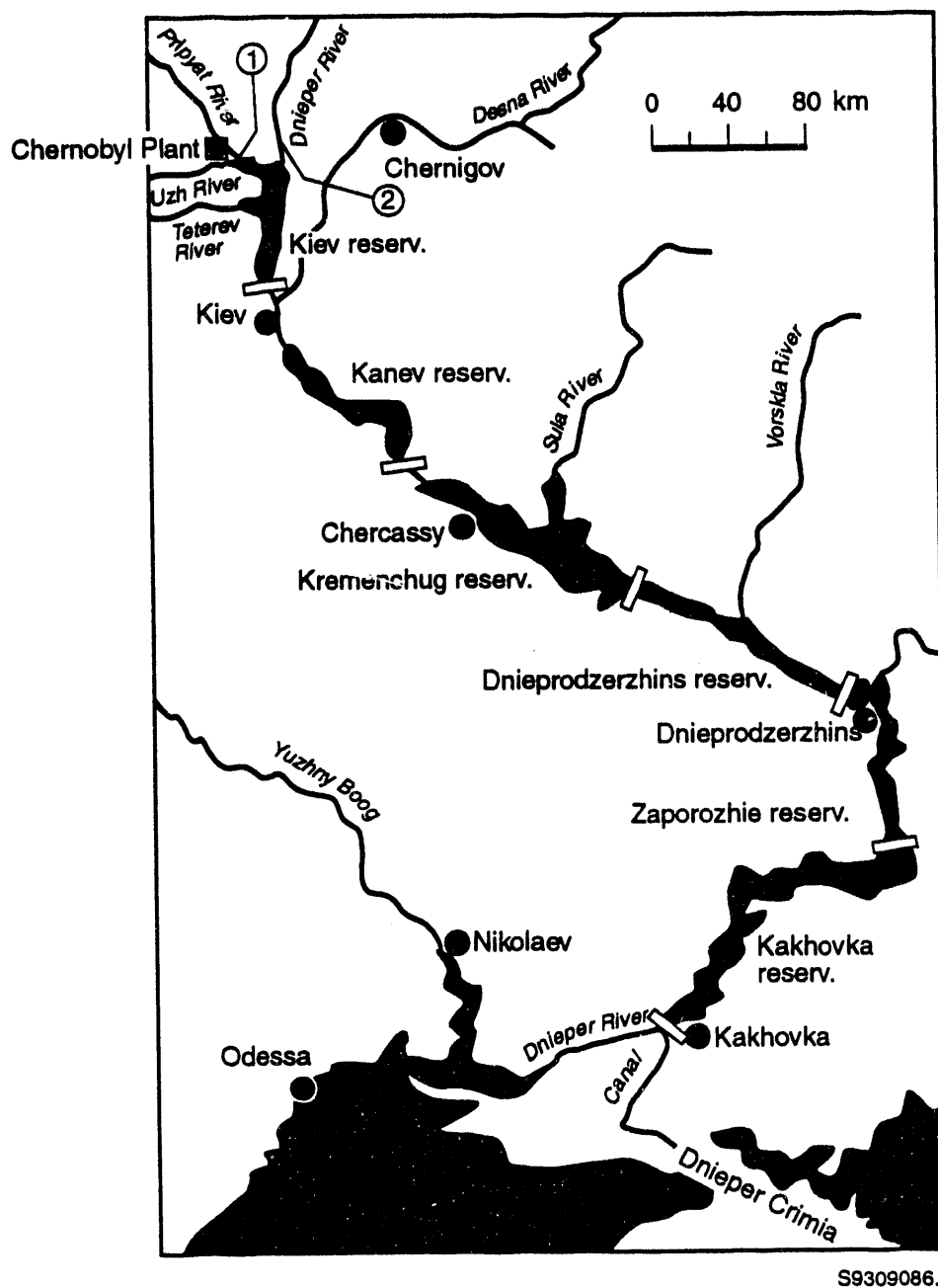
Figure 3. Map of the Pripyat-Dnieper System

Table 2. Radionuclide Content in Catchments of 30-km Zone of the Chernobyl Nuclear Power Plant

Catchment Number	Area, km²	Forest %	Swamp %	Meadow %	⁹⁰Sr Amount Ci	¹³⁷Cs Amount Ci
1	777	27	15	58	790	8450
2	255	21	13	66	350	5320
3	286	45	15	40	530	2190
4	120	15	-	-	80	680
5	37	60	-	-	650	140
6	497	14	13	13	1110	51440
7	1557	32	22	46	9160	93760
8	420	70	20	10	340	2270
9	477	35	7	58	160	6240
10	102	26	25	49	80	1670
11	122	34	17	49	70	1010
12	302	35	0	65	350	4760
13	105	46	13	41	50	1820
14	60	54	11	35	10	1520
15	77	57	28	15	20	2310
16	1177	34	25	41	180	32850
17	108	59	8	33	190	3360
18	108	85	7	8	230	3290
19	73	40	2	58	-	-
20	104	33	0	67	2 ?0	6300
21	222	33	18	49	880	11810
22	777	30	12	58	350	4180
23	576	54	4	42	120	2990
24	65	45	39	16	20	420
25	386	46	18	36	30	7500
26	116	13	15	72	180	4120
27	64	70	0	30	30	130
28	281	51	7	42	870	8790
29	86	90	5	5	180	490
30	333	30	0	70	590	1680
31	57	29	3	68	80	330

As a result of mechanical destruction and dissolution of the fuel component in the fallout, ^{90}Sr and ^{137}Cs were leached into the soil at approximately the same rate. However, because of the different fixation mechanisms between cesium and strontium in the catchment soils, radioactive contamination of the water systems differed. Although there was a decrease in the amount of ^{137}Cs in the exchangeable form as a result of fixation with soil, the mobile physical-chemical forms of ^{90}Sr increased (Konoplev et al. 1988, 1990a,b). These processes, working together with decay and radionuclide seepage from the upper soil layer, have led to a decrease in the magnitude of effective washout for ^{137}Cs for the watersheds in areas around Chernobyl. The effective washout for ^{90}Sr has mostly stayed at about the same level during the seven years since the accident.

The first studies relating to the washout of Chernobyl radionuclides from catchment to a receiving river were carried out as early as the summer of 1986, using artificial sprinkling on specially equipped runoff sites (Borzilov et al. 1988). The critical parameter describing the land surface washout process is the washout coefficient, k_w, defined as the fraction of the radionuclide load in the soil which has entered the water body with the overland flow. Since a radionuclide is either in dissolved state or adsorbed on suspended particles in a solid phase, it is convenient to express the washoff coefficient as the sum of "liquid" and "solid" washout coefficients ($K_w = K_L + K_s$). These coefficients are defined as (Konoplev et al. 1992)

$$K_L = \frac{\int_0^t C_w(t) \, q(t) \, dt}{h \int_s C_s \, ds} \tag{2.1}$$

$$K_s = \frac{\int_o^t C_a(t) \, q(t) \, dt}{m \int_s C_s \, ds} \tag{2.2}$$

where Ca = radionuclide concentration attached to suspended sediment in runoff water

Cw = dissolved radionuclide concentration in runoff water

Cs = radionuclide concentration on the surface of the soil

h = runoff water depth

m = mass of the moved suspended matter from the unit area

q = water discharge of the overland flow

s = surface area of the watershed

T = duration of surface runoff

Table 3 shows the standardized washout coefficients for the main long-lived radionuclides as a result of fluvial and snow-melt runoff based on experiments at the runoff sites (Voitsekhovitch et al. 1993a). Details of the experimental studies of the liquid and erosion washout processes and supplementary information about washout parameters from the areas contaminated by Chernobyl have been described by Borzilov et al. (1988) and Konoplev et al. (1990a,b, 1992).

After radionuclides fall onto the surface of the soil, they become fixed with soil and migrate into the depths of the soil. These processes result in a reduction in the magnitude of the radionuclide washoff coefficients of surface runoff. However, there was no significant drop in the K_L level for ^{90}Sr between the summer of 1986 and the autumn of 1989. This phenomenon can be explained by the fact

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Table 3. Liquid Washoff Coefficients (K_L) for ^{137}Cs and ^{90}Sr, Obtained at Experimental Sites in the 30-km Zone around the Chernobyl Nuclear Power Plant

Experimental Site	Date	Liquid Washoff Coefficients ($10^{-5}K_L mm^{-1}$)	
		^{137}Cs	^{90}Sr
Chernobyl	Jul 9 88	1.1	42
	Jul 10 89	1.0	45
Benevka	Oct 14 86	0.6	5.8
	Mar 87	0.2	0.6
	Sep 17 87	0.3	21
	Jul 8 88	1.0	20
	Jul 11 88	0.7	13
	Sep 29 88	0.9	17
Kopachi	Mar 87	0.4	1.1
	Apr 87	5.7	6.6
	Sep 16 87	0.1	2.0
	10 Jul 88	0.7	12
	Sep 27 88	0.8	10
Korogod	Mar 87	0.7	0.8
	Sep 18 87	0.4	11
	Jul 7 88	1.4	13
	Sep 24 88	1.5	8.8
	Jul 7 89	0.7	15
Doviyady	Jul 16 86	5.5	10
	Jul 16 86	3.4	10
	Oct 12 86	0.8	7.2
	Oct 16 86	0.6	12
	Oct 16 86	1.6	8.4

that the migration of the mobile soluble forms of ^{90}Sr into the lower soil layers is balanced by transformation of its non-exchangeable forms as a result of leaching of the fuel particles. As a result, the content of exchangeable forms of ^{90}Sr in the upper soil layer has not changed in the catchment areas, with the exception of areas in the near zone, where the trail includes "hot" particles and where in recent years rates of radionuclide leaching from the matrix of the "hot" particles have increased, as shown in Figure 4 and Table 4 (Voitsekhovitch et al. 1993a). As a result of these physical-chemical
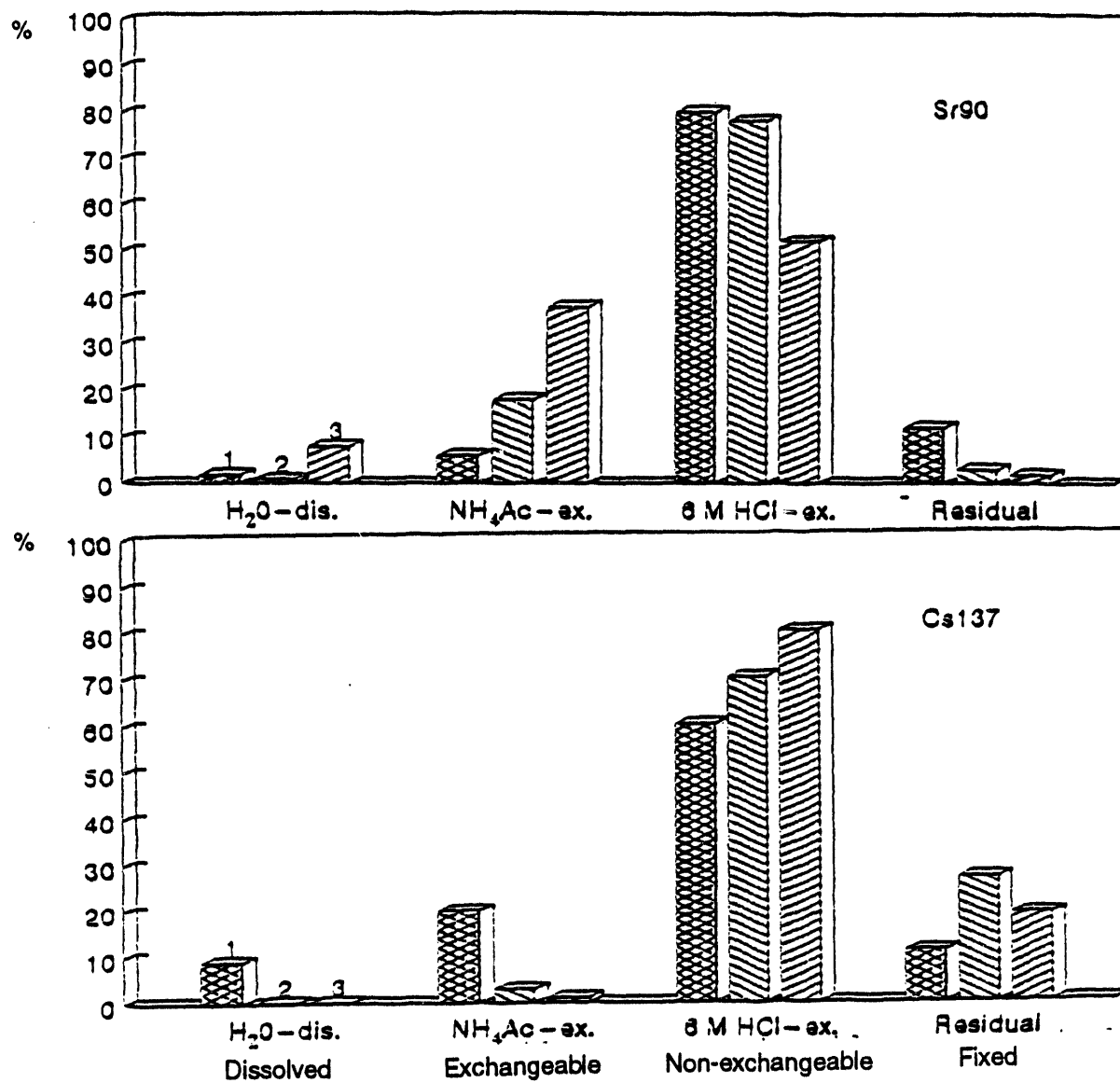
Figure 4. Trends of ^{90}Sr and ^{137}Cs Physical-Chemical Forms Transformation in the Floodplain Soils of the Pripyat River Near the Chernobyl Nuclear Power Plant

Table 4. Time Variation of Mobile Chemical Form in the Floodplain Soil of Nearest Zone Around the Chernobyl Nuclear Power Plant

Years	Fraction of Exchangeable Form of Radionuclide as % of the Total Radionuclide	
	^{137}Cs	^{90}Sr
1986 (autumn)	0.05 - 0.1	1 - 5
1987	0.1 - 0.15	6 - 8
1988	0.14 - 0.16	8 - 15
1989	0.2 - 0.3	15 - 23
1990	0.6 - 1.0	25 - 40
1991	1.0 - 1.4	40 - 60

transformations, the distributed, non-point sources of secondary ^{137}Cs contamination of Dnieper water have significantly diminished in magnitude during the last few years. In contrast, the current magnitude of ^{90}Sr fluxes to the receiving surface water from the watersheds is close to the values of the first years after the accident.

2.1.2 River/Reservoir Hydrological Data

The Dnieper/Pripyat river system is the main surface-water artery of Ukraine. River and reservoir hydrology of this system is measured by Ukrainian Hydrometeorological Institute (Tables 5 and 6). The hydrologic features of these rivers and their tributaries are typical for European rivers with plain watersheds and a forest-steppe landscape. The spring snow melt usually causes flooding of the Pripyat and Dnieper rivers near the Chernobyl area from early March to the middle of May. The historical maximums for water discharges (about 5000 m^3/s) and water elevations in the Pripyat River near Chernobyl were measured in May 1970 and May 1979. Since the Chernobyl accident, the spring water discharge did not exceed 1500 m^3/s in 1987, and was about 900-1300 m^3/s in 1988-1993.

Table 5. Surface-Water Elevation of the Pripyat River Across the 30-km Zone of Chernobyl During Spring Floods with Different Probabilities of Water Discharges

Probability of Exceeding the Water Discharge, %	Water Discharge m³/s	Corresponded Levels of Water Elevation in Different Cross-Sections along the Pripyat River				
		Chernobyl 26 km[a]	35 km[a]	Yanovbriadge 44 km[a]	51 km[a]	58 km[a]
1	6000	106.4[b]	109.5[b]	110.0[b]	110.4[b]	110.5
5	4000	105.8	108.8	109.4	109.7	109.9
10	3100	105.4	108.5	109.2	109.5	109.7
25	2000	105.0	108.0	108.6	109.2	109.5
50	1300	104.7		108.1		108.9

(a) Distance from the river mouth.
(b) Water surface elevation in meters above sea level.

Table 6. Main Hydrological Data for Dnieper Reservoirs

Parameters	Kiev	Kanev	Kremenchug	Dneprodzerzhin	Zaporozhie	Kakhov
NHD[a] (m above sea level)	103.0	91.5	81.0	64.0	51.4	16.0
LDC[b] (m above sea level)	101.5	91.5	75.75	63.0	48.5	12.7
Capacity for NHD (km³)	3.73	2.62	13.51	2.45	3.3	18.21
Capacity for LDC (km³)	2.56	-	4.50	-	2.47	11.4
Area of water shed (1000 km²)	239	336	383	425	463	482
Area of water surface for NHD (km²)	922	675	2250	567	410	2150
Area of water surface for LDC (km²)	670	-	1180	-	200	1920
Length (km)	110	123	149	114	129	230
Maximum width (km)	12.0	8.0	28.0	8.0	7.0	25.0
Average width (km)	8.4	5.5	15.1	5.1	3.2	9.3
Maximum depth (m)	14.5	21.0	20.0	16.0	53.0	24.0
Average depth (m)	4.0	3.9	6.0	4.3	8.0	8.5
Perimeter (km)	520	510	800	358	250	900
Minimum discharge in summer (m³/sec)	200	200	200	200	200	200
Maximum recorded discharge (m³/sec)	15300	23200	23900	24100	24500	19300
Annual Mean outflow volume (km³/y)	33.1	43.9	47.8	52.0	52.2	52.2
Averaged flow velocity (cm/sec)	3.0	7.6	2.0	7.1	6.4	1.6
Mean sedimentation rate (cm/year)	0.70	2.0	0.94	0.98	1.37	0.8
pH	7.2 - 8					

(a) NHD - Normal Head Level - Designed level for hydropower plant work.
(b) LDC - Level of Dead Capacity - Level of minimum reservoir capacity.

Until 1993, rainfall flooding had a maximum discharge below 900 m^3/s. High spring floods usually transport greater amounts of water and therefore larger amounts of radionuclides than rainfall-caused floods. However, even rainfall floods could significantly increase the radionuclide influx into the Pripyat River, thus also to the Kiev Reservoir. The highest floods on the Pripyat River since the accident have been in July 1988 with the maximum water discharge of 900 m^3/sec, October-November 1989 with 450 m^3/sec, and fall of 1990 with 580 m^3/s. During these rainfall-caused floods, radionuclides were washed out from the contaminated watersheds and flowed out from the low-elevation areas near the old floodplain-channel streams. However, as will be discussed in Section 2.1.6 (Radionuclide Dynamics During the Flood), the flooding of the most contaminated part of the Pripyat River floodplain near the Chernobyl Nuclear Power Plant occurred not under normal snow-melt or rainfall-caused flooding, but as a result of a rise in water elevation due to the formation of an ice jam in the Pripyat River channel downstream from the Chernobyl Nuclear Power Plant.

The Pripyat River carries sand, silt, and clay materials; more than 80% of the total sediment transport in rivers is usually due to the suspended sediment. Ordinary suspended sediment transport in the Pripyat River in summer has a range of 20-40 kg/s. During spring floods with Pripyat water discharges of more than 1500 m^3/s, the sediment transport rate can exceed 200-250 kg/s. During low-flow periods, suspended concentrations in the Pripyat River are 30-50 mg/L. During spring floods, the concentration can exceed 250 mg/L.

The sediment transport rate in the Dnieper River during middle-sized floods, with water discharge less than 2000 m^3/s, does not exceed 40-50 kg/s. Usually, in spring, sand accounts for 20-30% of sediment being transported; silt is 40-60%, and clay ranges less than 30%. During the low-flow periods, suspended solids in the Pripyat River mostly consist of organic/mineral silt and clay particles

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(60-70%). In winter, the organic/mineral silt and clay fraction of sediment transported in rivers is 70-90%. The suspended matter concentration in the Kiev Reservoir is usually less than 20 mg/L, with 5-15 mg/L being clay and organic matter (Table 6).

2.1.3 River/Reservoir Data - Primary Radionuclide Contamination

Immediately after the accident, the surface water bodies were affected by the direct precipitation of aerosol fallout onto the water surface. Radionuclide concentrations in the rivers during the period after May 1, 1986, revealed a sharp change in the water contamination level at the end of the fallout period. Total beta activity in the Pripyat River water exceeded 10^{-7} Ci/L in the first days after the accident but had decreased to 4.6×10^{-9} Ci/L by the end of May 1986.

Maximum plutonium concentrations observed in the Pripyat River in the first days after the accident were about 10 pCi/L but decreased to 0.2 pCi/L by August 1986. They were four orders of magnitude lower than the maximum permissible level of soluble plutonium for drinking water. Up to 98% of the plutonium in the water bodies was associated with suspended and bottom sediments. Therefore, the emphasis of the field and experimental studies on radioactive contamination of water bodies was on ^{90}Sr and ^{137}Cs (Voitsekhovitch et al. 1990, 1991; Vakulovsky et al. 1991). The rivers, creeks, lakes, and floodplain water located near the Chernobyl Nuclear Power Plant were initially contaminated by direct deposition of radioactive substances onto the water surface and riverbed. In small rivers, this mode of contamination continued through the whole month of May 1986. The level of radioactive contamination was determined by the rate of fallout deposition onto the river surface and dissolved in the water. The content of ^{90}Sr in various water bodies was determined from May 1, 1986,

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onwards. The highest levels were observed in the first few days of May 1986 in the Pripyat River, reaching 400 pCi/L. From the end of May until June, the ^{90}Sr content in the Pripyat River remained within the range 30-50 pCi/L. Ratios of ^{137}Cs adsorbed by each sediment size fraction to the total sorbed ^{137}Cs over several years are shown in Figures 5 and 6, showing clear preference for finer sediment by ^{137}Cs.

The Dnieper reservoirs were contaminated almost immediately after the accident by deposition of radioactive substances from the atmosphere. According to some estimations (Iz _ '' et al. 1991), the total amount of radioactive substances that were deposited on the aquatic surfaces of the Pripyat River and the Kiev Reservoir reached approximately 35 x 10^5 Ci. During first several days after the accident, the total specific activity of water in the Kiev Reservoir and the Dnieper River near a Kiev drinking water intake exceeded 100 pCi/L. Almost the whole activity (99%), except iodine, was associated with suspended particles; activity in a sample that was taken on April 30 from the Kiev Reservoir near the town of Lutezh (at the southern end of the reservoir) reached 10 μCi per kilogram of dry weight sediment.

Later, when the intensive radioactive release to the atmosphere from the damaged reactor ended, the aerosol component of reservoir contamination decreased rapidly and suspended particles precipitated to the bottom; by May 10, 1986, the total specific radioactivity of water in the lower part of the Kiev Reservoir had decreased to about 10^3 pCi/L.

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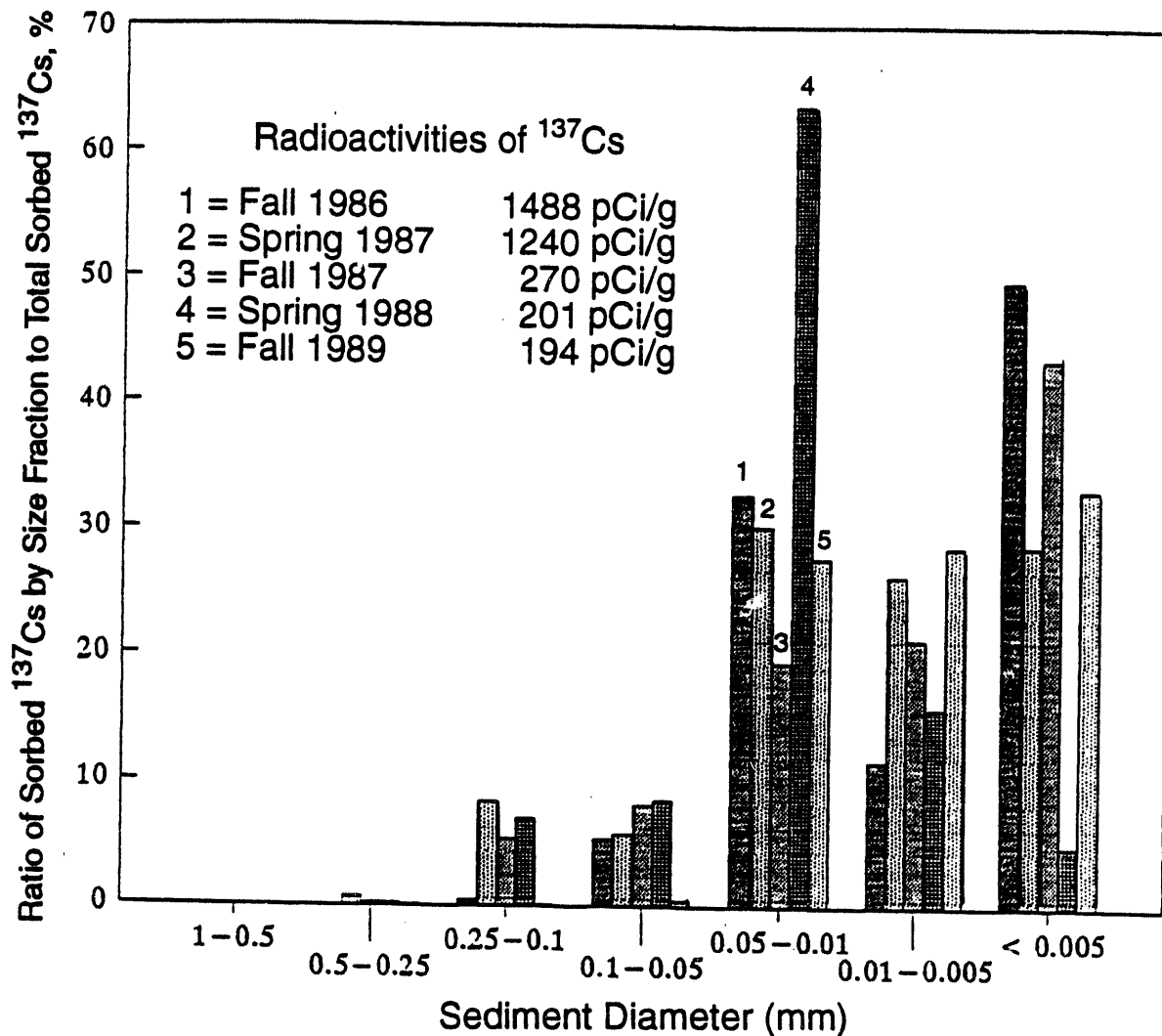
Figure 5. [137]Cs Distribution on the Suspended Particles of the Pripyat River near the Town of Chernobyl

The highest contamination levels in the waters of the reservoirs in the Dnieper cascade were also registered in the initial period after the accident. The total beta activity of the water in the period of aerosol fallout reached 100 μCi/L. The radioactivity of the water in this period came primarily from particles suspended in the water. The activity of the filtrate accounted for only about 10% of the total activity of gamma-emitters in the sample.
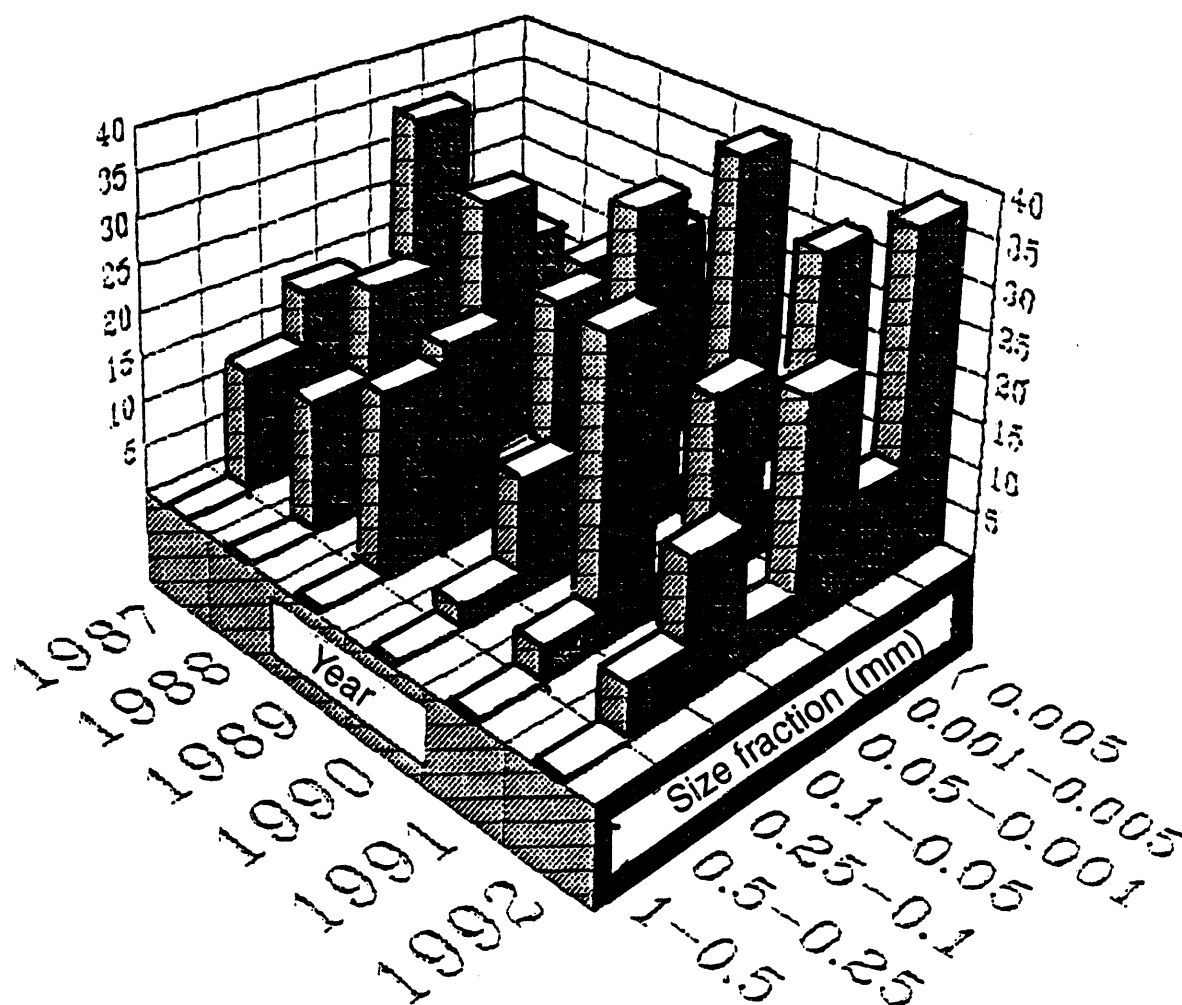
Figure 6. [137]Cs Distribution on the Suspended Particles of the Pripyat River near the Chernobyl Nuclear Power Plant

After the fallout period, the sharp drop in the intensity of emissions from the Chernobyl Nuclear Power Plant led to a reduction in the contribution by the aerosol component in reservoir contamination. Suspended particles settled quickly onto the beds of the reservoirs, and by May 7, 1986, the total beta activity of the water in the central districts of the reservoir also decreased to about 10 pCi/L.

Contamination by the radionuclide ^{131}I had a significant role in the risk of radiation exposure to populations through the aquatic pathway during the initial period. The highest ^{131}I content in the Dnieper River, which was observed in the Dnieper drinking water intake area, came from fallout of radioactive aerosols and reached 3000 pCi/L on May 3, 1986. Once atmospheric fallout of radioactive aerosols onto the water surface had ceased, secondary radionuclide migration processes became the main source of water contamination. The two most important of these processes were

a) radionuclide washout from contaminated catchment areas and river floodplains; and

b) radionuclide mass-exchange processes in the "bed-sediment/water" system. The intensity of secondary water-contamination processes was determined largely by the physical-chemical forms of the radionuclide fallout and by their rate of transformation in the "soil-water" system.

2.1.4 Radionuclide Influx to the Dnieper Reservoirs

Radionuclide levels in the Pripyat and Dnieper rivers obtained from the Ukrainian monitoring system for the post-accident period are presented in Figures 7 and 8 and in Table 7 (Voitsekhovitch et al. 1993a).

These data show quite different trends in the temporal variation of ^{137}Cs and ^{90}Sr fluxes. The annual flux of ^{137}Cs from the Pripyat River to the Kiev Reservoir decreased from almost 1500 Ci in 1986 to about 250 Ci in 1987 to 35 Ci in 1992. The annual flux of ^{90}Sr, however, has not changed significantly during 1987-1991; it was about 280 Ci in 1987, near 500 Ci in 1988, 388 Ci in 1991, and about 100 Ci in 1992 (Table 7). These data agree with the indirect estimates of the annual catchment radionuclide fluxes of ^{137}Cs and ^{90}Sr obtained from the process described in Table 3.
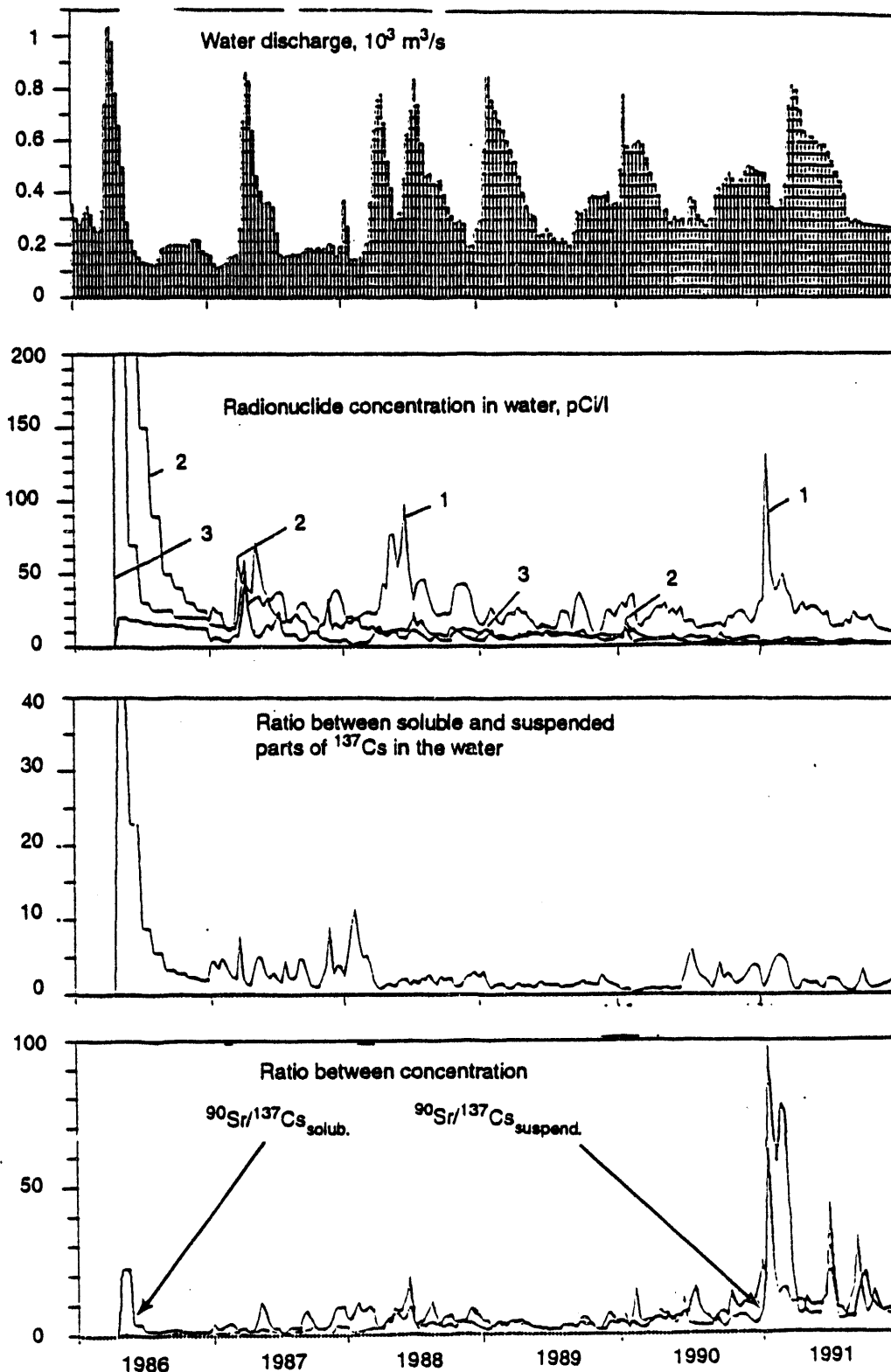
Figure 7. Time Variations of Water Discharge and of ^{137}Cs and ^{90}Sr Concentrations (daily averaged data) after the Accident for the Pripyat River, at the Town of Chernobyl. 1, 2, and 3 on the above figure represent ^{90}Sr, soluble ^{137}Cs, and particulate ^{137}Cs.
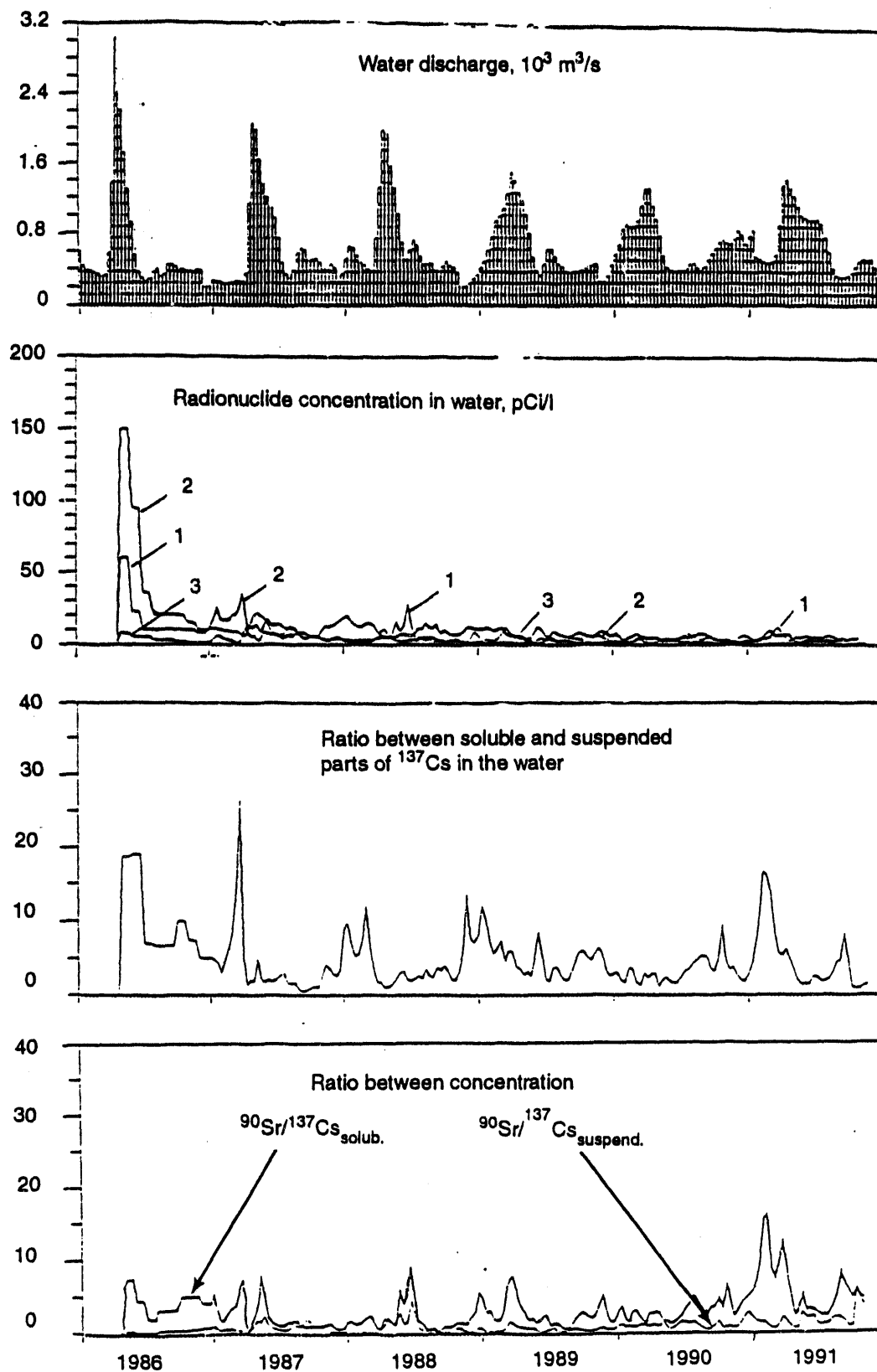
Figure 8. Time Variations of Water Discharge, and of ^{137}Cs and ^{90}Sr Concentrations (ten-day averaged data) and Their Ratio after the Accident for the Dnieper River at Nedanchychy. 1, 2, and 3 on the above figure represent ^{90}Sr, soluble ^{137}Cs, and particulate ^{137}Cs.

Table 7. Annual Dnieper and Pripyat Rivers Radionuclide Flux (Ci/y) and Washout Coefficients (K_L) from Their Catchment During the Period after the Accident (mm^{-1})

Years	Soluble ^{137}Cs	Suspended ^{137}Cs	K_L ^{137}Cs	^{90}Sr	K_L ^{90}Sr
Pripyat River at Chernobyl					
1986	1480	80		725	
1987	242	107	1.70×10^{-5}	277	8.6×10^{-5}
1988	162	97	0.74×10^{-5}	506	9.8×10^{-5}
1989	98	77	0.47×10^{-5}	243	5.0×10^{-5}
1990	58	65	0.26×10^{-5}	224	4.3×10^{-5}
1991	38	27	0.16×10^{-5}	388	7.1×10^{-5}
Total	2078	453		2363	
Dnieper River at Nedanchychy					
1986	720	50		280	
1987	244	113	0.14×10^{-5}	223	16.0×10^{-5}
1988	188	70	0.14×10^{-5}	141	7.1×10^{-5}
1989	155	34	0.14×10^{-5}	97	5.0×10^{-5}
1990	96	42	0.14×10^{-5}	92	5.2×10^{-5}
1991	71	32	0.14×10^{-5}	105	5.8×10^{-5}
Total	1474	341		938	

The decrease in flux values as well as the washout coefficients for ^{137}Cs in the Pripyat River and its catchments shown in Table 7 reflect the rapid fixation of ^{137}Cs in the soils. No similar phenomenon was observed for ^{90}Sr. This disparity can be explained by the fact that migration of mobile forms of ^{90}Sr into the surface unsaturated layers was compensated by transformation of ^{90}Sr from nonexchangeable to exchangeable forms and as a result of leaching from the "hot" particles to the environment. Data for the dynamics of mobile forms of ^{90}Sr and ^{137}Cs on the floodplain soils of the area near Chernobyl were given in Table 4. The differences in ^{90}Sr and ^{137}Cs fixation mechanisms in catchment

and floodplain soils are also reflected in their transport by the Dnieper and Pripyat rivers (Figures 7 and 8). Seasonal variations in ^{90}Sr and ^{137}Cs ratios in Figures 7 and 8 also reflect flooding of the areas near Chernobyl that had high levels of ^{90}Sr contamination in soils.

The water transport of radionuclides, especially ^{137}Cs, is determined primarily by the suspended materials resulting from erosion of small soil and sediment particles from the catchment and resuspension of bed sediment by river channel erosion processes. Chronological data on the 10-day-averaged ratio between ^{137}Cs associated with suspended sediments (particles up to 1 mm in diameter) and dissolved ^{137}Cs serve as an indicator of the importance of sediments in ^{137}Cs river transportation. The observed ratio of suspended and solution ^{137}Cs for the post-accident period is shown in Figures 6 and 7. The percentage of suspended-sediment sorbed ^{137}Cs varies from 20 to 80% depending on resuspension conditions, catchment erosion, and flow transportability. From 1987 to 1991, the contribution of the radionuclides associated with suspended sediments remained 30-40% of the total radionuclide flux in of the Pripyat River. Meanwhile, the specific activity of suspended ^{137}Cs in the Pripyat River by the end of 1986 had reached 3000-30,000 pCi/g. By 1990-1992 it had decreased to 30-300 pCi/g, as calculated for the suspended element in samples on ordinary filters or in special sediment traps in the field. The trend in ^{137}Cs fluxes for recent years indicates that while washout of soluble forms of radionuclide has decreased, changes in the amount eroded have been insignificant. As a result, there has been marked growth in the contribution of the suspended component relative to total radionuclide flux in the river. Transport of river sediment, however, does not play any significant role in ^{90}Sr migration. These data provide a clear indication that the time variation of radionuclide influx to the reservoir system depends on peculiarities of hydrological conditions and on the physical-chemical species of the radionuclides in the contaminated catchments.

2.1.5 Radionuclide Distribution in the Dnieper Reservoirs

The six reservoirs on the Dnieper River, which were described in Table 6, are the main source of surface water for consumption in Ukraine. During its near-900-km journey across the Ukrainian territory from the mouth of the Pripyat River to the Black Sea, Dnieper River water is used for drinking, municipal, and industrial needs and for irrigation. Canals transport the Dnieper's water from Kakhovlca Reservoir to the industrial Donbass region, to the Crimean Peninsula, and to the irrigated land of southern Ukraine. As a result, 20 to 30 million Ukrainians have been affected by radionuclides in the Dnieper's water since the Chernobyl accident.

The highest contamination levels for the Dnieper cascade reservoirs were registered in the initial period after the accident. Later, with the sharp decrease of the radioactive releases from the Chernobyl Nuclear Power Plant, the impact of the aerosol component on reservoir contamination became lower; a fairly rapid sedimentation on the Kiev Reservoir bottom took place, and by May 7, 1986, the total beta activity in water in the lower part of the Kiev Reservoir was already down to about 10 pCi/L.

For the post-accident years, almost 95% of the ^{137}Cs that entered the Dnieper River was deposited in the bottom of all the Dnieper reservoirs (Voitsekhovitch et al. 1993b). Thus, the contribution of ^{137}Cs discharged to a northeastern part of the Black Sea for this period (during which annual Dnieper River flow was below the norm) was insignificant relative to radionuclide amount in the northwestern part of the Black Sea.

Temporal and spatial distributions of radionuclide concentrations in the Dnieper reservoirs, measured by the Ukrainian Hydrometeorological Institute, are presented in Figures 9 and 10. The distribution of ^{90}Sr in the Dnieper reservoirs shows that fixation of the radionuclide by bottom sediments is not very firm (Figures 10 and 11), and that water in the lower reservoirs is affected by ^{90}Sr radiation to an even greater degree than was observed for ^{137}Cs (Voitsekhovitch et al. 1993a).

Most ^{90}Sr inflow to the Kiev Reservoir passes through the six reservoirs of the Dnieper cascade as transit elements and thus can enter the lower Dnieper area, where the radionuclide concentration is near the water irrigation standard of 7 pCi/L for ^{90}Sr. The level for ^{90}Sr was 5-10 pCi/L in 1991-1992. During 1992, the average ^{90}Sr content ranged from 20-30 pCi/L near the mouth of the Pripyat River to 1-5 pCi/L in the lower reservoirs. The reservoir water contamination level for ^{137}Cs for 1991-1993, was somewhat lower, 0.1-1 pCi/L, which is close to the background level caused by global radioactive fallout.

The same tendencies were observed for suspended matter being transported by water flow along the Dnieper reservoir system. Typical distributions of suspended matter in water and the associated ^{137}Cs contamination along the Dnieper cascade measured by the Ukrainian Hydrometeorological Institute in the summer of 1988 are shown in Table 8. Most of the suspended sediment released from the river to the reservoir is deposited on the bottoms of the upper parts of the reservoirs. However, some of the finest particles (usually with a size of less than 50 μm) could be carried away by flow to the next reservoir and on down to the lower parts of the cascade. A considerable flux of radionuclides into the lower reservoirs has been observed during storms and in periods of high water. Up to 50% of the ^{137}Cs influx to the reservoirs is carried with the fine sediment particles, and up to 80% of the river

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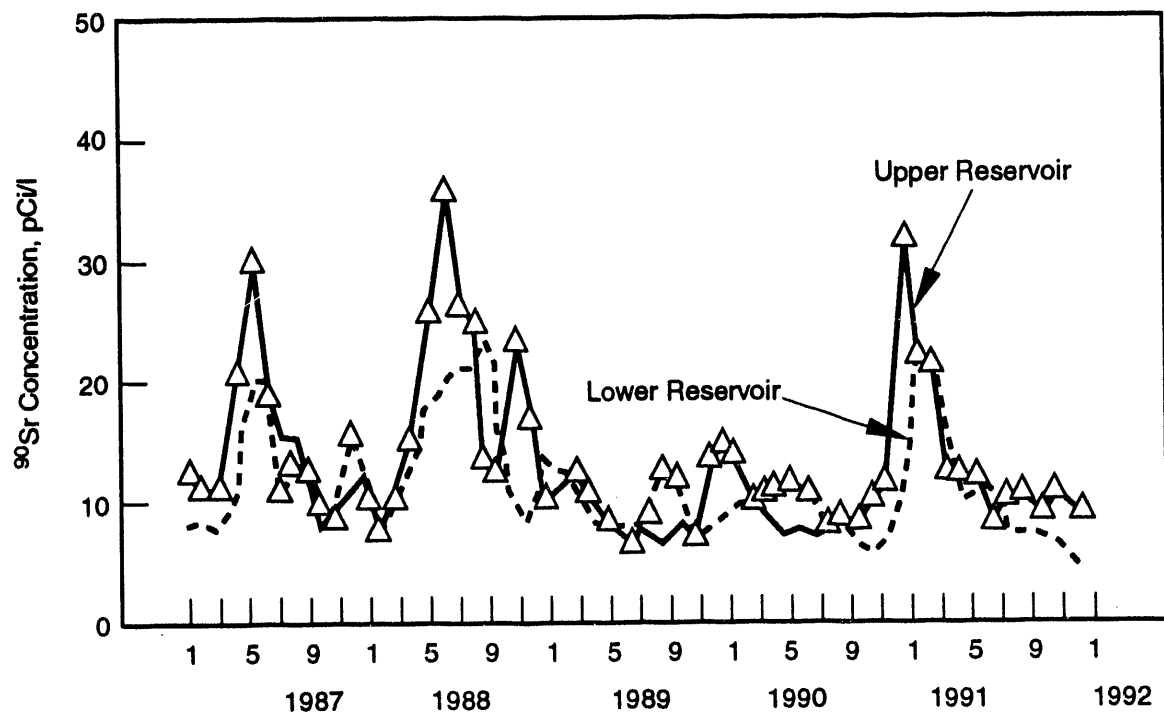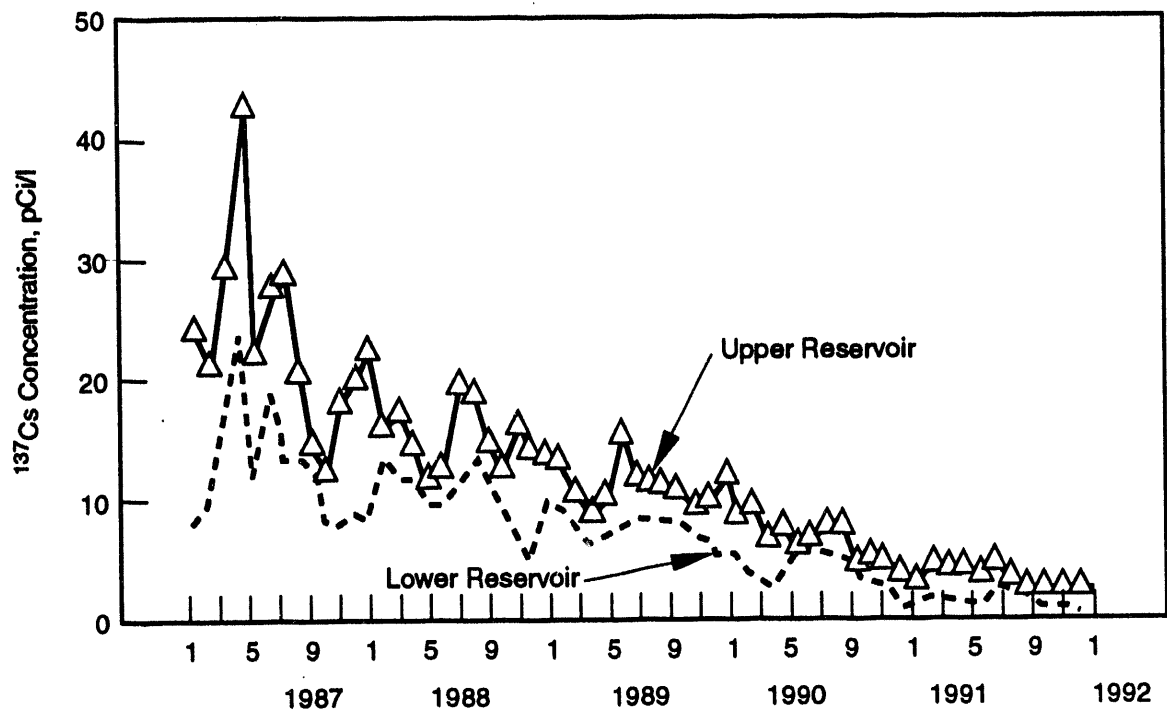
Figure 9. Radionuclide Contamination of the Kiev Reservoir after the Accident (Voitsekhovitch and Kanivets 1993).

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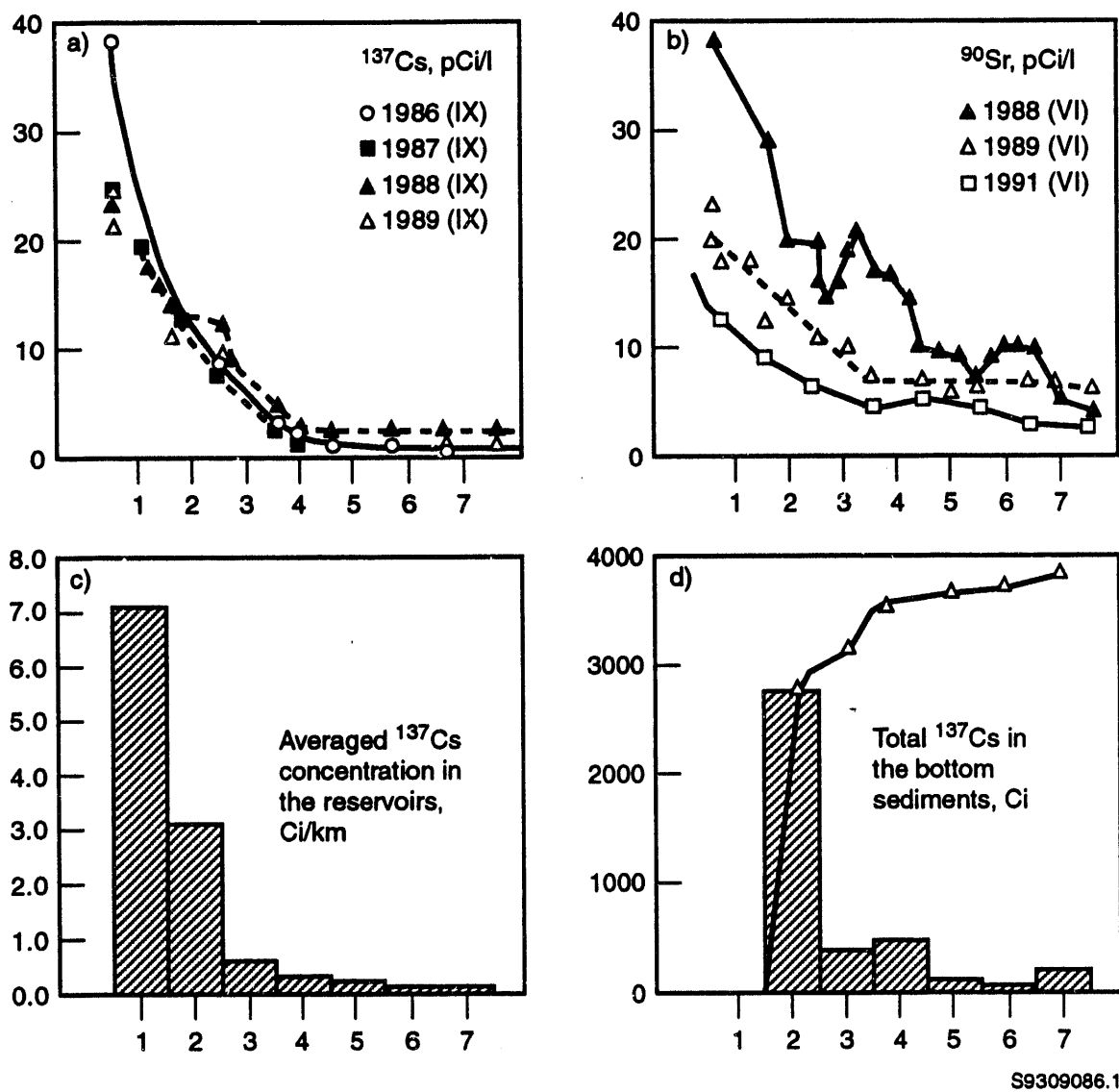
Figure 10. Radioactive Contamination of the Dnieper Reservoirs After the Chernobyl Accident
(a) ^{137}Cs Concentrations in Water, (b) ^{90}Sr Concentrations,
(d) Total ^{137}Cs in Bottom Sediment. In these figures, 1 indicates mouth of the Pripyat
River, 2 through 7 indicates six reservoirs in the Pripyat River from Kiev Reservoir
to Kakhovka reservoirs.
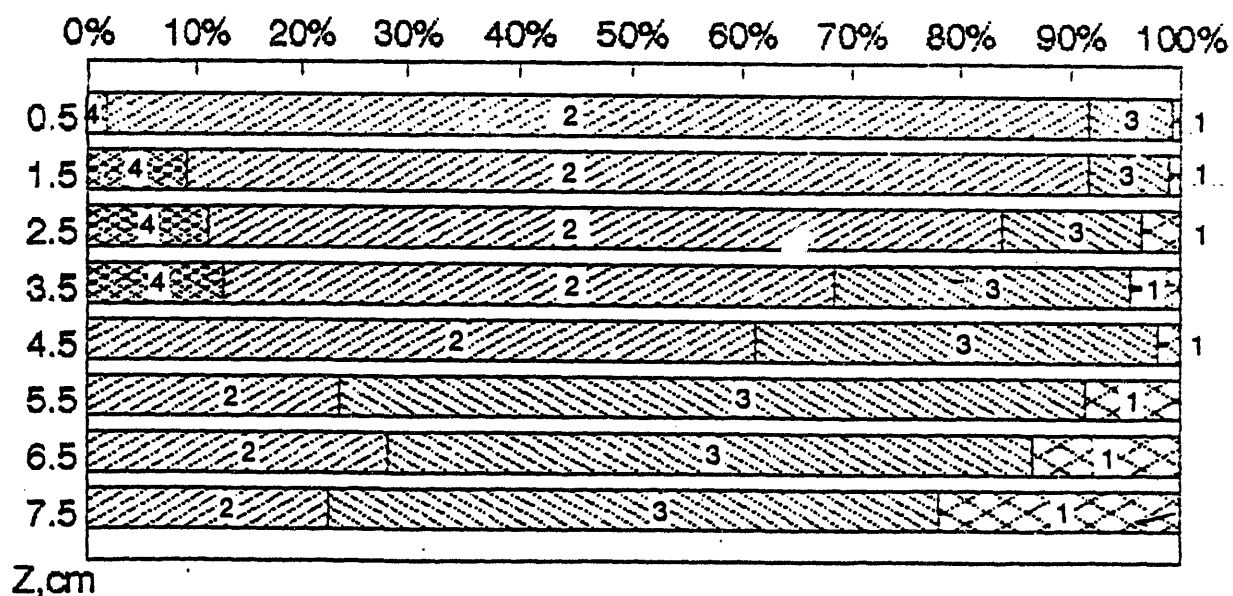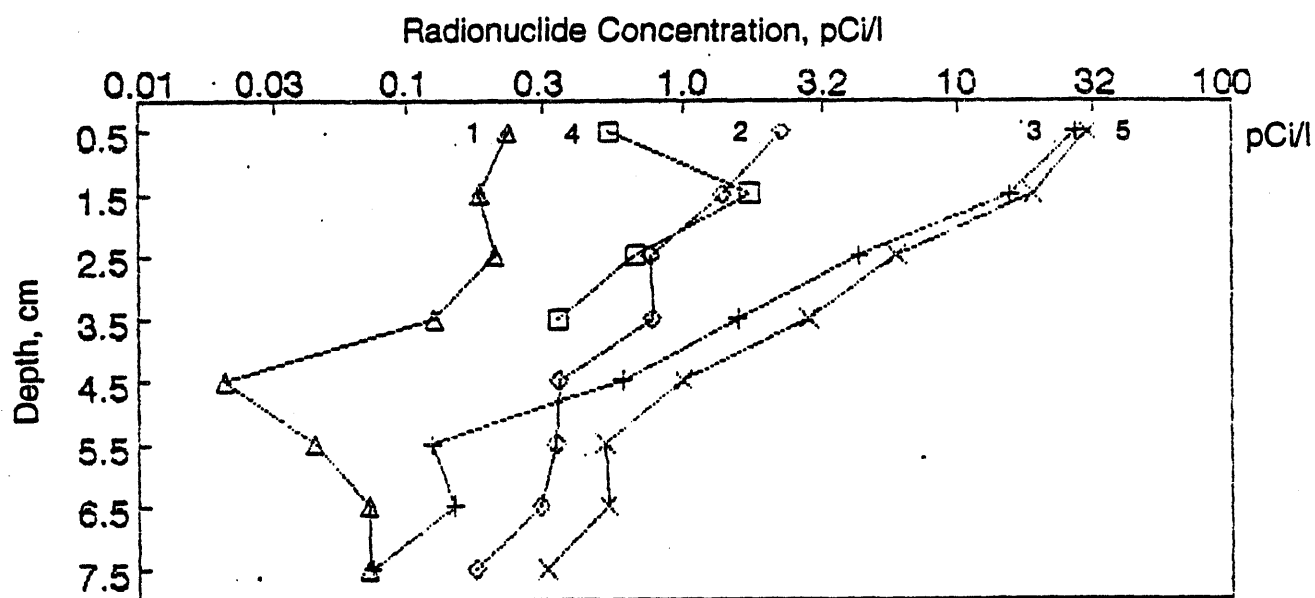
Figure 11. Vertical Distribution of Different Physical-Chemical Forms of ^{90}Sr in the Bottom Sediments of the Kiev Reservoir, in the Upper Part of the Area of Suspended Particles Deposition, May 1991 (Voitsekhovitch et al. 1993). 1 indicates water-dissolved form, 2 exchangeable form, 3 nonexchangeable form, 4 fixed form, and 5 the total.

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Table 8. Distributions of Suspended Sediments and their Associated Radionuclides along the Dnieper Cascade in 1988

Date	Region on Cross Section	Sediment g/m³	¹³⁷Cs pCi/g	Size Distribution for Diam. in mm, %					
				0.5-0.2	0.2-0.1	0.1-0.05	0.05-0.01	0.01-0.005	<0.005
23 May	Dnieper-Nedanchichi	22.7	117.6	2.9	17.3	4.0	52.9	11.7	11.2
22 May	Pripyat-Chernobyl	29.3	361.7	1.1	13.0	18.9	13.3	12.5	41.2
Kiev Reservoir									
27 May	upper	13.4	384.6	0.2	7.0	10.6	42.0	11.0	29.2
27 May	medial	5.7	629.0	0.1	0.2	7.6	62.1	5.0	25.0
27 May	lower	4.1	650.0	1.2	0.6	0.3	44.0	27.1	26.8
Kanev Reservoir									
1 June	upper	10.0	350.0	0.0	1.0	0.3	16.7	28.1	54.0
7 June	medial	4.0	227.0	1.1	0.2	7.8	43.3	17.5	30.0
8 June	lower	3.7	180.0	0.1	0.7	1.2	42.0	9.4	46.6
Kremenchug Reservoir									
14 June	upper	9.6	21.9	0.0	0.9	15.7	50.6	19.4	13.4
15 June	lower	6.1	30.8	0.0	3.3	1.0	38.7	20.7	36.3
Dneprodzerzhin Reservoir									
16 June	upper	4.0	58.8	2.5	0.3	2.1	58.5	26.3	10.3
18 June	lower	7.3	44.3	0.0	1.1	1.9	62.6	25.0	9.4
Dneprov Reservoir									
20 June	upper	7.1	20.0	1.2	2.1	0.9	40.6	38.1	17.1
21 June	lower	4.6	39.6	0.0	2.5	1.4	64.1	8.1	23.9
Kalhovka Reservoir									
23 June	upper	4.2	12.2	7.0	15.0	9.3	34.3	11.2	23.1
24 June	lower	2.4	20.1	0.0	0.6	6.0	19.9	7.3	66.3

suspended sediments are deposited in the upper parts of the cascade. This pattern indicates the important role of the sorption capacity of the suspended sediments and reservoir soils in the process of purification of contaminated water. The process of radionuclide accumulation in the reservoirs can be expected to continue.

As discussed previously, the bottom sediments of reservoirs were initially contaminated by the direct radioactive fallout to the water surface, thus original contamination levels of the bottom sediments in these reservoirs corresponded to the contamination levels in nearby coastal areas. But, due to the river hydrodynamics and sedimentation processes, the radionuclides in bottom sediments have been redistributed. At present, the bottom sediments of the Dnieper reservoirs contain approximately 5,000 and 2,000 Ci of ^{137}Cs and ^{90}Sr, respectively. The most contaminated is the Kiev Reservoir, where the maximum contamination level in bottom sediments exceeds 60 Ci/km^2 in the upper reservoir near the mouth of the Pripyat River. ^{137}Cs contamination of bottom sediments of the Dnieper reservoirs is presented in Table 9. In the future, water contamination levels in the reservoirs

Table 9. Averaged ^{137}Cs Contamination in Bottom Sediments of the Kiev, Kanev, Krementchug, and Kakhov Reservoirs in 1987 and 1991[a]

Dnieper's Reservoirs	^{137}Cs in Bottom Sediments	
	1987	1991
Kiev Reservoir	3580[b]	3000[b]
	3.9[c]	3.5[c]
Kanev Reservoir	495	830
	0.63	1.23
Krementchug Reservoir	315	580
	0.14	0.30
Kakhov Reservoir	36	180
	0.04	0.08
(a) Data of Ukrainian Hydrometeorological Institute, Kiev. (b) The storage of ^{137}Cs in the bottom deposition (Ci). (c) The averaged level of ^{137}Cs contamination (Ci^2/km).		

will largely depend on natural hydrologic and human-controlled processes of radionuclide migration. The radionuclide levels will further be controlled by the localization of radioactive elements in the reservoir bottom sediments, by the rate of interphase transformation of the non-exchangeable radionuclide forms into water, and by additional radionuclide influx from contaminated catchment areas. Such additional influx will in turn depend on the efficiency of remediation measures that are being undertaken within the Chernobyl impact area.

2.1.6 Radionuclide Dynamics During the Floods

The increase of radionuclide concentrations in the Kiev Reservoir, and subsequent increases in the downstream reservoirs after the initial post-accident period, come from three main sources:

- Radionuclides washing out from the contaminated watersheds of the Dnieper and the Pripyat rivers during snowmelting and heavy rains.

- Washing out of the radionuclides from the highly contaminated area on the Pripyat River floodplain across from the Chernobyl Nuclear Power Plant, especially from the left (east) bank floodplain near Pripyat. This is potentially the greatest source of ^{90}Sr contamination in the Dnieper reservoir system.

- Remobilization of radionuclides from heavily contaminated bottom deposit in the Kiev Reservoir as a result of resuspension or physical-chemical radionuclide transformation processes.

Fluxes from all three of these sources have been correlated with floods on the Pripyat and Dnieper rivers.

The hydrological situation in the Pripyat-Dnieper water system since the 1986 accident has been rather calm. All snow-melt floods have been at or below average levels (probability of occurrence

exceeding 50% in one year). The maximum migrations of radionuclides took place during a spring flood in 1987, a summer rainfall-caused flood in 1988, and in the winter of 1991.

The concentration of ^{137}Cs in the Kiev Reservoir during high-flood period increased from the normal 10-15 pCi/L to 20-40 pCi/L in 1987 and up to 5 pCi/L during flooding in 1991. The concentration of ^{90}Sr had similar trends: high in 1987 and in 1991-1993. The maximum ^{90}Sr concentration in reservoir water was about 30-40 pCi/L (Figure 9). During major rainfall floods on the Pripyat River (described in Section 2.1.2), it was usual for the ^{90}Sr concentration in the Pripyat River to increase from 10-20 pCi/L to 30-50 pCi/L (see Figures 6 and 9). Nonetheless, these rainfall floods did not lead to a significant increase in radionuclide concentrations in the Dnieper reservoirs, because of dilution by water from the Dnieper River. The maximum increase occurred during 1988 rainfall flooding of the Pripyat River, when the concentration of ^{90}Sr in the Kiev Reservoir increased from 8 to 25 pCi/L.

Flooding in the Chernobyl close-in floodplain area had its greatest impact on the contamination of the Dnieper Reservoirs in January 1991. Because of low spring floods, the close-in floodplain area (3 x 15 km), which contains more than 8000 Ci of ^{90}Sr, had not been flooded since the Chernobyl accident (Figure 12). Simulation of floodplain flow has indicated that the most dangerous situation, which would cause large increases in radionuclide concentrations, is a spring flood with a maximum discharge from 2000 to 3000 m^3/sec (Zheleznyak et al. 1992c), because during such floods the contaminated floodplain would be completely covered with water. Further increases in water discharge and water elevation in the river are not expected to lead to increases in water contamination because of the further diluting of washed-out radionuclides by the river flow. The probability of floods exceeding (PE) this magnitude for this area of the Pripyat River is 25% in one year (i.e., this magnitude represents the 4-year flood). During such a spring flood, the water covers all parts of the contaminated floodplain,
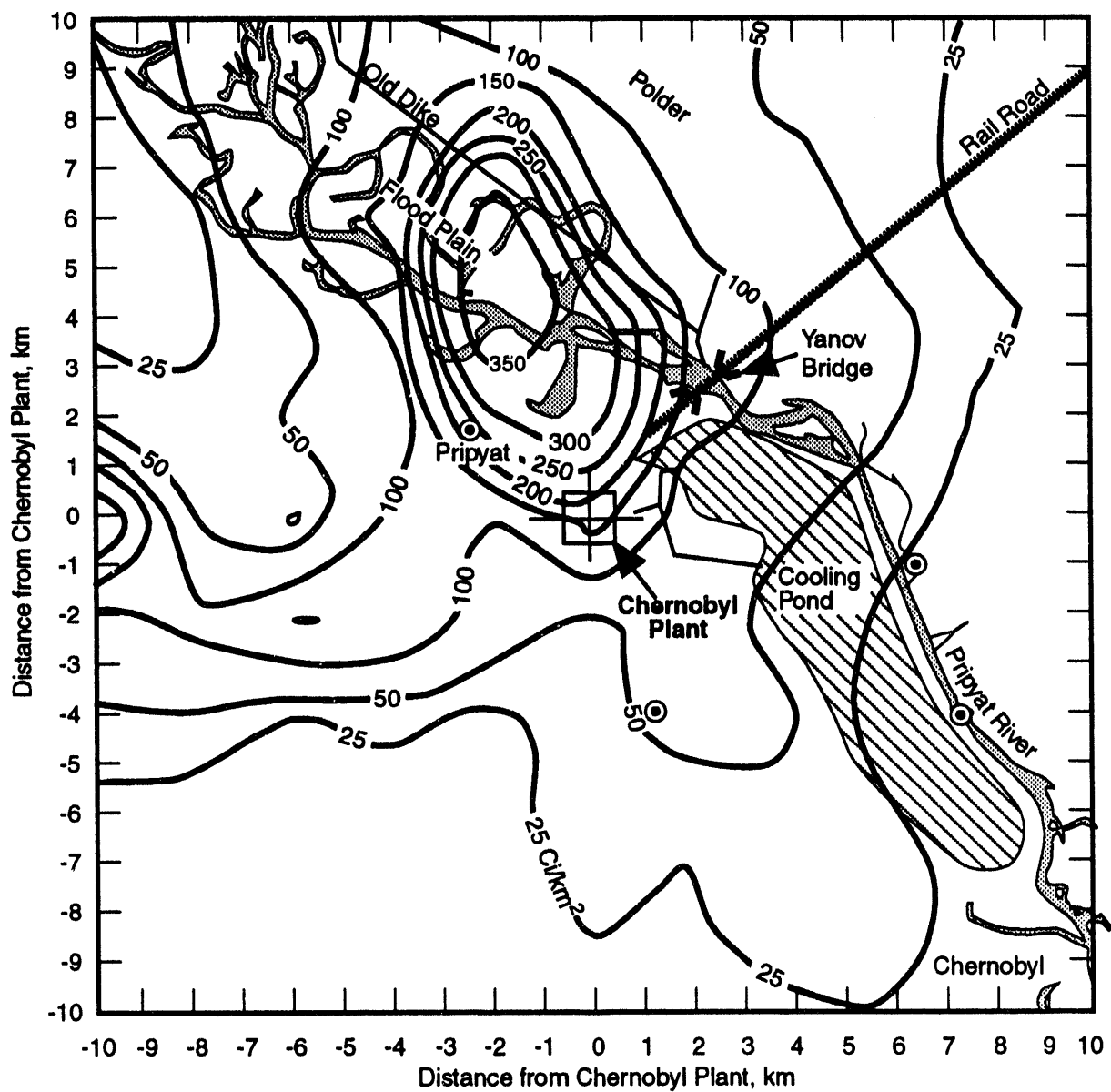
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Figure 12. ^{90}Sr Distribution in the Chernobyl Close-in Zone and on the Floodplain Area of the Pripyat River near the Chernobyl Nuclear Power Plant

but its depth is less than those of higher-PE floods. During flooding of this territory in such hydrological conditions, the ^{90}Sr concentration in the Pripyat water could increase up to 250 pCi/L, exceeding the Ukrainian drinking water standard level for radionuclides (100 pCi/L). Note that until 1991, the maximum permissible levels for ^{90}Sr and total ^{134}Cs and ^{137}Cs in drinking water were 400 and 1500 pCi/L, respectively. Since 1991, new drinking water standards for ^{90}Sr and ^{137}Cs were reduced to 100 and 500 pCi/L, respectively. On the basis of the results of mathematical modeling and field investigations, the Ukrainian government decided in September 1990 to construct an earth dike to prevent such flooding. At the time of the flooding in the winter of 1990-1991, only the preparations for construction had been done. The dike was completed at the end of 1992.

In January 1991, extremely low temperatures caused an ice jam to form in the Pripyat River channel between the Yanov Bridge and the town of Chernobyl. As a result, the Pripyat River elevation upstream of the jam increased abruptly, and the Pripyat floodplain near the Chernobyl Nuclear Power Plant was covered by water for the first time since the accident. Due to the water's interaction with the floodplain surface, which was contaminated heavily with ^{90}Sr, the concentration of ^{90}Sr in river water near the town of Chernobyl increased from 20 pCi/L to over 250 pCi/L. The total amount of ^{90}Sr transported by the Pripyat River increased from 0.5 to 10 Ci per day, and the total amount of ^{90}Sr released from the floodplain through the Pripyat River into the Kiev Reservoir during this period exceeded 90 Ci.

Fortunately, the impact of this release to the Kiev Reservoir was reduced because of dilution of the Pripyat River water by cleaner Dnieper River water and dispersion of contamination in the reservoir. As a result, the maximum concentration on the way from the Pripyat River mouth to the Kiev Reservoir dam (a distance of more than 80 km) diminished from 200 to 30 pCi/L.

2.2 Data Collected under Summer Flood Conditions in 1993

2.2.1 River Discharge and Water Elevation

Heavy rainfall on the Belarus and Ukrainian districts of the Pripyat River catchments during July 1993 caused unusually high flooding for the summer period in the upper tributaries of the river basin. Water discharge in the Pripyat River near the Chernobyl Nuclear Power Plant increased from 250 m³/s to more than 1200 m³/s at the end of August 1993. As a result of runoff flow over the radioactively polluted catchments and washing-out processes, radionuclides from watershed soils flowed down to the surface streams and to the Pripyat River.

The situation on the Dnieper River was less drastic than on the Pripyat. Maximum summer water discharges did not exceed 500 m³/s, which is rather low for the summer flow rate of the Dnieper River. Therefore, there were no significant changes in water discharges or their radionuclide contamination for the whole summer period on the Dnieper River.

Hydrological data describing the flood situation in the summer of 1993 are presented in Table 10. Supplementary data collected for further model simulation of contaminant fate in the Dnieper cascade include the following:

- water discharge and water elevation information for all tributaries during the period from July 1 to September 1, 1993;

- the operation mode of all dams in the Dnieper reservoir system;

- characterization of suspended matter in river in flows during prior months and the summer flood.

2.2.2 Radioactive Contamination of the Pripyat/Dnieper System

Due to flooding of contaminated territories of the Pripyat River channel and increased washing out from the watersheds during rainfall, ^{90}Sr concentrations in the Pripyat River increased in the first weeks of the flood. Near the Chernobyl area, the maximum ^{90}Sr concentration in Pripyat River water was about 20-25 pCi/L in early August; near the Pripyat River mouth, the concentration was elevated to 35 pCi/L. The peak concentration of ^{90}Sr in the water of small rivers inside the 30-km zone was sharper, reflecting an increase to 60-70 pCi/L from 15-20 pCi/L before the flood. Before the flood, the ^{90}Sr concentration in the Kiev Reservoir was in the range 7-10 pCi/L and that in the Kanev Reservoir was 3-5 pCi/L. The ^{90}Sr concentration in the water at the mouth of the Dnieper River has not exceeded 6-8 pCi/L.

The ^{137}Cs concentration in the Pripyat River did not increase significantly, and ^{137}Cs concentrations in water across from the Chernobyl site did not exceed 5-7 pCi/L. At the first stage of flooding in the Pripyat River in the middle of July, ^{137}Cs concentrations in water of the Kiev Reservoir were 2-5 pCi/L. In water of the Kanev Reservoir, the ^{137}Cs concentrations were 1-3 pCi/L. More detailed information for radionuclide concentration during the summer of 1993 is given in Table 10.

Table 10. Water Discharge (m³/s) and ^{90}Sr and ^{136}Cs Contents (pCi/L)

Date	Prip. Cher		Dnie. Nedch		Kiev Res.		Desna Letki	Kanev Res.	Kremenchug Res.	
	Discharged	^{90}Sr	Discharged	^{90}Sr	Discharged	^{90}Sr	Discharge	Discharge	Discharged	^{137}Cs*
Jul 12 93	240	15	390	5	682	8	205	858	1500	4.6/0.5
Jul 13 93	245		392		792		208	901	1490	
Jul 14 93	245		396		759		213	959	790	
Jul 15 93	245		400		737		217	937	1070	2.0/0.3
Jul 16 93	250		406		742		217	881	631	
Jul 17 93	250		410		419		219	597	344	
Jul 18 93	260		414		322		222	296	383	
Jul 19 93	265		417		792		224	950	1090	
Jul 20 93	270	19	420	6	887	9	226	1200	841	8.6/1.0
Jul 21 93	285		450		962		228	1230	788	
Jul 22 93	300		500		1200		232	1590	1350	
Jul 23 93	320		540		1410		233	1770	1120	
Jul 24 93	355		580		1038		237	1300	635	
Jul 25 93	375	18	600	6	612	10	236	850	313	
Jul 26 93	410		630		1200		238	1470	1160	
Jul 27 93	430		665		1220		235	1570	1350	
Jul 28 93	460		690		1640		233	1740	1460	
Jul 29 93	505	22	700	8	1730	10	232	2090	1090	4.5/1.7
Jul 30 93	580	27	710	7	2180	11	233	2310	1980	3.6/1.2
Jul 31 93	650	26	670		2410	9	232	3380	1340	6.3/2.4
Aug 01 93	690	25	650		2370	9	228	2610	626	
Aug 02 93	720	23	640		2440	12	228	1270	1250	
Aug 03 93	743	27	620	7	1460	11	228	1340	1700	6.0/1.7
Aug 04 93	780	26	610		1470		228	2040	1500	4.7/1.2
Aug 05 93	775		600		1610		225	2030	2030	
Aug 06 93	790		590		1580		222	1830	2260	
Aug 07 93	810		570		1290		218	1240	826	
Aug 08 93	825		550		1170		218	1280	1270	
Aug 09 93	870		525		1532		224	1870	2000	
Aug 10 93	840	20	510		1470		232	1750	1810	5.6/1.3
Aug 11 93	850		505	5	1150		236	1240	1880	
Aug 12 93	900	17	500		1180		238	1450	1570	
Aug 13 93	950		495	6	1178		240	1630	1290	
Aug 14 93	1000		487		1364		240	1640	1440	
Aug 15 93	1050	19	480	6	1327		244	1660	1060	
Aug 16 93	1075		473		1580		250	1640	1830	
Aug 17 93	1100		466		1580		256	1550	1810	
Aug 18 93	1120	18	468		1350		258	1560	1740	
Aug 19 93	1140		465		1300		260	1670	2590	
Aug 20 93	1180		460		1400		262	1290	1640	
Aug 21 93	1200	17	455		1320		262	1520	1360	
Aug 22 93	1200		450	4	1240		264	1330	1140	
Aug 23 93	1450	18	440	4	1215		278	1330	1440	
Aug 24 93	1120		433		1245		278	1340	940	
Aug 25 93	1100		425		1240		280	1530	1960	
Aug 26 93	1050		423		1370		282	1800	1610	
Aug 27 93	1000		422		1470		282	1790	1740	
Aug 28 93	950		422		1520		282	1580	1480	
Aug 29 93	920	15	425		1400		280	1690	1050	

* soluble/suspended forms

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3.0 Radionuclide Transport Modeling

3.1 Applied Models and Methodology

A system of computer models of radionuclide transport in the Pripyat River and the Dnieper reservoirs was developed and has been used at the Cybernetics Center of the Ukrainian Academy of Sciences, Kiev, since 1986 (Mikhalevich et al. 1987; Zheleznyak 1990; Zheleznyak et al. 1992a,b,c, 1993). The system, which is based on various mathematical models and data banks, has been refined in close collaboration with specialists from the Ukrainian Hydrometeorological Institute, SPA Typhoon, and other institutions. The approaches and methods used in the Ukrainian modeling of major processes are based on those developed at PNL (Onishi 1981; Onishi et al. 1982, Onishi and Trent 1985; Onishi and Thompson 1986).

The main purposes of developing the model system are as follow:

- predicting radionuclide transport in surface-water bodies,

- performing a detailed analysis of water and sediment contamination in selected rivers and reservoirs,

- estimating the efficiency of special hydraulic countermeasures designed to decrease the rate of radionuclide outflow from the Pripyat River and the Kiev Reservoir (e.g., bottom traps for contaminated sediments, dikes in floodplain, and underwater dams in reservoirs), and

- supporting the plans for Dnieper reservoir operation on the basis of optimization models that account for water pollution.

To accommodate the broad temporal and spatial scales being considered, a hierarchy of radionuclide transport models was developed (Zheleznyak 1990; Zheleznyak et al. 1992a,b,c). Hydrologic and water pollution databases were generated to support the modeling system.

The modeling of radionuclide transport in rivers and river-run reservoirs has some special characteristics. Radionuclide migration in rivers and reservoirs is affected by high flow velocities, short retention times, and large variability in water discharge during a year; since a large portion of the radionuclides are sorbed to sediment, radionuclide distributions are subject to large temporal and spatial variations in sedimentation and resuspension rates. Other processes that are important to rivers and reservoirs are channel flow and floodplain interactions during floods, the strong impacts of the hydraulic structures on flow parameters, and rapid water level changes caused by reservoir management. These differences necessitate the use of special approaches for modeling radionuclide transport in river/reservoir systems. Some of these modeling methods have been reviewed by Onishi et al. (1981), Codell et al. (1982), and Santschi and Honeyman (1989).

The river/reservoir models require several kinds of submodels: hydraulics submodels to describe the water, suspended sediment, and bottom sediment dynamics; and radionuclide submodels to examine the fate of radionuclides in different phases driven by these hydraulic processes.

The hydraulics submodels include mathematical descriptions of the following processes:

- wind circulation, including seiches and circulation driven by inflow/outflow currents;
- turbulent transport;
- suspended sediment transport;
- sedimentation and resuspension;
- wind-caused wave propagation and transformation;[a]

(a) Processes may be important for reservoirs only.

- wave-driven nearshore circulation;[a] and

- dynamics of temperature and density stratification.[a]

For long-term projections, precipitation and evaporation may also be taken into account, as well as water losses due to irrigation and industrial and municipal use.

The fate of radionuclides in general is simulated using the following types of submodels:

- a dissolved contaminant transport submodel;

- a particulate contaminant transport submodel; this may also include a separate description of contaminants transported by different types of sediment (e.g., clay, silt, mud and sand grains);

- a submodel that estimates the contamination dynamics in the active upper layer of bottom sediments;

- a submodel of contamination dynamics in deeper buried sediment layers;

- a submodel of contaminant transfer in interstitial waters;

- a submodel of contaminant transfer by bioturbation in bottom sediments; and

- a submodel of contaminant transfer by biota.

Modeling the transport and fate of the radionuclides in three different phases (radionuclides in solution, in suspended sediment, and in bottom sediments) is particularly important. Some suitable approaches for simulation of radionuclide dispersion have been developed by Onishi for one- (Onishi et al. 1982), two- (Onishi 1981; Onishi et al. 1982), and three-dimensional models (Onishi and Trent 1985; Onishi et al. 1993) and by Booth (1975) and Schuckler et al. (1976) for fully mixed box models.

The Pripyat-Dnieper system includes various types of water bodies, ranging from large rivers with their tributaries and floodplains to large reservoirs. The temporal and spatial scales of the processes under consideration may increase by more than two orders of magnitude when different modeling objects are considered. It is clear that no single model could describe such a wide range of processes satisfactorily. Therefore, a hierarchy of mathematical models of radionuclide dispersion that describes these processes has been developed by averaging the primitive three-dimensional equations over the spatial variables (Zheleznyak 1990; Zheleznyak et al. 1992a,b). All of the models account for the fate of the radionuclides in all three phases (radionuclides in solution, in suspended sediments, and in bottom sediment), as well as describing absorption-desorption and sedimentation-resuspension processes.

The contamination exchanges between water, sediment, and bottom deposition are described using the distribution coefficient, K_d, which is the ratio between contamination on particles and solution under equilibrium conditions. The other parameters used are radionuclide transfer rate coefficients, a, which are determined by the characteristic time of transfer between dissolved and sediment-sorbed radionuclides. The main factors affecting the sediment-contamination interaction are taken into account when the K_d is considered as a function of water quality, geochemical properties of the sediments, physical-chemical forms of radionuclides, sediment concentration, and so on (Onishi et al. 1981; Santschi and Honeyman 1989).

Using this approach, the description of the physical-chemical behavior of the radionuclides has been linked with the characteristics of the Chernobyl accident. More complicated radionuclide transfer submodels that distinguish the different kinds of physical-chemical forms of radionuclides in the solid phase (exchangeable and non-exchangeable forms) have been developed (Borzilov et al. 1989;

Konoplev et al. 1992). This more complicated approach requires detailed experimental data, which, as a rule, cannot be obtained without careful site-specific field investigations. It is only recently that the necessary data for the Pripyat-Dnieper system are being collected.

In the Cybernetics Center's modeling system, four models are used, depending on the spatial or temporal scale of interest (Zheleznyak et al. 1993). WATOX is a box model used to examine radionuclide dispersion in the large reservoirs. RIVTOX is a one-dimensional model used to examine processes in the rivers and estuaries. COASTOX is a two-dimensional lateral-longitudinal model designed to represent the reservoirs and floodplains. And finally, VERTOX is a two-dimensional vertical-longitudinal model designed to examine fine sediment-radionuclide interaction processes in the vicinity of hydraulic constructions designed as countermeasures, such as bottom sediment traps and dams. Each model is briefly discussed below. Details about WATOX are provided in the Appendix.

3.1.1 WATOX - Box Model

The WATOX computer code is a realization of the box-type (i.e., compartmentally averaged) model based on the set of ordinary differential equations describing water, sediment, and radionuclide transport.

Box models represent a reservoir as one or more compartments (boxes) in which water quality parameters are homogeneous. The models assume that the contaminated water discharged into the compartment is instantaneously mixed with the water already present. Therefore, the contaminant concentration in the outflow is identical with that in the compartment. The model variables are the

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compartment's volume, the suspended sediment concentration, and the concentrations of the radio-nuclide in solution, suspended sediments, and bottom deposition. The numerical solutions of model equations are obtained by the Runge-Kutta method.

WATOX has been the main tool for forecasting radionuclide dispersion in the Dnieper reservoirs during the spring flood periods, which last 3-4 months and more. Optimization methods are used to choose the reservoir system operation mode under the water quality criteria for the simulation period. Dissolved contamination, contamination on sediments, and contamination within the bottom sediments are considered, with a special treatment of contamination-sediment interaction. The parameterization of this processes is similar to the one used by Schuckler et al. (1976), but additional processes are included, as well as a supplementary submodel used to simulate temporal variations in the sedimentation and resuspension rates during flood propagation in the reservoirs. Model testing has shown the significance of this mechanism for the fate of ^{137}Cs in the reservoirs.

3.1.2 RIVTOX - One-Dimensional Channel Model

One-dimensional models describe the cross-sectionally averaged flow and contamination parameters in channels. The one-dimensional model RIVTOX was developed by averaging the two-dimensional COASTOX mode equations over the channel width. The one-dimensional Saint-Venant's equations and advection-dispersion equations with source terms are used to simulate the flow, suspended sediments, and radionuclide transport both in solution and in suspended sediments. The implicit finite-difference scheme used for numerical solution of the Saint-Venant's equations permits the simulation of flow in a channel network with relatively large time steps. The splitting method, with a

Holly-Preissmann fourth-order finite-difference scheme on the advection step, can be used to diminish the numerical diffusion in the advection-dispersion equations.

3.1.3 COASTOX - Two-Dimensional Lateral-Longitudinal Model

Two-dimensional lateral-longitudinal models are widely used to simulate pollutant flow and dispersion in shallow reservoirs, floodplains, and coastal waters. The model equations can be derived by averaging the primitive three-dimensional equations over the depth of the water body. Equations of this type have previously been used in the FETRA code to simulate radionuclide dispersion in coastal areas (Onishi and Thompson 1986). The COASTOX model, which was developed in the Cybernetics Center to simulate pollutant dispersion in the Dnieper reservoirs and in the Pripyat River (Zheleznyak et al. 1982b, 1993), contains radionuclide transport submodels similar to the ones used in FETRA. However, in COASTOX, other approaches are used for modeling suspended sediment transport and wind wave effects. Finite-element and finite-difference methods are combined to solve the model's equations.

3.1.4 VERTOX - Two-Dimensional Vertical-Longitudinal Model

The model VERTOX was derived from three-dimensional models of hydraulic and pollutant transport processes by averaging the equations over the flow width, resulting in a two-dimensional vertical-longitudinal model (Zheleznyak et al. 1993). This approach has previously been used for the simulation of radionuclides in the SERATRA code at PNL (Onishi et al. 1981). The main objects of the VERTOX application are zones where abrupt changes in the flow parameters occur. An important

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example of such a zone is flow at the bottom sediment traps designed to settle the contaminated suspended sediments in the Pripyat River channel.

The flow-governing equations are derived using a hydrostatic approximation. The advection-diffusion equation for suspended sediment transport is used to describe the sediment deposition and erosion rates. The submodel for radionuclide transport describes the radionuclide concentration in solution, the concentration in the suspended sediments, and the concentration in the bottom deposits. The exchanges between these forms are adsorption-desorption and sedimentation-resuspension processes.

3.2 Modeling of the Pripyat River Floodplain

As described in Chapter 2.0, one of the most significant radionuclide sources of radioactive contamination in the Pripyat River and thus the Dnieper River is the fuel particles resulting from fallout onto the Pripyat River floodplain across from the Chernobyl Nuclear Power Plant. The poten$\underline{\;\;\;}$ flooding of this territory has been simulated using the COASTOX (WATOX-2) computer code (Zheleznyak and Voitsekhovitch 1991; Zheleznyak et al. 1992b). As described above, this territory had not been flooded since the 1986 Chernobyl accident until 1991 because spring floods have been low. During flooding of this floodplain, the most critical source of radionuclide contamination in water is ^{90}Sr deposited in the floodplain. Because of the relatively low distribution coefficient (K_d) for ^{90}Sr, sediment-water interactions do not significantly impact ^{90}Sr migration within surface water. In such a

situation, the governing parameters of the model are the K_d and the rate of radionuclide exchange between water and bottom sediments ($A_{1,3}$). To obtain these parameters, special laboratory measurements were made by the Ukrainian Hydrometeorology Institute (Voitsekhovitch et al. 1993a,b). Soil samples from the floodplain were covered with water, and the subsequent changes in ^{90}Sr concentrations in the water and soil were measured. On the basis of these data, K_d and ($A_{1,3}$) values were determined.

Simulation of floodplain flow has demonstrated that the most dangerous situation, which would cause large increases in radionuclide concentrations, is a spring flood with a maximum discharge of 2000 m^3/sec. The probability of exceeding (PE) this flood magnitude for the area of the Pripyat River is 25%. During such a spring flood, water covers all parts of the contaminated floodplain, as in the simulated flow field shown in Figure 13.

For those simulations, it was assumed that the depth-averaged concentration of ^{90}Sr at the upstream boundary equals 50 pCi/L. This level of ^{90}Sr in the Pripyat River water would result from radionuclides washing out from the upstream watersheds. As shown in Figure 14, due to the desorption of ^{90}Sr from the floodplain sediment, the computed ^{90}Sr concentration in water increases by more than four times from inflow to outflow boundaries. The computed time for water to travel between these boundaries is 12 hours.
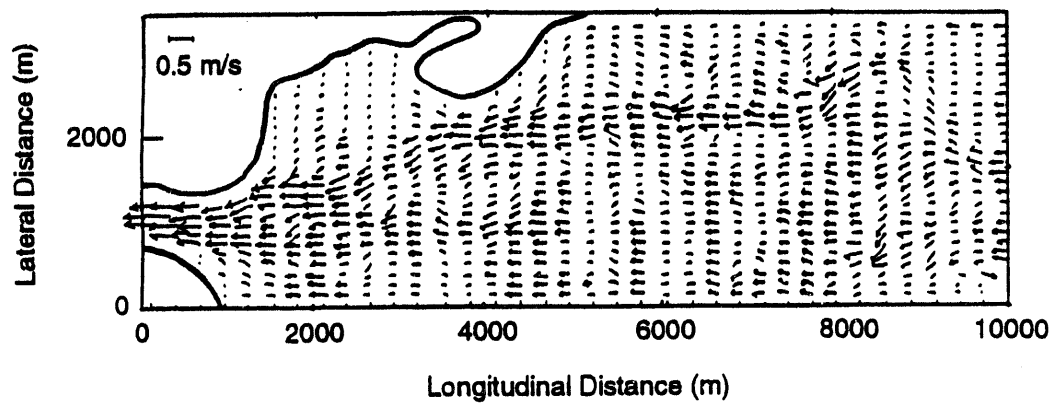
Figure 13. Predicted Depth-Averaged Velocities on the Pripyat River Floodplain During a 25% PE Spring Flood

S9306067.1
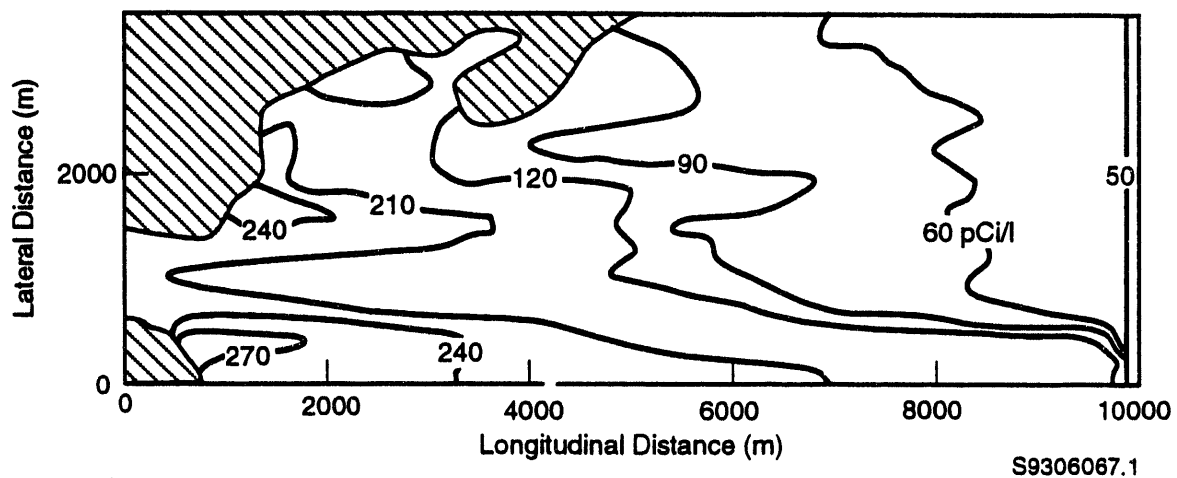
Figure 14. Predicted Depth-Averaged ^{90}Sr Concentration (—)(PCil^{-1}) and Depth Isolines (m) (---) During a 25% PE Spring Flood

The highest simulated flood (PE=1%) has a maximum discharge of 6000 m^3/sec. For such a discharge, the computed travel time is five hours, and the maximum ^{90}Sr concentration at the downstream boundary is 60 pCi/L. This increase in concentration above the bottom contaminated area is small compared to that for the flood with the maximum discharge of 2000 m^3/s because of the decrease in travel time and an increase in the water discharge and depth.

The computed results showing a significant increase in ^{90}Sr concentration in the Pripyat River during the flooding have stimulated the search for effective countermeasures. Several approaches have been proposed, and the potential effectiveness of each for reducing radionuclide concentrations in the Pripyat River has been evaluated through modeling. The creation of an earthen dike around the contaminated area, on the left (east) bank of the Pripyat River across from the Chernobyl Nuclear Power Plant, has been chosen as the best countermeasure. The predicted flow pattern with the dike installed is presented in Figure 15. This measure, supplemented by decontamination of soil on the right bank, could diminish the ^{90}Sr concentration at the downstream boundary to nearly the same level as at the upstream boundary. The simulated radionuclide distribution for this scenario is shown in Figure 16. The decision to construct such a dike was made in 1990.

In January 1991, before the starting of dike construction, an ice jam formed in the Pripyat River channel between the Yanov Bridge and the town of Chernobyl. The Pripyat River water elevation upstream of the jam increased rapidly. As a result, the Pripyat floodplain near the Chernobyl Nuclear Power Plant was covered by water for the first time since the 1986 accident. (The hydrological and radiological data for this case have been presented in Section 2.1.6.)

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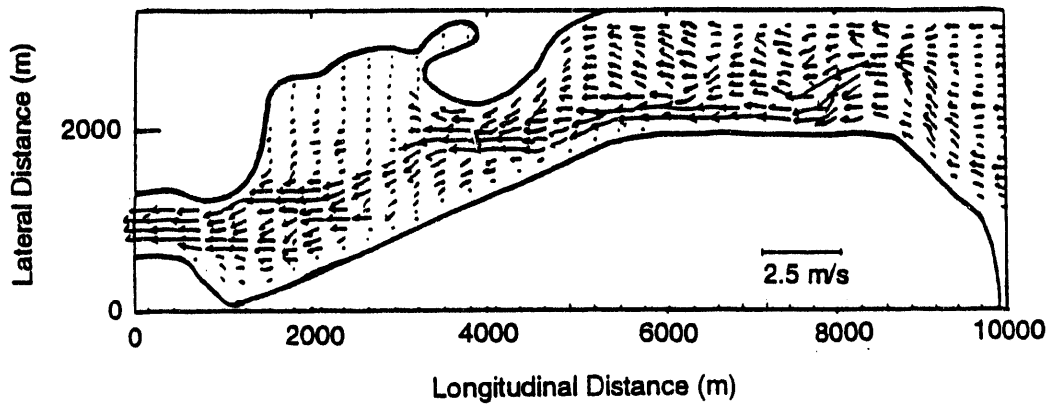
Figure 15. Predicted Depth-Averaged Velocities During the Same Flood as Presented in Figure 13 after Construction of the Dike

S9306067.2
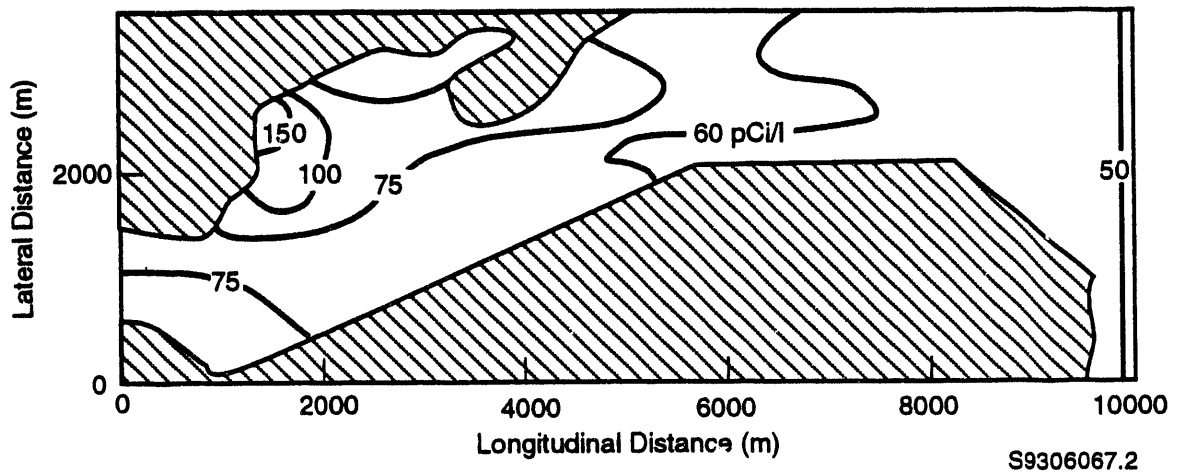
Figure 16. Predicted Depth-Averaged ^{90}Sr Concentration During the Same Flood as Presented in Figure 13 after Construction of the Dike

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During this flood, measured ^{90}Sr concentrations in Pripyat River water near the Yanov Bridge increased to 250 to 300 pCi/L. This level is very close to simulated values for the 25% PE flood, thus confirming the simulation results.

The Cybernetics Center's modeling system was then used to simulate ^{90}Sr propagation in the Kiev Reservoir and to predict radionuclide concentrations in the Dnieper River near Kiev. Dilution and dispersion of contamination in the Kiev Reservoir reduced the maximum predicted ^{90}Sr concentration from 200 pCi/L at the mouth of the Pripyat River to 30 pCi/L at the Kiev Hydropower Plant (more than 60 km downstream at the downstream end of the Kiev Reservoir) (Figure 17). This forecast, which was confirmed later by field measurements, was provided to the Ukrainian government. Such timely information on when and how strontium concentrations in the Dnieper's water near Kiev would increase allowed the government commission to change the municipal water supply arrangements in February 1991 to avoid use of Dnieper River water. The dike to prevent future flooding of this territory was completed before the 1992 spring flood.
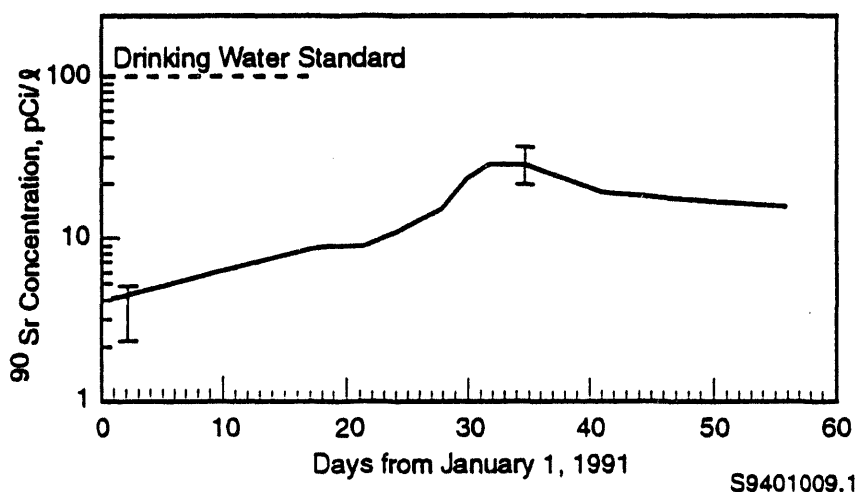
Figure 17. ^{90}Sr Concentrations Near Kiev Hydropower Plant (Downstream end of the Kiev Reservoir) Since January 1, 1991

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3.3 Modeling of Dnieper River Reservoirs

Each year since the accident, forecasts of ^{137}Cs and ^{90}Sr concentrations in the Dnieper reservoirs during spring flood (March-June) have been prepared in February or March. The basis for their development has been forecasts of spring runoff volume and maximum discharge prepared by the Ukrainian State Hydrometeorological Committee. The data on contamination distribution in the watershed and the averaged values of the radionuclide washoff coefficients were used to predict ^{137}Cs and ^{90}Sr dynamics in the tributaries that discharge into the reservoirs. The computed results show that the total amount of ^{90}Sr that might be washed out of the 60 km x 60 km zone around the Chernobyl Nuclear Power Plant during a 50% PE spring flood equals 270 Ci; the amount for a 25% PE flood is 460 Ci, that for a 10% PE flood is 670 Ci, and that for a 1% PE flood is 1240 Ci.

A small amount of ^{90}Sr is continuously being washed out from the watersheds with sediments (6%-8%). On the other hand, more than 85% of ^{137}Cs is transported from watersheds by the erosion of sediments. This ratio changes in the water bodies. In the rivers and reservoirs, 20% to 50% of ^{137}Cs is carried out by suspended sediments.

An example of the predicted concentration of ^{137}Cs in the Dnieper reservoirs is presented in Figure 18. Comparison of the simulated results with data measured during the 1993 flood by the Ukrainian Ministry of Water Management, Ministry of Health, and Hydrometeorological Committee demonstrates a reasonable agreement for the contamination concentrations and trends. The predicted increase in ^{137}Cs concentration level in the Kiev Reservoir and the Kakhovka Reservoir is more than an order of magnitude. This increase is a result of contamination-sediment interaction, a very important

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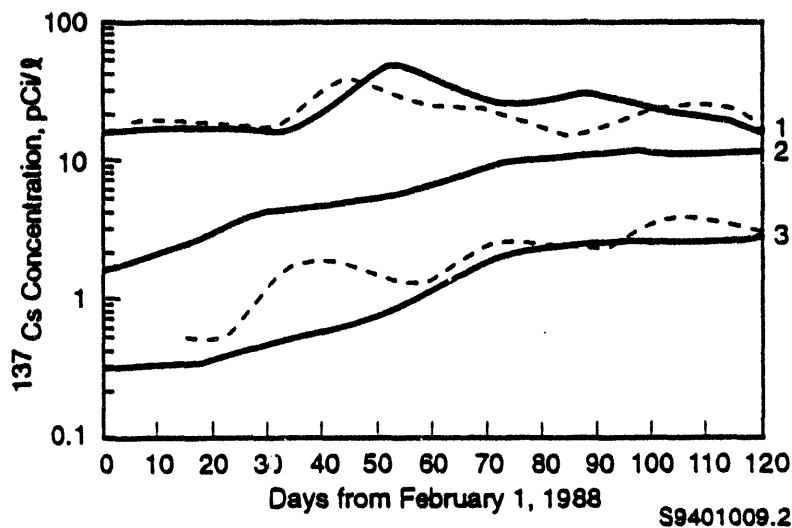
Figure 18. Predicted ^{137}Cs Concentrations in the Dnieper Reservoirs During the 1988 Spring Flood. Predicted (—) and Measured data (---). Time, days elapsed from 1 February 1988.
(1) Kiev Reservoir, northern part; (2) Dnieprodzerzhins Reservoir; (3) Kakhovka Reservoir.

mechanism for dispersion of cesium in water bodies. Therefore, a high value for the distribution coefficient should be used for successful description of ^{137}Cs transport (K_d = 5000 L/kg for simulated results in Figure 18).

Since 1988, the ^{137}Cs concentration in the Dnieper reservoirs has decreased due to the low discharges of the 1989-1993 spring floods and the diminishing of the ^{137}Cs washoff coefficient from the watersheds. However, the coefficient of ^{90}Sr washoff has not diminished in the same manner. Therefore, ^{90}Sr contamination is a more significant problem for the high spring floods in the Pripyat River watersheds. The simulation of processes on the floodplain described above has therefore been supplemented by forecasting of ^{90}Sr dispersion in the Dnieper reservoirs.

The results of the simulation of 25% PE flood on the Dnieper reservoir system are shown in Figure 19 for conditions before and after dike construction. For the after-dike simulation, only contamination discharged from watersheds was taken into account for the Pripyat River inflow into the reservoir. Overall, the predicted maximum ^{90}Sr concentration in the Kiev Reservoir is 150 pCi/L without the dike (higher than Ukrainian radiological standard of 100 pCi/L for drinking water) and 50 pCi/L with the dike (lower than the Ukrainian radiological standard for drinking water).

4.0 Evaluation of the 1993 Summer Flood

The 1993 summer flood on the Pripyat River, as described in Section 2.2, increased Pripyat River discharge to the Kiev Reservoir from 240-250 m³/s in the middle of July to 1100-1280 m³/s in the middle of August. Heavy rainfall over the Pripyat River watershed and the resulting sharp increase in Pripyat River inflow carrying radionuclides to the Kiev Reservoir caused concern about radioactive contamination of the Dnieper cascade among the population of Kiev and in the government. According to the authors' experience, the public in the Kiev region is psychologically more sensitive to the contamination of Dnieper River water by radionuclides than to any other environmental consequence of the Chernobyl accident.

Partially because of this public concern, the group of Ukrainian and U.S. scientists (the authors of this report), working together at PNL, received requests from both the Ukraine and the U.S. governments in July 1993 to evaluate the radioactive contamination of the Dnieper reservoirs under the impact of the Pripyat River flood while the flooding was progressing.

Taking into account the measured data on Pripyat/Dnieper contamination obtained during previous floods since the Chernobyl accident, special features of physical-chemical exchange processes (e.g., those among fuel particles, sediment, and water) in the zone near Chernobyl, and the results of previous modeling, it was assumed that only the ^{90}Sr concentration would change significantly under 1993 flood conditions.

To rapidly perform an emergency evaluation of the migration and fate of ^{90}Sr in the Dnieper reservoirs, the WATOX box model described above and discussed in more detail in the Appendix was used. As described above, less than 10% of the ^{90}Sr is transported into the reservoirs by sediments, and the direct exchange of ^{90}Sr with the bottom deposition is occurring very slowly. Thus the conservative approach of not taking into account the adsorption of ^{90}Sr by bottom sediment gives reasonable results for describing short-term processes of ^{90}Sr transport in the reservoirs. Thus, simplified forms (without radionuclide-sediment interaction terms) of the equations in WATOX provide the mathematical basis for evaluating ^{90}Sr dynamics in the reservoirs. The numerical solution of these equations on the basis of scenarios of discharge from the Pripyat, Dnieper, and Desna rivers into the reservoirs has been used to predict radionuclide dynamics in the Dnieper River.

An initial evaluation based on the first available data on ^{90}Sr concentrations in the Pripyat River was made on August 10, 1993. In a preliminary letter to the Ukrainian authorities through the Ukrainian Ministry of Chernobyl Affairs and to the United States Embassy in Kiev through Lawrence Livermore National Laboratory, we estimated that the maximum concentration of ^{90}Sr near Kiev (at the Kiev hydropower plant) would be approximately 15-17 pCi/L, and the corresponding concentration in Kiev drinking water would not exceed 7-8 pCi/L.

After this initial evaluation, we then carried out validation and testing of existing mathematical models with supplementary data on reservoir cross sections (information on 50 cross sections of all Dnieper reservoirs was included for the modeling). Information on dam operations was also used in the water balance estimation for each reservoir. For predicting radionuclide transport, a typical dam operation was used for each reservoir. Computer linkage to Ukrainian staff members in Kiev, who were responsible for monitoring the radionuclides in the water bodies, quickly brought to us necessary

initial data on water and radionuclide influxes into the reservoir system from the upper Dnieper reservoirs. Some other data were used to calibrate and test model of the Dnieper River reservoir system.

The following are results for two scenarios. One scenario represented the actual summer 1993 flood case (Figure 20). The second represented one of the potential worst cases, with the maximum level of ^{90}Sr contamination in the Pripyat River, with maximum summer water discharge, and with a very low flow rate from the Dnieper River to the Kiev Reservoir (Figure 21). The results permit some conclusions concerning Dnieper River water contamination.

The reservoir that is most sensitive to radionuclide influx into the reservoir system is the Kiev Reservoir. The level of ^{90}Sr contamination in the upper part of the Kiev Reservoir due to radionuclide influx to the reservoir could increase by 1.5-1.7 times, and the maximum ^{90}Sr concentration in water near Kiev could rise to 13-16 pCi/L. This maximum ^{90}Sr concentration then would be observed during the first 10 days of September. The expected maximum ^{90}Sr contamination for the middle part of the Kanev Reservoir would not exceed 10-12 pCi/L. The ^{90}Sr contamination in water in the middle part of the Krementchug Reservoir would reach 6 pCi/L. The predicted total radionuclide flux from flooded watersheds to the Kiev Reservoir during two months of flooding were about 85 Ci of ^{90}Sr from the Pripyat River and 16 Ci from the Dnieper River.

The reasonably good matches between the predictions and the measured data for the Kiev Reservoir demonstrate the acceptability of the simple methodology used for this emergency response modeling (see Figure 20). However, the lack of current data from the Ukrainian radiation monitoring system made it impossible to compare all simulation results with measured data for downstream parts of the Dnieper reservoir system. Furthermore, the uncertainty (estimated to be about 30%) of radionuclide

60

30

25

^{90}Sr Concentration, pCi/l
20

15

10

5

0

10　20　30　40　50　60　70　80　90

Days from July 1 1993

■■■■■ Pripyat/Mouth
✳✳✳✳✳ Kiev Res./Strakholesie
●●●●● Kiev Res./Glebovka
△△△△△ Kiev Res./Dam
☆☆☆☆☆ Kanev Res.
◊◊◊◊◊ Kremenchug Res.
✶✶✶✶ Kiev Res./Strakholesie – Measurements
△△△△△ Kiev Res./Dam – Measurements
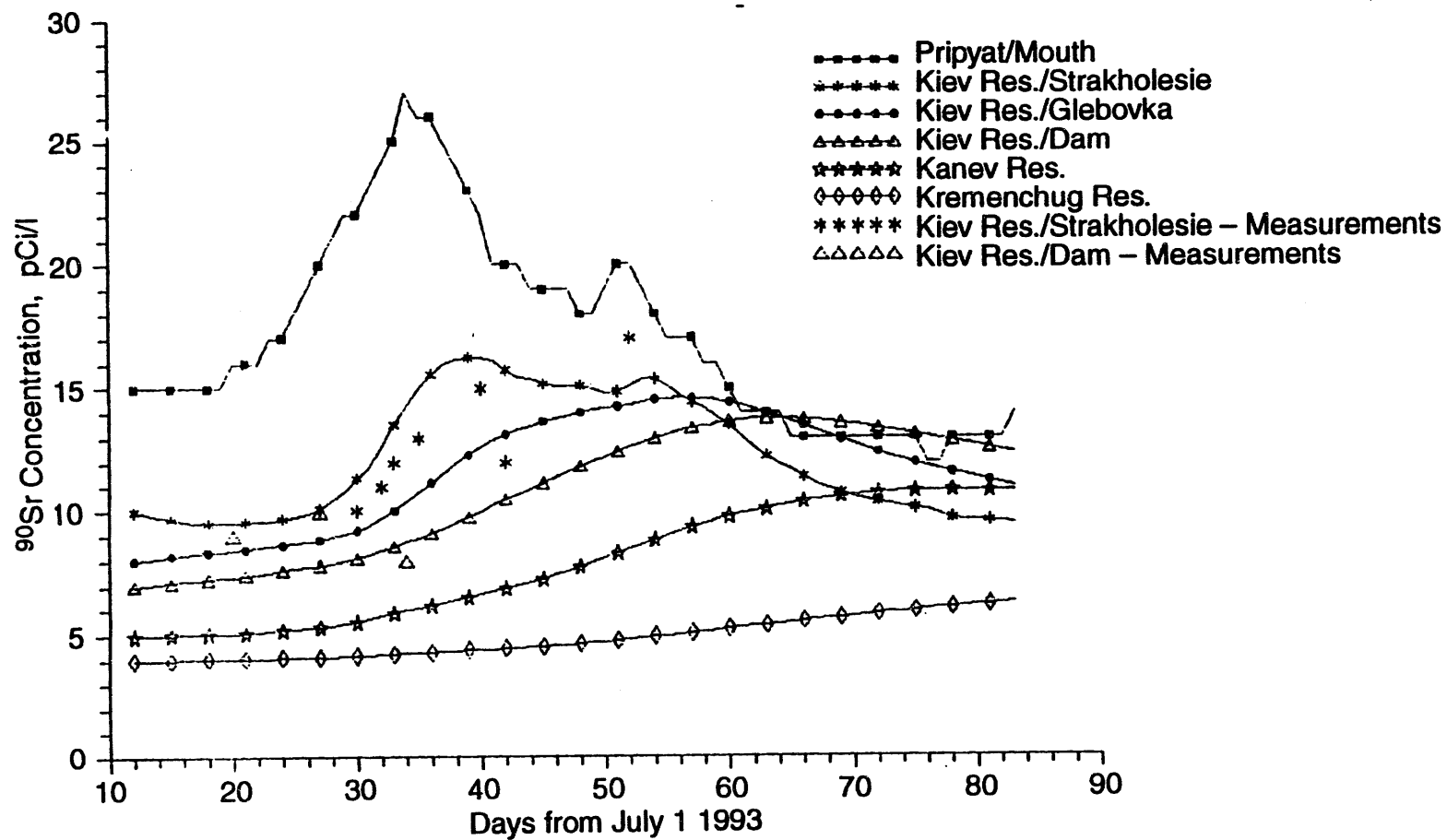
Figure 20. ^{90}Sr Concentration in the Pripyat River and the Dnieper Reservoirs During Summer 1993 Flood
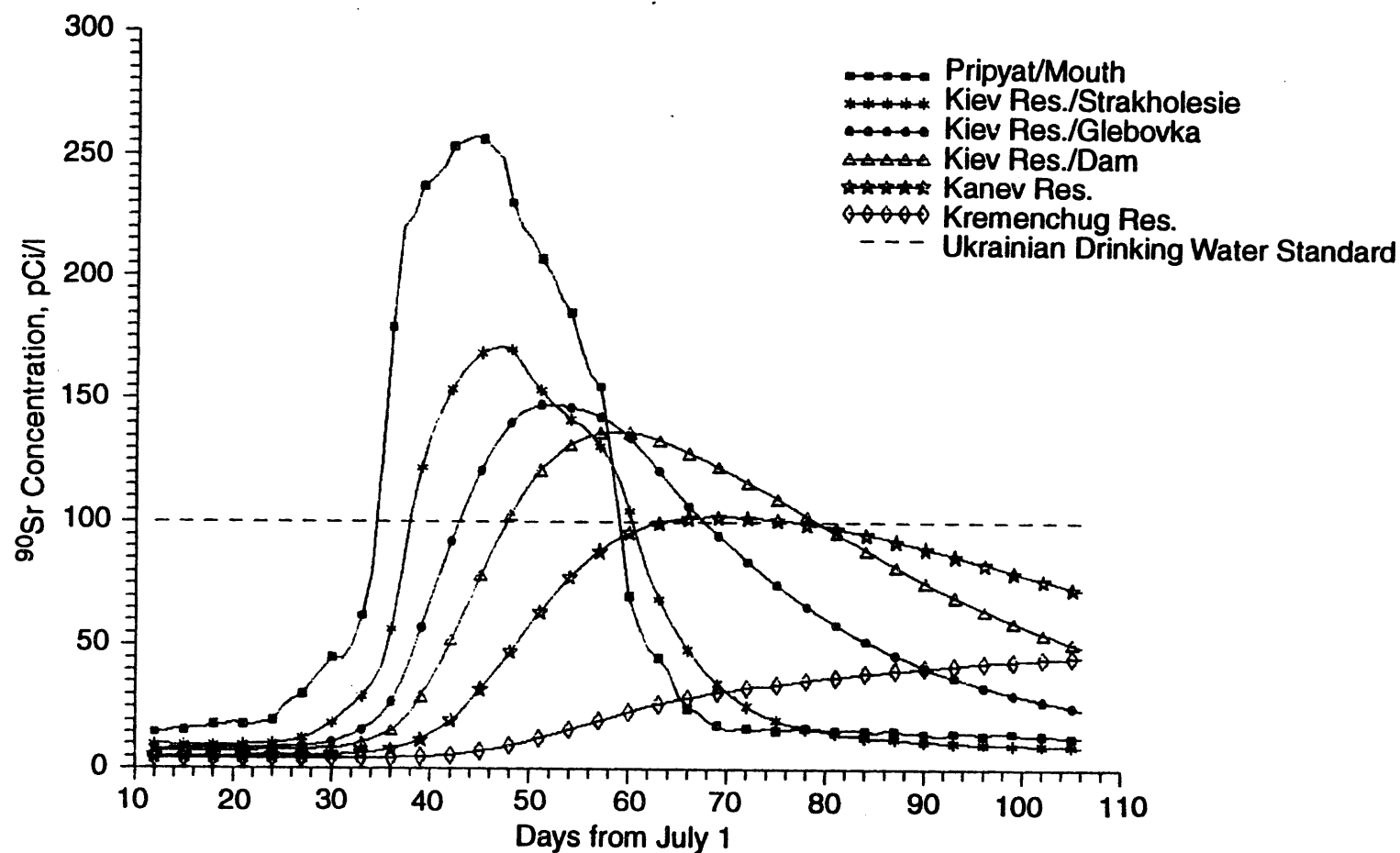
Figure 21. ^{90}Sr Concentration in the Pripyat River and the Dnieper Reservoirs for Scenario of the Pripyat Floodplain Flooding (Qmax = 2000 m^3/s)

levels measured by the routine Ukrainian monitoring system will mask changes in the radionuclide concentrations in the downstream reservoirs of the Dnieper cascade. The summer 1993 radionuclide flux to the Dnieper reservoirs would not change the situation significantly.

The second scenario (see Figure 21) gave an opportunity to estimate what would happen in one of the worst conditions for the Dnieper reservoirs. Two main factors influence the worst cases of reservoir contamination: a large water discharge from the Pripyat River carrying the maximum possible level of contamination and very low water discharge in the Dnieper River. Such a combination could occur as a result of a localized rainstorm over the Pripyat River watersheds that does not affect the flow condition of the Dnieper River. Under these conditions, the Pripyat River's highly contaminated floodplain across from the Chernobyl Nuclear Power Plant can be flooded, producing one of the worst conditions for Pripyat River contamination. In this scenario, maximum Pripyat River discharge during the flood is about 2000 m^3/s and the maximum possible ^{90}Sr concentration in the river is 150-250 pCi/L near the mouth of the Pripyat River (see Figure 21). As shown in Figure 21, in this case ^{90}Sr concentrations in almost all upper reservoirs of the Dnieper River cascade system would exceed the maximum permissible level for drinking water (100 pCi/L) for more than a month. This would be one of the worst situations for the Dnieper cascade and requires estimation of the potential radiation dose to the population of Ukraine.

5.0 Evaluation of Radiation Dose and Risk
from Use of Dnieper River Waters

One of the main concerns about consequences of the Chernobyl accident is the spread of radio-nuclides beyond the initially contaminated areas by radionuclides washing out overland and from the rivers. Expansion of the geographical scale of radionuclide contamination due to runoff and river flows spreading into the less contaminated downstream part of the Dnieper cascade requires more accurate evaluation of the supplementary risk to the population who live near the Dnieper cascade on the contaminated areas and consume both the radioactively contaminated Dnieper water and foods irrigated with water from the Dnieper reservoirs.

It is important to obtain a realistic understanding of actual risk to people living outside of the 30-km zone to set adequate criteria for measuring the effectiveness of existing water-protection constructions in the 30-km zone and to evaluate future countermeasures and water protective activity inside the 30-km zone, using dose/risk assessment approaches and cost-benefit analysis methodology.

Recently, several studies evaluated dose estimation associated with drinking Dnieper River water or consumption of fish from the river (Repin and Berkovsky 1992; Prister et al. 1992; Karatchev and Tkatchenko 1993). However, the methodologies and assumptions used in these studies varied, and thus it is very difficult to compare the results. The main reason for uncertainties relative to the results are different input data, different data bases for individual and collective dose analyses, different complexity of models, and different experimental parameters and validation of model results. Some of

the results of these previous studies and the available input data used for the studies are reviewed below. This study also reassessed collective dose to public through aquatic pathways.

5.1 Characterization of Water Use on the Dnieper Reservoirs

The main water uses contributing to individual and collective effective equivalent dose (EED) are drinking water, fisheries and fish consumption, and irrigation with water from the downstream part of the Dnieper cascade. According to official statistics, Dnieper River water is used in the municipal water system supplies for more than eight million people in 10 regions along the Dnieper's reservoirs and by the Crimea Republic (Table 11). The total population in this region is about 19 million.

The main consumers of drinking water from Dnieper's reservoir are the industrial regions of Dniepropetrovsk and Donatsk and the southern regions of Ukraine. Daily consumption of drinking water in these regions is usually accepted to be about 1.5 liters per day for one adult person.

The Dnieper reservoirs are also used intensively for commercial fishing. After the accident, there was no significant decrease in the fish catch in the reservoirs, even the Kiev Reservoir. Annual reports of statistical information by the Ukrainian State Department (Table 12) indicate that during 1986-1990 about 25000 tons of commercial fish were caught annually from all reservoirs on the cascade, including about 1200 tons per year from the most contaminated, the Kiev Reservoir. Fish consumption by professional fishers is expected to be about 70 kg per year. Annually averaged fish consumption for ordinary people in these regions (Table 11) is 17-21 kg per year. However, about 93% of the fish

Table 11. Dnieper Water Usage for Municipal Drinking Water System

Region	Water Source (reservoir)	Quantity of Water, 1000 m³/day	Population Consuming Water, in 10³ People
1. Kiev	Kanev reserv.	440	255
2. Cherkassy	Kremenchug reserv	80	226
3. Kirovograd	Kremenchug reserv.	157	371
4. Poltava	Kremenchug reserv.	108	257
5. Dniepropetrovsk	Zaporozhie reserv. Kakhovlca reserv. Dnieprodzerzinsk reserv.	1134	1980
6. Zaporozhie	Kakhovlca reserv.	575	977
7. Nikolaev	Kakhovlca reserv.	160	367
8. Kharkov	Dnieprodzerzinsk reserv.	241	419
9. Lugansk	Dnieprodzerzinsk reserv.	60	96
10. Donetsk	Dnieprodzerzinsk reserv.	1121	2156
11. Crimea Republic	Kakhovka reserv.	231	494
	Total	4307	7598[a]

(a) These data do not take into account the volume of water from the Desna River consumed by Kiev citizens. This source provides drinking water for more than 0.5 million people in Kiev and the Kiev region. The levels of ^{137}Cs contamination of Desna River near the water intake were close to the level of water contamination near the city water intake from the Dnieper River, particularly during the first years after the accident. Total consumers of contaminated drinking water from the Dnieper River in the districts downstream of the Kiev Reservoir could be about 8 million people.

Table 12. Fish Commercial Catch in Dnieper Reservoirs During 1983-1990, in Tons

Reservoirs	1983	1984	1985	1986	1987	1988	1989	1990
Kiev	1223	1485	1511	1271	1291	991	1261	1122
Kanev	563	641	716	772	627	631	719	569
Krementchug	6322	7010	9379	9686	9280	8754	10380	9199
Dnieprodzerzhins	1015	931	989	1404	1088	1354	1323	1201
Zaporozhie	644	679	733	863	740	822	887	808
Kakhovlca	8013	8683	9028	9701	8515	9527	10018	9938
Lower Dnieper	2745	2192	2402	2244	2728	2111	3855	3330

consumed are caught from artificial and natural ponds outside the Dnieper Reservoir system.

Therefore, the contribution of Dnieper fish to people's fish diet in these regions is 1.3-1.5 kg per year.

Recreational fishing could add about 30% per year to this total. However, most of the fish are

consumed locally by the fishers, collective farmers and their families, and by people who live along the

reservoirs. For the largest reservoirs, Krementchug and Kakhovlca, the fish are distributed more

widely to the adjacent regions. Thus previous collective dose estimations (Repin and Berkovsky 1992)

have assumed that the population of fish consumers was the same as that of drinking water consumers,

some eight million Ukrainians.

Perhaps the most important water use in the southern part of Ukraine is irrigation. More than

1.6 million hectares are irrigated with the Dnieper River water, 1.13 million hectares from the

Kakhovlca Reservoir alone (see Table 13). Irrigation is mostly carried out using overhead sprinklers,

ditches, and small canals. The most sensitive irrigated water usage according to Prister et al. (1992) is

Table 13. Volumes of Dnieper's Water Consumption for Irrigation in Different Regions of Ukraine
(Year 50%-probability of exceeding of annual river's water discharges)

Regions	Water Source (reservoirs or rivers)	Irrigation Area (1000 hectares)	Volume Consumption (km³)
1. Chernigov	Dnieper, Desna reserv.	16.0	0.030
2. Kiev	Kanev reserv.	117.6	0.187
3. Cherkassy	Kremenchug reserv.	48.3	0.077
4. Poltava	Kremenchug reserv.	43.9	0.088
5. Kirovograd	Kremenchug reserv.	47.0	0.127
6. Dniepropetrovsk	Zaporozhie reserv.	232.3	0.693
7. Zaporozhie	Kakhovlca reserv.	226.0	0.691
8. Kherson	Kakhovlca reserv.	412.9	1.429
9. Nikolaev	Kakhovlca reserv.	170.2	0.483
10. Crimea Republic	Kakhovlca reserv.	323.0	0.968
	Total	1637.2	4.773

flooding of rice crops (Table 14). Almost 50% of the irrigated lands are used for fodder crops, which determine contamination of meat and milk; vegetables are planted in not more than 10% of total irrigated land (Table 15).

5.2 Previous Estimation of Individual and Collective Long-Term Radiation Dose and Effects from Contamination of the Dnieper Aquatic Ecosystem

Several studies have estimated dose from the water pathway. The sources for most data used in those studies are as follows: The data on the contamination of water bodies for the period after the accident were obtained by the Ukrainian Hydrometeorological Institute (Voitsekhovitch et al. 1991, 1993a,b). The data on fish contamination are from the Institute of Sanitary Hygiene of Ukraine and the

Table 14. Specific Activity of Radionuclides in the Rice Crop, Bq/kg (Prister et al. 1992)

Year	^{137}Cs Grain	^{137}Cs Straw	^{90}Sr Grain	^{90}Sr Straw
KHERSON REGION				
Skadovsky District				
1972	0.24	0.56	0.03	0.41
1982	0.07	0.16	0.03	0.30
1985	0.06	0.10	0.01	0.12
1986	0.10	0.18	0.01	0.11
1987	0.16	0.29	0.02	0.15
1988	0.15	0.22	0.02	0.21
Kalanchaksky District				
1987	0.16	0.30	0.03	0.27
1988	0.16	0.26	0.03	0.23
CRIMEA REGION				
1987	0.14	0.26	0.02	0.23
1988	0.15	0.27	0.02	0.21

Table 15. Specific Activity of ^{137}Cs in Products Obtained from the Irrigated Lands in 1988, Bq/kg (Prister et al. 1992)

Region, District	Lucerne	W. Wheat	Tomato	Cabbage	Cucumber	Milk	Meat
Cherkassy, Kanivsky	0.34	0.11	0.01	0.002	0.01	0.22	1.11
Poltava, Kremenchutsky	0.34	0.15	0.01	0.001	0.01	0.19	1.11
Dniepropetrovsk, Nizhnednieprovsky	0.26	0.04	0.01	0.001	0.01	0.30	1.48
Kherson, Dnieprovsky	0.17	0.11	0.01	0.001	0.01	0.30	0.74
Crimea, Sympheropolsky	0.34	0.07	0.01	0.002	0.01	0.22	1.11
Reference districts without water use from Dnieper							
Kharkov, Lazovsky	0.08	0.04	0.001	0.001	0.1	0.11	--
Donetsk, Krasnoarmeysky	0.08	0.04	0.001	0.001	0.1	0.11	0.37

Institute of Hydrobiology of the Ukrainian Academy of Sciences, and from original studies of fish con-tamination in the Kiev Reservoir by Ryabov (1990). Other studies of fish contamination related to dose assessment were carried out by Prister et al. (1992), Karatchev and Tkachenko (1993), and others. Preliminary dose estimates related to drinking Dnieper River water were provided during the initial period after the accident by various scientists (Izrael et al. 1990). Dose contribution from irrigated produce has been estimated by Prister et al. (1992) and others.

Unfortunately, none of these past studies analyzed integral dose and risk to the population health due to total water use and water consumption from the Dnieper cascade system. This study does not analyze all these issues. However, we have evaluated some methodological problems and sources of uncertainty to mitigate these problems for future Chernobyl studies.

With regard to the methodological approaches, it can be stated that the assessment of individual doses from known environmental concentrations is relatively straightforward. The dose is the product of concentration, consumption, and dose commitment factor. Dose estimation is more difficult when the environmental concentration is not known and must be estimated. This is generally the case for the Chernobyl dose/risk assessment case studies. In general, most radiation dose estimates were calculated by computer codes based on the recommendations and parameters established by International Commission on Radiological Protection (ICRP 1977, 1979, 1990). For example, Napier et al. (1988) used the GENII computer code.

The study whose objectives were closest to those of the present study was carried out by Repin and Berkovsky (1992). They evaluated importance of the water consumption as a dose contributing factor relative to other radiation-dose-contributing factors. They used simple models for individual and

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collective dose estimations, with the effective dose coefficients, given as expected dose factor normalized on the unit of consumed radioactivity, 0.36×10^{-7} Sv/Bq for ^{90}Sr, 0.2×10^{-7} Sv/Bq for ^{134}Cs, and 0.14×10^{-7} Sv/Bq for ^{137}Cs (ICRP 1979). Repin and Berkovsky provided representative radiation dose estimates for the population living along the Dnieper cascade. Two kinds of exposure were assessed: exposure from external and internal uptakes of dose sources from the polluted terrestrial areas, and exposure from consumption of food products. Their study revealed that the largest contribution to dose for the Ukrainian population is through consuming bread and milk products. They also estimated total radiation dose exposure to the population living along the Dnieper River from sources that do not connect directly with drinking water use and other kinds of water consumption. Using these results, we estimated that the total radiation dose from exposure to ^{90}Sr, ^{134}Cs, and ^{137}Cs expected up to year 2056, for an average human age of 70 years at that time, for the population of approximately eight million people living along the Dnieper River is about 25000 menSv. About 5000 menSv of the effective equivalent dose (EED) is to human organs already exposed to radiation during 1986-1992.

These estimates were used to assess the contributions of the water pathway to the total radiation dose and to the total health risk for the population directly or indirectly consuming water from the Dnieper cascade polluted by the Chernobyl accident.

5.3 The Role of Different Water Uses in the Effective Equivalent Dose (EED) Formation

5.3.1 Drinking water

People living in the major cities along the Dnieper reservoirs generally use the public drinking water supply systems. Water treatment removes some portion of radionuclides, but the effectiveness of the public water treatment systems is not very high. The treatment factor for public water supply systems is no more than 3-4 times for ^{137}Cs, 1.2-1.5 for ^{90}Sr, and about 1 for ^{131}I. In this study, as a conservative estimation, we did not assume public water treatment to be a significant water remedial factor. Adults are assumed to consume about 1.5 liters of potable water per day. Neglecting removal of radionuclides by the water treatment system, people consuming Dnieper River water have taken up corresponding radiation doses from ^{137}Cs and ^{131}I and are expected to receive an equivalent dose in future from ^{90}Sr. Taking into account the problem of ^{90}Sr exposure of human organs, it is more accurate to estimate the expected radiation dose during the average human life (70 years) after the radionuclides were released to the environment.

The radiation dose of ^{131}I for the initial period, a main contributor to exposure during May and June 1986, was estimated using recommendations of ICRP Publication No. 30 and are presented in Table 16. Following this, the estimated individual dose for Kiev citizens due to uptake of ^{131}I through drinking water during first two months after the accident was about 2×10^{-4} Sv per person. According to the estimation for the lower part of the Kiev Reservoir in 1986, individual dose contribution from

Table 16. Estimation of ^{137}Cs Concentration in Different Fish Species Caught from the Kiev Reservoir, in Bq/kg (fresh mussels weight)

Fish Species	1987	1988	1989	1990	1991
Perch	1.5-3.0	1.5-3.4	1.2-3.4	0.7-1.7	0.6-1.3
Pike	0.8-2.8	0.9-1.6	0.8-1.5	0.6-1.3	0.5-1.1
Tench	0.7-1.7	0.6-0.9	0.5-0.8	0.2-0.8	0.3-0.5
Bream	0.5-1.0	0.4-0.9	0.3-0.7	0.2-0.5	0.1-0.3
Rudd	0.4-1.1	0.3-0.7	0.2-0.5	0.1-0.4	0.1-0.3

(a) Averaged data from different available sources originally obtained by I. Ryabov (Ecopolis), N. Tkachenko (Ukrainian Hygiene Center), and O. Nasvit (Institute of Hydrobiology).

^{90}Sr, ^{89}Sr, ^{134}Cs, and ^{137}Cs in drinking treated water was about 8.7 x 10^{-5} Sv per year.[a] Thus 70% of the radiation dose to the Kiev population during 1986 was due to ^{131}I in the drinking water. Monthly averaged data on water contamination of all Dnieper reservoirs by were used by Repin and Berkovsky (1992) to estimate the incremental individual and collective EED for internal exposure to ^{90}Sr and ^{137}Cs by eight million people living along the Dnieper reservoirs that was due to consumption of drinking water during 1986-1982.

The current study estimates that the total collective EED for people living in the 11 regions of Ukraine along the Dnieper River were approximately 216 menSv for 1986-1992 and will reach up to about 900 menSv by the year 2056. These estimates are preliminary because of the uncertainty of

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(a) Personal communications to B. A. Napier and W. L. Templeton at PNL.

available data on consumption of drinking water from the Dnieper River. The range and magnitude of the uncertainty introduced by different researchers due to different sets of input information is likely to be significant.

5.3.2 Fish Consumption

The main differences among previous studies reflect the large uncertainty related to contamination of different fish species. Concentrations of ^{137}Cs in different kinds of fish obtained by the Institute of Sanitary Hygiene and the Institute of Hydrobiology are presente⌐ in Table 16.

Using some preliminary parameters of radiation dose exposure from fish consumption obtained by Repin and Berkovsky (1992) and Karatchev and Tkatchenko (1993), the contribution from the fish pathway was evaluated here (Tables 16 and 17). The collective EED doses to all potential fish consumers (19 million people) would be about 80 menSv, resulting from exposures during 1986-1992 to ordinary consumers of fish. An additional 20 menSv could be contributed, if recreational fishermen in the same population (about 30%) are also taken into account. For people who also consume drinking water (about 8 million people), presumably taking into account that people living along the Dnieper River consume not less than 70% of the caught fish in their diet) received 70 menSv. Accurate evaluation and assessment of these results is very difficult. However, assessing different groups of consumers of water-related products (professional fishers, recreational fishers, or ordinary fish consumers) for individual or collective radiation dose exposure could produce significantly different results.

Table 17. Increment of Collective Effected Equivalent Dose of Internal Exposure to Population Living Along the Dnieper Reservoirs and Expected Risks Due to Different Water Usage and Water Intake During 1986-1992[a]

Types of Water Usage	No. of Exposed People[b] (million)	Annual Consumption of Products (kg/year)	1986 - 1992		Equivalent Radiation Risks	Contribution of the Pathways (%)
			EED (MenSv)	Cancer Effect		
Drinking water consumption	8	1.5	216	16	2.0×10^{-6}	4.4 1.9
Fish products consumption by all people living in the 11 regions and drinking water from Dnieper res.	19 8	1.4 2.0	100 70	7 5	3.7×10^{-7} 6.8×10^{-7}	1.4 0.8
Consumption of food products from irrigated areas by people who also drink water from Dnieper and consume fish	19 8		513 216	38 16	2.0×10^{-6} 2.0×10^{-6}	4.4 4.4
Total collective EED from sources that are linked with water usage	19 8		829 502		3.2×10^{-6} 4.6×10^{-6}	7.0 10.2
Total collective EED from sources which include those not linked with water usage	19 8		11832 4982	864 364	4.5×10^{-5} 4.5×10^{-5}	100 100

(a) Results reflect the EED estimates by Repin and Berkovsky (1992) and Karatchev and Tkashenko (1993).

(b) Two population groups referenced: 1) 8 million people who live along the Dnieper and drink water from the reservoir's water intake; and 2) 19 million people who consume fish products that are caught in the reservoirs but do not drink the Dnieper water.

Comparing individual radiation dose estimates from Karatchev and Tkachenko (1993) indicates that the main contributors to radiation dose for professional fishers would be the fish pathway. However, the analysis on collective dose estimates for ordinary consumers of fish from the Dnieper reservoirs indicates that the main factors in dose exposure will be drinking water and perhaps the irrigation pathway.

The main difficulty for decision-makers using these results is estimating the adequacy of the data on the basis of uncertainty analysis. Another problem is to transfer individual dose estimates on to the larger population groups.

5.3.3 Irrigation Water Use

Another important source of radionuclide intake to the human organism is agricultural products produced on the irrigated lands in the Dnieper River watershed. Prister et al. (1992) show that the contamination of Dnieper River water by ^{137}Cs resulted in a perceptible increase of its concentration in crops in comparison with those obtained in the Kharkov and Donetsk regions, where sources of irrigation water were not connected with the Dnieper drainage basin (see Table 15). The ^{137}Cs concentrations in crops are 2-4 times greater for those that are watered 3-6 times during the vegetation period and which, due to their physiological features, receive radionuclides by the nonroot (aerial) pathway; in contrast, for cucumber and cabbage, which are covered with a cuticular nonwettable layer, ^{137}Cs contamination is similar for the two regions being compared (Table 15). Differences in the ^{137}Cs content in forage cause differences in radionuclide levels in cow's milk and meat. In the uncontaminated control regions, radionuclide concentrations in cow's milk and meat are 1.5-2.5 times less than those in milk and meat where Dnieper River water is used for irrigation.

Using soil contamination data in the Dnieper River drainage basin and experimental data on radionuclide transfer factors from soil to agricultural plant via the root pathway, Prister et al. (1990) have shown that, for the irrigation case, radionuclide uptake in the crops is mainly determined by aerial

contamination. However, contamination of rice is of special interest because rice grows in flooded lands. Several research teams carried out observations in 15 farms of Crimea during harvest to obtain the information used.

An accurate estimation of the contribution of irrigation pathways to radiation dose exposure has not been achieved yet. Many uncertainty factors control the processes relating to contamination of irrigated plants. We hope to perform a more accurate assessment during the next stage of our study. Meanwhile, some recently obtained study results indicate that for an individual who lives in the middle or upper districts of Ukraine along the Dnieper River, most of the radiation dose due to aquatic factors comes from consumption of drinking water and fish. For southern regions where there is more consumption of irrigated agricultural products, the significance of water use for irrigation and the radiation exposure for population corresponding to this pathway increases especially when the calculated individual radiation dose is used to estimate the dose to all consumers of irrigated food products (mostly in the same eleven regions, with their population of about 19 million people). So, for collective dose estimates, irrigation as a dose-contributing factor for the water pathway increases significantly. This is the main difference between using the individual or the collective radiation dose estimates to assess the contribution of the irrigation pathway to radiation risk for large contaminated areas where water use is complex.

Thus, it is very important to compare the effects of the different contributors to the total radiation dose and to the appropriate risk for people's health for different population groups.

5.4 Description of Some Approaches for Radiation Risk Estimation from Dnieper Water Use

The main purposes of the radiation risk assessment were to provide key information to decision-makers and to determine the effects of a variety of policy actions. Radiation risk estimates are usually based on the correlation between radiation dose exposure for population and a statistically defined cancer effect for population. This study did not intend to develop a new methodology for risk estimation based on water use. However, analysis of some previous data shows that the uncertainty of radiation dose (risk) estimations is connected with the range of partial dose (risk) contributors. It must be assumed that dose estimates in previous studies are correct. In this case, based on the recommendations of ICRP Publication No. 60 (ICRP 1990), the simplest way to adequately estimate the radiation risk is to use the recommended value of the specific radiation risk coefficient (7.3×10^{-2}) multiplied by the values of the radiation dose estimates from each dose contributor. So the first stage of estimating risk from water use for people living along the Dnieper River is to assess the radiation dose components from each water pathway (drinking water, fishing, irrigation). The ratio between different radiation risk components from different types of water use would be similar to the ratio between appropriate dose estimates for the same types of water use.

For the southern Ukrainian regions, radiation doses from drinking water come mainly from ^{90}Sr (10 times more than from ^{137}Cs). Radionuclide uptake through consumption of fish caught in the Dnieper reservoirs contributed most to dose in 1987-1989, but its contribution is now decreased by 2-5 times. However, for the same period, relative contribution of radiation dose through drinking water rose by an order of magnitude. Even more changes, two orders of magnitude and more, on

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relative contributions of different water pathways take place for fishermen. The EED to fishermen from only ^{137}Cs in fish reached 2 menSv/year during 1987-1989.

The contribution of the Dnieper cascade to the collective EED in Ukraine was estimated here on the basis of previous work by Repin and Berkovsk. (1992) and Karatchev and Tkachenko (1993), using the actual radiation situation and water use on the Dnieper reservoirs in 1989. The EED from drinking water was calculated as about 40 menSv, the EED from fish consumption was about 13 menSv; the EED from irrigation (including crops, milk, and meat from irrigated areas) was very conservatively estimated as about 100 menSv for 1989. However, Repin and Berkovsky (1992), taking into account the large uncertainty related to the irrigation pathway contribution, have assumed that the internal radiation dose contribution from consumption of irrigated products could be as much as that of the drinking water pathway.

Analyzing the results presented in Table 17, and a value of 0.073 Sv^{-1} for the specific radiation risk factor (ICRP 1990), the total expected human cancer effect due to the use of Dnieper River water in 1986-1992 will be 61 people with cancers in the total population of about 19 million. This value could increase if hydrological (and radiological) conditions on the Dnieper reservoirs change. If we take into account the size of the affected population (about 19 million), we estimate the individual risk from total water usage to be no more than about 3-5 x 10^{-6}. For the same population of Ukraine (19 million), total radiation risk from all pathways is estimated to be in the range 4.5 x 10^{-5}.

Thus, it could be concluded from this study that radioactive contamination of the Dnieper aquatic system and the resulting radiation pathways is not a dominant factor for radiation risk compared with other radiation risk contributors. The contributions to risk from consumption of drinking water, fish,

and irrigated food products could compose only 5-10% of the total radiation risk resulting from the Chernobyl accident, which exposed the same people during 1986-1992. However, providing a water-protective countermeasure inside the Chernobyl close-in zone would remain important for several reasons:

1. There were no higher floods on the Pripyat River during most of the years after the accident (maximum water discharge during 1986-1992 was about 1200 m³/s; the discharge of higher floods would be 4000-5000 m³/s and more).

2. Most (90%) of the internal individual radiation dose for the Ukrainian population due to drinking water consumption was contributed by ^{131}I during the first months after the accident in 1986. However, most water-protective activities were implemented much later. Clearly it is very important to develop an emergency response and forecast methodology to evaluate the consequences of potential similar accidental cases on the large rivers to develop effective countermeasures.

3. It is necessary to recalculate more accurately all dominant contributions by the water pathway to the radiation dose exposure. It is also very important to understand how to estimate the effectiveness of the countermeasure activities carried out during 1986-1993.

The Pripyat/Dnieper River aquatic system is the only link among all the population (about 19 million) who consume the Dnieper water and have been exposed to radionuclides as dispersion and migration processes take place inside the 30-km zone around Chernobyl. A number of questions remain to be answered: How can the recent findings of radionuclide migration studies and a long-term estimation of radionuclides dispersion in surface water and in groundwater be applied to modernize monitoring of water bodies? How can retention factors be estimated for the Chernobyl area's landscape and how can self-purification of water bodies, as a water-remedial environmental factor, be estimated for comparisons with the expected effectiveness of water-protective activities? How can the most adequate technologies for remediation or clean-up activities be identified? How can general health risk from water use be estimated by taking into account the fact that existing chemical contamination of the Dnieper

River system and synergistic effects might create a risk that significantly exceeds the radiation effect. All these issues must be evaluated using risk-benefit analysis methodology, as one of the main tasks of the next stage of the Ukraine/USA joint Chernobyl case study.

6.0 Summary and Conclusions

This report describes the joint activities of Program 7.1.F, "Radionuclide Transport in Water and Soil Systems," of the USA/CIS Joint Coordinating Committee on Civilian Nuclear Reactor Safety to study hydrogeochemical behavior of radionuclides released from the Chernobyl Nuclear Power Plant in Ukraine. The study evaluated radionuclide distributions in the Pripyat-Dnieper river system and their potential human impacts based on field data and modeling. The joint activities also included rapid evaluation of the radionuclide distribution in this river system during the 1993 summer flood to assist the Ukrainian government in their emergency response, during the flood.

Approximately 50 million curies (or 4%) of the fission products and activates in Reactor Unit No. 4 were released to the atmosphere during the 11 days following April 26, 1986, including 1.3 and 0.24 million curies of ^{137}Cs and ^{90}Sr, respectively. A significant portion of these radionuclides were deposited on the watersheds of the Pripyat and Dnieper rivers in Ukraine, Belarus and southwestern Russia. Consequently, there has been long-term influx of ^{137}Cs and ^{90}Sr into these rivers, which pass through six reservoirs before discharging into the Black Sea, about 1000 km downstream. Radionuclide composition of the fallout over these areas was heterogeneous, varying with direction and distance from the Chernobyl Nuclear Power Plant. Much of the ^{90}Sr was deposited within a 30-km zone around the plant; it was originally associated with hot fuel particles that gradually change forms to become more soluble and exchangeable through mechanical destruction and dissolution of the fuel component. On the other hand, ^{137}Cs was deposited in three distinct areas, and its association with hot fuel particles was limited to those deposited near the Chernobyl Nuclear Power Plant. Field data collected within the 30-km zone indicate that although ^{137}Cs and ^{90}Sr leached into the soil at approximately the same rate,

the effective washout of ^{137}Cs from the local watershed decreased with time, because the amount of ^{137}Cs in the exchangeable form decreased as a result of fixation with soil. In contrast, the effective washout of ^{90}Sr has stayed at about the same level for seven years since the accident.

Radionuclide levels in the Pripyat and Dnieper rivers rose almost immediately after the accident, then decreased significantly. Total beta activity in the Pripyat River water was above 0.1 μCi/L in the first day after the accident, but had decreased to 4.6 nCi/L by the end of May 1986. The highest measured ^{90}Sr level in the Pripyat River was 400 pCi/L in the first few days of May 1986, and levels decreased to 30-50 pCi/L within the next two months. Plutonium concentrations in the river reached 10 pCi/L in the first days after the accident but dropped to 0.2 pCi/L by August 1986. Up to 98% of the plutonium was associated with suspended and bottom sediment. Cesium-137 shows a clear affinity to fine sediment, and the percentage of suspended sediment-sorbed ^{137}Cs varied from 20 to 80%. The highest ^{131}I content measured at the Dnieper River drinking water intake for the City of Kiev was 300 pCi/L on May 3, 1986.
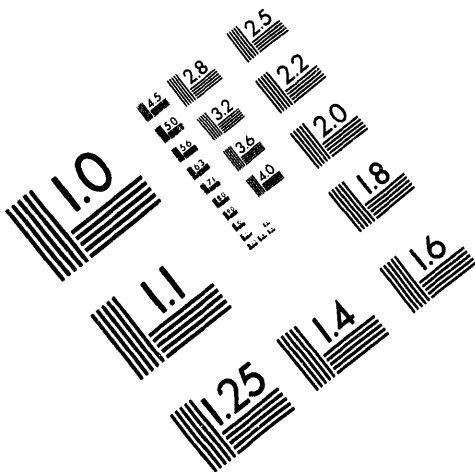
In recent years, ^{137}Cs and ^{90}Sr concentrations in the Pripyat and Dnieper rivers have become lower. During 1992, the average ^{90}Sr concentrations were 20-30 pCi/L near the mouth of the Pripyat River and 1-5 pCi/L in the lower reservoirs of the Dnieper River. Concentrations of ^{137}Cs were somewhat lower than those of ^{90}Sr, averaging 0.1-1 pCi/L in the Dnieper reservoirs for 1991-1993. This level is close to the background level caused by global radionuclide fallout.

Despite the general pattern of falling concentration, flooding of the Pripyat River has proved to be a serious radiation problem. The Pripyat River floodplain (approximately 2 km wide and 10 km long) directly across from the Chernobyl Nuclear Power Plant received a significant amount of ^{137}Cs and ^{90}Sr

deposition after the accident with ^{90}Sr concentrations of up to 1000 μCi/m^2, accounting for approximately half of all ^{90}Sr entering the Pripyat River. During 1991 winter flooding of the Pripyat River caused by an ice jam, the peak ^{90}Sr concentration at Yanov Bridge (at the downstream end of the floodplain) was above 250 pCi/L, exceeding the current Ukrainian drinking water standard of 100 pCi/L for ^{90}Sr. Thus, the assessment and control of the radionculide migration during flooding are critically important from the viewpoint of public health.

Despite remediation measures, the problem of increasing of ^{90}Sr concentrations in the Pripyat and Dnieper rivers during high floods still remains. In July-August 1993, heavy rainfall over the Pripyat River catchment in Belarus and Ukraine caused severe flooding, significantly raising ^{90}Sr concentrations in the river. Because of heightened public concern about radionuclide levels in the river and the need of the Ukrainian government to make an emergency response, we conducted an emergency evaluation of radionuclide distributions in the Dnieper River while the flooding was occurring. Near the Chernobyl area, the maximum ^{90}Sr concentration in the Pripyat River rose to about 20-25 pCi/L in early August; near the Pripyat River mouth, the concentration reached 35 pCi/L. The peak ^{90}Sr concentration in the Kiev Reservoir (a major source of drinking water for Kiev) was 12 pCi/L. However, by the end of August 1993, the ^{90}Sr concentration at the mouth of the Dnieper River at the Black Sea was still only 6-8 pCi/L. If the 10-km dike had not been constructed, ^{90}Sr concentrations in the Pripyat River, and thus also in the Dnieper River, would have been much higher.

Unlike ^{90}Sr, ^{137}Cs concentrations in the Pripyat River during the flood did not rise significantly from the pre-flood levels. Concentrations of ^{137}Cs in river water around the Chernobyl site reached only 5-7 pCi/L. In the middle of July, ^{137}Cs concentrations in the Kiev Reservoir and further downstream in the Kanev Reservoir were 2-5 pCi/L and 1-3 pCi/L, respectively.

Centimeter

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 mm

Inches

1.0
1.1
1.25 1.4 1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
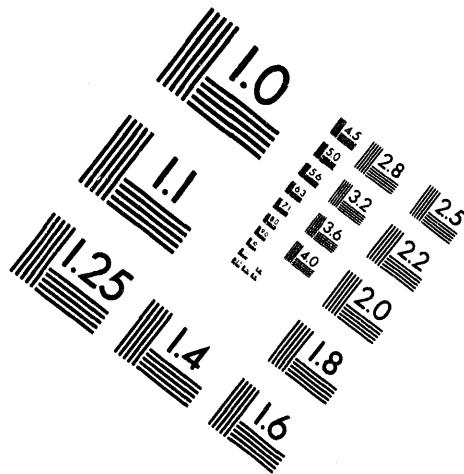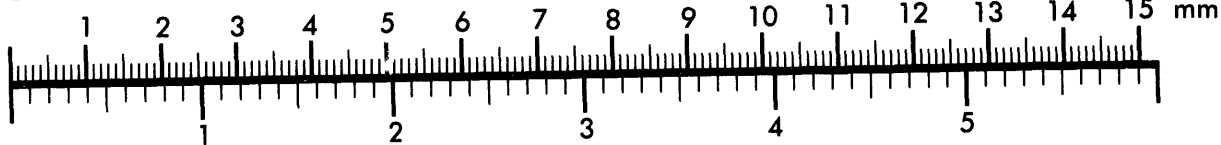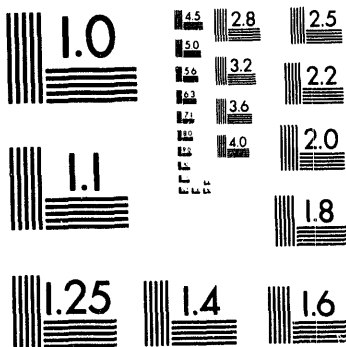
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2 of 2

Based on the measured radionuclide levels, additional modeling results, and the assumption of water purification in a water treatment station, ^{90}Sr concentrations in the city of Kiev's drinking water were estimated to be less than 8 pCi/L. Estimated ^{137}Cs concentrations for Kiev's drinking water were two orders of magnitude lower than the drinking water standard of 500 pCi/L for ^{137}Cs. Thus the water was determined to be safe for Kiev citizens to drink during the 1993 summer flood.

About 19 million people in Ukraine consume water from the Dnieper River between Kiev and the Black Sea and thus are exposed to the impacts of the radionuclides in the river through drinking water, irrigation, and fishing; 8 million consume the Dnieper River water as their drinking water. With the most current water use information available to us, we calculated collective effective equivalent dose (EED) of internal exposure to the population and expected risks due to differential water usage. It was estimated that during 1986-1992, the 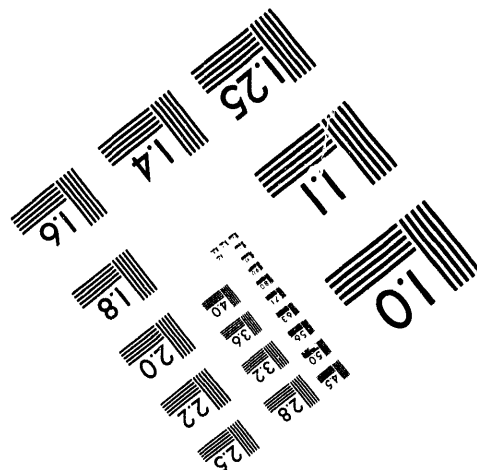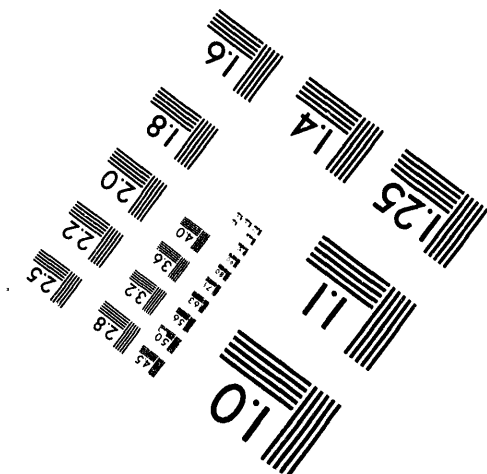collective EED for the 19 million people that resulted from 8 million people drinking the Dnieper River water, and 19 million people consuming fish or irrigated food products were 216, 100, and 513 menSv, respectively, totalling 829 menSv. The irrigation pathway is clearly the dominant pathway among the aquatic pathways for these 19 million people. The total aquatic pathway contribution constitutes about 7.0% of the total collective EED of 11,832 menSv resulting from all pathways. If only the 8 million people who not only drink river water but also consume fish and irrigated food products are considered, their collective EEDs for drinking water and consuming fish and irrigated food products are 216, 70, and 216 menSv, respectively, totalling 502 menSv. For this population, the total EED from all pathway sources is 4,982 menSv; thus the water pathway contribution to collective EED constitutes 10% of the total pathway contributions. (The collective EED from all pathways for these 8 million people over the period 1986-2056, corresponding to an average human lifetime of 70 years, is estimated to be approximately 25,000 menSv). The equivalent radiation risks from the aquatic pathway for the 19 million and 8 million people are 3.2x10^{-6}

and 4.6×10^{-6}, respectively, as compared to 4.5×10^{-5} from the total pathways. The expected human cancer effects resulting from drinking Dnieper River water and consuming radioactively contaminated fish and irrigated food products are estimated to be 16, 7, and 38 people with cancers, totalling 61 people in the total population of 19 million. Of the 8 million who drank the water, there will be 16, 5, and 16 people with cancer, totalling 37 people with cancers. The total number of people who will get cancers due to all pathways are expected to be 864 and 364 among the 19 million Ukrainians and 8 million who drink the Dnieper River water.

Field data evaluation and modeling revealed that flooding is a critical factor that increases radionuclide concentrations in the rivers. The construction of the 10-km dike in the floodplain across from the Chernobyl Nuclear Power Plant proved to be effective for reducing ^{90}Sr concentrations in the Pripyat River. However, despite construction of the dike, radionuclide migration and interaction between the floodplain and the Pripyat River remains a major long-term problem. This surface and groundwater interaction must be assessed in the future.

Even though the aquatic pathway contributes only 7 to 10% of the total dose from all the pathways, radionuclide migration into and within the rivers is important for determining potential dose to people. This is the case mainly because most of the practical current and future remediation will be within the 30-km protection zone to control and reduce potential radionuclide migration in the aquatic pathways. It is important to obtain a realistic understanding of actual risks from the aquatic pathway to people living outside the 30-km zone to develop adequate criteria for measuring the effectiveness of current and future remediation and water protection activities inside the 30-km zone, based on dose/risk assessment and cost-benefit analysis.

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Appendix

Equations of the Box Model WATOX

Appendix

Equations of the Box Model WATOX

For modeling, the Dnieper River reservoir system was considered be made up of a set of fully mixed compartments (boxes). The box model used for this study describes temporal dynamics of water volume V_i (t) and compartmentally averaged concentrations of suspended sediments S_i (t) and radionuclides in water C_i (t), on suspended sediments C_i^s (t), and in the active upper layer of the bottom deposition C_i^b (t) for each compartment.

The water-balance equation for the set of the compartments is

$$\frac{dV_i}{dt} = Q_{i-1} - Q_i + R_i - Q_i^w + \sum_{j=1}^{m_i} Q_j^t \tag{1}$$

where m_i =   number of tributaries

Q_{i-1} =   water discharge into compartment i

Q_i =   discharge from compartment i

Q_j^t =   discharges from tributary j to compartment i

Q_i^w =   total water intake (e.g., drinking and irrigation water intakes) from compartment i

R_i =   difference between precipitation and evaporation rates.

t =   time.

Transport equations for the box model were derived by integration from the transport equation of the two-dimensional lateral-longitudinal model over the surface-water body (Onishi 1981; Zheleznyak

A.1

et al. 1992c, 1993). Integrating the two-dimensional suspended sediments transport equation from the COASTOX model (Zheleznyak et al. 1992c, 1993) with appropriate conditions yields

$$\frac{d(V_i S_i)}{dt} = Q_{i-1} S_{i-1} - Q_i S_i + q_i^b - q_i^s + R_i^h - S_i Q_i^w + \sum_{j=1}^{m_i} Q_j^t S_j^t \qquad (2)$$

where S_i = compartmentally averaged suspended sediment concentration

S_{i-1} = suspended sediment concentration in inflow from compartment i

R^h = sediment flux into the compartment due to overland and coastal erosion processes

S_j^t = sediment concentration of tributary j

q_i^b and q_i^s = compartmentally integrated rates of sediment resuspension and sedimentation, respectively. These rates are calculated as follows:

$$q_i^s = \begin{cases} F_i W_o (S_i - S_i^*) & S_i > S_i^* \\ 0 & S_i < S_i^* \end{cases} \qquad (3)$$

$$q_i^b = \begin{cases} 0 & S_i > S_i^* \\ F_i W_o (S_i^* - S_i) & S_i < S_i^* \end{cases} \qquad (4)$$

where S_i^* = the near-bottom equilibrium sediment concentration that corresponds to the sediment capacity for steady uniform flow with the same local parameters

F_i = the bottom surface area

W_o = sediment fall velocity.

The value of F_i is defined by the Bijker method through the compartmentally averaged current velocity $U_i = Q_i L_i / V_i$, where L_i is compartment length.

The temporal dynamic of the mass of the contaminated bottom sediment, M_i^b, is

$$\frac{dM_i^b}{dt} = q_i^s - q_i^b \tag{5}$$

$$M_i^b = \rho_s(1 - \epsilon)Z_* F_i \tag{6}$$

where Z_* = the effective bed thickness

ρ_s = bottom sediment density

ϵ = porosity.

The radionuclide transport equations describe advective transport of solutes and with sediments, as well as radionuclide exchange processes between water (phase 1), suspended sediments (phase 2), and bottom sediments (phase 3). Radionuclide-sediment interactions resulting from physical-chemical exchange between phases and sedimentation-resuspension processes are also considered, as described by Onishi et al. (1982). The adsorption/desorption process is simulated by a sorption-adsorption submodel using the transfer rate coefficients A_{ij} and the distribution coefficient K_d as the main parameters of the processes. A second submodel is governed by sedimentation and resuspension fluxes, whose rates q_i^b and q_i^s were determined in Equations (3) and (4).

The model equations based on the mass conservation and the interaction models are written as follows:

$$\frac{d(V_i C_i)}{dt} = Q_{i-1}C_{i-1} - Q_i C_i - A_{1,2}(K_d C_i - C_i^s)$$
$$- A_{1,3}(K_d C_i - C_i^b) - \lambda V_i C_i + \sum_{j=1}^{m} Q_j^t C_j^t \tag{7}$$

$$\frac{d(V_i S_i C_i^s)}{dt} = Q_{i-1} S_{i-1} C_{i-1}^s - Q_i S_i C_i^s + A_{1,2}(K_d C_i - C_i^s)$$
$$+ C_i^b q_i^b - C_i^s q_i^s - Q_i^w C_i^s S_i + R_i^h C_i^h - \lambda V_i S_i C_i^s + \sum_{j=1}^{m} Q_j^t S_j^t C_j^{st} \tag{8}$$

where $A_{1,2}$ = radionuclide transfer rate between water and suspended sediment

$A_{1,3}$ = radionuclide transfer rate between water and bed sediment.

$$\frac{d(M_i^b C_i^b)}{dt} = C_i^s q_i^s - C_i^b q_i^b + A_{1,3}(K_d C_i - C_i^b) - \lambda M_i C_i \tag{9}$$

where C_i = radionuclide

C_i^s = radionuclide concentration associated with suspended sediment in compartment i

C_i^b = radionuclide concentration associated with bed sediment in compartment i

C_j^t = concentration in tributary j

C_j^{st} = suspended-sediment-solved radionuclide concentrations in tributary j

C_i^h = radionuclide concentration associated with sediments discharged into compartment i due to overland and coastal erosion

λ = radionuclide decay rate.

The exchange rate coefficients in this model may be written

$$A_{1,2} = \frac{V_i S_i}{1 + K_d S_i} \left[\frac{\delta_{1,2}}{t_s} + \frac{\delta_{2,1}}{t_{ds}} \right] \tag{10}$$

$$A_{1,3} = \frac{M_i^b}{1 + K_d \dfrac{M_i^b}{V_i}} \left[\frac{\delta_{1,3}}{t_{sb}} + \frac{\delta_{3,1}}{t_{dsb}} \right] \tag{11}$$

where t_s and t_{ds} = the time scale of the adsorption and desorption processes, respectively, for the water-suspended sediments system

A.4

t_{sb}, t_{dsb} = the time-scale of the adsorption and desorption process, respectively, for the water-bottom sediment system. $\delta_{1,p}$ and $\delta_{p,1}$ determine the direction of the contamination transfer and can be written

$$\delta_{1,p} \atop p\pm1 = \begin{cases} 1 & K_d C_i^1 > C_i^p \\ 0 & K_d C_i^1 < C_i^p \end{cases} \tag{12}$$

$$\delta_{p,1} \atop p\pm1 = \begin{cases} 1 & K_d C_i^1 < C_i^p \\ 0 & K_d C_i^1 > C_i^p \end{cases} \tag{13}$$

Note that C_i is used for $p = 1$, C_i^s for $p = 2$, and C_i^b for $p = 3$.

Equations (2) and (5)-(7) can be transformed to more appropriate forms for numerical solution by taking into account the equations of water and bottom sediment mass conservation, (1) and (4). Substituting them into these equations yields the following governing equations:

$$\frac{dS_i}{dt} = \frac{1}{V_i} \left[Q_{i-1} S_{i-1} - Q_* S_i + q_i^b - q_i^s + R_i^h + \sum_{j=1}^{m} Q_j^t S_j^t \right] \tag{14}$$

$$\frac{dC_i}{dt} = - \left[\lambda + \frac{Q_*}{V_i} + \frac{K_d}{V_i}(A_{1,2} + A_{1,3}) \right] C_i$$
$$+ \frac{1}{V_i} \left[\sum_{j=1}^{m_i} Q_j^t C_j^t + Q_{i-1} C_{i-1} + A_{1,2} C_1^s + A_{1,3} C_i^b \right] \tag{15}$$

$$\frac{dC_i^s}{dt} = \frac{1}{V_i S_i} \left\{ - \left[A_{1,2} + \kappa_i^h + q_i^b + Q_{i-1} S_{i-1} + \sum_{j=1}^{m}(Q_j S_j) + \lambda V_i S_i \right] C_i^s \right.$$
$$\left. + Q_{i-1} S_{i-1} C_{i-1}^s + R_i^h C_i^h + q_i^b C_i^b + \sum_{j=1}^{m} Q_j^t S_j^t C_j^{st} + A_{1,2} K_d C_i \right\} \tag{16}$$

$$\frac{dC_i^b}{dt} = \frac{1}{M_i^b}\left[-\left(A_{1,3} + q_i^s + \lambda M_i^b\right)C_i^b + q_i^s C_i^s + A_{1,3}K_dC_i\right]$$ (17)

where $Q_* = Q_{i-1} + R_i + \sum_{j=1}^{m} Q_j^t$

The radionuclide transport submodel contains six constants: λ, K_d, t_s, t_{ds}, t_{sb}, and t_{dsb}. The number of model constants can be reduced if the reversibility of the adsorption-desorption processes is considered, i.e., $t_s = t_{sb}$, $t_{ds} = t_{dsb}$.

The computer system WATOX includes a numerical procedure to solve equations (1) and (10)-(13). In the simulations for this study, WATOX used the 10-day-averaged hydrological and radiological data for the Dnieper reservoir system.

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