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Radioactive Contamination of the Techa River, South Urals, Russia

ABSTRACT

The Techa River Scenario is based on data from the Techa River area, Ural region, Russia. The main source of radioactive contamination of the Techa River is the Mayak Nuclear Materials Production Complex. During the period 1949-1952, about 10^{17} Bq of liquid radioactive wastes were discharged into the river system Techa-Iset'-Tobol-Irtysh-Ob'. The input data for the scenario include environmental parameters and estimates of discharges of ^{90}Sr and other radionuclides into the Techa River. Available test data include measurements of ^{90}Sr concentrations in water, sediments, and the floodplain downstream from the site of radionuclide discharge; measurements of ^{90}Sr and ^{137}Cs concentrations in local agricultural products and in fish; and estimates of doses to biota and to inhabitants of riparian settlements situated downstream along the Techa River.

INTRODUCTION

A number of factors have contributed to the radioactive contamination of the Techa River and the surrounding area (Table 1) (Nikipelov et al., 1990; Romanov, 1995; Kryshev et al., 1997; Sources, 1997):

- dumping of radioactivity from PA "Mayak" into the hydrosphere (1949-1956);
- the radiation accident at PA "Mayak" in 1957 (Kyshtym accident);
- wind resuspension of radionuclides from the banks of a reservoir for liquid radioactive wastes (Lake Karachai) in 1967; and
- current releases and dumping from PA "Mayak".

The main source of radioactive contamination of the Techa River, and the primary focus of this scenario, is the dumping of liquid radioactive wastes from the Mayak Nuclear Materials Production Complex (PA "Mayak"). This complex was put into operation in 1948. It incorporates uranium-graphite reactors for plutonium production and radiochemical facilities for its separation. The Mayak complex also reprocesses waste fuel from nuclear reactors. Since 1948, PA "Mayak" has released into the environment about 1.8×10^{17} Bq of radionuclides, and an area of 25,000 km^2 has been contaminated. About 3.7×10^{19} Bq of radioactive wastes, a source of potential radiation hazard, has been accumulated in the vicinity of PA "Mayak" (Romanov, 1995; Sources, 1997).

The input data for the scenario include environmental parameters and estimates of discharges of ^{90}Sr and other radionuclides into the Techa River. Available test data include measurements of ^{90}Sr concentrations in water, sediments, and the floodplain downstream from the site of radionuclide discharge; measurements of ^{90}Sr and ^{137}Cs concentrations in local agricultural products and in fish; and estimates of doses to biota and to inhabitants of riparian settlements situated downstream along the Techa River.

BACKGROUND

The main source of radioactive contamination of the Techa River is the Mayak Nuclear Materials Production Complex, located in the Chelyabinsk Region on the shore of Lake Irtyash, between the towns of Kyshtym and Kasly (Fig. 1).

In June of 1948, the first industrial nuclear reactor A for plutonium production was put into operation. The reactor was located near Lake Irtyash at a distance of about 1 km from Lake Kyzyltash, the waters of which were used for cooling the uranium-graphite reactor. The area of Lake Kyzyltash was 19 km^2, and the water volume was 83×10^6 m^3. The flowing variant of the reactor cooling was also used for the later industrial plutonium-graphite reactors constructed at the industrial complex “Mayak”.

Urgent testing of the plutonium production technology was accompanied by a number of technological accidents. This led to contamination of some water bodies with radionuclides up to levels substantially exceeding the sanitary permissible norms.

The other reactors were put into service as follows: AB-1 on 15 July 1950, AB-2 on 6 April 1951, AI on 22 December 1951, and AB-3 on 15 September 1952 (Kruglov, 1995). In 1949, a radiochemical plant for plutonium extraction from irradiated nuclear fuel was put into operation in PA “Mayak”. During 1987-1991, five of the reactors were put out of service.

In the period 1949-1952, about 10^{17} Bq of liquid radioactive wastes was discharged into the river system Techa-Iset’-Tobol-Irtysh-Ob’. About 95% of the activity entered into the Techa River during the period from March 1950 to November 1951. The average daily discharge during this period amounted to 1.5×10^{14} Bq d^{-1}, with the following radionuclide composition: ^{89}Sr, 8.8%; ^{90}Sr, 11.6%; ^{137}Cs, 12.2%; ^{95}Zr and ^{95}Nb, 13.6%; ^{103}Ru and ^{106}Ru, 25.9%; and isotopes of the rare-earth elements, 26.8%.

The Techa River is the right tributary of the Iset’ River, and in turn has several small tributaries, which usually dry up in summer. The original length of the Techa River is 243 km, and its drainage area is 7,600 km^2. The depth of the Techa River varies from 0.2-0.5 m to 3 m in backwaters, and its width is 15-20 m. The annual water flow rate at its mouth is 1-4 m^3 s^{-1}. The maximum water flow rates are observed in April.

In 1949, 39 riparian settlements were located on the banks of the Techa River area. The total population was 124,000. For the local population, the Techa River was the main (and sometimes, the only) source of household and drinking water supply. The population of riparian settlements was exposed both to external radiation due to the increased gamma radiation background near the river and to internal radiation from the mixture of radionuclides entering the human organism with water and food products.

Beginning in 1951, Lake Karachai was used for discharge of technological radioactive solutions. In the following five years, radioactive discharges to the Techa River system decreased drastically. In 1952 they amounted to 3.5×10^{14} Bq y^{-1}, and in the period from 1953 to 1956, to between 2×10^{13} and 8×10^{13} Bq y^{-1}. To reduce the radionuclide transport, a system of bypasses and industrial reservoirs for storage of low-activity liquid wastes was constructed in the upper reaches of the Techa River during the period 1956-1965.

A number of investigations have been carried out in the territory of the Techa River (Academy, 1991; Aarkrog et al., 2000; Akleev et al., 2000; Akleyev and Kisselyov, 2002; Burkart et al., 1997; Cabianca et al., 2000; Chesnokov et al., 2000; Chumichev and Dem'yanchenko, 1993; Degteva et al., 1994; 1996; 1998; 2000a; 2000b; Ilyin and Gubanov, 2001; Kossenko and Degteva, 1994; Kossenko, 1996; Kozheurov and Degteva, 1994; Kryshev, 1996a; 1996b; 1997; Kryshev et al., 1996; 1997; 1998a; 1998b; Kryshev and Ryazantsev, 2000; Makhon'ko, 1993-1998; Martyushov et al., 1997; Mokrov, 1996; 2002; Mokrov et al., 2000; Sources, 1997; Trapeznikov et al., 1993; Vorobiova et al., 1999; Winkelmann et al., 1998). The results of these investigations have been used for the development of this Scenario.

INPUT INFORMATION

Hydrological information

The catchment area of the Techa River is located to the west of the Ural range of mountains. The surface of the catchment area is a weakly elevated plain with lots of lakes and bogs. The most abundant soils in the catchment area are gray forest soils and leached chernozems. Boggy peat and meadow soils are dominant in the waterlogged plots. The climate is continental, with considerable variations in the air temperature. Winters are cold and last about 6 months; summers are hot and last about 3 months. The average annual rainfall is 420 mm y^{-1}, of which nearly half (up to 200 mm) falls in summer months and about 15% in winter (Sources, 1997; Kryshev et al., 1997).

The Techa River is part of the hydrological system Techa-Iset'-Tobol-Irtysh-Ob', which belongs to the Kara Sea basin. Prior to operation of the Mayak Nuclear Materials Production Complex, the Techa River flowed out of Lake Irtyash and then through Lake Kyzyltash, downstream of which the Mishelyak River flowed into it (Fig. 1). Following the commissioning of the Mayak complex, the upper reaches of the Techa River were considerably affected due to the construction of a system of industrial water bodies and bypass canals (Fig. 2). At present, a tail reach of the dam of water body 11 must be taken as the source of the Techa River. The Techa River is the right tributary of the Iset' River (Fig. 3).

The channel water flow from the Kasli-Irtyash lake system occurs through the Techa River. It has several tributaries, which are shallow and can dry up in summer (with the exception of the Mishelyak and Zyuzelga Rivers). The Techa River is 243 km long, and its catchment area is 7600 km^2. The river depth varies from 0.5 m to 2 m, and its width is, on the average, 15-30 m. Some reaches of the Techa River are frozen through to the bottom in cold winters. The average water flow at the river mouth is about 7 m^3 s^{-1}. The maximum water flow is observed in April, amounting, on the average, to 29 m^3 s^{-1} in the river mouth. In April 1951, the average water flow for the month was 60 m^3 s^{-1}. In its hydrochemical regime, the Techa River belongs to the bicarbonate-calcium type. The main hydrological and hydrochemical parameters of the Techa River are presented in Tables 2-4 (Resources, 1973; Trapeznikov et al., 1993; Sources, 1997; Kryshev, 1997).

Waste waters from the radiochemical plant were discharged to Koksharovsky pond (water body R-3), located at a distance of about 1.5 km from the site of discharges. Contaminated water from this pond entered Metlinsky pond (water body R-4) and then the Techa River through the dam locks of water body 4.

For modelling purposes, the Techa River can be divided in four “segments”:

1. Koksharovsky pond (Reservoir R-3), site of discharge of radionuclides;
2. Metlinsky pond (Reservoir R-4);
3. The upper part of the Techa River (upstream of the village of Muslyumovo); and
4. The middle and lower parts of the river (downstream of the village of Muslyumovo).

The upper part of the river channel (upstream of the village of Muslyumovo) is heavily overgrown with aquatic plants. The river channel is meandering. The river width amounts to 30 m, and its depth varies from 0.5 m to 2 m. The current is slow. Peat-silt and clay deposits prevail in bottom sediments. The bogs stretch along the river channel. The most waterlogged parts of the floodplain (Asanov bogs) are located near the inflow of the Zuzelga River and in front of the village of Muslyumovo. The width of the waterlogged floodplain varies from 300 m to 1 km. The central part of the floodplain is formed of peat-bog soils, and its edges, of soddy meadow soils. The peat layer depth varies from 0.1 m to 3 m. The underlying grounds for peat are primarily clay and loam. Physical-chemical characteristics of the floodplain soils and bottom sediments are given in Tables 5 and 6 (Kryshev et al., 1997). There are small lakes in the floodplain, which are connected to the river by brooks. In flood periods the bogs are watered considerably.

In the middle and lower reaches of the river (downstream of the village of Muslyumovo), the banks of the Techa River are steep, and its channel is well defined. The river width is, on the average, 20 m, and its depth is 0.5-1 m. The floodplain is weakly waterlogged. In the middle reaches of the river, the floodplain width decreases to a few tens of meters, whereas near the mouth of the river it extends to 3 km. The dry floodplain is formed primarily of soddy meadow soils. The river bed is covered in sand and silt or sand and gravel. Rapids and sandbars occur frequently. The flow velocity is 0.3-0.8 m s^{-1}. The time that it takes for water to pass along the river from its source to its mouth is about 8 days.

Radioactive contamination of the Techa River

Radioactive discharges to the Techa River

Since March 1949, waste waters from the radiochemical plant have been discharged to the Techa River. The site of discharge into the Techa River was at a distance 200 m downstream from Lake Kyzyltash, and the contaminated waters flowed through Kaksharovsky and Metlinsky ponds (water bodies R-3 and R-4). The nearest riparian settlement (Metlino) was located at a distance of 7 km from the site of discharge. The scheme of the upper reaches of the Techa River in 1949-1951 is shown in Fig. 2a.

The main sources of radioactive contamination of the Techa River were discharges of radionuclides during the period 1949-1956 (Table 7). During this period, about 10^{17} Bq of radionuclides entered the river ecosystem, including 1.2×10^{16} Bq of ^{90}Sr and 1.3×10^{16} Bq of ^{137}Cs (Degteva et al., 1994; Kryshev et al., 1997; 1998a; 1998b; Sources, 1997; Ilyin and Gubanov, 2001; Mokrov, 2002). The total volume of radioactive discharges was about 76,000,000 m^3. Alpha releases were relatively low, amounting to about 2 TBq, including both plutonium and uranium isotopes (Sources, 1997).

During the period of the most intensive discharges, from March 1950 to November 1951, the radionuclide composition was as follows: ^{89}Sr, 8.8%; ^{90}Sr, 11.6%; ^{137}Cs, 12.2%; ^{95}Zr and ^{95}Nb, 13.6%; ^{103}Ru and ^{106}Ru, 25.9%; and other isotopes, 27.9%.

Three time periods with different intensities of discharges can be distinguished within the period 1949-1956:

- January-November 1949, with a total discharge of beta-emitters of 1.85×10^{15} Bq. The contributions of ^{90}Sr and ^{137}Cs to the activity of the discharges were about 4% and 11%, respectively.
- December 1949-November 1951, with a maximum activity of discharges of about 10^{17} Bq for total beta-emitters. The contributions of ^{90}Sr and ^{137}Cs to the activity of the discharges were 12-15% and 12-21%, respectively.
- December 1951-December 1956, with the total activity of discharges of beta-emitting nuclides decreased considerably to 5.2×10^{14} Bq. The contributions of ^{90}Sr and ^{137}Cs to the activity of the discharges were 17-38% and 4-15%, respectively (Sources, 1997; Kryshev et al., 1997).

Estimates of the radionuclide discharges into the Techa River are given in Table 7 (Sources, 1997; Kryshev et al., 1997; Ilyin and Gubanov, 2001).

Exposure of the population

In 1949, 39 riparian settlements were located on the banks of the Techa River area (Fig. 4; Table 8). The total population was 124,000. For the local population, the Techa River was the main (and sometimes, the only) source of household and drinking water supply. There were few wells in the area, and only part of the population used them for limited purposes, because the well water was not as good to taste as the river water. The Techa River was used for watering of cattle, breeding of waterfowl, irrigation of agricultural crops, catching of fish, swimming and bathing, laundering, etc.

An extraordinarily powerful flood in April to May 1951 led to the radioactive contamination of the land adjacent to the river. The floodplain areas were used by inhabitants of the riparian settlements for cattle-breeding and making hay. Up to this point, radionuclides had been ingested mainly with water, but after 1951, contaminated food began to play a role, especially milk and vegetables from flooded kitchen gardens.

During the summer of 1951, a radiation survey of all areas adjacent to PA "Mayak" found that the Techa River bed and floodplain were highly contaminated with radionuclides. This led to an enhanced radiation impact on the population residing on the banks, especially in the upper reaches of the river. Some riparian settlements located in the upper reaches of the Techa River were evacuated in 1953-1956.

In 1953, use of the Techa River for all household and drinking needs was officially banned, as well as the catching of fish, breeding of waterfowl, and bathing. The most contaminated part of the floodplain was removed from land utilization. Simultaneously, the digging of wells was initiated, but this was carried out off and on. By the end of 1954, all population and livestock on the banks of the Techa River were provided with water from underground sources. However, the consumption of river water and the use of the Techa River for other household purposes continued, although on a smaller scale, even after a special "river police" was set up in 1956.

As is evident from the description of the radiation situation, the population of the riparian settlements was exposed both to external radiation due to the increased gamma radiation background near the river and to internal radiation from the mixture of radionuclides entering the human organism with water and food products. The main nuclides responsible for the internal exposure of the population living on the shore of the Techa River are ^{90}Sr and ^{137}Cs. Estimated values of dietary parameters (1996 estimates) are provided in Table 9 (Kryshev et al., 1998a; Cabianca et al., 2000).

Countermeasures

Construction of a complex of hydraulic structures

During the initial period of operation of the Mayak complex, radioactive wastes were discharged to the Techa River. Lake Kyzyltash (water body R-2) was used as a cooling pond to cool plutonium-producing reactors. Waste waters from the radiochemical plant were discharged to Koksharovsky pond (water body R-3), located at a distance of about 1.5 km from the site of the discharges. Contaminated water from this pond entered Metlinsky pond (water body R-4) and then the Techa River through the dam locks of water body R-4 (Figs. 1-2).

Water bodies R-3 and R-4 were settling reservoirs for water contaminated by radionuclides, which remained there for a few days. Due to radioactive decay and sorption of radionuclides on suspended matter and in bottom sediments, the water activity decreased by a factor of ten or more by the time of its intake to the Techa River. At the same time, as the river water activity decreased, there was a redistribution of relative contributions of various radionuclides to the total activity of the mixture. About 70% of ^{90}Sr, 80-90% of ^{89}Sr, ^{103}Ru, ^{106}Ru, ^{137}Cs, ^{140}Ba, ^{141}Ce and ^{144}Ce, as well as 98-99% of ^{95}Zr and ^{95}Nb settled in the bottom sediments of water bodies R-3 and R-4 (Sources, 1997). However, the part of the activity that did not settle in water bodies R-3 and R-4 turned out to be sufficient for intensive contamination of the Techa and Iset' rivers.

By their migration characteristics, ^{95}Zr and ^{95}Nb are the least transportable of these radionuclides. They settled practically entirely in the bottom sediments and floodplain of the Techa River within 10-20 km of the source of discharges. The radionuclides ^{103}Ru, ^{106}Ru, ^{140}Ba, ^{141}Ce and ^{144}Ce also have a weak migration capacity and settled for the most part near the source of discharges, whereas ^{137}Cs is more mobile and spread over a long distance from the site of discharges. Strontium-90 typically has the greatest migration capacity. Its concentration in the Techa River mouth decreased only a factor of 3-5, in spite of increased river flow.

Among the factors responsible for spreading radioactive contamination to the floodplain were unusually high floods in the springs of 1950 and 1951. Concurrency of the discharges of industrial waste waters and the flooding of vast areas played a fateful role in radioactive contamination of the floodplain lands in the upper reach of the river, especially in the area of the Asanov bogs, where radionuclides were deposited for many years.

In 1951, repositories of the radiochemical plant were filled with high-activity wastes, and use of the internal-drainage Lake Karachai (water body R-9) for discharge of technological radioactive solutions was begun. In the following five years, radioactive discharges to the Techa River system decreased drastically. In 1952, they amounted to 3.5×10^{14} Bq y^{-1}, and during the period from 1953 to 1956, to between 2×10^{13} and 8×10^{13} Bq y^{-1}.

To reduce the radionuclide transport, a system of bypasses and industrial reservoirs for storage of low-activity liquid wastes was constructed in the upper reaches of the Techa River during the period 1956-1965 (Figs. 1, 2b). In addition to the already existing reservoirs R-3 and R-4, in 1956 the Techa River was dammed in the vicinity of the village of Asanovo, and reservoir R-10, with an area of 18.6 km^2, was constructed (Fig. 2b). As a consequence, the release of radioactive substances into the river decreased to 2×10^{10} Bq d^{-1} (7.3×10^{12} Bq y^{-1}).

In 1963, reservoir R-11, with an area of 48.5 km^2, was constructed immediately adjacent to reservoir R-10 to form the end of the cascade of industrial reservoirs. The construction of the left-bank and right-bank bypasses for interception of surface runoff was completed in this period. The total volume of the cascade of technological water bodies is 400×10^6 m^3. The annual water filtration from reservoir R-11 to the Techa River is about 10×10^6 m^3 y^{-1}.

Current sources of radionuclide input to the Techa River

Filtration through dam 11

As mentioned above, a system of industrial water bodies is used for the storage of liquid low-level wastes. Water bodies R-10 and R-11 from the construction of dams, together with water bodies R-2, R-3 and R-4, have a radioactivity level of about 1.2×10^{16} Bq (Table 10; Sources, 1997). The concentration of ^{90}Sr in the water of water body R-11 is about 2.2 kBq L^{-1} (Sources, 1997). The dam of water body R-11 does not completely prevent the filtration of contaminated water from the water body. During the period 1984-1994, the runoff of ^{90}Sr as a result of filtration through dam R-11 was, on the average, 1.4×10^{10} Bq y^{-1} (Table 11; Mokrov, 1996).

Runoff from the waterlogged floodplain

Downstream of the dam of water body R-11 are the Asanov bogs, with an area of about 30 km^2 contaminated with ^{90}Sr and ^{137}Cs. These bogs are a source of input of radionuclides to the Techa River.

Assessments have indicated that, in the period of intensive discharges of radionuclides (1949-1956), about 10^{16} Bq of the mixture of radionuclides settled in the river bed in the upper reaches of the Techa River between the villages of Metlino (dam 4) and Muslyumovo. Of this amount, 2.5×10^{15} Bq were accounted for by ^{90}Sr, and 1.3×10^{15} Bq by ^{137}Cs. More recent assessments (1962-1965) have indicated that the floodplain of the upper reaches of the Techa River from dam 11 to Muslyumovo contained 2.7×10^{14} Bq of ^{90}Sr and 3.5×10^{14} Bq of ^{137}Cs. In this case, only 7.4×10^{11} Bq of ^{90}Sr and 7.4×10^{12} Bq of ^{137}Cs were in bottom sediments of the upper reaches of the Techa River (Sources, 1997).

At present, the inventory of ^{90}Sr in the waterlogged floodplain of the upper reaches of the Techa River (dam 11 to Muslyumovo) is estimated to lie between 3.6×10^{13} and 4.4×10^{13} Bq, and the inventory of ^{137}Cs between 1.9×10^{14} and 2.3×10^{14} Bq. The ^{90}Sr runoff from the waterlogged floodplain was estimated to lie between 1.4×10^{12} and 1.7×10^{12} Bq $year^{-1}$ (Sources, 1997). The inventory of radionuclides deposited in the floodplain in the middle and lower reaches of the

Techa River (downstream of Muslyumovo) is 10-100 times lower than in the waterlogged floodplain (Mokrov, 1996).

Runoff through bypass canals

At present, the tail reach of the dam of water body 11 should be treated as the source of the Techa River (Fig. 2). The bypass canals were constructed to regulate the runoff from the catchment area. The water runoff from the Kasli-Irtyash system of lakes to the Techa River occurs through the left-bank canal constructed in 1963. The runoff of the Mishelyak River occurs now through the right-bank canal constructed in 1972. The water entering the Techa River through the bypass canals is contaminated with radionuclides (Mokrov, 1996). In the period 1984-1994, the average annual input of ^{90}Sr to the upper reaches of the Techa River through the bypass canals was 6.4×10^{11} Bq y^{-1}. Contamination of the left-bank canal was caused by filtration of water from water body R-10, in which the water level is higher than in the canal. The main source of contamination of the right-bank canal is the input of radionuclides with water runoff from the surface of the catchment area.

So, at the present time, the main sources of radionuclide intake to the Techa River are the transport of ^{90}Sr through bypasses and the Asanov swamps. In the period 1981-1994, about 6×10^{11} Bq $year^{-1}$ of ^{90}Sr, on average, entered the Techa River through the bypasses. The contribution of washout from the catchment area of the swamped upper reaches of the river is lower by approximately one order of magnitude.

DATA FOR MODEL TESTING

Materials and methods

Measurements of radioactive contamination of the Techa River started at the same time as release control (July 1951). The methods that were used to perform the measurements have been published by Gusev et al. (1959) and Vorobiova et al. (1999). The most common technique for the measurement of activity of beta-nuclides was the use of an end-window counter that was calibrated with an uranium-oxide standard. In order to subtract the influence of gamma rays, measurements were made with and without a 2,000 mg cm^{-2} aluminum filter that was judged sufficient to absorb all beta particles. Total activity of gamma-nuclides was measured by a gas-flow counter that was placed inside a lead shield. Filters of 1.6 mm Al and 5 mm Pb were used. The count rate of samples was compared with that from a ^{60}Co source, which had been calibrated against a radium standard. The historical methods of radiochemical separation and analysis were sufficient to permit the measurements of ^{90}Sr, ^{137}Cs and some other radionuclides.

At present, standard methods are used for sample collection and analysis in investigations of the environmental contamination (Marey and Zykova, 1980; Vakulovsky, 1986; Makhon'ko, 1990). The volumes of water samples for radionuclide analysis were 10-20 liters.

The activity of ^{137}Cs was determined by standard gamma spectrometric methods using highly sensitive semiconductor detectors and multichannel pulse analyzers. Measuring errors did not exceed 20%. The activity of ^{90}Sr was determined by radiochemical methods from the daughter nuclide ^{90}Y using a low-background beta radiometer. Relative measuring error did not exceed 15%.

Radioactive contamination of the river ecosystem

Dynamics of radioactive contamination of the river water

As mentioned above, the main sources of radioactive contamination of the Techa River were discharges of radionuclides in the period 1949-1956. In 1951, the average total activity of water was 10^6 Bq L^{-1} in water body R-3 and 3.7×10^5 Bq L^{-1} in water body R-4 (Fig. 1). In this case, the activity of ^{90}Sr in the settling water bodies was 60-170 kBq L^{-1} and of ^{137}Cs, 90-100 kBq L^{-1}. The specific activity of the river water decreased with distance from the source of discharges and was 2.6×10^4 Bq L^{-1} in the Techa River mouth, i.e., approximately 40 times lower than in water body R-3. In 1951, the specific activity of ^{90}Sr in the Techa River mouth was 11 kBq L^{-1} and that of ^{137}Cs, 0.6 kBq L^{-1}. At a distance of about 200 km between water body R-4 and the river mouth, the river water contamination with ^{137}Cs decreased by a factor of about 150 and with ^{90}Sr, by a factor of only about 5 (Kryshev et al., 1997; 1998a; Sources, 1997).

Subsequently, the specific activity of the river water decreased with time, as the intensity of discharges was reduced. In the period 1951-1956, the contributions to the total activity of the river water were 25-50% due to ^{90}Sr and 2-16% due to ^{137}Cs. In ensuing years, the contribution to the total activity of the river water due to ^{90}Sr increased, whereas the concentration of ^{137}Cs in the river water decreased considerably.

The highest concentrations of ^{90}Sr in the river water were observed in 1950-1951 (Kryshev et al., 1997; 1998a; Ilyin and Gubanov, 2001). In 1951, the concentration of ^{90}Sr in the river water near the village of Muslyumovo at a distance of 78 km from the site of discharges was 27 kBq L^{-1}, and the concentration of ^{137}Cs was 7.5 kBq L^{-1}. Subsequently, the activity of these radionuclides in water decreased considerably. By the early 1980s, the concentration of ^{90}Sr in water decreased by a factor of approximately 10^3, as compared to the year 1951. In the period 1991-1997, the average annual concentration of ^{90}Sr in the river water varied from 6 to 26 Bq L^{-1} and was much higher than the background concentration. There was no tendency for a decrease in the activity of ^{90}Sr in water with time. In 1995, for example, radioactive contamination of the Techa River water near the village of Muslyumovo was higher by a factor of 1.5-2.7 than in 1994 (Makhon'ko, 1996). According to the observed data, the concentration of ^{90}Sr in the river water near the village of Muslyumovo was somewhat higher than in the lower reaches and the mouth of the Techa River. The concentration of ^{137}Cs in the river water was 30-90 times lower than the concentration of ^{90}Sr. The concentration of $^{239,240}Pu$ in the Techa River water was 0.004-0.019 Bq L^{-1}, which is 300-1200 times lower than the current standards.

Radioactive contamination of the bottom sediments and river floodplain

According to the observed data, the bottom sediments of settling water bodies R-3 and R-4 and the upper reaches of the Techa River (Fig. 2) are the most highly radioactively contaminated areas. In 1952-1953, the specific activity of bottom sediments in the upper reaches of the Techa River was as high as 2.5×10^4 kBq kg^{-1}. In this period, the activity of bottom sediments in the lower reaches of the Techa River was approximately 100 times lower. Major contributions to the activity of bottom sediments in the upper reaches of the Techa River were due to ^{137}Cs, ^{103}Ru, ^{106}Ru and the isotopes of rare-earth elements, whereas the contribution due to ^{90}Sr was relatively small. However, with distance from the site of discharges, the contribution to the activity of bottom sediments due to ^{90}Sr increased noticeably, whereas that due to ^{137}Cs decreased. On the whole, it may be concluded that the desorption washout of ^{90}Sr from the river bed and its downstream transport play an important role (Sources, 1997). In the period 1956-1961, the specific activity of bottom sediments decreased by approximately an order of magnitude, with increasing contributions due to the long-lived radionuclides ^{90}Sr and ^{137}Cs.

The floodplain in the upper reaches of the Techa River (from dam 11 to the village of Muslyumovo), which is part of a flat waterlogged plain, is most highly contaminated (Fig. 1). As the water level rises in the period of seasonal floods, the river spills over its banks, flooding the adjacent lands. The total area of contaminated floodplain lands removed from agricultural utilization is about 28 km^2. Of this area, bogs account for 51%, meadows for 35%, and forests and bushes for 14% (Martyushov et al., 1997).

Increased sorption properties of boggy floodplain soils and bottom grounds make them long-term sources of secondary contamination of the Techa River ecosystem. Radioactive contamination of the floodplain has a mosaic character, which is partly related to special features of the surface relief. In low-lying waterlogged plots, the contamination levels, as a rule, are higher than in elevated plots. The contamination levels of the floodplain vary from background values to values exceeding background by a factor of 10^3-10^4. The maximum contamination levels of the floodplain in the area of the Asanov bogs are as high as 42,000 kBq m^{-2} (1135 Ci km^{-2}) for ^{137}Cs and 10,000 kBq m^{-2} (270 Ci km^{-2}) for ^{90}Sr. There is a tendency for the soil contamination levels to decrease with distance from dam 11 in the downstream direction and from the river channel in the transverse direction. The decrease in the soil contamination levels in the transverse direction towards the floodplain boundary is more pronounced than that with distance from the dam. The maximum contamination levels are observed in the channel-side part of the floodplain within 50-100 m of the river channel. The vertical distribution of radionuclides in the floodplain soil is determined by their migration properties, as well as by physical and chemical characteristics of the soil. The migration capacity of radionuclides increases with increasing degree of the soil watering. In this case, ^{90}Sr is the most mobile radionuclide. Depending on watering, its content in the top 1-10 cm soil layer varies from 74% in normally watered soils to 24% in constantly flooded soils (Martyushov et al., 1997). Similar results were obtained for the floodplain of the middle and lower reaches of the Techa River (Molchanova et al., 1994).

The sorption of ^{137}Cs by bottom grounds leads to more considerable reduction in the radioactive contamination levels of the river water than is the case for ^{90}Sr. As a result, the Techa River mouth is contaminated with more mobile (from a migration standpoint) ^{90}Sr to a greater extent than with ^{137}Cs. Herbaceous and woody plants in the upper floodplain of the Techa River are contaminated for the most part with ^{90}Sr and ^{137}Cs at levels of 0.1-7 kBq kg^{-1}, as also are soils.

Radioactive contamination of the floodplain downstream of the village of Muslyumovo is characterized by considerable nonuniformity. The range of variation of the river floodplain contamination density is 30-6100 kBq m^{-2} for ^{90}Sr, 30-5600 kBq m^{-2} for ^{137}Cs, and 0.4-4.1 kBq m^{-2} for $^{239,240}Pu$. As the distance from the source of discharges increases, the floodplain contamination density decreases, remaining, however, higher than the regional background.

Contamination of local agricultural and natural products

The needs of the rural population living in the Techa River basin with respect to staple food products (potatoes, milk, meat and vegetables) are met almost completely by local products. At present, the consumption of local food products is one of the main sources of additional exposure to the population. For 1991-1994, the specific activity of ^{90}Sr in milk, beef and potatoes was, on the average, 1.5, 0.3 and 0.8 Bq kg^{-1}, respectively, whereas that of ^{137}Cs was somewhat higher (5.3, 34 and 4.1 Bq kg^{-1}, respectively; Sources, 1997; Kryshev et al., 1998a; 1998b). Note that the contamination levels of milk and potatoes in private farms are, as a rule, higher than in collective farms (Burkart et al., 1997). Maximum contamination levels exceed average levels by approximately an order of magnitude. In addition, increased radioactive contamination levels are typical of some natural products (waterfowl and fish).

Dose estimates

Doses to biota were estimated from the observed data, using the methods described by the IAEA (1976). Internal exposure from incorporated radionuclides and external exposure from the environmental components were estimated, taking into account differences in the behaviour and dosimetric parameters of the parent and daughter nuclides, and the buildup factor of scattered gamma-quantum radiation (Kryshev and Sazykina, 1990). The highest estimated doses to aquatic organisms were obtained for the upper reaches of the Techa River during the period of maximum discharges of radionuclides (1950-1951). In this period, the internal dose rates in Metlinsky pond (water body R-4) were as high as 0.01 Gy d^{-1} for phytoplankton, 0.03 Gy d^{-1} for zooplankton, 0.3 Gy d^{-1} for macrophytes, 0.4 Gy d^{-1} for mollusks and 0.09 Gy d^{-1} for fish (Kryshev et al., 1997; Kryshev and Ryazantsev, 2000).

The main dose-forming nuclides for mollusks were $^{89,90}Sr$, ^{106}Ru and ^{144}Ce, and for fish, $^{89,90}Sr$ and ^{137}Cs. The doses to aquatic biota decreased noticeably with distance from the site of discharges. However, even in the river mouth they were considerably (10^2-10^3 times) higher than the natural background. After the cessation of intensive radioactive discharges and the construction of a system of protective water bodies in the upper reaches of the Techa River, the doses to aquatic biota noticeably decreased. This decrease occurred essentially along the whole length of the river, with the exception of industrial water bodies R-3, R-4, R-10 and R-11.

Current levels of exposure to aquatic organisms in the Techa River are 1-50 mGy y^{-1}, i.e., within the range of low doses (Kryshev et al., 1997; 1998a; 1998b). At the same time, doses to aquatic biota in the industrial settling water bodies still remain higher than in the river. For example, doses to fish from incorporated radionuclides in water bodies R-3 and R-4 may be as high as 5-7 Gy y^{-1}. Doses to fish in water body R-10 are somewhat lower and amount to 2-4 Gy y^{-1} (Kryshev and Sazykina, 1998). The frequency of deformities in the posterity of pike (*Esox lucius*) dwelling in water body R-10 under chronic exposure was found to be approximately 10 times higher than in the control (Lake Alabuga). The observed types of deformities were the following: absence of yolk sac, absence of fin edging, body depigmentation, and absence of eyes. The total frequency of anomalies in the posterity of pike from water body B-10 was about 13-30%, as compared with 1.1% in the control (Pitkyanen, 1978; Smagin, 1996). At the same time, it has been shown that chronic exposure under conditions of water body R-10 does not lead to radiation injuries of the pike population. A comparative analysis of doses to the population and biota shows that in all cases, doses to natural biota were considerably (over 10-100 times) higher than doses to humans (Kryshev and Sazykina, 1996; Kryshev et al., 1998a; 1998b). This difference is most noticeably manifest for the period of increased radioactive discharges in 1950-1951.

Doses to the human population were estimated by the procedure described by the EPA (1988), Drozhko et al. (1993), and the IAEA (1996). This procedure takes into account the following main factors of the dose formation: external exposure from radionuclides on the soil surface and plant cover; internal exposure from inhalation of radionuclides; and internal exposure from ingestion of radionuclides with food. External doses in the Techa River basin were calculated from measured gamma radiation dose rates near the waterline and in the streets, dwellings and personal plots. Using these data, the average annual dose rates were estimated at sites typical for the residents in various villages on the Techa River. About 95% of the total external dose to the rural population was shown to have been accumulated in the period 1950-1956, when dose rates in the floodplain were the highest (Degteva et al., 1994; Drozhko et al., 1993). Additional information for dose assessment for the human population is presented in the Tables 12-15 (Degteva et al., 1994, 2000a; 2000b; Kozheurov and Degteva, 1994).

SUMMARY OF TEST DATA AND DOSE ESTIMATES

Measured concentrations of radionuclides (^{90}Sr, ^{137}Cs, ^{95}Zr, ^{106}Ru) in the river water during the period 1951-1956 are presented in Table 16. Annual average concentrations (measured and modelled) of ^{90}Sr in Techa River water from 1949 to 1994 are given in Table 17. Tables 18 and 19 present data on the specific activity and radionuclide composition of bottom sediments of the Techa River for specified time periods. Concentrations of ^{90}Sr and ^{137}Cs in various components of the floodplain ecosystem are provided in Table 20 for the Asanov bogs during the period 1991-1994. Radionuclide concentrations in the floodplain at different locations in 1991 are given in Table 21.

Average data for 1991-1994 on the content of radionuclides in local agricultural products, waterfowl and fish are given in Table 22. Table 23 compares radionuclide concentrations in river water, sediment, floodplain soil, fish, and milk at Muslyumovo in 1992-1993. Concentrations of ^{90}Sr and ^{137}Cs in fish from the Techa River in 1977-1993 are given in Table 24.

Estimated internal doses to biota in the Techa River in 1950-1951 are shown in Table 25. Comparisons of estimated external dose rates to biota and humans are given in Table 26 for 1950-1951 and 1992. Estimated external doses for inhabitants of selected locations along the river are provided in Table 27, and estimated average absorbed doses (external plus internal) for selected organs are provided in Table 28 for inhabitants of several locations.

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TABLES OF INPUT DATA

Table 1. Parameters of radioactive contamination of the Urals (Nikipelov et al., 1990; Academy of Science, 1991; Sources, 1997; Kryshev et al., 1997; 1998b; Ilyin and Gubanov, 2001).

Contaminated area	Time period	Pathway of contamination	Activity (Bq)	Radionuclide composition (%)	
Techa River	1949-1956	Aquatic	10^{17}	^{89}Sr	8 (1-12)
				$^{90}Sr + {}^{90}Y$	21 (8-42)
				^{137}Cs	11 (8-18)
				$^{95}Zr + {}^{95}Nb$	12 (8-24)
				$^{103}Ru + {}^{106}Ru$	24 (12-51)
				U + Pu	2
				Others [a]	22 (13-27)
Eastern Ural radioactive trace resulting from the Kyshtym accident	1957	Aerial	7.4×10^{16}	$^{90}Sr + {}^{90}Y$	5.4
				$^{95}Zr + {}^{95}Nb$	24.9
				$^{106}Ru + {}^{106}Rh$	3.7
				^{137}Cs	0.036-0.35
				$^{144}Ce + {}^{144}Pr$	65.96
Wind resuspension from the banks of Lake Karachai	1967	Aerial	2.2×10^{13}	$^{90}Sr + {}^{90}Y$	34
				^{137}Cs	48
				$^{144}Ce + {}^{144}Pr$	18

[a] Other radionuclides include primarily ^{91}Y, ^{140}Ba, ^{141}Ce, and ^{144}Ce.

Table 2. Hydrological characteristics of the Techa River (Resources, 1973; Trapeznikov et al., 1993; Kryshev, 1997; Sources, 1997).

Parameter	Segment 1	Segment 2	Segment 3	Segment 4
Length (km)	-	-	71	168
Average width (m)	-	-	20	23
Average depth (m)	1.0	3.1	1.2	1.0
Surface area (m^2)	8×10^5	1.3×10^6	-	-
Surface of catchment (km^2)	-	-	3.7×10^3	7.6×10^3
Annual water flow ($m^3\ s^{-1}$)	-	0.7	2.0	7.0
Spring water flow ($m^3\ s^{-1}$)	-	3.0	9.0	31
Annual sediment transport (kg s^{-1})	-	0.11	0.33	2.0
Spring sediment transport (kg s^{-1})	-	1.0	3.0	20

Table 3. Annual and monthly water flow and sediment transport in the Techa River (Kryshev, 1997).

Months:	1	2	3	4	5	6	7	8	9	10	11	12
Segment 3, water flow, $m^3 s^{-1}$												
Average	1.1	1.0	1.4	9.0	3.6	1.9	1.2	1.5	1.0	1.2	0.9	0.8
1950	-	-	-	-	3.6	1.6	1.3	1.5	2.6	2.2	1.9	1.7
1951	1.5	1.4	1.4	33	7.6	6.4	3.8	5.6	5.4	4.0	1.6	1.3
1952	1.8	1.6	2.0	11.8	6.7	1.6	1.4	1.8	2.0	1.2	0.3	0.2
1953	0.4	0.5	0.6	11.7	3.1	1.6	0.7	0.8	0.7	0.7	0.2	0.2
1954	0.2	0.2	0.2	10.1	3.4	1.7	0.5	0.3	0.5	0.7	-	-
Segment 4, water flow, $m^3 s^{-1}$												
Average	2.0	2.1	2.3	31	14	7.1	4.1	4.9	4.6	5.4	4.0	2.0
1949	1.4	1.5	1.7	25.6	15.6	5.6	3.7	3.5	3.8	3.4	3.0	1.1
1950	1.3	1.5	1.1	16.3	5.9	3.5	3.0	3.2	5.6	5.2	2.9	1.7
1951	1.9	1.7	1.9	60.4	12.4	9.2	5.4	6.5	5.9	5.3	2.1	1.5
1952	1.4	1.2	1.5	19.3	10.3	2.9	2.3	2.5	3.0	2.3	0.9	0.7
1953	0.6	0.7	1.2	17.7	4.3	2.3	1.8	1.5	1.7	1.6	0.6	0.6
1954	0.6	0.5	0.6	17.2	5.0	2.5	1.0	1.0	1.3	1.4	1.2	0.9
Segment 4, sediment transport, $g s^{-1}$												
Average	30	30	40	19,900	1,900	680	890	220	130	180	160	50

Table 4. Hydrochemical characteristics of the Techa River (Trapeznikov et al., 1993; Kryshev, 1997).

Parameter	Segment 1	Segment 2	Segment 3	Segment 4
pH	6.7-8.6	4.8-6.9	7.3	7.3
Ca^{2+} (mg L^{-1})	46-150	72-215	53	53
Mg^{2+} (mg L^{-1})	40-470	44-95	22	27
Na^{+} + K^{+} (mg L^{-1})	-	-	22	24
Turbidity (g m^{-3})	-	-	-	200

Table 5. Physical-chemical characteristics of soils in the Techa River floodplain (Kryshev et al., 1997).

Parameter	Peat-bog soil	Soddy meadow soil	Alluvial soil
Layer depth (cm)	35	30	30
Specific density (kg m^{-3})	1600-2100	2600	2700
Water content (%)	58-93	12-39	10-32
pH of aqueous extract	6.7	6.6	6.8
Humus (%)	60-90	10-40	1.5-20
Exchangeable cations (mg-equiv. per 100 g dry basis)			
Ca^{2+}	125	24	11
Sr^{2+}	0.34	0.1	0.06
Mg^{2+}	27	9.3	4.7
Na^{+}	2.9	1.3	1.2
K^{+}	0.56	1.3	1.0

Table 6. Physical-chemical characteristics of bottom sediments of the Techa River (Kryshev et al., 1997).

Parameter	Peat	Silt	Sandy Silt	Sand
Layer depth (cm)	50	5	50	5
Specific density (kg m^{-3})	2100-2200	2100	2200-2600	2600
Water content (%)	19-28	33	35-40	20
pH of aqueous extract	6.7	6.6	6.5	6.8
Humus (%)	22-60	5-30	0.25-0.75	0.07-0.35
Exchangeable cations (mg-equiv. per 100 g dry basis)				
Ca^{2+}	28	7.9	14	7.8
Sr^{2+}	0.06	0.05	0.03	0.01
Mg^{2+}	8.7	2.6	3.2	2.1
Na^{+}	0.58	0.43	0.35	0.25
K^{+}	1.3	0.89	0.43	0.56

Table 7. Assessment of the radionuclide discharges (Bq y^{-1}) into the Techa River during 1949-1956 (Kryshev et al., 1997; Sources, 1997; Ilyin and Gubanov, 2001).

Year	^{89}Sr	^{90}Sr	^{137}Cs	^{95}Zr	^{106}Ru	^{144}Ce
1949	6.7×10^{13}	1.9×10^{14}	3.0×10^{14}	1.7×10^{14}	4.6×10^{14}	6.0×10^{12}
1950	4.4×10^{15}	6.0×10^{15}	6.4×10^{15}	3.4×10^{15}	6.8×10^{15}	2.2×10^{15}
1951	4.7×10^{15}	6.2×10^{15}	6.5×10^{15}	3.6×10^{15}	6.9×10^{15}	2.4×10^{15}
1952	5.2×10^{13}	9.5×10^{13}	3.5×10^{13}	2.8×10^{13}	2.6×10^{13}	1.0×10^{13}
1953	1.1×10^{13}	2.0×10^{13}	7.4×10^{12}	5.9×10^{12}	5.5×10^{12}	2.0×10^{12}
1954	4.5×10^{12}	8.1×10^{12}	3.0×10^{12}	2.4×10^{12}	2.2×10^{12}	8.2×10^{11}
1955	2.8×10^{12}	5.0×10^{12}	1.8×10^{12}	1.5×10^{12}	1.4×10^{12}	5.0×10^{11}
1956	7.2×10^{12}	1.3×10^{13}	4.8×10^{12}	3.8×10^{12}	3.6×10^{12}	1.3×10^{12}

Table 8. Riparian villages situated downstream on the Techa River in 1949-1951 (Degteva et al., 1994).

Settlement	Distance from site of discharge (km)	Population
Metlino	7	1242
Techa-Brod	18	75
Asanovo and Nazarovo	33	898
M. Taskino	41	147
Gerasimovka	43	357
Geologorazvedka	45	238
Nadyrov Most	48	240
Nadyrovo	50	184
Ibragimovo	54	184
Isaevo	60	434
Podsobnoe Hoz.	65	487
Muslyumovo	78	3230
Kurmanovo	88	1046
Karpino	96	195
Zamanikha	100	338
Vetroduyka	105	163
Brodokalmak	109	4102
Osolodka	125	362
Panovo	128	129
Cherepanovo	137	222
Russkaya Techa	138	1472
Baklanovo	141	480
N. Petropavlovka	148	919
2-Beloyarka	155	386
Lobanovo	163	626
Anchugovo	170	1093
V. Techa	176	979
Skilyagino	180	492
Bugaevo	186	1074
Dubasovo	200	703
Bisserovo	202	465
Shutikha	203	1109
Progress	207	205
Pershino	212	1143
Ganino and Markovo	215	220
Klyuchi	223	1309
Zatecha	237	1135

Table 9. Average daily consumption of food products (kg d^{-1}) by adult inhabitants in the riparian villages of the Techa River (Kryshev et al., 1998a; Cabianca et al., 2000).

Food product	Average consumption	Range of variation
Milk	0.55	0.5-1.0
Meat	0.18	0.1-0.3
Bread	0.36	0.3-0.5
Potatoes	0.57	0.2-1.0
Vegetables	0.24	0.1-0.4
Fruits, berries	0.10	0.05-0.2
Waterfowl	0.01	0.005-0.03
Fish	0.06	0.03-0.1

Table 10. Parameters of the technological water bodies at the PA "Mayak" site (Sources, 1997).

Water body	Area (km^2)	Volume (10^6 m^3)	Total activity (Bq)
Lake Kyzyltash (R-2)	19	83	8.1×10^{14}
Kashkarovsky Pond (R-3)	0.5	0.75	1.6×10^{15}
Metlinsky Pond (R-4)	1.3	4.1	2.7×10^{14}
Reservoir R-10	16.4	76	8.5×10^{15}
Reservoir R-11	44	217	9.6×10^{14}

Table 11. Input of ^{90}Sr (10^{12} Bq y^{-1}) to the upper reaches of the Techa River (Mokrov, 1996).

Year	Filtrate of dam 11	Left-bank canal	Right-bank canal
1984	0.0037	0.26	0.021
1985	0.0044	0.24	0.03
1986	0.0074	0.31	0.028
1987	0.012	0.59	0.024
1988	0.019	0.47	0.045
1989	0.021	0.68	0.074
1990	0.016	1.10	0.18
1991	0.018	0.29	0.24
1992	0.01	0.26	0.24
1993	0.027	0.45	0.52
1994	0.019	0.44	0.33
On average	0.014 ± 0.007	0.46 ± 0.25	0.16 ± 0.15

Table 12. Typical life patterns for different age groups of the Techa riverside residents (Saurov, 1992; Degteva et al., 2000a; 2000b).

Period of time spent at site (h y^{-1})	Age group (years)			
	< 7	7-15	16-59	> 60
Shoreline (summer time)	45	150	150	150
Residence area (outdoors)	2235	2130	1410	2490
Residence area (indoors)	6480	5760	3960	6120
Far from the river (uncontaminated territory)	0	720	3240	0

Table 13. Conversion-factor ratios for absorbed dose in organ to absorbed dose in air, for 500-keV photons (Petoussi et al., 1991; Eckerman and Ryman, 1993; Degteva et al., 2000a; 2000b).

Organ	Age group (years)		
	< 7	7-17	> 17
Red bone marrow	0.85	0.76	0.73
Bone surface	1.37	1.22	1.18
Large intestinal wall	0.75	0.67	0.64
Small intestinal wall	0.73	0.65	0.62
Stomach wall	0.78	0.69	0.66
Testes	0.94	0.83	0.80
Ovaries	0.71	0.63	0.61
Uterus	0.72	0.64	0.62

Table 14. Mean daily intakes of ^{90}Sr (Bq d^{-1}) for adult residents of the village of Muslyumovo (Kozheurov and Degteva, 1994).

Year	Intake	Year	Intake	Year	Intake
1950	5698	1959	9.3	1968	4.8
1951	1288	1960	8.9	1969	4.5
1952	1265	1961	8.2	1970	4.2
1953	236	1962	7.7	1971	3.8
1954	52.5	1963	7.1	1972	3.6
1955	37.7	1964	6.6	1973	3.3
1956	18.9	1965	6.1	1974	3.1
1957	16.1	1966	5.7	1975	2.8
1958	13.5	1967	5.2	1976	2.6

Table 15. Coefficients of transfer from ^{90}Sr intake in adults to the intake in children of age *t* for different calendar years (Kozheurov and Degteva, 1994).

Age (years)	1950	1951	1952	1953	1954	1955
0-1	0.110	0.128	0.146	0.164	0.182	0.200
1-2	0.240	0.332	0.424	0.516	0.608	0.700
2-3	0.360	0.470	0.584	0.696	0.808	0.920
3-4	0.470	0.570	0.670	0.770	0.870	0.970
4-5	0.570	0.652	0.734	0.826	0.898	0.980
5-6	0.660	0.726	0.792	0.858	0.924	0.990
6-7	0.750	0.800	0.850	0.900	0.950	1.000
7-8	0.830	0.864	0.898	0.932	0.966	1.000
8-9	0.910	0.928	0.948	0.964	0.982	1.000
9-10	0.970	0.976	0.982	0.988	0.994	1.000
> 10	1.000	1.000	1.000	1.000	1.000	1.000

TABLES OF TEST DATA AND DOSE ESTIMATES

Table 16. Measured concentrations of radionuclides in water (Bq L^{-1}) of the Techa River (Kryshev et al., 1997; Sources, 1997; Mokrov et al., 2000).

Segment	Year	^{90}Sr	^{137}Cs	^{95}Zr	^{106}Ru
1	1951	150,000	78,000	30,000	40,000
	1952				
	1953				
	1954				
	1955				
	1956				
2	1951	60,000	105,000	16,000	20,000
	1952	4,400	1,500		
	1953	1,600	1,800	400	
	1954	2,800	1,200	150	
	1955	1,000	1,000	400	600
	1956	2,400	1,060	520	200
3	1951	50,000	14,000		
	1952	4,800	7,000		
	1953	1,300	430		
	1954	1,500	150		
	1955	650	170	80	
	1956	700	70	60	
4	1951	8,000	450		
	1952	1,600	110		
	1953	500	43		
	1954	800	120		
	1955	420	50		27
	1956	340	60		4

Table 17. Average annual concentrations of ^{90}Sr in Techa River water ($Bq\ L^{-1}$)[a].

Year	Metlino (7 km)	Muslyumovo (78 km)	Pershino (212 km)
1949	1,000	200 (0)	70 (0)
1950	70,000	20,000 (520)	7,500 (250)
1951	80,000	30,000 (3000)	8,200 (1400)
1952	3,600	3,300 (510)	1,500 (720)
1953	1,400	810 (240)	460 (500)
1954	1,300	820 (500)	680 (460)
1955	700	620 (460)	380 (410)
1956	670	390 (410)	460 (290)
1957		240 (318)	230 (252)
1958		260 (296)	210 (225)
1959		320 (300)	220 (212)
1960		300 (226)	290 (155)
1961		220 (207)	330 (137)
1962		370 (144)	240 (113)
1963		150 (159)	130 (135)
1964		110 (133)	105 (106)
1965		100 (70)	70 (56)
1966		100 (104)	68 (63)
1967		110 (81)	67 (68)
1968		100 (89)	65 (60)
1969		90 (81)	63 (53)
1970		70 (94)	50 (42)
1971		48 (32)	33 (26)
1972		47 (32)	18 (26)
1973		74 (40)	16 (29)
1974		76 (42)	18 (23)
1975		78 (61)	30 (37)
1976		70 (53)	29 (34)
1977		68 (51)	23 (31)
1978		59 (53)	24 (40)
1979		56 (50)	24 (33)
1980		30 (39)	16 (23)
1981		14 (30)	10 (18)
1982		18 (29)	18 (18)
1986		16 (23)	17 (16)
1984		23 (26)	13 (15)
1985		25 (18)	10 (13)
1986		33 (20)	11 (12)
1987		28 (20)	13 (12)
1988		17 (16)	9 (10)
1989		24 (20)	11 (11)
1990		23 (17)	10 (10)
1991		12 (16)	6 (10)
1992		14 (14)	6 (8.9)
1993		13 (13)	5.6 (8.1)
1994		10 (12)	5 (7.4)

[a] Values without parentheses are assessments from observed data (Sources, 1997; Kryshev et al., 1998a). Values in parentheses are from a model assessment by Mokrov et al. (2000).

Table 18. Specific activity of bottom sediments in the 0-10 cm layer (kBq kg^{-1}) during the periods 1952-1953 and 1956-1961 (Sources, 1997).

Location	1952-1953	1956-1961
Water body 3	2,300-2,700,000	
Water body 4	590-590,000	
Techa River[a]		
18 km	5,000-25,000	1,800-2,600
34 km	1,100-3,700	180-340
49 km	700-1,100	80-200
79 km	110-780	15-30
132 km	260-590	7-11
194 km	100-280	7-18

[a] Distance from point of discharge (at water body 4).

Table 19. Radionuclide composition of bottom sediments in 1953 and 1963-1964 (% of the total activity of beta emitters; Sources, 1997).

Location and time period	$^{90}Sr + ^{90}Y$	^{137}Cs	Others
1953			
18 km	6	47	47
34 km	5	34	61
49 km	60	21	19
1963-1964			
49 km	6	92	2
55 km	12	86	2
132 km	60	36	4
185 km	95	2	3

Table 20. Radioactive contamination of the ecosystem of the Techa River floodplain in the area of the Asanov bogs during the period 1991-1994 (Martyushov et al., 1997; Sources, 1997).

Ecosystem component	^{137}Cs	^{90}Sr
Soil (kBq m^{-2})	400-3000 (42,000) [a]	300-850 (10,000) [a]
Bottom sediments (kBq kg^{-1})	70-270 (1200)	2-2.5 (18)
Grass (kBq kg^{-1})	0.1-1.2 (7)	1-4.2 (47)
Tree leaves (kBq kg^{-1})		
Birch	0.5-3.6	0.9-7.3
Willow	1.4-4.9	4-7
Alder	0.04-1.1	0.3-1.3

[a] Values in parentheses are the maximum observed levels of radioactive contamination.

Table 21. Radioactive contamination of the floodplain (kBq m^{-2}) in the middle and lower reaches of the Techa River in 1991 (Makhon'ko, 1993; Kryshev et al., 1997).

Settlement	^{137}Cs	^{90}Sr	$^{239,240}Pu$
Muslyumovo	300 ± 270 (5600) [a]	670 ± 460 (6100) [a]	2.8 ± 0.8 (3.7) [a]
Brokokalmak	830 ± 760 (4200)	420 ± 340 (1600)	1.6 ± 1.2 (4.1)
Russkaya Techa	60 ± 20 (85)	60 ± 40 (115)	0.5 ±0.2 (0.7)
N. Petropavlovka	500 ± 300 (1150)	30 ± 10 (44)	0.8 ± 0.4 (3.0)
Pershinskoe	30 ± 20 (74)	70 ± 30 (110)	0.4 ± 0.2 (2.6)
Zatecha	48 ± 15 (63)	60 ± 8 (68)	0.4 ± 0.2 (0.7)
Regional background	2.2 ± 0.4	1.5 ± 0.4	0.1-0.2

[a] Values in parentheses are the maximum observed levels of radioactive contamination.

Table 22. Radionuclide content in local food products (Bq kg^{-1} wet weight) in the riverside settlements on the Techa River during the period 1991-1994 (Kryshev et al., 1997; 1998a; 1998b).

Product	^{137}Cs	^{90}Sr
Milk	5.3 ± 3.5 (35)	1.5 ± 1.1 (26)
Beef	34 ± 10 (140)	0.3 ± 0.1
River waterfowl	64 ± 30	1.2 ± 0.7
Potatoes	4.1 ± 2.3 (44)	0.8 ± 0.2 (6.5)
Fish	18 ± 8 (400)	450 ± 110

[a] Values in parentheses are the maximum observed levels of radioactive contamination.

Table 23. Radionuclide concentrations (Bq kg^{-1}) in samples near Muslyumovo in 1992-1993 (Burkart et al., 1997).

Sample	^{137}Cs	^{90}Sr
Techa water	0.41-0.59	7.4-18
Techa sediment	37,000-40,000	420-610
Soil from floodplain		
0-5 cm	18,000-21,000	7,100-16,000
5-10 cm	21,000-25,000	6,200-12,000
10-15 cm	3,300-3,900	5,700-9,600
15-20 cm	280-320	5,500-9,600
20-25 cm	300-350	3,900-7,900
25-30 cm	1,100	340-790
Fish		
Meat	43	330
Bone	43	930
Whole fish (pike)		15,000
Milk		
Private farms	1.2-13	0.7-25
State dairy company	0.9-3.6	0.1-0.31

Table 24. Radionuclide concentrations in fish (Bq kg^{-1} fresh weight) from the Techa River (Trapeznikov et al., 1993; Kryshev, 1997).

Year	^{137}Cs	^{90}Sr
1977	-	960
1978	41	850
1980	18	1600
1981	12	230
1990	26	340
1992	18	450
1993	43	560

Table 25. Estimates of the internal exposure rate to biota (Gy d^{-1}) during the period of maximum radioactive discharges to the Techa River, 1950-1951 (Kryshev et al., 1997; 1998a; 1998b; Kryshev and Sazykina, 2000).

Organisms	Metlinsky pond (R-4)	Muslyumovo (78 km[a])	Zatecha (237 km[a])
Phytoplankton	0.01	0.004	0.0003
Zooplankton	0.03	0.01	0.0008
Macrophytes	0.3	0.08	0.01
Mollusks	0.4	0.09	0.007
Fish	0.09	0.05	0.004

[a] Distance from the source of radioactive discharges.

Table 26. Comparative estimates of the exposure rate to the population (Sv y^{-1}) and biota (Gy y^{-1}) from radioactive contamination of the Techa River (Kryshev et al., 1997; 1998a; 1998b; Kryshev and Sazykina, 2000).

Exposed objects	1950-1951	1992
Humans	0.1-1	2×10^{-4}
Aquatic organisms		
Algae	4-30	3×10^{-3}
Mollusks	3-30	2×10^{-2}
Fish	1-20	4×10^{-3}

Table 27. Levels of external irradiation for inhabitants (adults born in or before 1934) in selected riverside villages on the Techa River (Degteva et al., 1994).

Settlement	Distance from the site of release (km)	Dose (cGy)
Metlino	7	101
Muslyumovo[a]	78	5.4
Brodokalmak[a]	109	2.4
Russkaya Techa[a]	138	1.9

[a] Settlements still existing.

Table 28. Average organ absorbed doses (external plus internal) for residents of the Techa riverside villages (cGy; period of dose accumulation, 25 y) (Degteva et al., 1994).

Settlement	Distance from the site of release (km)	Red bone marrow	Bone surfaces	Upper large intestine	Lower large intestine
Metlino	7	164	226	133	146
Muslyumovo[a]	78	61	143	21	37
Brodokalmak[a]	109	14	31	5.2	8.7
Russkaya Techa[a]	138	22	53	7.1	13
Pershino[a]	212	15	34	5.0	9.0
Zatecha[a]	237	17	40	5.7	11

[a] Settlements still existing.

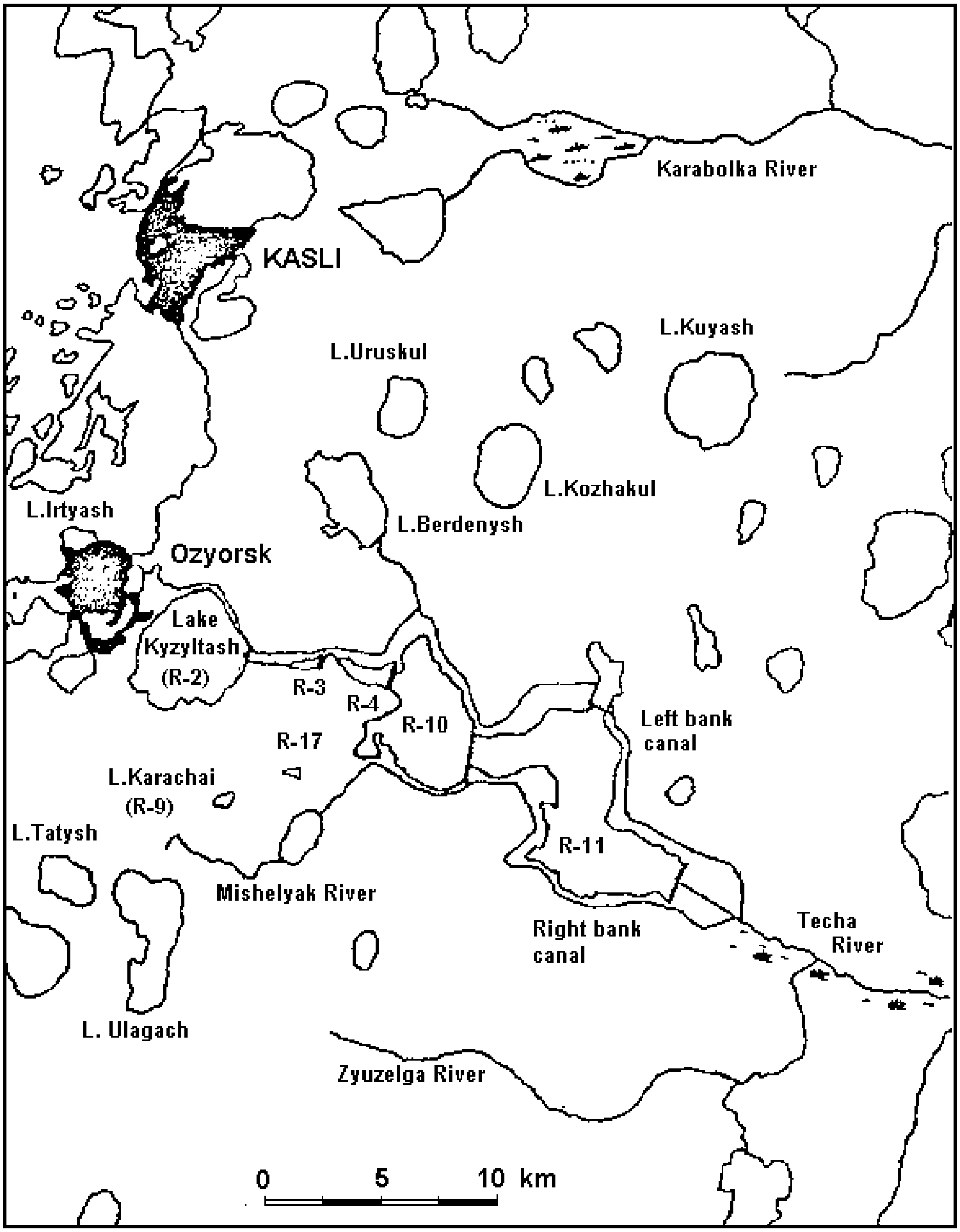

Fig. 1. The scheme of water bodies at the Mayak site.

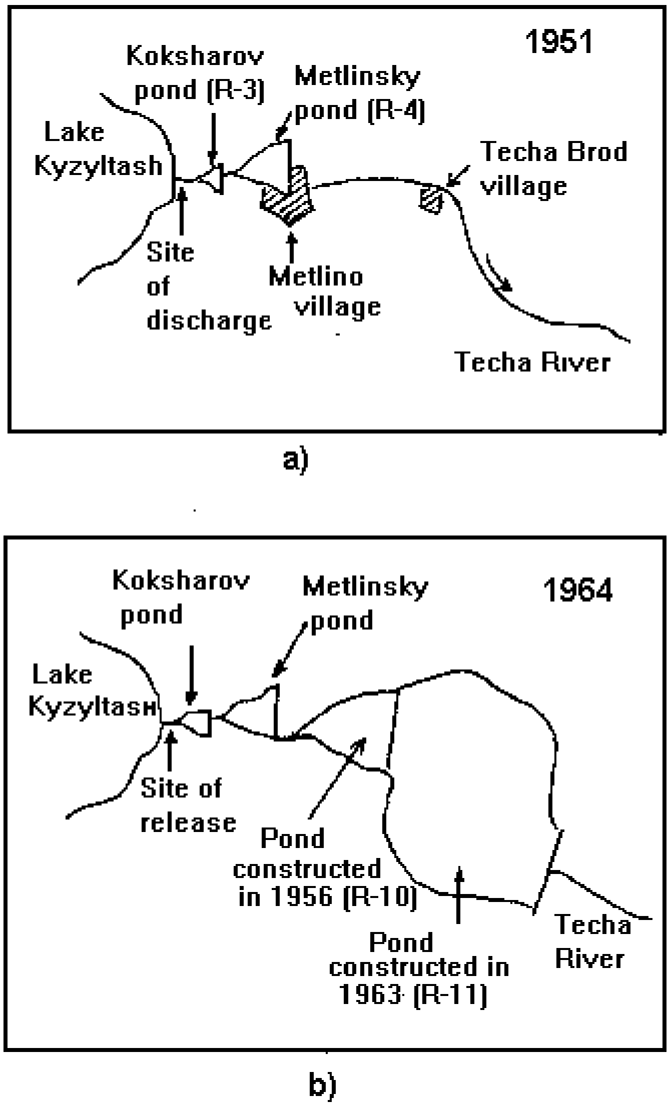

Fig. 2. Map of the upper reaches of the Techa River in (a) 1951 and (b) 1964.

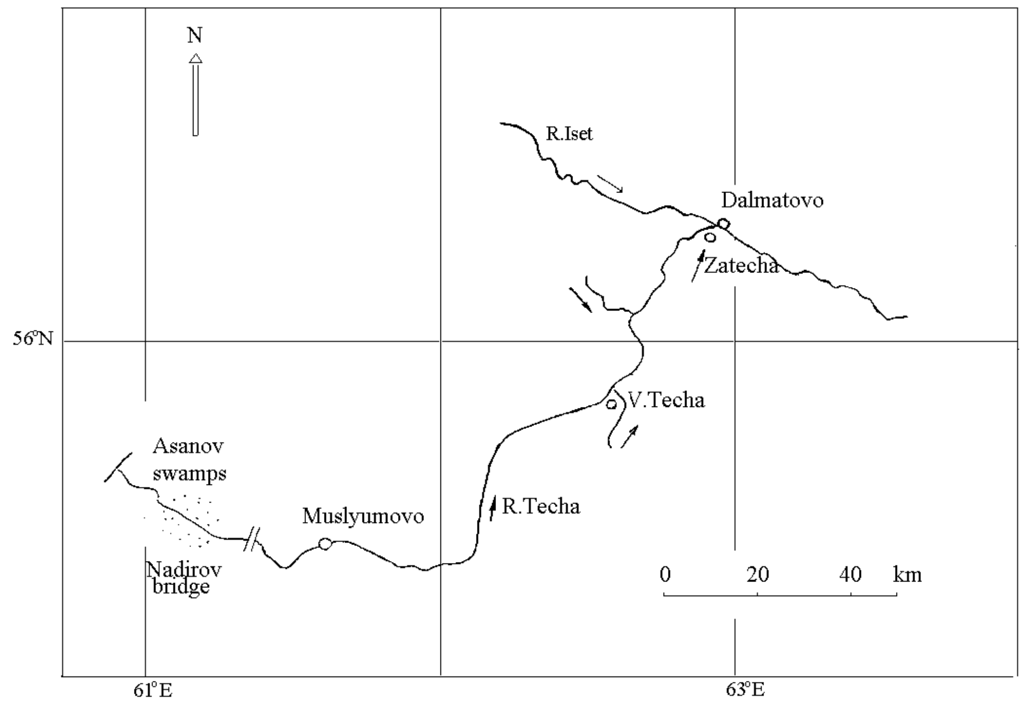

Fig. 3. Hydrographic system of the Techa River.

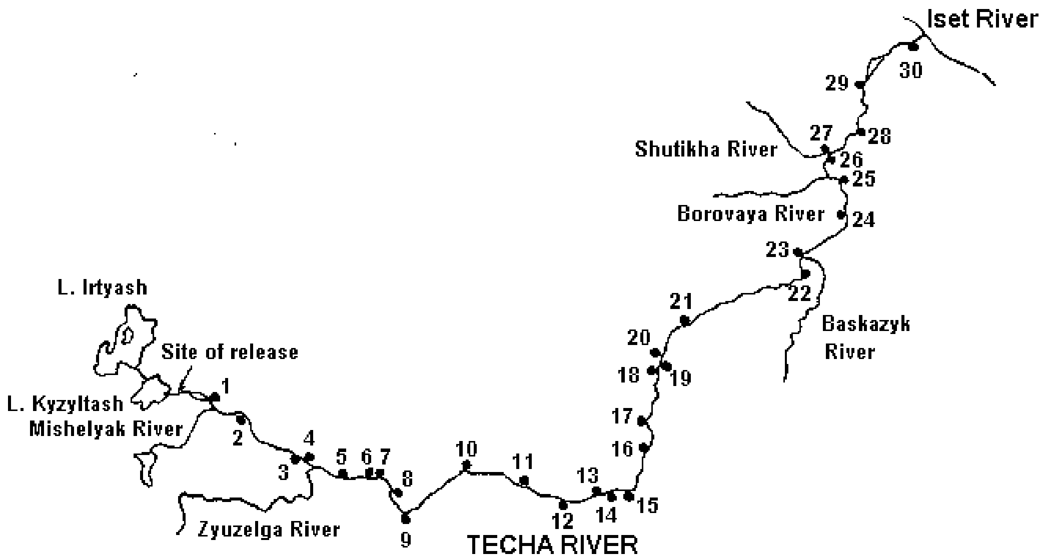

Fig. 4. The Techa River and the villages located on its banks before the radioactive contamination (1949). 1-Metlino; 2-Techa Brod; 3-Asanovo; 4-Nasarovo; 5-M. Taskino; 6-Nadyrov Most (N. Bridge); 7-Nadyrovo; 8-Ibragimovo; 9-Isaevo; 10-Muslyumovo; 11-Kurmanovo; 12-Karpino; 13-Zamanikha; 14-Vetroduika; 15-Brodokalmak; 16-Osolodka; 17-Panovo; 18-Cherepanovo; 19-Russkaya Techa; 20-Baklanovo; 21-Nizhne-Petropavlovka; 22-Anchugovo; 23-Verhnyaya Techa; 24-Bugayevo; 25-Dubasovo; 26-Bisserovo; 27-Shutikha; 28-Pershino; 29-Klychi; 30-Zatecha. Downstream distances are provided in Table 8.