A method of estimating the strength of a stationary source of radioactive substances entering a river is proposed. The method is based on statistically reliable measurements of the concentration of radionuclides in bottom deposits. The stationary model of the transport of a radioactive impurity in a two-dimensionally uniform flow is used to determine a relation between the concentration of radionuclides in bottom deposits and the strength of the source. The model is based on the two-dimensional equation for turbulent diffusion and takes account of the interaction of radioactive substances between the water mass (solution, suspension) and bottom deposits.

The source of $^{60}$Co entering the Don River with contaminated underground waters as a result of an incident, which occurred in 1985, in a storage site for liquid wastes from the Novovoronezh nuclear power plant is examined as an example. The average yearly inflow of the radionuclide is estimated to be $\sim 1 \cdot 10^{10}$ Bq/yr, which is several times less than the estimates made by experts.

In problems of monitoring and in radioecological monitoring, it is often necessary to estimate the active sources of the radioactive substances flowing into river systems. Conventionally, this is done using models of contaminant transport in water together with measurements of the radionuclide concentration in water. Such models have been investigated quite completely, and they can be easily used to identify the sources of contamination of rivers and reservoirs by chemical substances [1]. For this, statistically reliable measurements of the concentration of a contaminant in water at certain points of the river channel, which are located at various distances from the source, are conducted. After the measurements have been completed, the model chosen can be used to estimate quite accurately the intensity of the source of the contaminant provided that the source can be assumed to be stationary or instantaneous.

This method of estimating sources of radionuclide discharges is often difficult to use in the practice of radioecological investigations. This is due to the extremely low concentration of radionuclides in water, which is difficult to measure in a statistically reliable manner. Indeed, most of the most dangerous long-lived radionuclides entering a river or reservoir, mainly as a result of sorption and sedimentation, rapidly leave the water and enter the bottom deposits. Examples of such radionuclides are $^{137}$Cs, $^{239}$Pu, $^{152,154}$Eu, $^{60}$Co, $^{103,106}$Ru, and others, which are most important from the sanitary standpoint. Consequently, in practice, such radionuclides are present in water in trace quantities, but they are detected in bottom deposits with good statistical reliability [2].

In the present paper, a method is proposed for estimating the strength of a stationary source of certain long-lived radionuclides which enter river systems. The method is based on statistically reliable measurements of the concentration of...
these radionuclides in bottom deposits. A stationary model of the transport of a radioactive impurity in a uniform two-dimensional flow will be used to obtain a relation between the concentration of radionuclides in bottom deposits and the source strength [3, 4]. Such a model has been used to predict and reconstruct the radionuclide contamination of water, bottom deposits, and flood-plain soils of the Enisei River downstream from discharges from the Krasnoyarsk Integrated Mining and Chemical Plant [2].

The model is based on the two-dimensional equation for turbulent diffusion and takes account of the interaction of radioactive substances between the water mass (solution, suspension) and bottom deposits. The following simplifying assumptions are used in this model:

• the process of mutual exchange of radioactive impurity between the water and bottom deposits is proportional to the concentration of radionuclides in the liquid and solid phases;
• the sorption and desorption of radionuclides between the solution and the solid phase are assumed to be instantaneous and equilibrium processes and to follow a linear isotherm with a constant distribution coefficient;
• the process of exchange between the bottom and water mass occurs within an equally-accessible top layer of bottom deposits of thickness 𝑡;  
• the radioactive impurity is transported in the water volume by the water flow and is disseminated by turbulent diffusion; the radioactive impurity is distributed uniformly over the depth of the river, and only the transverse component of convective diffusion is taken into account; it is assumed that the diffusion in the longitudinal direction is negligibly small compared with advective transport;
• the morphometric characteristics of the channel are constant over the entire section of the river studied; the overall flow rate of the tributaries is negligibly small compared with the flow rate of the main channel.

The system of equations describing the transport of radionuclides in the river downstream from the discharge source is

\[
\begin{align*}
\frac{\partial C_1}{\partial t} &= D_y \frac{\partial^2 C_1}{\partial y^2} - V \frac{\partial C_1}{\partial x} - \lambda_1 C_1 + \frac{C_1 \alpha_{T_1} U}{H} - \frac{\beta}{H} (C_1 \alpha_{p_1} - C_2 \alpha_{p_2}) + \frac{C_2 \alpha_{T_2 \varnothing}}{H} + F_t; \\
\frac{\partial C_2}{\partial t} &= -C_2 \lambda - \frac{C_2 \alpha_{T_2 \varnothing}}{h} - \frac{\beta}{H} (C_2 \alpha_{p_2} - C_1 \alpha_{p_1}) + \frac{C_1 \alpha_{T_1} U}{H} - \frac{\gamma C_2 \alpha_{p_2}}{h},
\end{align*}
\]

where $C_1$ and $C_2$ are the concentrations of a radionuclide in the water mass and bottom deposits, respectively, Bq/m$^3$; $x$ and $y$ are the coordinates along and transverse to the flow, respectively, m; $D_y$ is the turbulent diffusion coefficient along the y axis, m$^2$/day; $v$ is the average flow velocity, m/day; $\lambda$ is the decay constant of the nuclide, 1/day; $U$ is the average rate of settling of suspended particles of the size considered, m/day; $H$ is the average depth of the river on the section studied, m; $t$ is the thickness of the exchange layer, m; $\varnothing$ is the coefficient of mass transport of radionuclides as a result of roiling (wash-out) of contaminated bottom deposits, m/day; $F_t$ is the distribution of the sources of the radionuclides; $\beta$ is the coefficient of mass transfer of radionuclides between the water mass and the bottom deposits as a result of diffusion, m/day; $\gamma$ is the coefficient of mass transport of radionuclides contained in the interstitial water between the effective layer of bottom deposits and the bottom layer, m/day; $\alpha_{T_1}$ and $\alpha_{T_2}$ are the fractions of the $i$th radionuclide, sorbed by the suspension and the solid phase of the effective layer of bottom deposits, respectively; $\alpha_{p_1}$ and $\alpha_{p_2}$ are the fractions of the $i$th radionuclide present in dissolved form in water and the effective layer of bottom deposits, respectively.

Let us examine stationary dissemination of radionuclides along the river with constant discharging of radioactive substances. As conservative simplifications, we shall assume that the turbulent diffusion coefficient is constant and is independent of the coordinates. There are no concentrated sources of radionuclides along the river section considered. Then, the system of equations can be reduced to the simpler form

\[
\begin{align*}
D_y \frac{\partial^2 C_1}{\partial y^2} - V \frac{\partial C_1}{\partial x} - \lambda_1 C_1 + \lambda_{12} C_2 &= 0; \\
\lambda_{21} C_1 - \lambda_{22} C_2 &= 0,
\end{align*}
\]

where $\lambda_{12}$ and $\lambda_{21}$ are the coefficients of mass transport of radionuclides between the water mass and the bottom deposits, and the bottom deposits and the effective layer of bottom deposits, respectively; $\lambda_{22}$ is the coefficient of mass transport of radionuclides between the bottom deposits and the effective layer of bottom deposits.