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Development of a hydrogeological model for the Kyiv conurbation

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Abstract The Kyiv conurbation is the major water consumer in the areas contaminated by radionuclides of Chernobyl origin. The risk of accidents that may affect the quality of the surface water which is used as a major source to supply the three million population, has lead to consideration of groundwater as an alternative water supply source. Therefore a permanent action flow and transport model has been developed to study the peculiarities of water exchange in the multilayered aquifer system and to determine the extent of groundwater contamination by radionuclides.

INTRODUCTION

As a consequence of the accident at the Chernobyl Nuclear Power Plant, soil contamination with ^{137}Cs occurred in the Kyiv region; the surface contamination density varies by several tens of kBq m^{-2}. As a result of infiltration by precipitation water, the contamination has reached aquifers, although the radionuclide has been partially removed by absorption in the subsurface. The most populated area within the contaminated region is the Kyiv Urban Agglomeration (KUA) that extends over an area of 60–70 km radius around Kyiv City (Fig. 1).

The geology the area under study includes Archean and Protezoic crystalline rocks and their weathering products, and sedimentary deposits of Permian, Triassic, Jurassic, Cretaceous, Paleogene, Neogene and Quaternary age. According to the geological structure of the KUA area, the main groundwater aquifers are related to the Quaternary, Eocene, Cenomanian-Callovian and Middle Jurassic (Bajocian) deposits. The last two aquifers are intensively exploited and are of practical significance for the organization of a centralized water supply. The upper aquifers (Eocene and Quaternary) that receive the recharge, have an influence on the quality of the deep aquifers through vertical exchange.

The heterogeneity of the unconsolidated deposits is relevant to hydrogeological modelling and to the migration of radionuclides in the subsurface, and has been studied at the Radioecological Centre, NAS of Ukraine (Shestopalov *et al.*, 1996).

Development of the hydrogeological model

A complex hydrogeological model of the area under study was developed which includes the regional groundwater flow model of the KUA, covering an area of about

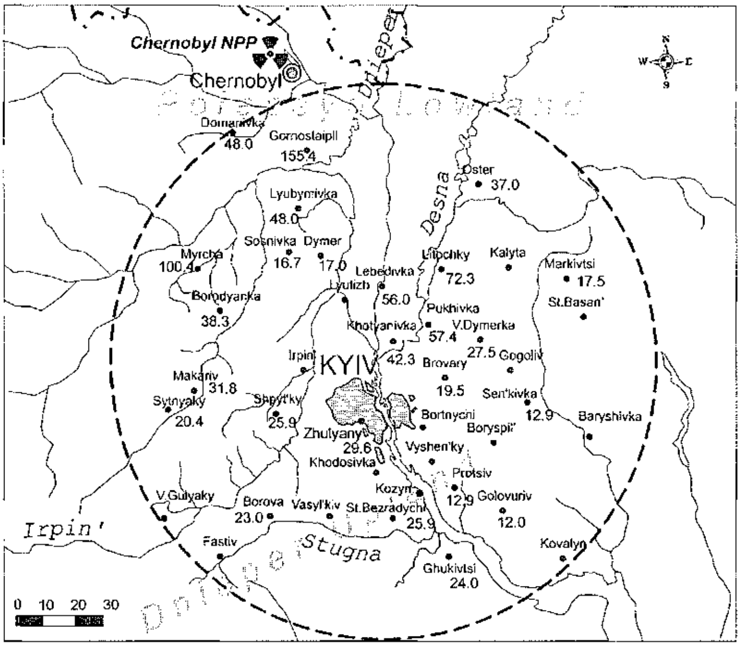

Fig. 1 Location map of the area under study: circle encloses the Kyiv urban agglomeration (KUA). Values indicate surface contamination density (kBq m^{-2}) for ^{137}Cs.

15 000 km^2, and a set of complimentary local models for Kyiv City itself (about 900 km^2) and for the eastern parts of the Kyiv province (about 1500 km^2).

In these models four aquifers and three confining beds were specified. The calibration was accomplished using the inverse problem solution. Based on the primary solution of the natural steady state problem, the transient inverse problem was solved in conditions disturbed by water intakes. During the inverse transient problem solution, the flow parameters of the aquifers were refined, and the infiltration recharge rate specified for zones of increased vertical natural and artificial infiltration. The validity of the solution was estimated by comparison between observed and modelled groundwater levels, and drawdown rates, and control of the modelled groundwater discharge to the rivers, using actual observation data from river flow gauges. The allowable difference between observed and modelled data was 5%.

Based on the models developed, a modelling forecast was performed to assess the possible lateral inflow of contaminated groundwater from the Chernobyl exclusion zone into the Kyiv water intakes, and to study the possibility of increasing the groundwater withdrawal for potable water supply to Kyiv City.

The model predictions proved that there is no contaminated groundwater inflow from the Chernobyl region, suggesting that the contamination of groundwater within the KUA area results mainly from infiltration of precipitation water through the contaminated soil surface. Predicted groundwater flow directions for 1998, for the most intensively exploited Cenomanian-Callovian aquifer (Fig. 2), show that the depression cone around the Kyiv water intakes does not extend to the highly contaminated Chernobyl zone, and that groundwater flow within that zone is directed northeast, away from Kyiv.

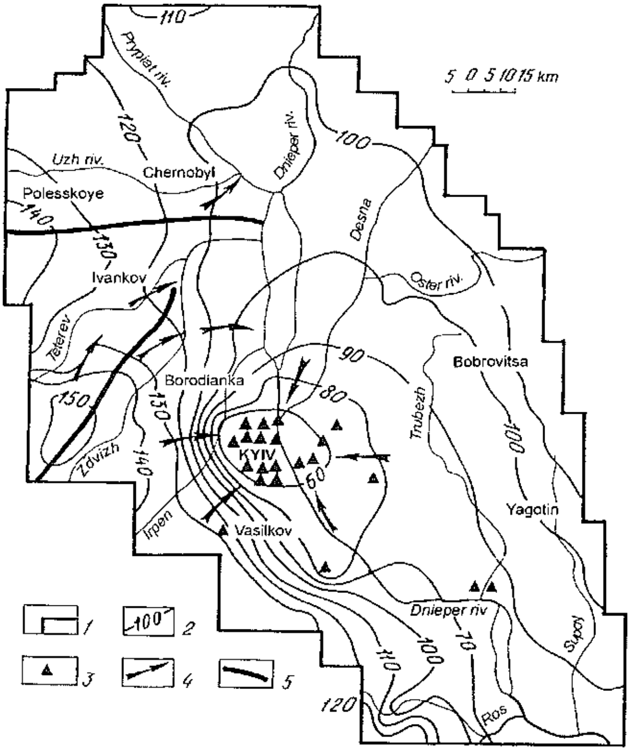

Fig. 2 Map of the piezometric head contours for the most exploited Cenomanian-Callovian aquifer obtained during the transient inverse problem solution for the year 1998: 1 – model boundary; 2 – piezometric head contours (m); 3 – operating water intake wells; 4 – direction of groundwater flow; 5 – watershed line.

Good prospects for intensification of groundwater exploitation for the purposes of the centralized water supply of Kyiv City were identified in the eastern part of Kyiv Province. Due to additional water intakes in this region, the total groundwater abstraction could be increased by 800 000 m^3 day^{-1}.

The hydrogeological model developed provides a basis for the groundwater management within the KUA. It also serves as the hydrogeological base for transport models aimed at groundwater quality monitoring in conditions of possible contamination by radionuclides of Chernobyl origin.

DEVELOPMENT OF TRANSPORT MODELS

Study of vertical transport pathways

Two main pathways of fast vertical radionuclide transport in the subsurface were identified. During intensive pumping at wells with construction faults an increased downward water migration through unconsolidated rocks, fractures and caves may occur from the drill annular space. The rapid contamination of the deep aquifer through this migration pathway was proved experimentally at the Kyiv water intake site, where a tracer experiment was carried out (Shestopalov, & Rudenko, 1997). The NaCl indicator was injected into a drill hole at some tens of metres distance from the abstraction well, out of which groundwater was pumped from 250 m depth. An increase in the Cl ion concentration of the abstracted water was detected 20 hours after indicator injection.

Besides this artificially induced migration pathway, there are natural zones of abnormally fast migration, which are associated with circular and linear landscape depression forms which cover up to 10% of the total area of the KUA. To identify these active zones, results from the analysis of large scale topographic maps, aerial photo interpretation, radon–toron emanation profiling, physical, mechanical, chemical and electrical soil characteristics, groundwater levels and groundwater chemistry were considered.

The active zones were found to be characterized by high emanation ability, high permeability and high electrical conductivity compared with the usual values for unconsolidated rocks. The soil cross section in these zones differs to that of the background areas. Analysis of radionuclide content in the solid phase of soil profiles proved there was more intensive vertical migration in the active zones than in the background areas. The groundwater level regime in these zones was found to be closely related to the atmospheric precipitation intensity. Abnormally high rates of groundwater recharge and formation of spreading groundwater dome after intensive rainfall periods were observed.

Modelling of radionuclide transport in groundwater

The extremely urgent problem of forecasting the radionuclide migration through the geological environment was addressed by modelling advective transport in the unsaturated and saturated zones in the KUA regions contaminated with radionuclides from Chernobyl.

Along with the experimental and field investigations, mathematical modelling of migration processes was performed based on geological data, groundwater filtration and sorption characteristics, initial surface density of radionuclide contamination and recent observations of radionuclide concentrations in different aquifers. Regional scale modelling in saturated zone conditions was performed using the MODFLOW-MT3D code. For local modelling of the vertical fast migration in unsaturated-saturated conditions, a special one-dimensional code was developed at the Radioecological Centre NASU, using effective algorithms constructed at Kyiv University (Gladkiy *et al.*, 1981).

During model calibration, the inverse problems were solved first on a local model for separate characteristic depressions (fast migration zones) to obtain their vertical transport parameters (vertical dispersion coefficient, downward flow velocity, and distribution coefficient for equilibrium sorption, K_d). The prediction results for local models within the fast migration zones confirmed field observations that within the central parts of the depressions the vertical infiltration flow rate is increased by up to 5–7 times relative to the background areas, causing local contamination of the Quaternary aquifer. The local modelling also showed that the lateral spreading of the contamination plume around a single depression is relatively slow, only reaching several hundred metres during the modelled 30 year period. However, if the areal distribution of such depressions is taken into account, they may cause significant input to the total contamination of the groundwater system.

Regional scale modelling was performed after characterization of the fast migration zones and identification of their distribution density over the studied KUA area. During the model calibration, predicted concentrations for the years 1991, 1995 and 1998 were compared with available field observation data to achieve 5% verifiability. Then the forecasting model was run to the year 2010.

Predicted concentrations of ^{137}Cs in groundwater of the Quaternary and Eocene aquifers for 2010 are given in Figs 3 and 4. According to the modelling results, the concentrations gradually increase in all aquifers within the KUA area, but are significantly below the maximum allowable concentration for ^{137}Cs (4 Bq l^{-1}).

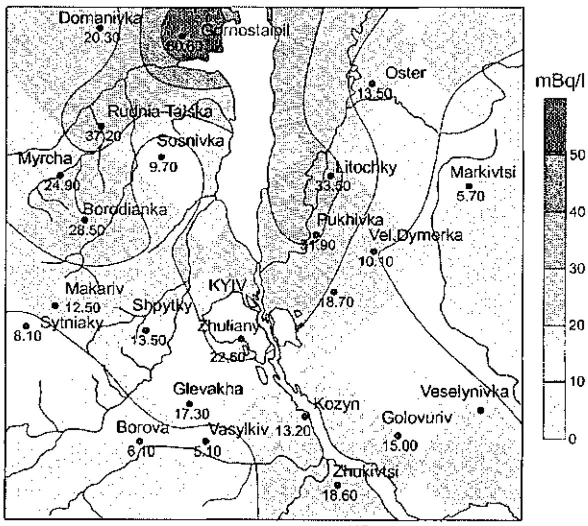

Fig. 3 Predicted concentrations of ^{137}Cs in groundwater of the Quaternary aquifer within the KUA area, predicted to 2010 (mBq l^{-1}).

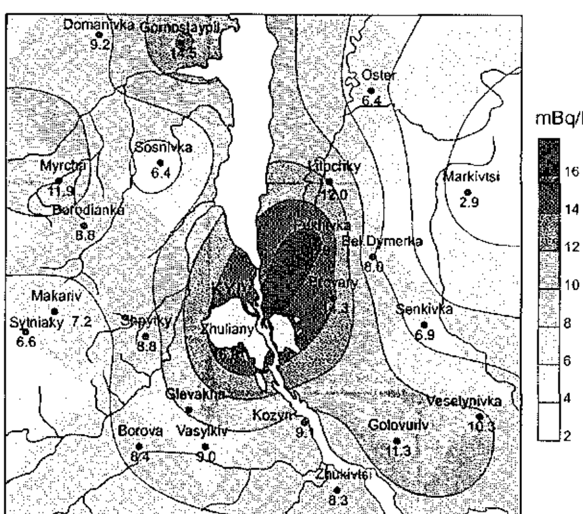

Fig. 4 Predicted concentrations of ^{137}Cs in groundwater of the Eocene aquifer within the KUA area, predicted to 2010 (mBq l^{-1}).

According to the predictions, maximum contamination of the Quaternary aquifer is likely in the northern part of the KUA area, associated with the greatest soil surface contamination. Maximum contamination of the Eocene aquifer is observed in the central part of the KUA, related to the depression cone of the groundwater intakes.

CONCLUSIONS

- Since the Chernobyl accident radioactive contamination has occurred in both the upper Quaternary aquifer and the deep aquifers within the Chernobyl exclusion zone, and at large distances from the Chernobyl Nuclear Power Plant.
- It has been shown that vertical downward pathways of radionuclide migration contribute most to the contamination of the multilayer aquifer system. The lateral pathways of regional contamination processes are of secondary importance because of low lateral flow rates relative to the regional scale of the area under study.
- Field observations and modelling have shown that fast migration zones associated with dish-like and linear depression topographic forms of different origin, are especially significant in natural vertical transport of long-lived radionuclides from the surface to groundwater. In the central active parts of these zones, the downward infiltration flow may be several times greater than in the background areas, providing vertical preferential pathways for radionuclide penetration into the groundwater system.
- Besides natural vertical migration pathways, it was shown that artificially created migration pathways occur due to technical imperfections of wells. Their contribution to the total radioactive contamination of the deep aquifers is not large, but misinterpretation of locally increased concentrations can happen, if their presence is not recognised as the cause.
- Despite the degree of groundwater contamination by radionuclides from Chernobyl, the observed and predicted concentrations are much lower than the maximum allowable concentrations, and the confined aquifers remain the most reliable source of water supply within the affected regions.
- The hydrogeological model of the KUA territory, which should continue to be refined as new field observation data arise, is an efficient instrument for groundwater resources and quality management.

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