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A PERMANENT MATHEMATICAL MODEL OF FILTRATION AND MIGRATION CONDITIONS BETWEEN THE PRIPYAT AND UZH RIVERS OF THE CHORNOBYL EXCLUSION ZONE

(Представлено членом редакційної колегії д-ром геол. наук, проф. О.Є. Кошляковим)

Background. *Over the past 8–10 years, the radio-hydroecological and hydrogeological conditions of the Chornobyl Exclusion Zone have changed significantly. Under the influence of the decommissioning of the water-containing cooler, the levels, speed and direction of movement of groundwater have changed on a regional scale. New radiation-hazardous objects were created: Storage of spent nuclear fuel (SSNF-2) and Centralized storage of spent nuclear fuel (CSSNF). The impact of climate change on the regime of water bodies has also increased. To study the impact of radiation-hazardous objects on the water environment of the exclusion zone, to forecast changes in hydrogeological conditions under the influence of climate change and man-made loads, it is necessary to create an updated model of filtration and migration conditions with the possibility of its further adjustment and improvement.*

Methods. *In creating and developing a constant mathematical model based on the finite difference method, the geological and hydrogeological conditions of the research area were considered. Spatial constructions were also carried out to visualize the geological structure using GIS technologies. The filtering scheme was drawn up for computational operations. The QGis program was used to construct the surfaces of geological horizons, and the Visual MODFLOW program was used to develop the filtration model.*

Results. *A model of filtration and migration conditions of the Pripyat-Uzh interfluve of the Chornobyl Exclusion Zone was constructed. The distribution of groundwater levels and heads in the Buchach aquifer was obtained. Forecasts of the paths, directions and time limits of the spread of pollutants with underground water from radiation-hazardous objects have been made. We carried out forecasts of the impact of changes in the boundary conditions of the aquifer on the hydrodynamic parameters of groundwater to justify project decisions on improving the network of observation wells and determining the conditions of flooding of the Chornobyl nuclear power plant site. Forecasts of the impact of global warming on the underground water regime have been carried out.*

Conclusions. *The forecast field of pressure distribution demonstrates the possibility of improving the radiological state of groundwater as a result of: increasing the thickness of the aeration zone and its sorption capacity and accelerating self-purification due to the growth of underground flow gradients. It is important that the unloading of polluted groundwater will not take place in the Pripyat River, but in the isolated residual lakes of the former cooling pond. It will take about 20 years for groundwater to reach the lakes from the Chornobyl nuclear power plant site.*

Keywords: *geofiltration model, finite-difference method, numerical modeling, groundwater level, filtration coefficient, Chornobyl Exclusion Zone*

Background

Many radiation-hazardous facilities were designed, built, and operated in the Chornobyl Exclusion Zone. To study the impact of these objects on the environment, forecasting changes in hydrogeological conditions under the influence of climate change and man-made loads, it is necessary to create a permanent model of filtration and migration conditions between the Pripyat-Uzh rivers of Chornobyl Exclusion Zone.

At the end of the 90-s of the last century and the beginning of the 2000-s, the main attention was paid to modeling the migration of strontium-90 into groundwater and Pripyat River from local radioactive waste disposal facilities, which are considered the most dangerous ones (Smith, & Gaganis, 1998). Another popular object of modeling was the area around the cooling pond of the Chornobyl Nuclear Power Plant (ChNPP), which was planned to be drained. Therefore, many predictive models of the distribution of groundwater pressures were performed for various scenarios of water removal. In the first case, detailed models were created, and parameterized according to research results. One of the most famous models was created for the training ground near the burial in trench No. 22-T of the "Red Forest" Point of temporary localization of radioactive waste (PTLRW) (Bugai, Dzhepo, & Skalskyy, 1998, Bugai et al., 2001, 2012, 2018, Shabalin, 2023). In the second case, a model of the Uzh-Pripyat interriver and a more detailed local model around the cooling pond, including the section between it and the Pripyat River, were created (Bugai et al., 2018, 2019). However, after the descent of the cooling pond of the ChNPP and the effects of global warming on GWT in 2014–2019, hydrogeological models for this area were not created.

Modern information technologies for modeling hydrogeological objects allow to fully automate the entire modeling process, namely, from the creation of the model to the presentation of the results of the forecast of natural and anthropogenic processes (Bukaty, 2008; Sato, 2022). Currently, there are a large number of modeling systems that allow building two- or three-dimensional models of geofiltration processes: Visual Modflow, PMWIN, FREEWAT, Feflow, AquaveoGMS and others (Groundwater Modelling Syst., 2000; Harbaugh, 2005; The Official U.S.G.S MODFLOW, 2012). The scope of geofiltration calculations is extremely wide – the assessment of groundwater reserves, their balance characteristics, protection of areas from flooding, determination of water inflows, groundwater velocity, head gradients, distribution of groundwater pollution, forecasting the impact on the hydrogeological status and more.

At present, numerical simulation of geofiltration is mainly used (Shestopalov et al., 2001; Bugai et al., 2018, 2019). It provides a grid breakdown of the filtration area and is based on the finite-difference method of solving differential equations. In this case, partial derivatives are replaced by finite increments, and the differential equation itself is reduced to a system of algebraic equations. These equations include such basic hydrodynamic parameters as heads and filtration coefficients, several equations are equal to the number of blocks of grid breakdown. Thus, numerical simulation is to solve the filtration equations on a computer, and the boundary conditions and structure of the filtration field must be determined.

For the joint description of headless and head filtration, the well-known differential equation in partial derivatives is used (*The Official U.S.G.S MODFLOW, 2012*):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}, \quad (1)$$

where: K_{xx}, K_{yy} and K_{zz} – values of the filtration coefficient along the coordinate axes *x, y, z* (*L* /*t*); *h* is the head (*L*); *W* is the volumetric flow per unit volume representing water sources and/or effluents, with *W*<0.0 for leakage from the groundwater system and *W*> 0.0 for the flow into the system (1 / *t*); S_s is the specific capacity of the porous medium (1 / *t*);*t* is the time (*t*).

Equation (1) describes non-steady-state filtration in heterogeneous and anisotropic media. Assumptions and simplifications are made for specific natural conditions that do not contradict the given equation.

The particle tracking algorithm used in the model, which we built using the MODPATH module, can be implemented for both stationary and transient flow fields. For simplicity, the algorithm is first described for a stationary flow and then extended to transient flow systems. The partial equation describing the conservation of mass in a stationary three-dimensional system of groundwater flows can be expressed as:

$$\frac{\partial}{\partial x}(nv_x)+\frac{\partial}{\partial y}(nv_y)+\frac{\partial}{\partial z}(nv_z)=W, \quad (2)$$

where v_x,$v_y$and v_z are the main components of the mean linear vector of groundwater velocity; *n* – porosity; *W* is the volume of water generated or consumed by internal sources and effluents per unit volume of aquifer (Pollock, 2012).

The finite-difference approximation of equation (2) can be considered as the equation of mass balance for a cell of a finite size grid with a volumetric aquifer, considering water coming in and out of the cell and for water produced or consumed inside the grid cell.

Methods

Natural and man-made conditions on the territory of 20 km of the Exclusion Zone.

Studies of the engineering-geological and geological-hydrogeological conditions of the area around the Chornobyl NPP have been conducted since 1973. The depth of the research is due to the complexity of the construction structures that were designed in the territory adjacent to the Chornobyl NPP. The results of this work are numerous reports, maps, geological sections of drilled wells. After the 1986 accident, radio-hydroecological monitoring of radioactive contamination of surface and underground waters is carried out on the territory of the Chornobyl Exclusion Zone. Since 1996, the Institute of NPP Safety Problems of the National Academy of Sciences of Ukraine has been conducting radio-hydroecological monitoring, hydrogeological observations, and field experiments at the Chornobyl NPP industrial site and around the "Shelter" – Object.

These experiments are taking place in the local and 10-kilometer zone today. Thus, the entire long-accumulated geodatabase is in the reports, maps, sections, and data of hydrogeological, hydrogeochemical, and radiochemical regime observations, which are concentrated in electronic resources. It is being successfully used to create a hydrogeological model in 20 km of the Exclusion Zone. Data from 340 exploration and observation wells drilled were used during the entire period of research in the area to construct the roof surfaces, the soles of the Kyiv marl and the soles of the aquifer of the Buchak horizon. For example, in work (Sato, 2022), 12 wells with a depth of 35 m, three wells at 10 m and two at 4 m were used for hydrogeological modeling.

The model area was selected between the rivers Pripyat and Uzh (fig. 1).

These rivers and the cooling pond, lake Azbuchyn, Semikhody, and PrIpyatsky Zaton are defined in the model as boundary conditions of the first order. Apart from Pripyat and Uzh, rivers such as Sakhan, Ilya, Maryanivka, and Hlynytsia have a natural load on the territory. Converted into drainage canals in the floodplain of the Uzh and Sakhan rivers, as objects of man-caused load, belong to the boundary conditions of the third order. Small rivers and canals are set in the filtration model considering the water level, actual size and conductivity of their bottom sediments.

The Chornobyl nuclear power plant, the objects which were built after the accident, water management facilities: wells of the Pripyat water intake, groundwater drainage, cooling pond with drainage channels, household filtration fields ChNPP effluents are included in the objects of man-caused load. New man-made conditions that emerged after the 1986 Chornobyl accident include radionuclide contamination of the earth's surface, temporary localization of radioactive waste, and long-term radioactive waste disposal site "Pidlisny". In 1986, to prevent the spread of radionuclides with groundwater, a "wall in the ground" was created to the east of the Chornobyl nuclear power plant. The wall in the vertical plane covers the aquifer at its full thickness to a depth of 35–40 meters to the water-resistant layer representing the Kyiv formation marl. The wall is 0.6 m wide and filled with clay material (Comprehensive Assessment, 2020).

The boundaries separating the fluvioglacial from alluvial deposits were obtained from a digital terrain model (DEM) raster map from a satellite of the Japan Aerospace Exploration Agency (JAXA) with a resolution of 40 m.

Relief marks in the floodplains of the Pripyat, Uzh, and Sakhan rivers, and on the first floodplain terrace and in the floodplain range from 100 to 116 m (Baltic altitude system), relief marks on fluvioglacial sediments reach values of 162 m. According to research (Panasiuk, 2014), the filtration coefficient on alluvial deposits is 30 m/day, and on fluvioglacial deposits – 12 m/day. The filtration model consists of three layers of geological sediments (fig. 2).

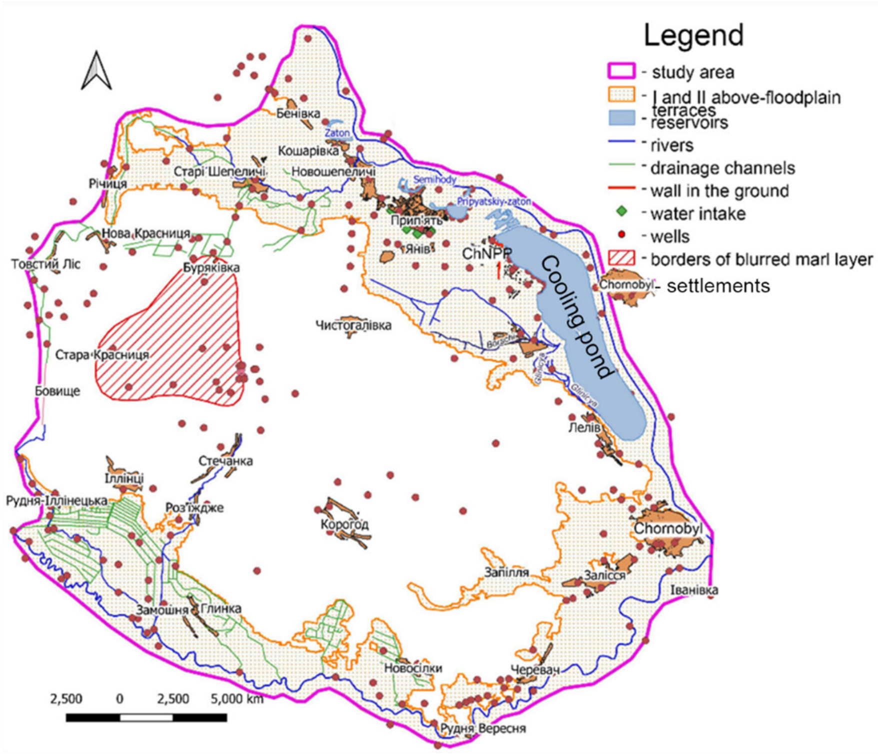

Fig. 1. Natural and man-made conditions of the district

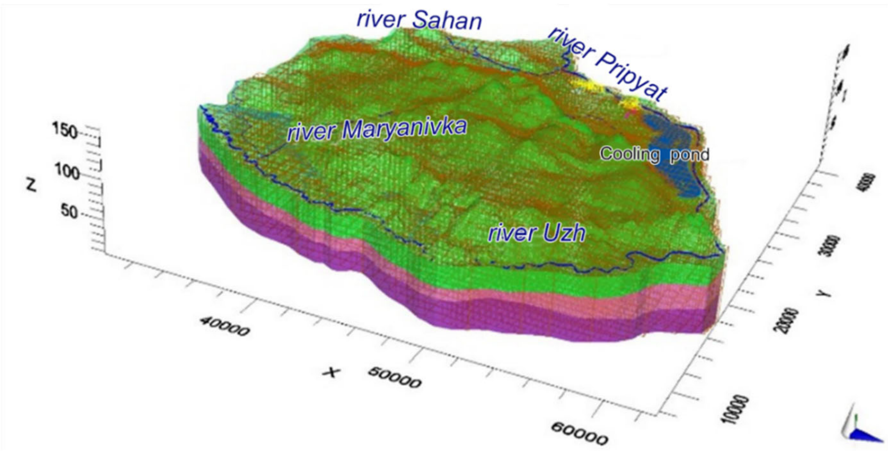

Fig. 2. Scheme of a three-dimensional filtering model

There are two aquifers – the upper headless Quaternary sediment and the lower head Buchak horizon with a filtration coefficient of 8 m/day, separated by a weakly permeable (k = 0.0003 m/day) layer of Kyiv marl. However, in the area of the settlements of Stara Krasnytsia and Buryakivka, the layer of marl clays is blurred and, in this area, two aquifers are interconnected (Scheme of water protection measures, 1993). In lithological terms, the first aquifer consists mainly of sand. Sandstones and loams are found in the form of lenses of small areas and power, which do not impede the movement of groundwater on a regional basis. Accordingly, the first aquifer behaves as a single groundwater reservoir. For the second aquifer in the model, the groundwater head was introduced as the boundary conditions of the first order in the form of isopies with a step of 5 m.

The horizontal surfaces of the model area were divided by a grid into rows and columns, vertically – by the thickness of the geological layers. The calculation of groundwater movement in the model has been performed separately for each unit. This principle of replacing a continuous domain with a discrete one is the basis for the numerical solution of differential filtration equations.

The "wall in the ground" is made of clay and considered in the model by changing the filtration coefficient in the cells of the calculation grid through which it passes.

The calculation of the infiltration recharge of the pressureless aquifer was performed based on the results of observations of the groundwater regime in the Chornobyl region. Infiltration data are obtained by simulation in the filter fields – according to water supply data.

The conformity of the filtration model was achieved by solving the problem, which reproduces the existing hydrogeological conditions in the study area. In the process of analysis of the obtained solution, the filtration coefficient, conductivity of bottom sediments of small rivers, and infiltration recharge were adjusted. As a result, the correlation coefficient between the data obtained in observation wells and those calculated using a mathematical geofiltration model is 0.85 (fig. 3).

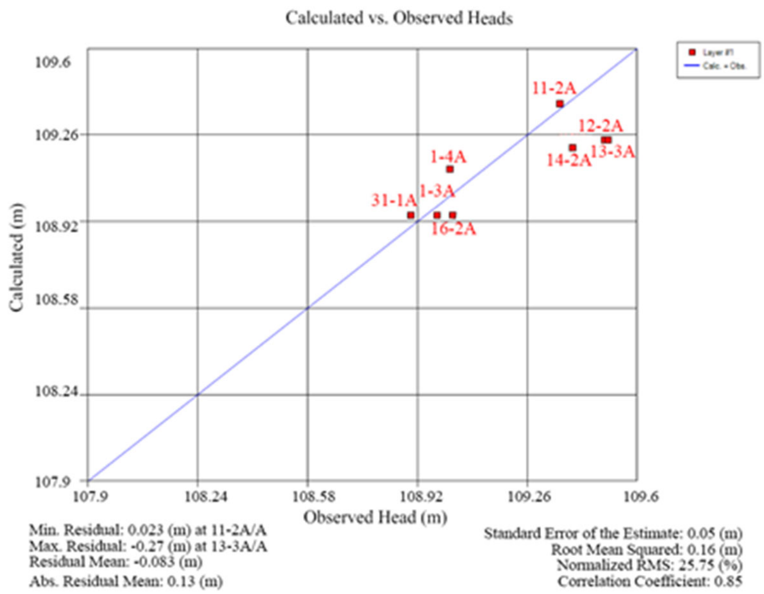

Fig. 3. Correlation of RGV data from observation wells and calculated using the model

Results

Distribution of heads and levels of groundwater, hydroisogypsum and the direction of vectors of the velocity of groundwater flow, was obtained by calculation on the model shown in figure 4.

Figure 4 clearly shows that in the area with the highest groundwater levels on fluvioglacial sediments, the groundwater flow velocity is the lowest (due to a smaller flow gradient). Naturally, in the alluvial deposits of the floodplains of the Pripyat, Uzh and Sakhan rivers, the groundwater flow rate is much higher, especially in the area of residual lakes in the area of the former cooling pond. Naturally, in the alluvial deposits of the floodplains of the Pripyat, Uzh and Sakhan rivers, the groundwater flow rate is much higher, especially in the area of residual lakes in the area of the former cooling pond.

According to the calculations of MODPATH / MOD-PATH3DU, using equation (2) simulated the flow path and time of a conservative migrant passage or a conservative component of a pollutant during its convective transfer with groundwater from radiation-hazardous objects: PTLRW, Radioactive waste disposal site "Buryakivka", Central storage of spent nuclear fuel and NBK-OU Complex (fig. 5). Tracking pathways are used to predict the location of groundwater flow and the duration of their achievement if they start from a known place at a certain time.

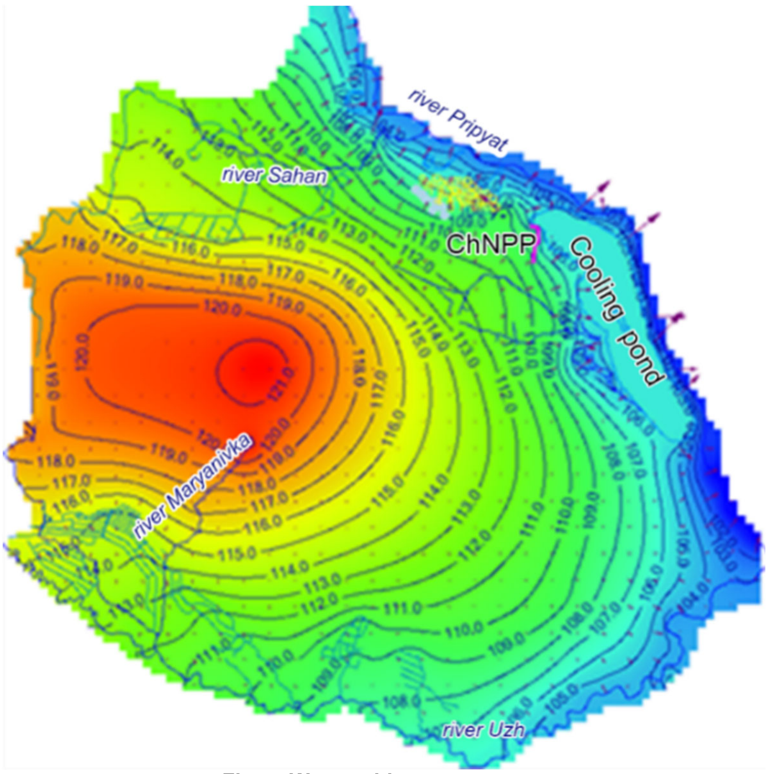

Fig. 4. Water table-contour map

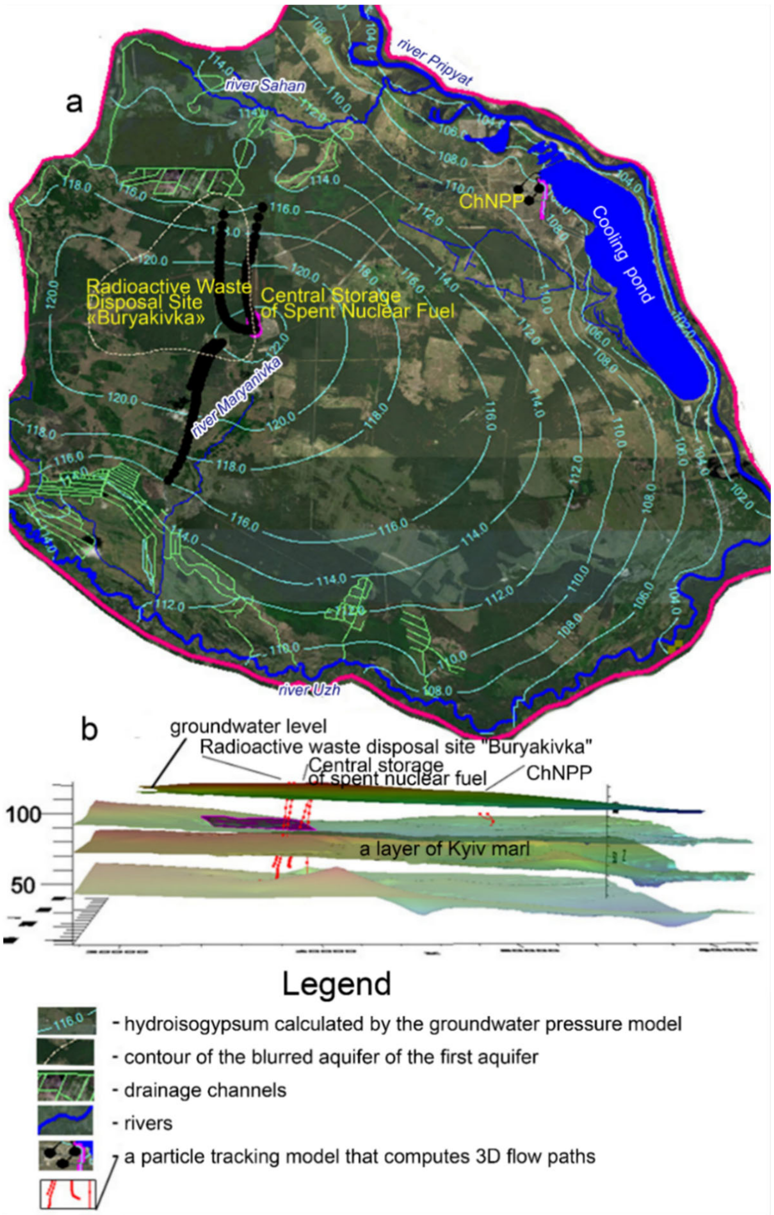

Fig. 5. View of the flow paths of groundwater particles in 2-dimensional (a) and 3-dimensional (b) images

Figure 5a shows the vector of the direction of movement of groundwater particles. The markers on the lines correspond to 10 years. In the Chornobyl area, groundwater is discharged into the residual lakes in the area of the former cooling pond in 10–20 years from the points planned by us. In the area of the Central storage of spent nuclear fuel and the Radioactive waste disposal site (RWDS) "Buryakivka" (Shabalin, 2023), groundwater moves in opposite directions and reaches the floodplains of the Sakhan and Uzh rivers in 400-450 years, respectively. Under natural conditions, as mentioned above, CSF and RWDS "Buryakivka" are located in the area where the layer Kyiv marl blurred. Figure 5 b in the three-dimensional image shows the trajectory of the movement of particles from the groundwater of the territories of the Central storage of spent nuclear fuel and the RWDS "Buryakivka" in 70–90 years reaches the Buchak aquifer. From the territory of the Chornobyl NPP, the groundwater of the Quaternary aquifer is not filtered through the Kyiv marl layer but is discharged into the nearest water body.

This geofiltration model was used to perform work on "Scientific and engineering support of drilling and installation of observation wells of radio-hydro ecological monitoring", which was used to investigate how the level of groundwater will change with the destruction of the "wall in the ground" and under conditions when the water in the cooling pond dries to 103.5. This had to be done to check whether the new wells would fail if the hydrogeological conditions changed.

Figure 6 shows four variants of simulated groundwater levels at the Chornobyl industrial site under different hydrogeological conditions. The first figure (a) shows the groundwater level model, which had been built according to data as of 04.10.2017. The marks of the water surface in the cooling pond were 105.7 m. The filtration coefficient of the wall in the ground is 1E-05 m/day.

The groundwater level in the area where the new wells were drilled under current hydrogeological conditions according to the model is approximately 108.8 m. According to the model, the groundwater level in the territory where new wells were drilled under current hydrogeological conditions is approximately 108.8 m. In a modeled variant without the wall, it will decrease to the level of 107.5 m, which is 1.3 m lower (fig. 6b). When draining the cooling pond to the level of 103.5 m with a "wall in the ground" (fig. 6c), the calculated groundwater level in the model will be approximately 108.25 m – a decrease of only 0.5 m. In the conditions of the destroyed wall and the drained cooling pond to 103.5 m, the groundwater level will decrease to 106 m, which is 2.8 m lower than the groundwater level in the current state. The changes associated with the last two options lead to an improvement in the radiological state of groundwater due to an increase in the thickness of the aeration zone and its sorption capacity, and an acceleration of self-cleaning due to an increase of the flow gradient. At the same time, the unloading of contaminated groundwater will not take place in the Pripyat River, but in the isolated residual lakes of the former cooling pond.

The work on "Scientific and engineering support of drilling and installation of observation wells of radio-hydro-ecological monitoring" also included drilling and equipment of shallow wells for the study of the upper layer of the aquifer. According to the simulation results, the range of filter installation marks is determined and it is 104–106 m.

***Impact of global climate warming*.** The impact of global warming was modeled by a decrease in the aquifer infiltration recharge.

According to the Chornobyl meteorological station data, a decrease in the amount of precipitation per year is observed (fig. 7).

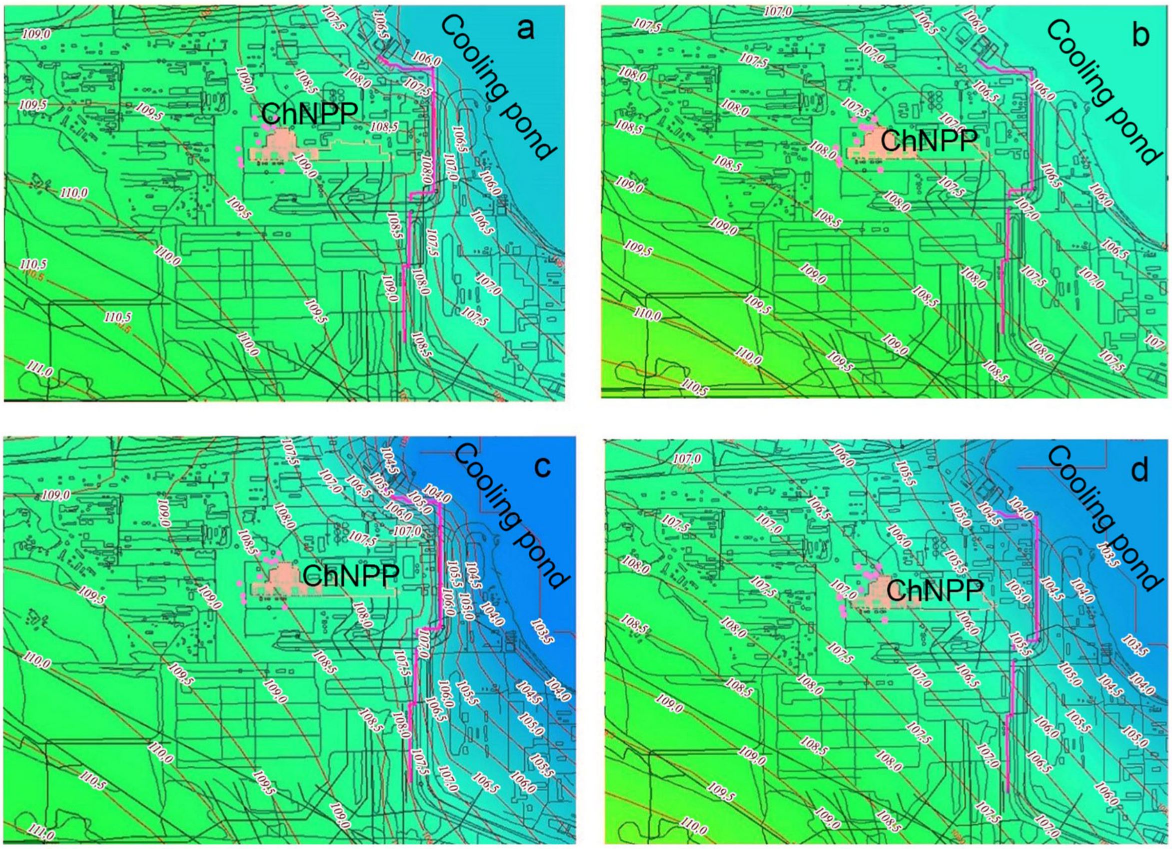

Fig. 6. The result of modeling the groundwater level in the area of the Chornobyl industrial site with changes in hydrogeological conditions, namely with the "wall in the ground" and the level of the cooling pond as of 04.10.2017 - 105.7 m (a); and without a wall (b); levels of groundwater with a "wall in the ground" and drainage of the cooling pond to the mark of 103.5 (c); without a wall and when draining the cooling pond to the mark of 103.5 (d)

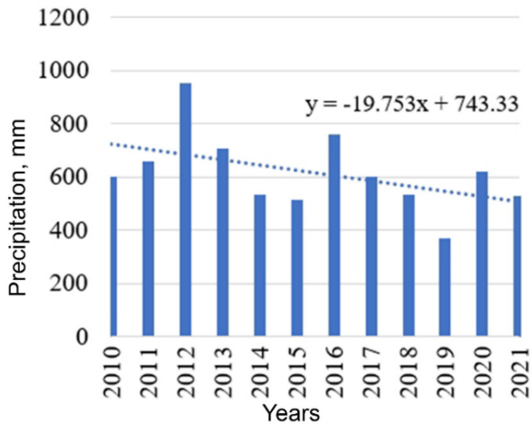

Fig. 7. The schedule of changes in the amount of precipitation by year

The precipitation nature has also changed – long-term precipitation during the growing season has changed to short-term showers that do not have time to moisten the aeration zone and reach the aquifer. The increase in temperature (Martazinova et al., 2022) has a very significant effect on aquifer nutrition along with the decrease in the amount of precipitation.

Average seasonal and average annual values of air temperature increased almost constantly with intensity from 0.3 (until 2011) to 0.45–0.6°C/10 years (Osadchyi, Shevchenko, & Krasovs'ka, 2021). It leads to intensive evaporation of groundwater, shallowing of small rivers and the occurrence of fire-hazardous situations with a decrease in the amount of precipitation and its nature.

An example of a modelled situation of a reduction in the groundwater level due to global warming is shown in figure 8.

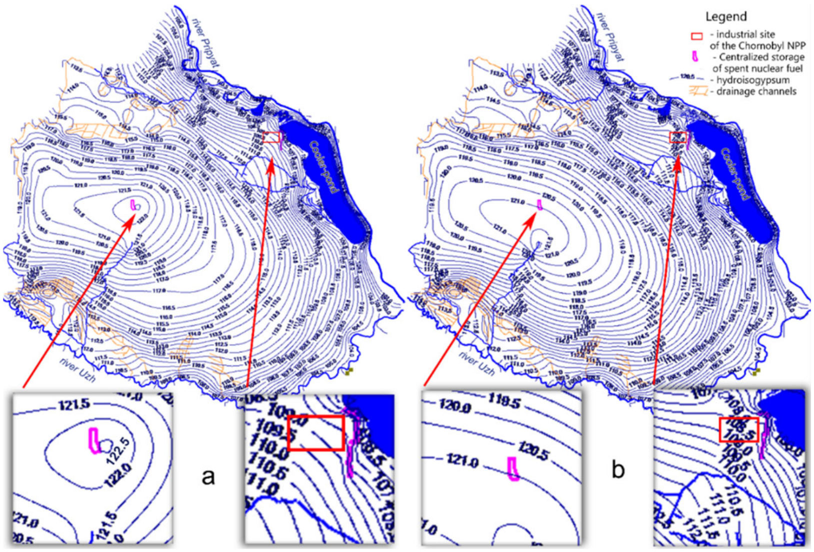

Fig. 8. Comparison of predicted groundwater levels at multi-year average values of the amount of infiltration nutrition of the Quaternary aquifer (a) and when it is reduced to 25–30 % (b)

Therefore, with average multi-year values of infiltration recharge, the maximum absolute mark (Baltic system of elevations) of the groundwater level on the territory of the Centralized Storage of Spent Nuclear Fuel is 122.5 m, and on the ChNPP industrial site – 108.5–109.5 m. When the infiltration recharge is reduced to 25–30 %, the groundwater level on the territory of the Centralized storage of spent nuclear fuel will decrease by 1.5–2 m, and on the site of the ChNPP, the groundwater level will reduce by 0.5 m. The results of modeling changes in radio-hydroecological conditions under the influence of global warming should be taken into account when planning the construction of a network of observation wells in radiation-hazardous objects of the Exclusion Zone.

The hydrogeological model made it possible to expand the possibilities of hydrogeological modeling and brought us as close as possible to the creation of perhaps the first hybrid hydrogeological-climatic model in Ukraine. The evolution of the model can be seen in the simulation of the hydrogeological situation based on pre-calculated climate scenarios with its filling with quantitative values of indicators reflecting modern climate changes (solar albedo, maximum and minimum daily air temperature, wind direction and speed and associated evaporation from the soil surface, etc.). Based on the presented hydrogeological model, a permanent migration model of convective transfer and hydrodynamic dispersion will be created, which will provide real information about the rates and directions of the spread of radionuclides in the underground environment after the descent of the cooling pond, and will also allow obtaining forecasts of changes in the radiohydrogeological situation under the influence of construction, operation or removal from the operation of radiation-hazardous objects against the background of the influence of climate change.

Discussion and conclusions

For the first time, a continuously operating hydrogeological model with high spatial discreteness has been built for the Uzh-Prypyatinterriver thanks to the use of data from 340 exploration and observation wells, which takes into account the fundamental change in the hydrogeological situation (levels, flows and directions of flows) after the descent of the Chornobyl NPP cooling pond. For the first time, the boundary separating fluvioglacial and alluvial deposits is displayed with high accuracy in the model, the boundaries of the hydrogeological "window" between the first and second aquifers, as well as of the "wall in the ground" that remained after the liquidation works in 1986; the distribution of groundwater heads on the Chornobyl nuclear power plant site, the hydrodynamic interaction between aquifers located above each other according to the data of bush wells drilled in 2019–2020 were taken into account. In addition to the data obtained by drilling wells, for the first time when creating the model, the results of deciphering the digital model map were used for relief from a satellite image. Thanks to forecast constructions that take into account the most likely scenario of climatic changes with a decrease in infiltration nutrition, the magnitude of the reduction of GWT by area was calculated.

The main scientific result is the heads distribution field obtained according to the third, most probable option (leaving the wall in the ground with a gradual decrease of the GWT due to a decrease in the level in the cooling pond to the mark of 103.5 m), which will ensure an improvement in the radiological state of groundwater due to an increase in the thickness of the zone aeration and its sorbent capacity and acceleration of self-cleaning due to the growth of flow gradients. At the same time, the unloading of contaminated groundwater will not take place in the Pripyat River, but in the isolated residual lakes of the former cooling pond. It will take up to 20 years for groundwater to reach the lakes from ChNPP industrial site. The time of migration of conservative tracers from other most dangerous areas of radioactive waste localization was also established.

Thus, for the first time, after the lowering of the cooling pond, the actual distribution of groundwater pressures was obtained, zones of vulnerability to radioactive contamination of groundwater and underground waters of the second aquifer from the surface in the sediments of the Buchak series were identified, and the geological-hydrogeological basis for the creation of a permanent migration of radionuclides model was laid.

Authors' contribution: Mykola Panasiuk – conceptualization, data provision, correction and improvement of the model, writing; Natalia Sosonna – hydrogeological simulation, data validation, formal analysis, preparation of illustrations, translation; Igor Kovalenko – hydrogeological simulation, writing (original draft), design of figures; Mykhailo Buzynnyi – radiological data, translation; Oleksii Shevchenko – review of publications, selection of scientific novelty, conclusions, revision and editing.

References

Bugai, D. A., Dzhepo, S. P., Skalskyy, & A. S. (1998). Forecasts of geomigration, risk assessments and principles of water protection activities in connection with radioactive contamination of groundwater in the Chornobyl exclusion zone. In O.V. Voytsekhovych (Ed.), *Radioecology of water objects in the zone of influence of the accident at the Chornobyl NPP. Vol. 2. Forecasts of water pollution, assessments of water use risks and effectiveness of water protection countermeasures for aquatic ecosystems in the zone of influence of the Chornobyl accident* (pp. 218–252). Kyiv [in Ukrainian].

Bugai, D. A., Dzhepo, S. P., Skalskyy, A. S. et al. (2001). Migration of strontium-90 into groundwater from buried radioactive waste "Red Forest". *Problems of the Chernobyl Exclusion Zone*, 7, 20–31 [in Russian].

Bugai, D. et al. (2012). Radionuclide migration at experimental polygon at Red Forest waste site in Chornobyl zone Part 2: Hydrogeological characterization and groundwater transport modeling. *Appl. Geochem.*, 27(7), 1359–1374. https://doi.org/10.1016/j.apgeochem.2011.09.028

Bugai, D. O., Dzhepo, S. P., Skalskyy, O. S., Kubko, Y. I., & Saprykin, V. Yu. (2018). Hydrogeological monitoring and mathematical modeling of radioactive contamination of groundwater in the Chornobyl Exclusion Zone and at the uranium facilities of the former Prydniprovs'kogo chemical plant (Kamyanske). *Geol. Journal,* 4 (365), 47–57 [in Ukrainian]. https://doi.org/10.30836/igs.1025-6814.2018.4.148466

Bugai, D., Dubas, V., Dyachenko, T. et al. (2019). Environmental impact assessment of the drowdown of the Chornobyl NPP Cooling Pond as a basis for its decommissioning and remediation. Vienna, IAEA. IAEA-TECDOC-1886.

Bukaty, M.B. (2008). Numerical methods of modeling the geomigration of radionuclides: Study guide. TPU Publishing House [in Russian].

Comprehensive assessment of cumulative environmental impacts of radiation-hazardous facilities in the Chornobyl Exclusion Zone. (2020). *Research report.* IPS NPP of NAS of Ukrain [in Ukrainian].

Groundwater modeling system. Version 3.1. Tutorial manual. (2000). In Environmental Modeling Research Laboratory of Brigham Young University. USA.

Harbaugh, W. A. (2005). MODFLOW-2005. The U.S. Geological Survey modular ground-water model—the ground-water flow process, U.S. Geological Survey Techniques and Methods 6–A16. https://pubs.usgs.gov/tm/2005/tm6A16/PDF/TM6A16.pdf. Accessed 3 Nov 2020

Martazinova, V. F., Horodetska, N. S., Rybchenko, L. S. et al. (2022). Features of the current state of the temperature-humidity regime of Ukraine since the beginning of the XXI century under the influence of changes in large-scale atmospheric circulation. *Meteorology. Hydrology. Environment monitoring*, 2, 22–34 [in Ukrainian].

Osadchyi, V., Shevchenko, O. & Krasovs'ka, A. (2021). Formation features of river underground runoff under global warming conditions. *EGU General Assembly 2021.* https://meetingorganizer.copernicus.org/EGU21/EGU21-15311.html

Panasiuk, M. (2014). Determination of the filtration coefficient of alluvial sands in the area of the ChNPP industrial site. *Safety Problems of Nuclear Power Plants and Chornobyl*, *23*, 124–130 [in russian].

Pollock, D. (2012). User Guide for MODPATH Version 6–A Particle-Tracking Model for MODFLOW. U.S. Geological Survey Techniques and Methods. https://pubs.usgs.gov/tm/6a41/

Sato, H. (2022). The Effect of Groundwater Bypass at the Fukushima Daiichi Nuclear Power Plant in 2014 by Detailed Facies Analysis and 3D Groundwater Simulation. In K. Nanba, A. Konoplev, T. Wada (Eds.), *Behavior of Radionuclides in the Environment III. Fukushima* (pp. 177–198). Springer.

Scheme of water protection measures for protection against radiation pollution of surface and underground waters in the ChNPP exclusion zone/volume II of the report: Assessment of the state of the geological environment and forecasts of radiation pollution. (1993).

Shabalin, B. H. (2023). Modeling of radionuclide geomigration from localized sources of pollution. In O.L. Shevchenko, V.V. Dolin (Eds.), *Radiohydrogeochemistry of catchment areas of the Chornobyl Exclusion Zone* (pp. 33-45). Naukova dumka [in Ukrainian]

Shestopalov, V. M., Lyal'ko, V. Y., Sytnykov, A. B. et al. (2001). *Water exchange in hydrogeological structures and the Chornobyl disaster*. In 2 parts. Institute of Geol. Sciences of the National Academy of Sciences of Ukraine [in Russian].

Smith, L., & Gaganis, P. (1998). Strontium-90 migration to water wells at the Chornobyl nuclear power plant: Re-evaluation of a decision model. *Environ. Eng. Geosci.,* 4(2), 161–174.

The Official U.S.G.S MODFLOW (A Modular Tree Dimensional Finite Difference Groundwater Flow Model). (2012). In Waterloo Hidrogeologic. https://pubs.usgs.gov/tm/2005/tm6A16/PDF/TM6-A16ch2.pdf

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ПОСТІЙНА МАТЕМАТИЧНА МОДЕЛЬ ФІЛЬТРАЦІЙНИХ І МІГРАЦІЙНИХ УМОВ МЕЖИРІЧЧЯ ПРИП'ЯТЬ – УЖ ЧОРНОБИЛЬСЬКОЇ ЗОНИ ВІДЧУЖЕННЯ

В с т у п . ***За останні 8–10 років значно змінилися радіогідроекологічні та гідрогеологічні умови Чорнобильської зони відчуження. Під впливом виведення водоймища охолоджувача з експлуатації в масштабах регіону змінилися рівні, швидкість та напрямки руху підземних вод. За цей час були створені нові радіаційно небезпечні об'єкти: сховища відпрацьованого ядерного палива (СВЯП-2 та ЦСВЯП). Також посилився вплив зміни клімату на режим водних об'єктів. Очевидно, що для вивчення впливу радіаційно небезпечних об'єктів на водне***

середовище зони відчуження, прогнозування змін гідрогеологічних умов під впливом змін клімату та техногенних навантажень необхідно створити оновлену модель фільтраційно-міграційних умов з можливістю її подальшого коригування та вдосконалення.

Методи. ***У процесі створення і розробки постійно діючої математичної моделі на базі методу скінчених різниць розглядалися геологічні та гідрогеологічні умови району досліджень, проводились з використанням ГІС-технологій просторові побудови для візуалізації геологічної будови, складено фільтраційну схему для обчислювальних операцій. Для побудови поверхонь геологічних горизонтів використовувалась програма QGis, для розробки фільтраційної моделі – програма Visual MODFLOW.***

Результати. ***Побудовано модель фільтраційних та міграційних умов межиріччя Прип'ять – Уж Чорнобильської зони відчуження. Отримано розподіл рівнів ґрунтових вод та напорів у бучацькому водоносному горизонті. Виконано прогнози шляхів, напрямків та часових меж поширення забруднювачів з підземними водами від радіаційно-небезпечних об'єктів, а також прогнози впливу змін граничних умов водоносного горизонту на гідродинамічні параметри ґрунтових вод для обґрунтування проєктних рішень із вдосконалення мережі спостережних свердловин та визначення умов підтоплення проммайданчика ЧАЕС. Здійснено прогнози впливу глобального потепління на режим підземних вод.***

Висновки. ***Прогнозне поле розподілу напорів демонструє можливість покращення радіологічного стану ґрунтових вод внаслідок: збільшення товщини зони аерації та її сорбційної ємності, прискорення самоочищення завдяки зростанню градієнтів підземного потоку. Важливо, що розвантаження забруднених підземних вод відбуватиметься не в річку Прип'ять, а в ізольовані залишкові озера колишнього ставка-охолоджувача. Для того щоб підземні води потрапляли до озер з проммайданчика ЧАЕС, знадобиться близько 20 років.***

Ключові слова: ***геофільтраційна модель, скінченно-різницевий метод, чисельне моделювання, рівень ґрунтових вод, коефіцієнт фільтрації, Чорнобильська зона відчуження.***

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