https://doi.org/10.26565/2410-7360-2025-63-02
UDC 622.841:622.847:556.3

Received 12 October 2025
Accepted 17 November 2025

Groundwater level modeling during the coal mines´ decommissioning

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ABSTRACT

Problem Statement and Purpose. Abandoned or non-operating coal mines that were closed due to flooding pose environmental hazards, primarily due to the risk of groundwater contamination, subsidence, and waterlogging of surrounding areas resulting from flooding and rebounding groundwater levels. Estimating the risk of flooding with the help of the numerical hydrogeological modelling for areas inhabited by coal mines that were built at the beginning of the last century is challenging, since information on operational parameters (such as mine workings' features, pumping rates, etc.), has not been preserved to date or is limited. A study examined the capabilities of groundwater flow numerical modelling in predicting groundwater rebound and its accuracy in areas surrounding old, closed coal mines.

Data and Method. As pilot study areas, the Saxony coal mine region (Germany) and the Central Donbass (Ukraine) coal mines group area were established. Both pilots integrate more than 20 minefields of former interconnected coal mines with more than 100 years of mining history and a similar excavation method. In this study, the numerical modelling software packages were used as a tool for the numerical groundwater flow simulations and predictions in a three-dimensional groundwater system of coal mines areas. All of them contain a three-dimensional (3D), finite-element groundwater flow code. Additionally, adjustments in the form of calculation decisions (such as sensitivity analysis and multivariate simulations on a block-simplified model) were developed and implemented to address hydraulic system parameter uncertainties and the insufficiency of historical mining data (lack of pumping rates information, number of mining horizons, mine workings features, and geometry).

Result and discussion. This study demonstrates the conceptual approach and numerical groundwater flow evaluation for the condition in which pumping isn't maintained and no dewatering measures are provided in the area to prevent flooding at the critical level. The developed numerical hydrogeological model covers all common steps of precise and complete numerical simulations, including transient conditions simulations, that reconstruct the full range of mining stages during the mines' life. The special methodology of calibration was adjusted for this purpose – the cycle of steady-state, transient, and prediction simulations of the groundwater level until the lowest possible RMSEs between observed and simulated groundwater levels in the model were achieved.

Keywords*: non-operational coal mines, groundwater rebound, groundwater numerical modelling, conceptual hydrogeological model, drain nodes hydraulic condition, hydrogeological parameters.*

In cites: Boiko Kateryna, Ulitskiy Oleg, Boiko Pavlo (2025). Groundwater level modeling during the coal mines´ decommissioning. *Visnyk of V. N. Karazin Kharkiv National University. Series Geology. Geography. Ecology*, (63), 23-34. https://doi.org/10.26565/2410-7360-2025-63-02

1. Introduction. The numerical modeling has been extensively tested recently as a tool for predicting hydrogeological problems associated with mines flooding at the pilot sites in countries where the typical situation with abandoned coal mines takes place – England, China, Ukraine, Germany, and Spain. The reason we need to use numerical hydrogeological modeling at sites like old worked-out coal mines (Ukraine, Germany) is that modern scientific approaches can simulate groundwater level rebound, predict flooding, and address data gaps on the technical parameters of the mineral extraction process. The range of environmental issues posed by coal underground mining includes soil degradation, pollution of groundwater and surface water, and surface subsidence, which occur during the operational period and continue into the postmining period. Partly, deformational subsidence zones forming during the postmining period are caused by groundwater table recovery and iterative changes in the pore-fluid pressure state in the rock mass. The rock mass, characterized by significantly altered mechanical and groundwater conductivity properties during caving and extraction, exhibits reduced resistance to geostatic pressure during uncontrolled flooding in mines and during groundwater table recovery [1]. Assessing the risks of area flooding due to the groundwater rebound during the postminig period as for coal mines that were operating from the beginning of last century and were closed also then proved to be very difficult [2], especially when high-risk sites are flooded [3], because information about the condition of mine workings, the presence and features of voids and the integrity of the worked-out space, and then about operational parameters such as the intensity of excavating, the number of worked-out seams and the depth step, has not been preserved to our times, or is limited. Hence, what is common for `usual` parameters for the transient calibration, namely, parameters of `historic stresses` for the groundwater flow during the excavation, seems to be unknown. Moreover, transient calibration cannot be performed on some preliminary models, as the following predictions for groundwater rebound may fail. On this basis, some solutions that apply analytical and mapping approaches, as well as the decision to use transient calibration during modelling of the area of old (in some cases, abandoned) mine workings, were developed. It was first tested in the Central Donbas area, where the groundwater rebound process is more detectable and visible nowadays, and then proposed for groundwater level prediction at the Lugau-Oelsnitz coalfield (the Saxony mining region).

In contrast to half-analytical and box-type models previously developed for the Saxony mining region [4] and for other mining regions across the EU, the numerical groundwater flow model enables the reconstruction of the specific features of groundwater behavior within the entire desired catchment area, including coal mine fields. The latter has been demonstrated by the example of a numerical groundwater model, built for the Central Donbass study area [5, 6], the finite difference numerical models of groundwater flow throughout the entire life cycle of the Western Donbass area, taking into account the stochastic heterogeneity of disturbed rock masses, were proposed and tested in the following works [7, 8].

2. Materials and Methods

Study Areas. In the Toretsk-Yenakiieve mining and urban agglomeration (which is geographically linked to the Central Coal Mining Region of Donbas, Fig. 1), 28 mines were operating before the restructuring of Ukraine's coal industry, most of which were constructed in the early 19th century. Today, more than 90% of the mines in the agglomeration are flooded. Only the mines of the "Toretskvuhillya" State Enterprise remained operational until early 2022. Due to military operations, mines are switching to emergency mode, leading to uncontrolled flooding and potentially significant disturbances in the area's hydrogeological regime, groundwater contamination, and extensive flooding.

The hydrogeological stratification scheme of the studied territory is represented by aquifers of modern and Upper Quaternary alluvial deposits of floodplains, first supra-floodplain terraces and valley bottoms (a, adQ_{III-IV}), undivided Lower-Upper Quaternary aeolian-deluvial deposits (vd Q_{I-III}), as well as the aquifer complex of Upper and Middle Carboniferous deposits (C_2-C_3) [5].

The Lugau-Oelsnitz coalfield region (Fig. 2) is one of the large coal deposits' industrial sites in south-west Saxony (Germany), which has been mined continuously. Namely, the region was renowned for its coal deposits and significantly shaped Germany's industrial revolution and economic growth in the 19th century [9] and achieved a production capacity surpassing 2 million tonnes of extraction produced by the 11 coal trades, reaching an excavation depth of 800-900 m [10] by the beginning of the 20th century.

The geological structure in the study area belongs to the Permo-Carboniferous formation, while the stratigraphical cross-section is built from Ordovician, Carboniferous, Permian, and Cenozoic deposits. Productive coal seams compose the upper Carboniferous formation, which is presented as coarse and fine sandstones with layers of claystone and siltstone in grey facies. The Permian Rotliegend is the thickest unit in the study area [11], consisting of a distinctive alternating sequence of conglomerate, siltstone, and mudstone, thin lacustrine carbonates, pyroclastic horizons, and alternating layers of siltstone, medium- and coarse-grained sandstone. The Carboniferous-Permian boundary is marked by the occurrence of the "grey conglomerate" of the Lower Rotliegend. Similar to the Carboniferous units, the Rotliegend sediments represent erosion debris, which, after a long period of dormancy in the Upper Carboniferous, accumulated in an overlying Rotliegend depression formed above it.

Thus, the upper part of the Rotliegend (Mülsen formation) may play the most crucial role in groundwater recharge zones and groundwater storage. The permeability of Mussel formation can reach 10^{-4}-10^{-5} m/s in some cases [12].

Upper Carbon layers and deposits of the Haertensdorf formation are considered low-permeability deposits and are classified as an aquitard, as are volcanic and siltstone deposits of the Planitz formation. Ordovician phyllites are characterized by low permeability properties (permeability – 10^{-9}-10^{-7} m/s). That's why in hydrogeological modelling, they serve as the last division of the hydrogeological system without assuming the discharge into the upper layers.

Mining features. The group of Central Donbass mines is characterised by the exploitation of the geological environment of most coal mines in the region throughout the entire period of operation, to maximum depths of 1,000-1,300 m (-1,000 -1,100 masl.), and by a total volume of excavated space of 705 thousand m^3. The total mine water inflow amounted to 193.8 thousand m^3/day.

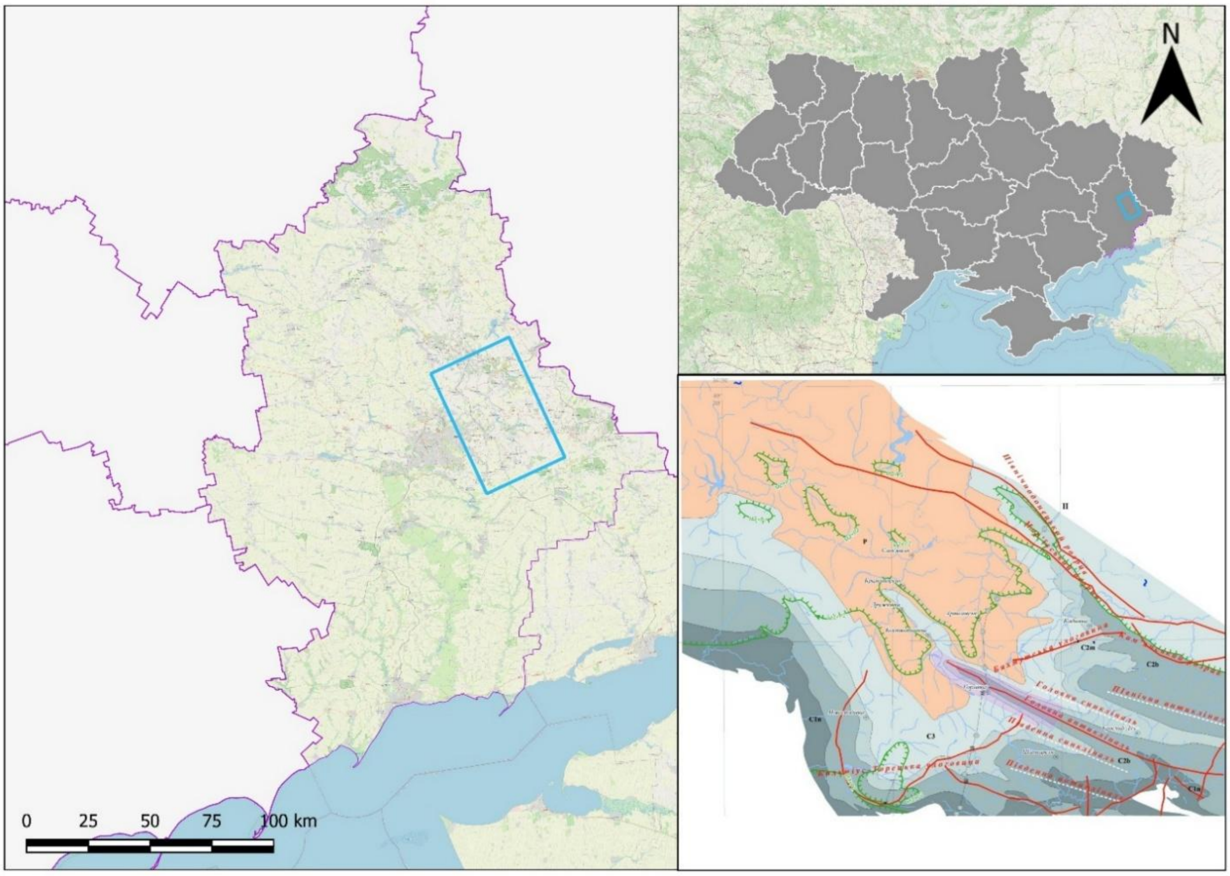

Fig. 1. The location of the Central Coal Mining Region of Donbas study area
(including the geological extract in the lower right frame)

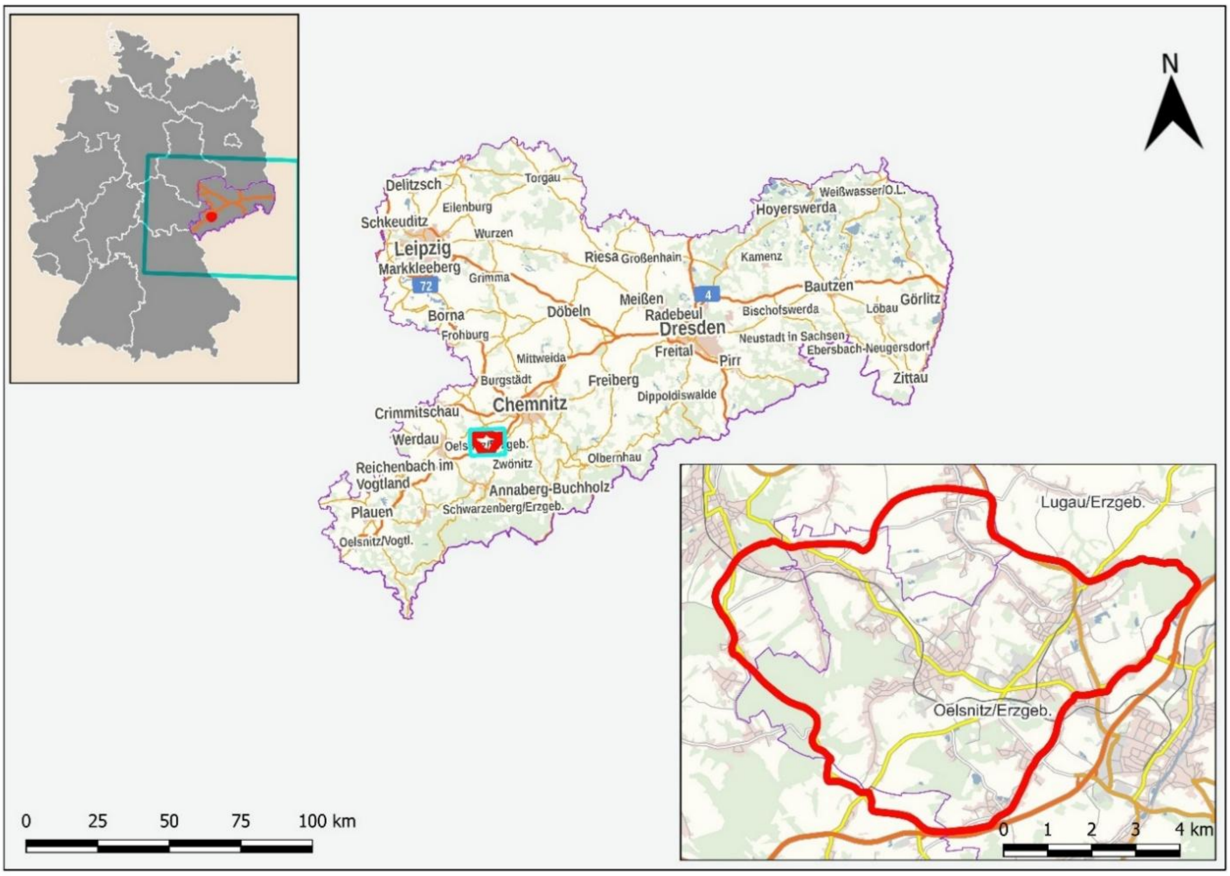

Fig. 2. The location of the Lugau-Oelsnitz study area (Base map – the Precenozoic geological map – the source: https://www.luis.sachsen.de/fachbereich-geologie.html)

The excavation within the Lugau-Oelsnitz coal field expanded through the carbon operational layers (coal seams). It covered the depth interval from the absolute mark +180 m a.s.l. to the absolute mark -450 m a.s.l. The average thickness of coal seams varies from 0.5 m to 5.0 m. Mining operations took place at 21 primary mines and operational cross-sections.

According to the calculations, provided by Dr. M. Eckart [4] a raw volume of 150 million m³ can be considered as a total volume of extracted deposits, while only 30% - 45-47 million m³ - of that volume, considering the reduction of the initial volumes by subsidence and backfilling, that happened during the mining history, may be used as a defining value of the residual underground volume and could be reasonable for the prediction calculations of mines flooding.

According to the long history of mining, mining plans and other technical parameters, such as pumping rates, groundwater inflows to the mining horizons, the location of horizons and horizon depth intervals, as well as production progress for each period of time, etc., are not saved. Hence, no reference information for the water rates information in the form of groundwater inflows into the mine workings, nor in the form of pumping rates recorded values, exists. To estimate the importance of the numerical modelling calibration criteria, which, in normal database conditions, act as measured inflow rates during the mining stage, the approach described below was developed.

Modelling tools and approaches. To simulate the groundwater rebound process, recent worldwide scientific studies [13, 14, 15] employ a numerical model that integrates various hydrogeological parameters of a three-dimensional hydrogeological system, including void storage information, water inflows during the excavation or pumping records, as well as hydrogeological data – the strata permeability, porosity, and storativity, etc. By inputting these parameters, the numerical model predicts the spatial and temporal distribution of groundwater recharge and enables the estimation of geofiltration parameters, as well as the effects of fluctuations in water budget components, in a post-mining groundwater system [16] and during groundwater table rise. These predictions are critical for anticipating potential environmental risks and formulating appropriate management strategies for water management and ecological sustainability.

In this study, the numerical modelling software packages were used as a tool for the numerical groundwater flow simulations and predictions in a three-dimensional groundwater system of coal mines areas. All of them contain three-dimensional (3D), finite-element groundwater flow code (equations). They are used worldwide to design dewatering or depressurization systems, predict local and regional environmental impacts of mine dewatering, and to solve various popular hydrogeological issues.

Whereas the 3D numerical modeling requires the incorporation of mine workings` features plans in addition to geological (hydrogeological) structure scheme, the scientific approach proposed and described in the article substantiates the possibility of using drains nodes for the transient calibration to simulate the extraction stage and corresponding groundwater table drawdown, the subject to appropriate calibration with a known amount of water inflow into the mine workings. It is a reasonable argument that the restoration of groundwater levels in a coal basin depends not only on the cavity. Throughout all stages – both excavation and mine closure – groundwater inflow velocity and volume are key factors in understanding the drainage of aquifers within the coal fields' catchment areas [5, 15].

The study presents the results of a numerical experiment, based on a deterministic model, to calculate the time required to flood a 100-meter-thick rock strata (reflecting the typical step between the horizons of mine workings in the Central Donbas region).

The physical character of the experiment's conclusion enables to state that the amount of water inflow into the mine, which can be determined by the modified Darcy‘s formula (1) [17], is the main operating parameter of the positive water balance during the modeling of groundwater level rebound, but taking into account the increased hydraulic conductivity due to the intensification of man-made fracturing of coal rocks during the caving.

$$Q_i = KF\frac{\Delta H}{m_0}, \qquad (1)$$

where K – the hydraulic conductivity, m/day; F – the filtration area, sq m, m_0 – the aquitard thickness, m, ΔH – the hydraulic head difference, m.

Groundwater inflow rates also served as a criterion for the model calibration, after they were calculated for each drain node, as a proposed missing transient simulation parameter – mine workings' plans – at the Lugau-Oelsnitz coal-field site. The rebound phenomenon occurs when these voids are slowly refilled with groundwater after mining ceases, leading to a 'rebound' of the water table towards its pre-mining position. Thus, the process of groundwater rebound should be considered to consist of several stages and hydrodynamic processes – mine workings flooding (which is mainly subject to the laws of hydraulics) and groundwater table recovery to the priming stage (which is subject to the laws of geofiltration).

Setting up a numerical experiment to validate geofiltration conditions. A deterministic hydrogeological model was created during the research, reflecting the actual geological structure of the section at a specific interval between working horizons of the "Central" mine ("Toretsvugillya" State Enterprise, Toretsk), allows assessing the nature of the interaction between the "mine workings – groundwater – rock mass" system in terms of the flooding of mine workings at the inter-horizontal interval and determine the degree of influence of changes in the coefficient of voids filling (C_f) and the hydraulic conductivity (K) and other parameters of geofiltration on the rate of water saturation of a 100-metre-thick rock mass with existing mine workings (Fig. 3).

The interval between the mining horizons of 816 m and 916 m of the "Central" mine was analysed. Within the specified interval, the total volume of mine workings, the geometry of which can be accurately reproduced, is 2% of the calculated cube of the rock mass, the volume of which is $3 \cdot 10^8$ m^3. This value was obtained based on information about the location and area of the mining workings at the horizon. Hydraulic boundaries were set due to the tectonic structures (non-permeable fractures) around the mine fields, so that the only sources of groundwater recharge are inflows from adjacent aquifers and infiltration. The aquifer system is represented by sandstones of series C_2^5, C_2^6, and C_2^7. According to the results of formation tests conducted within the research area [18], aquifers at depths of 816 and 916 m are associated with the zone of slow water exchange. They are characterised by hydraulic conductivity values of 0.0015-0.0004 m/day.

First, the amount of inflow on the horizon 916 m with the help of Eq.1 was estimated. The obtained value (1215 m^3/day) is well correlated with the recorded long-term average inflow. The flooding simulation was performed using a groundwater inflow value estimated from the total water inflow. The time interval was set at 30 days, and the model was stationary, reflecting the period of disconnection of the hydrogeological conditions of the mine workings as a disturbing factor. An additional geofiltration parameter was used – the specific yield coefficient, taken from the literature on the study of the hydrogeological conditions of the territory, 0.0012 [18].

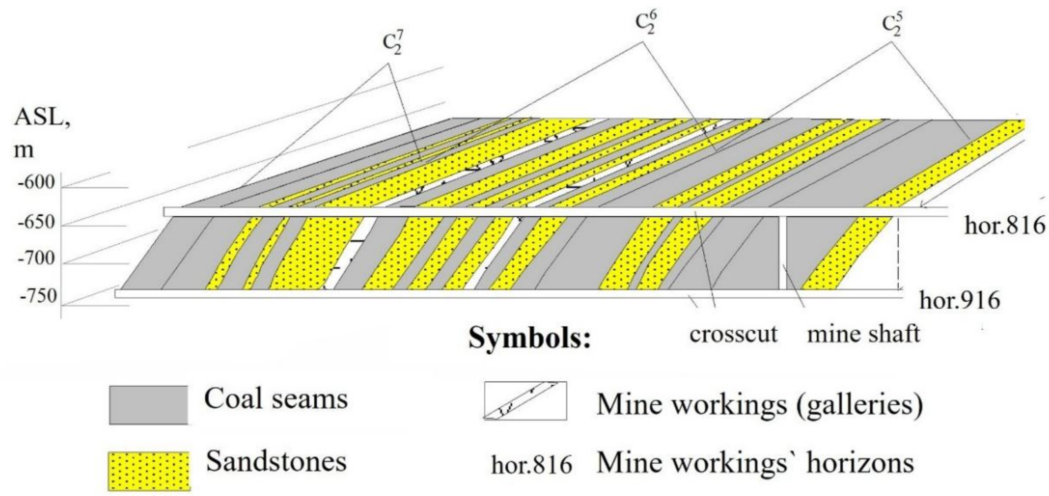

Fig. 3. Scheme of a deterministic hydrogeological model developed for a rock block at an horizon interval of 100 m with an approximation by a finite difference mesh

The results obtained were compared with the current observed groundwater level data. Based on a graphical analysis of actual observations of rising groundwater levels in mines of the southern wing, as well as a comparison of the calculated (Eq.1) and the exact time of flooding of inter-horizon intervals using the example of the mines of the Gorlovka-Yenakiieve group, it was established that the current rates of mine flooding are pretty compatible with the hydraulic conductivities, which are increased relative to natural ones. After all, the average calculated groundwater rebound time for the studied group of mines (taking into account recalculating the groundwater level rise time for some intervals at a 100 m thickness) is 185 days. In contrast, the average actual rebound time for the specified thickness is 138 days. This acceleration in the rate of groundwater level rise is explained by an increase in the permeability of the rock mass around the mine workings, resulting from prolonged undermining by extraction operations.

To assess the degree of influence of increased hydraulic conductivity or porosity of the rock mass on the acceleration of mine flooding and rising groundwater tables, a sensitivity test was performed for the specified parameters. The dependencies shown in the first graph (Fig. 4a) indicate a significant acceleration in the flooding rate as hydraulic conductivity changes. Thus, at the maximum (within the range of the given values) hydraulic conductivity (K = 0.03 m/day) and at a constant volume of the excavated space (V=6635.8 thousand m^3, coefficient of voids filling C_f=1), the flooding time increases from the calculated 180 to 120 days.

At the same time, the maximum deviation of the flooding time at the accepted maximum filtration coefficient (K=0.03 m/day) when the filling coefficient C_f changes from 1 to 0.38 is only 15 days (flooding acceleration by 15 days) (Fig. 4b). Thus, the calculation model is more sensitive to changes in the hydraulic conductivity, which characterises the rock mass as a whole within the mine field and is taken into account in further calculations.

The experiment setup and its results, verified

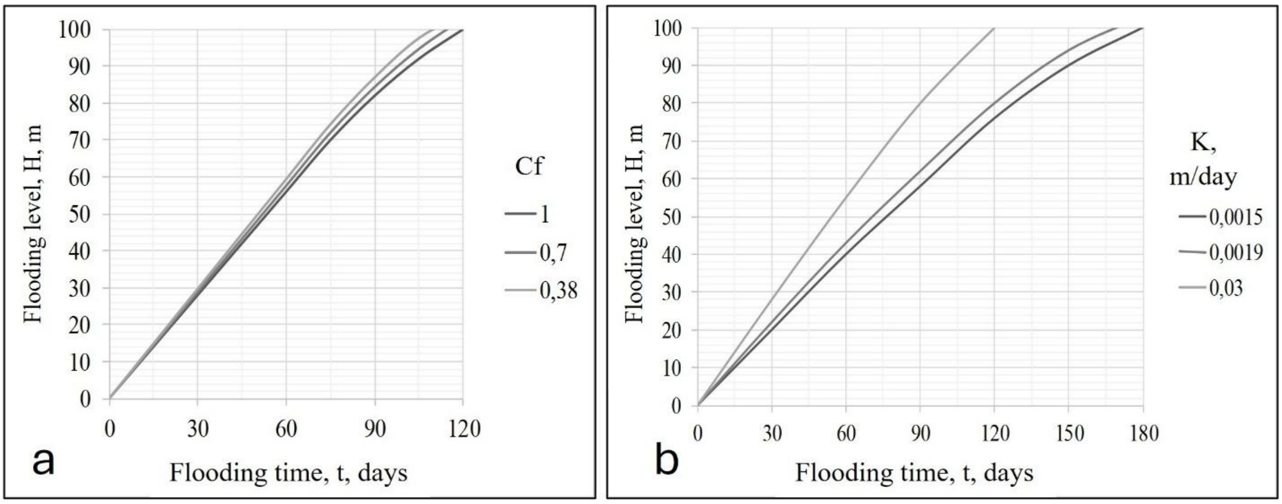

Fig. 4. a – the graph demonstrating how the flooding time of a 100-metre block of rock mass varies with different values of hydraulic conductivity (0.03; 0.0019; 0.0015 m/day) and with the coefficient of voids filling C_f =1; b – the graph demonstrating how the flooding time of a 100-metre block of rock mass varies with different values of C_f (1; 0.7; 0.38) and at K=0.03 m/day

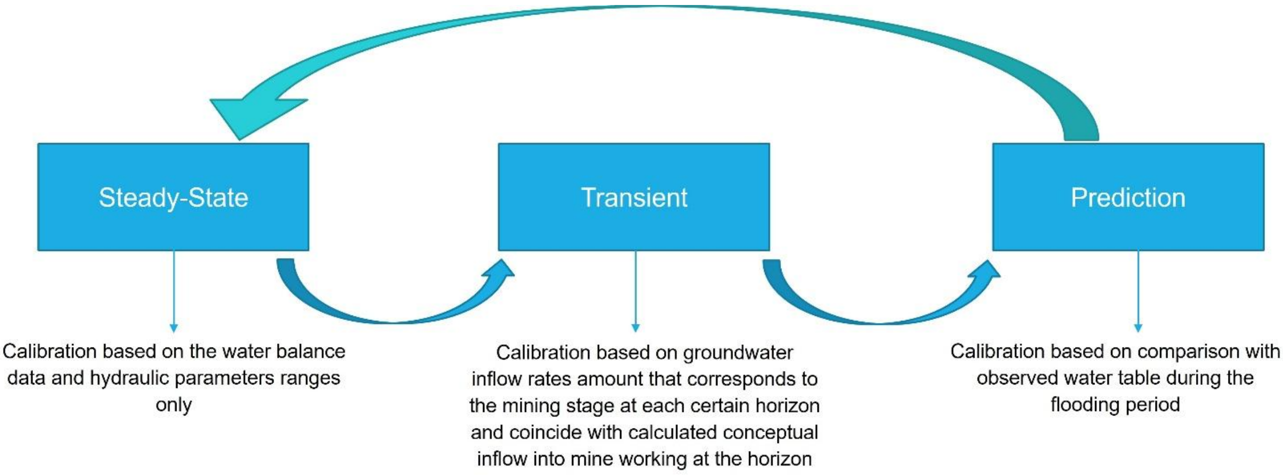

Fig. 5. Scheme of the generally accepted sequence of numerical hydrogeological modelling, taking into account the specifics of calibration in conditions of insufficient input data

by actual data on tracked flooding (groundwater levels recorded marks) using a semi-analytical numerical hydrogeological model, demonstrate the importance of considering and calibrating the hydraulic conductivity within the 3D geological space above the mine workings. The transient simulation of groundwater level dropping (that actually happened in the past but is necessary to be performed as a transient simulation stage), considering the statement above, may be a subject of inflow rates (within drain nodes) calibration into the drain network designed for each working horizon and serving as a hydraulic head boundary during the excavation.

Setting up the numerical flow model for the Lugau-Oelsnitz coal mines area. The area of a constructed numerical model corresponds to a polygon with a maximum 7,8 km spreading from the North to South, and a maximum of 11 km in the W-E direction. The total model domain area is 48 km^2. It includes 20 blocks that correspond to the coal mines fields. Model hydraulic boundaries include surface zoning into precipitation recharge zones, constant-head boundary conditions, and river boundaries. Direct recharge by infiltration of precipitated water occurs throughout the basin considered in the numerical model.

Steady-state simulation. Steady-state simulations were performed to specify initial hydrogeological parameters of the inner hydrogeological structure and to establish the natural groundwater flow distribution (groundwater levels), based on the known topography, 3D geological/hydrogeological structure, and known water balance components.

Transient simulation. Transient simulations were conducted to reproduce the mining period and model the maximum groundwater drawdown resulting from mining operations in the investigated area.

The coal layer of the numerical hydrogeological model comprises elements of the 11th operational coal seams that were mined during the operational period at the study area. The lowest operational coal seam, "Kneisel Flöz", and the upper productive seam, "Grund flöz" are presented at the central and western part of the area, and according to the geological layering and dip direction, were mined at the final stage of the operational period. Whereas mines located in the eastern part of the area were processing the upper group of the carbon deposits in the coal seams "Neuflöz 1-4", "Öberflöz", "Hoffnungföz". This conceptual understanding enables the development of ideas about the mine's life cycles and their average periods, including the number of productive horizons within operational stages.

The duration of the transient simulations corresponds to the supposed time frame of the mining operational period at the Lugau-Oelsnitz mining area, which took place from approximately 1860 to 1871 and 1971. The mining operations were simulated with the help of drains nodes. Drains nodes are considered as zero-pressure conditions. Each drain was included in the simulation at a specific time (60 drains in total), corresponding to the start of the new mine-horizon excavation stage.

As long as any mining plan has not been preserved till the present time, the mining schedule and drains locations were established according to the

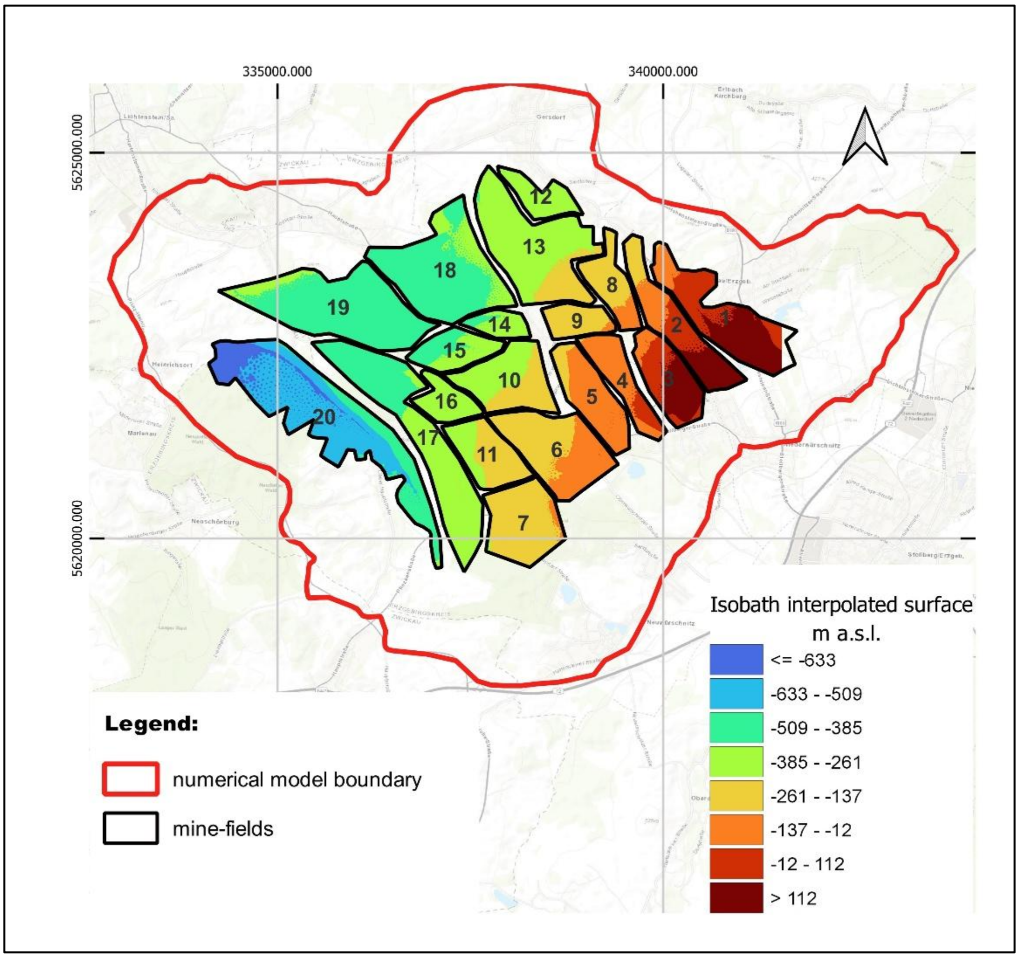

Fig. 6. Natural interpolated distribution of isobath surfaces created to assign drain nodes

following approach. For these purposes, every coal seam layer was interpolated within the mining field (block) and classified based on the natural distribution of depth interval divisions. The location of potential drains at each interval corresponding to the operational coal seam distribution was chosen as the geometrical center, and the relevant groundwater inflow rates were calculated based on the area and interval thickness.

The groundwater inflow rate equivalent for each drain is calculated as shown in Table 1.

Where:

- Area – is an area of coal seam interval within each block, estimated based on the interpolated surface;
- Q by area – the inflow rate calculated with the seam thickness assumed based on the geometries of coal seams, and the area, established on interpolated surfaces;
- Voids Volume – the volume from the initial information on existing residual volumes, recalculated for the identified depth interval;
- Q by Volume – the inflow rate calculated based on information on residual volumes;
- Average interval of each stage of mining – 10 years. This period was established based on the duration of "operation life" at each mine and the maximum depth of each mine.

Table 1

The groundwater inflow to the mining interval calculation example

Block No.	Depth Interval, masl	Area, km^2	Q m^3/day by area	Voids Volume, m^3	Q m^3/day by Volume
20	-512 – -641	1.8	246	1350500	370

Predictive simulations. Predictive simulations were carried out to reconstruct the phase related to the start and duration of mine working flooding, and to compare the obtained groundwater level recovery velocity with measurements from monitoring observation wells. Results from predictive simulations were obtained and compared with groundwater rebound velocities observed in 2003 and 2014 for two monitoring wells. The predictive simulation involved 211 time-step intervals. In physical terms, the duration of predictive simulations corresponds to the time interval from 1971 to 2061.

3. Results and discussion. Based on steady-state conditions simulations, the hydrogeological parameters of the major hydrogeological units were derived. Initially, parameters were obtained from the literature review [12, 19, 20].

The main calibrating criteria in a steady-state simulation were a convergence with conceptual water balance components. Though the uncertainties in some values still exist, such as river baseflow measurements (it was possible to check the appropriateness of calculated baseflow for the river Würschnitz only, as a referencing parameter was given by Kolitsch, S. 2008 [19]), the general distribution of the water balance components satisfies the features of the groundwater system.

This is demonstrated by the fairly accurate water balance inputs obtained during calibration in the Lugau-Oelsnitz study area (Table 2).

Though uncertainties in some values still exist, such as river baseflow measurements (it was possible to check the appropriateness of calculated baseflow for the river Würschnitz only, as a referencing parameter was given [19]), the overall distribution of water balance components corresponds to the characteristics of the groundwater system (Fig. 7).

In general, the depth to the groundwater table within the area of investigation ranges from 0,5 to 2 m, which could indicate the permanent effect of hydraulic boundaries unaffected by the mining operations. From initial sets of simulations, it can be observed that the maximum groundwater level drawdown occurs at +175 m a.sl., at a depth of 147 m below the surface. The maximum drawdowns are related to the East-centre part of the investigated area. The simulation results also show that the process of groundwater table rebound was completed between 2014 and 2017, when natural absolute levels, similar to the modelled initial levels, were achieved (Fig. 4). Thus, the process of groundwater rebound might have lasted 43-46 years. The position of the groundwater level (2018-2020, according to the predictive simulation results) at the eastern bor-

Table 2

The water balance components calculated based on the numerical simulations and obtained from the conceptual model

	Conceptual value	Numerical model value
Recharge, m^3/s	0.26	0.18
Constant-Head inflow, m^3/s	1.10	1.50
Total inflow, m^3/s	**1.36**	**1.68**
Constant-Head outflow, m^3/s	-0.20	-0.18
Rivers baseflow, m^3/s	-0.97	-1.30
Evapotranspiration, m^3/s	-0.02	-0.02
Total outflow, m^3/s	**1.39**	**1.50**

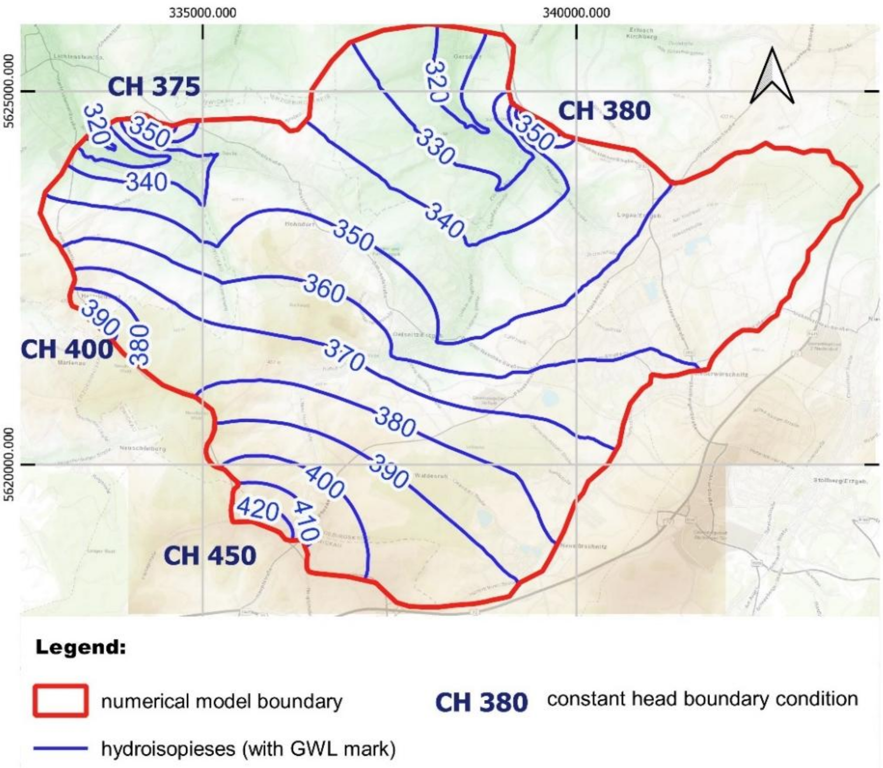

Fig. 7. Groundwater conceptual flow within the Lugau-Oelsnitz study area simulated in natural conditions

der of the model has been demonstrating the ongoing groundwater recovery.

Drains network design approach that might recreate the excavation period was also proposed as a tool for the numerical model of the Central Donbass specific coal mines area, which combines a group of mines – 'K. Marks', 'Krasny Profintern', 'Krasny Oktyabr', 'Yunkom' – characterised by the same flooding regime.

By adjusting the filtration parameters within a specified range, we achieved piezometric contours that most accurately reflected the actual flood levels recorded on the final date of existing observations – 1 August 2019. The most accurate with respect to the recorded data is the flood level distribution surface shown in Figure 8.

The time interval during which such a distribution of absolute flood level marks was achieved in the model is 520 days, whereas the actual time required to raise the level to the specified marks based on observation data is 450 days. This can be explained by the fact that the flooding pattern inferred from the measurement data in the shafts differs slightly from the flooding behavior of the array within the depression cone. Thus, the rise in the flooding level in the mine shaft apparently occurs much faster than at the edges of the depression cone [21]. This is confirmed by the modelling results, which indicate the influence of the aquifer's capacitive parameters on the nature of groundwater-level recovery during mine flooding.

4. Conclusion. The hydrogeological conditions differ at each study area: the carboniferous formation of productive coal layers of Lugau-Oelsnitz mining field is considered more as aquitard – the groundwater system consumes main groundwater inflow from the upper high permeable formation of the Rotliegend (Müsseln formation) that also plays an essential role in groundwater storage, while the Central Donbass hydrogeological conditions are marked with the outcropping of the carboniferous formation to the surface, which determines the predominance of the overall influence of groundwater recharge from precipitation. Nevertheless, the sensitivity test performed after the deterministic model of the Central Donbass coal-mines fields reconstruction, as well as calibrations performed on steady-state and transient stages of groundwater flow modelling for the totally numerical model built for the Lugau-Oelsnitz coal-mines area, demonstrate that the groundwater system and mine waters in most abandoned coal mines with a long mining history may be considered as a joint system during the groundwater table rebound after the mines closure. The connection can be observed between mines flooding and dynamic equilibrium with the local hydrogeological regime.

Based on the calibrations of numerical hydrogeological models for mining regions in Germany and Ukraine, which share similar characteristics in terms of coal mining features, long-term mine operation and similar post-operational conditions, it has

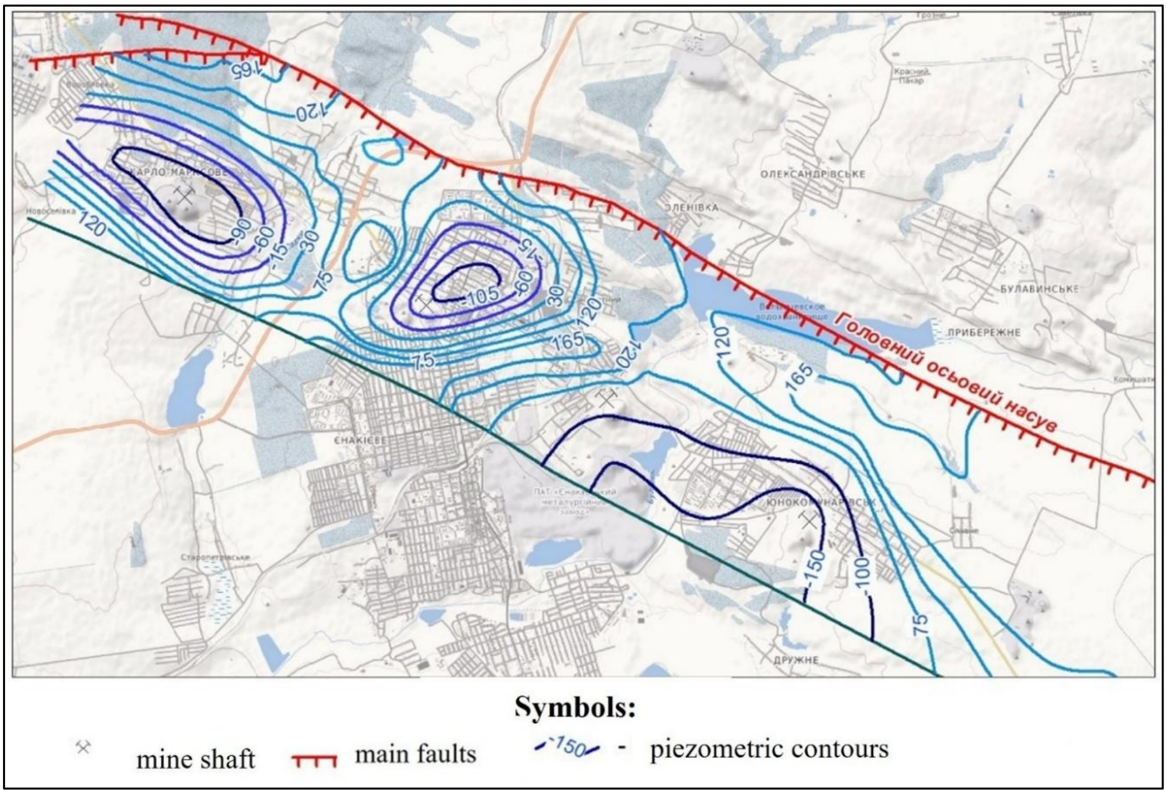

Fig. 8. Modelled piezometric contours obtained for the Central Donbass specific coal mines area

been established that the permeability and capacity parameters of the anthropogenically damaged rock mass within the interval of flooding levels differ significantly from natural ones, namely: the hydraulic conductivity and the specific yield can increase by an order of magnitude from that characteristic of the water-bearing strata, which is explained by the presence of technogenic fracturing of the bedrock.

Considering these conditions, the approach, which enables the reconstruction of the coal extraction period in mines (if the data has been lost due to the age of the mines themselves) by approximating the inflow value at the drainage node at each extraction interval, has proven itself to be quite effective in the process of numerical hydrogeological modelling of the disturbed geofiltration regime within mine fields.

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Authors Contribution: All authors have contributed equally to this work
Conflict of Interest: The authors declare no conflict of interest

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Моделювання рівня підземних вод у процесі виведення вугільних шахт із експлуатації

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Недіючі вугільні шахти, які були закриті шляхом затоплення (мокрої консервації), становлять небезпеку для навколишнього середовища, насамперед через ризик забруднення ґрунтових вод, просідання ґрунту та заболочування прилеглих територій. Оцінка ризику затоплення за допомогою чисельного гідрогеологічного моделювання для територій, на яких розташовані вугільні шахти, що побудовані на початку минулого століття, є складним завданням, оскільки інформація про експлуатаційні параметри не збереглася до наших днів або є обмеженою. Під час дослідження було вивчено потенціал чисельного моделювання динаміки підземних вод для прогнозування відновлення рівня підземних вод під час затоплення шахт та ступінь його точності. В якості пілотних досліджуваних територій були обрані ділянки видобутку у вугільному басейні Саксонії (Німеччина) та група шахт Центрального Донбасу (Україна). Обидва пілотні проекти характеризуються тим, що об'єднують понад 20 шахтних полів колишніх гідравлічно пов'язаних вугільних шахт з більш ніж 100-річною історією видобутку, та є подібними за схемами експлуатації. Програмні продукти, що були використані під час дослідження, містять тривимірний код кінцевих елементів, що використовується для обчислення характеру руху підземних вод. Крім того, були розроблені та впроваджені підходи калібрування у вигляді розрахункових рішень (таких як аналіз чутливості та багатовимірні моделювання на спрощеній блоковій моделі) для усунення невизначеностей гідрогеологічних параметрів та проблем недостатності історичних технічних даних, таких як швидкість відкачування, кількість горизонтів видобутку, особливості видобутку та контури гірничих виробок. Розроблена узагальгююча чисельна гідрогеологічна модель охоплює всі загальні етапи повного циклу чисельного моделювання геофільтрації, включаючи моделювання етапу неусталеної фільтрації, характерного саме для періоду експлуатації. Для цієї мети була розроблена спеціальна методологія, що включає цикл калібрувань усталеної та неусталеної фільтрації, а також калібрування прогнозних параметрів з метою досягнення найменших похибок моделювання між спостережувальними та модельованими рівнями підземних вод.

Ключові слова*: недіючі вугільні шахти, відновлення рівня підземних вод, чисельне моделювання геофільтрації підземних вод, концептуальна гідрогеологічна модель, гранична умова дрени, гідрогеологічні параметри.*

Внесок авторів: всі автори зробили рівний внесок у цю роботу
Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів

Надійшла 12 жовтня 2025 р.
Прийнята 17 листопада 2025 р.