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DEVELOPMENT OF METHODS FOR FORECASTING THE DURATION OF RECOVERY GROUNDWATER LEVEL

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Abstract

The change in the natural balance of surface, ground and underground waters is one of the urgent environmental problems of coal-mining regions, which is associated with negative phenomena and processes that accompany the exploitation and liquidation of mines. Management of groundwater inflows at various stages of the post-exploitation existence of mines that are being liquidated is difficult due to the lack of study of water migration in the disturbed massif. The purpose of the work is to develop methods of forecasting the time of restoration of the natural surface of depressed groundwater wells in the regions of mine closure. The hydrofiltration scheme of coal mine flooding was considered, and its connection with the shift of artificial rocks and the earth's surface during cleaning operations was carried out. A hydrogeological forecast of the ecological consequences of the exploitation and closure of coal mines has been made. Based on the monitoring of the water surface level in the vertical shafts of mines that are being liquidated, methods have been developed for determining the duration of restoration of the natural level of groundwater for a separate mine and the region as a whole.

Introduction

For more than two hundred years, over 21 billion tons (up to 12 km^3) of rocks, including about 15 billion tons (10 km^3) of coal, have been extracted from the depths of Donbas by coal mines. As a result of such activity, deformations occurred with a violation of the geomechanical balance and integrity of 600 km^3 of the rock massif in the zones affected by mining operations, and on 50% of the area, the subsidence of the day surface amounted to an average of 1.5÷2.0 m, with a simultaneous increase in the permeability of the rocks and an increase in the interaction of surface and groundwater [1]. During the historical development of Donbas, approximately 970 mines were built, of which about two hundred are currently in operation at a maximum depth of 1,450 m [2]. The critical acceleration of the closure and liquidation of coal mining enterprises, starting from the 1990s, mainly by the method of wet conservation (self-rehabilitation flooding), led to imperfect accounting of object-territorial and regional changes in environmental parameters of natural-technogenic geosystems "mining area - geological environment". As a result of these circumstances, a large complex of irreversible and dangerous changes in the ecological state of the subsoil was accumulated.

The most dynamic changes in the geological environment of Donbas are associated with significant inflows of underground water into mining operations. Their total volume at the maximum development of mining operations was 25.0 m^3/s (1990). Of these, 12.0 m^3/s were natural resources, which indicates active drainage of surface water sources and hydraulic interconnection of mines [2].

The intensification of man-made environmental changes in Donbass was influenced by the mining of 129 rivers and creeks, 26 reservoirs (683 cases), as well as continuous subsidence of the earth's surface on an area of up to 8,000 km^2.

A significant complication for the mine closure process is the presence of about 250 previously flooded and semi-flooded mines that are hydraulically connected to the working ones. According to the available estimate, the total volume of mining products of these mines exceeds 2.3 km^3 and contains up to 1.6 km^3 of water, which can significantly accelerate the regional intensification of the flooding of the territories of cities and towns, the migration of pollutants into surface and underground water intakes and the river network, as well as increase the danger of emergency water breakthroughs into working mines.

The total water inflow to the mine consists of: inflow of underground water (aquifers drained by mining operations); mine waters coming from flooded workings and neighboring mines; water supplied to the mine for laying, irrigation, drilling wells and for other purposes; surface water and precipitation. The mode of water entering the workings depends on a set of interacting natural (climatic, geomorphological, hydrogeological) and technological (shape and size of mining workings, depth and intensity of deposit development, development systems) factors [3].

The zone of water cracks is a disturbed massif of rocks, through the cracks of which underground and surface waters enter the mine workings. There are zones of natural water supply cracks associated with large tectonic disturbances and karst phenomena, and artificial ones - with the displacement of mining rocks over the produced space and the deformation of rocks, as a result of which cracks are formed, which cause the connection of aquifers and surface waters with the produced space .

In the Donetsk pool, on an area of up to 15,000 km^2, as the depth of mining operations increased (up to 900÷1300 m) and the ground-water level decreased under the influence of mine drainage, the regional imbalance in the "mineral skeleton of rocks - underground water" system grew. The consequence of the new hydrogeological conditions was the development of the local-regional depressed surface of groundwater. The deepening of the zones of active water exchange from 150÷250 to 450÷550 m with the corresponding increase in the infiltration of atmospheric precipitation and the inflow of man-made surface waters from rivers, reservoirs, ponds and other water bodies into aquifers led to a change in the natural balance. As a result of the mine water exchange, the leveling of hydrochemical conditions due to the mixing of surface and underground waters and the increase in their mineralization due to the leaching of salts from rocks and pore solutions was noted. As a result of long-term drainage in the area of mining operations in the zone of pressure-free filtration (cracked soil horizon), a regional pit of depression with a depth of 40÷50 m was formed. Within the mine fields, the depth of local lower pits of depression of groundwater levels in the coal complex reaches the depth of coal working layers, that is, 800-1000 m. The volume of drained rocks is 150-200 km^3 [1]. Large radii of influence of depressed surfaces indicate a high level of depletion of water resources in the area of activity of mining enterprises and water intake structures [4]. In Donbas, a quasi-equilibrium system "mine water - mineral skeleton" was formed for some time in the upper zone of the geological environment. This led to a change in the natural configuration and direction of underground water flows, man-made increase in the activity of interconnection with surface waters, and a change in the structure of the sources of the formation of their resources [1].

A change in hydrogeological conditions causes the following negative changes in the geological environment and ecosystem: depletion of underground water reserves; separation of gravity water from water-resistant rocks; drainage of wells, watercourses and reservoirs; violation of the water-salt regime of the rocks of the aeration zone; deterioration of the quality of underground and surface waters.

Negative phenomena and processes accompanying the liquidation of mines and cuttings belong to one of the urgent environmental problems of the coal-mining regions. They have a multi-vector nature and are in one way or another related to the restoration of natural levels of groundwater drained during the period of exploitation. The main ones include flooding and waterlogging of the earth's surface, changes in the chemical composition of underground and surface waters, activation of the shift of the earth's surface above workings, deterioration of the physical and mechanical properties of mining rocks, as well as the extrusion of mine gases [5].

Human intervention with the use of powerful machinery for the extraction of minerals, their transportation and processing has changed not only the landscape, but also the massif of rocks [6].

The flooding of mines in Donbas from 1996 to 2014 led to the flooding of 20 to 40% of the areas adjacent to them. Management of groundwater inflows at various stages of the post-exploitation existence of mines that are being liquidated is difficult due to the lack of study of water migration in the disturbed massif [7]. The issues related to the restoration of the surface of underground water depressions in the regions of mine closures during the restoration of the natural level of underground water, which were drained during the period of exploitation, remain practically unexplored. This situation is caused by the fact that during the period of operation of individual sites and mines in general, the possible level of underground water was not determined purposefully. At the stage of closing and liquidation of coal mines, the study of this issue is relevant, since the reliability of the hydrogeological forecast and the development of measures to mitigate environmental consequences depend on the degree of its study.

To achieve the goal, the basic hydrogeofiltration scheme of coal mine flooding was previously considered and a scheme of a possible circular cycle of surface, soil and underground water circulation under the influence of treatment works was developed.

Principle hydrogeofiltration scheme of coal mine flooding

According to the environmental condition, all mining regions of Ukraine can be divided into three groups: *1* - partial, *2* - significant, *3* - critical deterioration of the environment [2].

Mining regions with a partially deteriorated state of ecological parameters of the environment include those where ecological threats to the population and the environment occur mainly in limited areas and are of a short-term nature. These are the majority of construction materials extraction areas, some chemical raw materials (due to the small depths and areas of mining operations), lignite, as well as the majority of oil and gas extraction areas.

Mining regions and areas with a significantly deteriorated state of the environment are territories where the deterioration of the eco-parameters of the natural environment has a steady development and in some areas or objects exceeds the standards for its components (geological environment, soils, surface and underground waters, air, biodiversity) within the influence zones of individual mining enterprises and their complexes. This group may include areas of extraction of mangapa ores, uranium, mercury, and partially iron ores.

Mining regions with a critical state of the environment are the oldest and spatially developed complexes of a predominantly underground method of deposit development, where environmental problems have been accumulating for decades due to the use of imperfect mining technologies with irreversible violations of the environmentally safe state of the subsoil over large areas (thousand km^2) and depths (up to 1.5 km) with the simultaneous accumulation on the earth's surface of areas of its subsidence and large volumes of solid and liquid waste. In these conditions, any further development of mining operations or their termination due to the closure of mining enterprises with subsequent uncontrolled flooding can be the impetus for emergency situations and environmental disasters of various levels, in particular transboundary ones. Such areas in Ukraine include the Donetsk, partially Lviv-Volyn coal and Kryvorizka iron ore basins.

The main factors that determine the ecological state of the mining regions of Ukraine are [2]:

1 - violation of the geomechanical and hydrogeofiltration equilibrium of the rock massif due to mining operations with the extraction of large volumes of mineral raw materials and groundwater, the formation of water-permeable zones of man-made fracturing;

2 - accumulation of waste from mining and processing complexes;

3 - violation of the hydrogeological regime of the territory.

All other factors (development of dangerous geological processes, pollution of the surface atmosphere, soil, underground and surface water, reduction of biodiversity, etc.) are mostly derived from these three [2].

The most critical state of the environment has developed in Donbas as a result of the accelerated decommissioning of mines and the influence of factors of the armed conflict (disruption of energy supply, reduction of environmental monitoring points, etc.).

The most indicative of the complexity and complexity of the factors of the transition to the post-mining state is the mining region of Donbass (Donetsk coal basin) together with the Western Donetsk coal district, which covers an area of up to 15,000 km^2 within three regions - Luhansk, Donetsk, Dnipropetrovsk and forms one from the largest technological and geological systems. At present, the "Principle hydrogeofiltration scheme for the flooding of a Donbas coal mine" has been developed [2]. This scheme (Fig. 1) shows that the violation of the equilibrium geomechanical state of the subsoil, the level and hydrogeochemical regime of underground waters and the deformation of the earth's surface are the main factors in the development of potential ecological and technogenic threats of post-mining under the scheme of self-rehabilitation flooding (wet conservation).

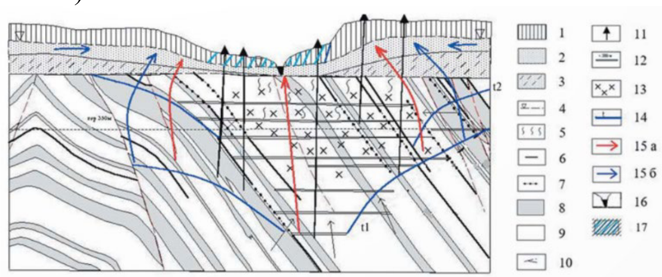

Fig. 1. Basic hydrogeofiltration scheme of coal mine flooding in Donbas [2]: *1* - zone of downward unsaturated filtration (aeration zone); *2* - zone of distribution of groundwater; *3* - poorly permeable rocks of the bottom of the soil aquifer; *4* - the level of the soil aquifer; *5* - zone of development of regional water-permeable fracturing in the covering part of coal-bearing rocks (area of lateral filtration; *6* - coal seams; *7* - worked coal seams; *8* - sandstones; *9* - siltstones; *10* - tectonic disturbances; *11* - surface mine structures; *12* - underground mine workings; *13* - zones of man-made fracturing; *14* - underground water level of deep horizons during mine flooding for different periods of time (*t*); *15a* - directions of mineralized groundwater movement; *15b* - directions of underground water movement during mine flooding (radial and lateral streams); *16* - river bed (regional groundwater drain); *17* - areas of flooding and active surface subsidence

The schematic diagram of the movement of surface, soil and underground water (Fig. 1) made it possible to develop on its basis the movement of water flows that occur directly under the influence of treatment works during coal mining and after its termination. This allows us to move from a qualitative assessment of the water exchange processes taking place to the quantitative parameters of the shift of artificial rocks and the conditions for the formation of mold on the earth's surface.

Groundwater level change during treatment works and after their completion and flooding of mining works

Over half a century, a significant amount of experimental material has been accumulated on the shear parameters of rocks forged by treatment works and the conditions for the formation of shear molds on the Earth's surface [8-17]. These and some other information were summarized, which made it possible to propose, for various mining technical and mining-geological conditions, empirical dependences for determining the parameters of the displacement processes of artificial rocks and the earth's surface for engineering calculations [18]. In particular, it is possible to determine the dimensions of the workings $L_н$ at which the shift of the earth's surface begins and its maximum subsidence occurs η_m. In addition, for various mining and geological conditions, the angles of total displacements ψ and limit angles δ are known. Knowing these parameters allows one to determine [18] the dimensions of the zone of forged rocks with a break in their continuity (I) and the zone of parallel subsidence of rock layers (II) with the possible formation of horizontal delamination cracks along the layering (Fig. 2).

The following circumstances were taken into account during the development of the principle scheme for changes in the level of groundwater during clean-up operations and after the flooding of mine workings:

- the water pumped out of the mine workings during mine operation contains almost 50% of surface water [2]. The main amount of surface and ground water enters the mine workings from the zones of influence of the mine workings and to a large extent under the influence of cleaning works;

- volumes of drained rocks under the influence of cleaning works are several times larger than the sizes of the zones that fall into the zone of their possible landslide. Taking into account the usually insignificant size of coal seams between the boundaries of mine fields (20÷100 m), it can be argued that when mines are flooded in one region, in almost all cases, a hydraulic connection will be observed between mining workings and drained rocks in the zones of influence of cleaning workings individual mines of the region;

- the depressed surface of groundwater (the free surface of pressure-free or piezometric surface of groundwater) decreases at the point of its exit to the surface of the earth or water pumping. For drainage and water intake wells, the radius of influence of the depressed surface is usually hundreds of meters, and for mines and quarries - several kilometers (sometimes several tens of km). Large radii of influence of the depressed surface indicate a high level of depletion of water resources in the area of activity of mining enterprises [4].

Based on the above circumstances, for a separate mine during its operation, the lower part of the depressed surface of groundwater (8) will be at the level of the sump of the shaft or the water surface in the mine reservoir (Fig. 2).

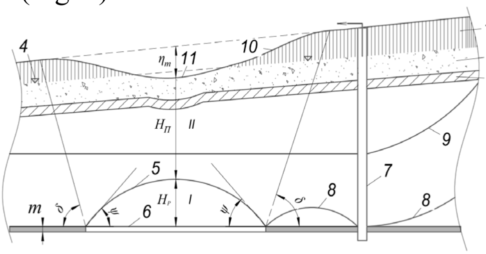

Fig. 2. Schematic diagram of changes in the level of underround water during the cleaning works and after their completion and flooding of the works: *1* - zone of downward unsaturated filtration (aeration zone); *2* - zone of distribution of groundwater; *3* - poorly permeable rocks of the bottom of the soil aquifer; *4* - the level of the soil aquifer; *5* - boundary of the zone of forged rocks with a break in their integrity; *6* - layer being developed; *7* - a vertical trunk through which water is pumped during mine operation; *8* - the level (piezometric surface) of underground water during the period of operation of the mine; *9* - groundwater level (piezometric surface) in different periods of flooding (*t*); *10* - displacement trough on the earth's surface; *11* - areas of flooding of the displacement trough in the zone of maximum ( ) displacement of the earth's surface; *m* - capacity of the developed layer; - angles of complete shifts of forged rocks; *δ* - limit angles; I - zone of rocks with a break in their integrity; II - a zone of parallel subsidence of rock layers with possible stratification

When water pumping is stopped (flooding of the mine), the level of water in the shaft will rise when it comes from the zones of directly forged rocks, as well as from zones that were not subject to displacement during cleaning operations, but were previously drained. The current level of water in the shaft characterizes the degree of flooding of fake rocks by the liquidated mine. It determines the position of the lower part of the depressed surface (9), which in configuration is close to the horizontal surface. During the period of incomplete flooding of the mine, the water levels in different parts of the mine field may differ slightly from each other due to the different composition of the coal seam.

The final flooding of the mine must be considered taking into account the position of the depressed surface in the neighboring mine fields. Depending on the ratio of the position of the depressed surfaces in the forged rocks of the neighboring mines and the degree of their flooding, the possibility of flooding the earth's surface of some part of the mine (11) will depend to a large extent.

Monitoring the position of the water surface in the shafts of mines that are being closed, taking into account the peculiarities of the formation of the depressed surface of groundwater in the region as a whole and the maximum subsidence of the earth's surface, allows to make a geological forecast of the environmental consequences of the operation and closure of coal mines.

Methods of determining the period of restoration of natural water levels

The methodology for a separate mine was developed based on the results of monitoring the water surface level in the shafts of the May Day group of coal mines of the Luhansk region as of November 1, 2017.

According to data [19], it is known that shaft No. 1 of the "Pervomaiska" mine was flooded to the mark -156 m. The sump of this shaft is located at the mark -602 m. The shaft was flooded at 446 meters (602-156). The flooding period from September 2015 to November 1, 2017 was 769 days. The average rate of water level rise in the trunk was 0.58 m/day (446:769). In this period, the water inflow occurred only from the zones of influence of the Pervomaiska mine's cleaning workings. This was caused by the lack of hydraulic connection with other mines during this period. If we conditionally assume that the hydraulic connection with the workings of other mines will continue to be absent, then the rate of raising the level in the shaft will decrease proportionally as the area - the depressed surface - increases. The area of the depressed surface before the outfall was stopped was equal to the area of the treatment works on the lower horizon (-602 m). The area of drained rocks near the earth's surface is approximately 3-4 times greater than the area of the treatment works (Fig. 2). Therefore, the area of the depressed surface will also be 3-4 times greater than the area of the cleaning products. With a constant influx of underground water entering the mine from various sources and an increasing depression surface, the rate of rise of the water level in the shaft will decrease. Such a decrease in speed is inversely proportional to the areas of depressed surfaces at the beginning of flooding and after the complete end of this process. In this case, the rate of water level rise depends on the ratio of the areas of depressed surfaces

$$\frac{S_1}{S_2} = \frac{V_1}{V_2}, \tag{1}$$

where S_1 is the area of treatment works on the lower horizon;

S_2 - the area of the depressed surface at the time of complete flooding of the mine;

V_1, V_2 are the rates of water level rise in the trunk, respectively, for areas S_1 and S_2.

It follows from equation (1) that

$$V_2 = \frac{S_1 \times V_1}{S_2}. \tag{2}$$

If we take the final depressed surface (S_2) by analogy with its shape around the water pumping points close to the circle, then its area will be equal to

$$S_2 = \frac{\pi R_2^2}{4}, \tag{3}$$

$$S_1 = \frac{\pi R_1^2}{4}. \tag{4}$$

With the approximate ratio $R_2 \approx 4R_1$, equation (2) can be reduced to the form

$$V_2 = \frac{V_1}{16}. \quad (5)$$

In this case, before the restoration of the natural groundwater level, the average rate of water rise in the trunk was according to equation (5) $V_2 = V_1/16 = 0.58/16 = 0.036$ m⁄(day)

With this average speed, the water level in the shaft should rise in the absence of hydraulic communication with other mines. According to the absolute marks (-156 and 162 m), the length of the flooded part of the trunk after November 1, 2017. is 318 m. The duration of flooding of this part (t_2) at the average rate of rise of the water level in the trunk ((0.200+0.036)/2=0.118 m⁄day) will be t_2=318/0.118=2695 days or 7.4 years. The total duration of flooding up to the -156 m mark, t_0=7.4+2.1=9.5 years.

Such a technique is valid only under the condition of complete absence of hydraulic connection with productions of other mines, which does not correspond to reality.

A completely different technique is needed to predict the duration of recovery of the natural water level after the exploitation and flooding of a group of mines in a region that are hydraulically interconnected. Let's consider this technique using the example of the initial position of the depression surface for the primordial group of mines as of November 1, 2017.

The location of the depressed surface in the region of the closing mines and its maintenance at this level is ensured by pumping water through shaft № 3 of the "Zolote" mine. The total depth of this shaft according to the markings (-707.9 and +157.1) is 865 m. If you stop pumping water through shaft № 3, then the inflow of water in it to the level of -156.0 m will occur faster compared to the inflow into the shaft № 1 of the "Pervomaiska" mine. This will be caused by an additional water inflow of 1060 m^3/h. from the side of already flooded mines [19]. Based on the ratio of the total inflow to shaft № 3 (1,500 m^3/h) and from previously flooded mines (1,060 m^3/h), the average speed of its flooding will exceed the increase in the water level in shaft № 1 of the Pervomaiska mine. In quantitative terms, the average speed of flooding of trunk № 3 to the -156 m mark will be

$$V_1 = 0{,}58 \times \frac{1500}{1060} = 0{,}82 \text{ m/day}$$

The depth of the flooded part of shaft № 3 to the -156 m mark is:

H_1=707.9-156.0=551.9 m.

Time of flooding of this part of the trunk:

t_1=551.9/0.82=673 days or 1.8 years.

The depth of the unflooded part of the trunk № 3:

H_2=865.0-551.9=313.1 m.

If we take the shape of depression surfaces at the time of restoration of the underground water level for the "Zolote" mine and the entire region as close to circles, then the ratio of their radii, based on Fig. 3, is approximately 1:6.9 (Fig. 3).

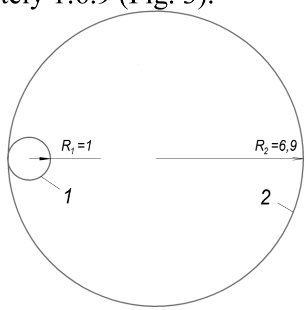

Fig. 3. The ratio between the areas and radii of depression surfaces at the time of the end of mine flooding: *1*, *2* - circles of depressed surfaces, respectively, for the "Zolote" mine and the entire region; R_1, R_2 are the radii of depression surfaces, respectively, for the "Zolote" mine and the entire region

If R_1=1 is accepted, then R_2=6.9 and $S_1 \cdot V_1 = S_2 \cdot V_2$, and $V_2 = V_1/6.9$^2 =0.82/47.61=0.017 m/(day)

The V_2 flooding rate remains approximately constant for all mines in the region, as S_2 varies little. The time for flooding the remaining part (313.1 m) of trunk № 3 will be

t_2=313.1/0.017=18418 days or 50.5 years.

The total duration of restoration of the natural level of underground water in the region after the cessation of water pumping through shaft № 3 of the "Zolote" mine will be

$t_0 = t_1 + t_2$=1.8+50.5=52.3 years.

Thus, the forecast for the restoration period of the natural water level in the regions of Donbas is long-term, as it can last more than fifty years.

The lack of smoothness of curved depression surfaces for the mines of the Central District of Donbass is associated with mining-geological conditions (steeply falling layers) and low permeability of rocks in the direction perpendicular to their layering. This circumstance causes an increase in the duration of the leveling of the curve of the depression surface, and therefore will lead to an even longer period of restoration of the natural level of underground water in case of complete flooding of the mines of this region. The duration of the process for mines working steeply dipping layers can significantly exceed the period of restoration of the natural water level for mines with gently lying layers.

It should be noted the possible catastrophic environmental consequences in the event of stopping the pumping of groundwater through the shafts of the "Yuny Komunar" coal mine and the 2-bis mine from cinnabar extraction. In this case, the threat of duration of negative environmental consequences will increase for several tens of years.

Conclusions

On the basis of the conducted research, the peculiarities of the duration of recovery of the groundwater level during the flooding of coal mines in the regions of Donbas have been determined. They are as follows:

1. The duration of restoration of the underground water level during the flooding of a separate mine, which is not hydraulically connected with other enterprises, is about 10 years.

2. Taking into account the insignificant coal targets of coal between the boundaries of mine fields, practically all mines of each region of Donbas are hydraulically interconnected due to the saturation of drained rocks.

3. The duration of the natural recovery of the underground water level in the regions of the closure of mines in the case of gently lying layers is not less than fifty years. This period is significantly increased for the region of mines that developed steeply falling layers, and is caused by the hydrogeological features of the restoration of the depressed surface of groundwater to the natural level.

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