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Conjugated effects between surface- and groundwater mineralization within the drainage zone of Dombrovsky quarry

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SUMMARY

The hydrogeofiltration structure and water balance of the Dombrovsky quarry depression cone were analyzed. The radius of the quarry depression was about 1.5 km. Environmental threats are following the modern transformation of the quarry from a drainage system into a source of aquifer feeding by highly mineralized water. The assessment of gravel and pebble drinking water horizon pollution and mineralization of Limnitsa river, which is a regional local drainage, is carried out. The value of salts annually transported into the gravel and pebble aquifer is assessed to 648 kt. During nearest 2.5 years the front of highly mineralized groundwater will discharge to Limnitsa river that provide the growth of surface water mineralization to 0,81 g/l. The liquid body of Dombrovsky quarry is came to quasi-equilibrium water balance and hydrochemical state with groundwater aquifer that determines the additional threat of drinking water source pollution.

Introduction. Potash salt layers that occurs near the city of Kalush in the Ukraine (Ivano Frankiv region, Carpathian Foredeep Basin) is located only about 20 m below the surface and is suited to opencast mining. The ore is rich in kainite (KMg $(Cl/SO_4)\cdot 3H_2O$), halite (NaCl), and langbeinite ($K_2Mg_2(SO_4)_3$) (Roman Żurek et al., 2018). Three aquifers are exists in geological section: the first aquifer from the surface level, a gravel-pebble aquifer, and salt mirror water (Malkova et al., 2020). For water supply of Kalush, waters confined to highly permeable gravel and pebble deposits - aquifer I, II and III above floodplain terraces are used. Other aquifers have no practical significance and are not used for domestic and drinking water supply.

The hydrogeological and hydrogeochemical study of Dombrovsky quarry drainage zone within Kalush-Golinsky potassium salt deposit is of great importance from the position of environmental security. The quarry, being a drainage, after its flooding, collects highly mineralized solutions flowing out of tailings, salt dumps and accumulation tanks. After its flooding and partial restoration of the natural regional flow regime, these highly mineralized solutions move in the direction of local natural drains towards the Limnitsa river bed, along the Sivka river bed, and towards Kalush.

The aim of the work is to calculate the water-salt balance of the quarry after its flooding, using the plane characteristics of the area to predict the pollution of Limnitsa river, which is the regional local drain.

Drainage influence zone. The study area is located in the Dniester basin with its right tributaries Limnitsa river and Sivka rivers. According to indicators of water quality Limnitsa belongs to the cleanest river in Ukraine and has the nature protection status of the water reserve of local importance. Limnitsa water mineralization is 149 mg/dm^3. On the left bank of Limnytsa in the floodplain the coastal water intake of the centralized water supply of Kalush is situated. River Sivka originates in Dolyna district flows towards to the Dniester river 20 km from Kalush. In the past, before the start of mining, the river crossed the quarry from west to east. To divert the river beyond the quarry a canal 250 m long from the northern side of the quarry was built and the old riverbed was re-drained. The annual level regime of the Ivano-Frankivsk lowland rivers is characterized by the passage of floods throughout the year. These floods are caused in winter by snowmelt during periods of frequent thaws, in spring by general snowmelt, and in summer by heavy rainfall. The Sivka is characterized by an unstable level regime. The water may rise by 3-4 m. Catastrophic floods were also observed in August 1927, January 1954, July 1957.

The depression cone was created in the groundwater aquifer during the operation of Dombrovsky quarry (1965-2008) due to dewatering the quarry by pumping. Levels of gravel and pebble aquifer began to decrease toward the sources of water along the less permeable base of the aquifer. The radius of the quarry depression was about 1.5 km. Owing to quarry filling with water solution the drainage influence zone of the quarry is gradually decreasing and will reduce to almost 100-200 m in the low-water period when reach the quasi-equilibrium state. After stabilization of the natural regime, drainage and unloading of gravel and pebble horizon, as before the operation of the quarry, will occur through the river Limnitsa, which drains the pebbles. Due to backwater of the gravel-pebble aquifer the pit brines are discharged into the horizon that thereby reducing the depression. So the freshwater inflow to the quarry decreases. As a result, the Dombrovsky quarry reaches a quasi-stable equilibrium: the amount of groundwater that is discharged into the quarry is equal to the amount of highly mineralized water that enters the aquifer. Thus, water with mineralisation from 6 to 30 g/dm^3 moves towards the Limnitsa river, which is local regional drain (Figure 1).

Earlier we calculated the kinetic rate constant of salt dissolution and the rate constant of diffusion in the liquid body of quarry that allowed us to calculate the volume of salt body, which annually dissolved in the broadsides and bottom of the Dombrovsky quarry (Malkova et al., 2020; Malkova et al., 2020). The results provided a comprehensive understanding of the water-salt balance of the quarry and the ability to predict salt contamination of groundwater and surface freshwater. The quarry is become now in quasi-stable equilibrium when the inflow of water from the gravel-pebble aquiferand the outflow of highly concentrated brines from the quarry depend on hydrometeorological conditions.

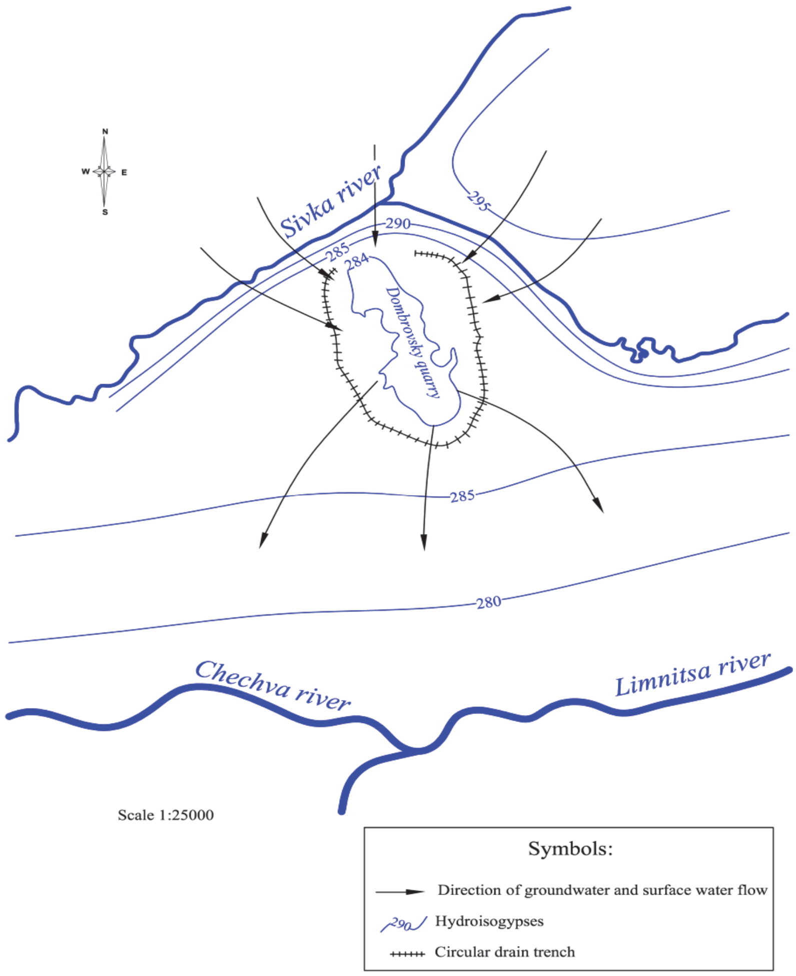

Figure 1 *Schematic of hydroisogyps and groundwater flow directions in the local regional drain*

The depth of hydrometeorological factors influence (depth of variation of seasonal changes of upper layer) is amounted to 20 m; variations depend on water availability of the year, character of flood water inflow and annual rainfall. Kinetic and diffusion processes occurring below the 20-m layer are stabilizers of water-salt balance of the quarry. The surface layer is characterized by dynamic changes of water level in the quarry in accordance with the changes of mineralization and hydrochemical conditions. Thus, Dombrovsky quarry is a quasi-equilibrium system, in which the amount of water coming from the aquifer is equal to the intrusion of highly mineralized water into the gravel-pebble aquifer from the quarry.

In order to predict the pollution of the local natural drain the Limnitsa river we calculated the water-salt balance of the quarry using plane futures of the territory. The basis of calculations is the total salt delivery depending on hydrometeorological conditions of the region. Both the plane-radial flow and mixed hydraulic-filtration flow of oversaline (unconfined) groundwater to Dombrovsky quarry occurs now. So we calculated approximately volume of inflow on the periphery of the quarry by 2 schemes:

1) plain flow at the boundary of the quarry scarp. Inflow to the quarry at the periphery or perimeter of its ledge B = 1000 m. Slope of water surface in aquifer is I = 0.005 (Dolin et al., 2010). Value of filtration coefficient K according to pumping data of 2013 is on average 30 m/day. According to the known Darcy formula for plane unconfined flow its flow rate Q is equal:

$$Q \ = KHBi = 2{,}7 \cdot 10^3 \, {m^3}/{day} \qquad (1)$$

2) planar-radial flow at the conditional radius of a «large well»:

$$r_k = \sqrt{\frac{S}{\pi}} = 0{,}56\sqrt{1{,}8 \cdot 10^6} = 751 \text{ m} \quad (2)$$

$$R = B + r_k = 1000 + 751 = 1751 \text{ m}, \quad (3)$$

where r is the small radius of the quarry, m, R is the conditional radius of a «large well», m, S is the area of the quarry, m^2.

Then the inflow is:

$$Q_k = \frac{\pi k(H^2 - h^2)}{\ln R/r_k} \quad (4)$$

$$0{,}5Q_k = \frac{\pi k(H^2 - h_k^2)}{2\ln R/r_k} = \frac{0{,}68k(H^2 - h_k^2)}{lg R/r_k} \quad (5)$$

$$Q = \frac{0{,}68 \cdot 18^2 \cdot 0^2}{lg 1750/751} = 600 \ \text{m}^3/\text{day} \quad (6)$$

Knowing the mineralization of the surface layer, it is possible to calculate the average annual salt supply from the quarry:

$$G = \frac{C_1 + C_2}{2} \cdot S \cdot h = \frac{3+27}{2} \times 1{,}8 \cdot 10^6 \times 20 = 5{,}4 \times 10^8 \ \text{kg}/\text{year}, \quad (7)$$

where G is amount of salts, which gets into aquifer from the quarry, kg, C_1 is mineralization of upper layer, g/dm^3, C_2 is mineralization at 20 m depth, g/dm^3, h is thickness of unequilibrium layer, m. This amount of salts annually goes in the direction to Limnitsa river. The contour of potassium propagation by groundwater flow towards to local drain is illustrated at Figure 2.

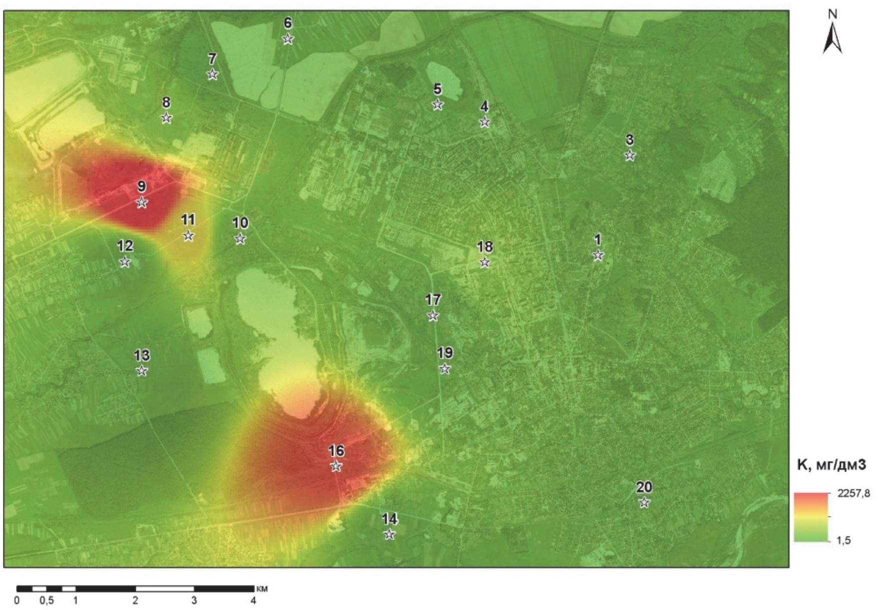

***Figure 2** Spatial illustration of Potassium propagation by groundwater flow (created by the data of LLC «Noosphere Group» (2020))*

The rate of groundwater flow movement between the quarry and Limnitsa is 200 m/year. The coefficient of gravity water loss for heterogeneous rock, represented by pebbles and sand (rocks of the corresponding alluvial terrace), according to literature data, is estimated by the value μ = 0.1. The rate of contamination of gravel-pebble aquifer is:

$$V_{cont} = V_1 \cdot B \cdot m \cdot \mu = 250 \times 2 \cdot 10^3 \times 18 \times 0{,}1 = 9 \cdot 10^5 \ \text{m}^3/\text{year}, \quad (8)$$

where V_1 is a rate of contaminated water movement for half a century of the quarry exploitation, m/year, B is a flow width, m, m is an average thickness of the aquifer, m.

According to the geographical entsyclopedia of Ukraine, the annual rainfall is 778 mm. Evaporation from the upper water layer is about 350 mm per year. The layer which brings the system to equilibrium is W_f = 428 mm = 0.43 m. The volume of water, which penetrates into the gravel and pebble horizon annually is:

$$V_w = W_f S = 0{,}43 \times 1{,}8 \cdot 10^6 = 7{,}7 \cdot 10^5 \ \text{m}^3, \quad (9)$$

For a quantitative understanding of the situation regarding the pollution of the Limnitsa and Dniester rivers, it is advisable to calculate the amount of salts that annually enters to the Limnitsa river (volumetric characteristic):

$$G_{Lim} = \mathrm{B}m\mu V_1 C = 2000 \cdot 18 \cdot 0{,}1 \cdot 0{,}627 \cdot 40 = 0{,}9 \cdot 10^5 \text{ kg/year} \quad (10)$$

where B is the width of polluted water flow, m, m is the thickness of gravel-pebble aquifer, m, C is the mineralisation of gravel-pebble aquifer before discharging into the Limnitsa river, g/dm^3.
Calculating the annual flow of Limnitsa:

$$\mathrm{Q}\ {}^{\text{aver}}/_{\text{year}} = 21{,}3\ {}^{\text{m}^3}/_{\text{sec}} \times 31{,}5 \cdot 10^6 \text{sec} = 6{,}71 \cdot 10^8 \text{ m}^3/\text{year} \quad (11)$$

The mineralization increase for the year is:

$$\Delta\mathrm{C} = \frac{\mathrm{G}}{Q^{aver}/_{year}} \approx \frac{5{,}4 \cdot 10^8}{6{,}71 \cdot 10^8} = 0{,}81 \text{ gm/dm}^3 \quad (12)$$

An increase in salinity by almost 1 g/dm^3 would mean an increase in chlorine and sodium in the Dniester river by about 10%, which is a critical feature for the Dniester water system.
The flow rate of the groundwater aquifer is:

$$V_{aq} = \frac{k \cdot I}{\mu} = \frac{30 \cdot 0{,}005}{0{,}1} \cdot 365 = 547{,}5\ {}^{m}/_{year} \quad (13)$$

The predicted pollution of the Limnitsa river will occur in about 2.5 years. Dombrovsky quarry is actually a powerful source of feeding-intrusion of highly mineralized water into the gravel-pebble aquifer used for local water supply. In summer the quarry temporarily becomes a local drain (discharge of the aquifer into the quarry leads to a small depression), after autumn rains and floods the depression decreases.

Recommendations and conclusions. Dombrovsky quarry has become to semi-natural quasi-equilibrium system (during the intra-annual cycle), which depends on the regional hydrometeorological conditions. Now the quarry has been conversed from the drainage zone to the source of groundwater pollution that provides the underground flow of dissolved salts in the direction to Limnitsa river, which is the regional local drain. This is the center of deterioration of hydrogeoecological conditions and an increase in the pollution of runoff in the transboundary Dniester river. The value of salts annually transported into the gravel and pebble aquifer is assessed to $6{,}48 \cdot 10^{11}$ g (648 kt). During nearest 2.5 years the front of highly mineralized groundwater will discharge to Limnitsa river that provide the growth of surface water mineralization almost 1 g/dm^3.
The liquid body of Dombrovsky quarry is came to quasi-equilibrium with groundwater aquifer that determines the existing threat of drinking water source pollution.

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