Pit Waters as a Source of Thermal Energy

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ABSTRACT

The authors considered in this paper the environment pollution caused by mine water dumping. Discussed is an example from the Upper-Silesian Coal Basin (UCB), where increased temperature of mine water is observed as effect of higher value of the Earth's natural heat stream. Changes in temperature distribution caused by mine water recirculation are estimated. A computational example using the authors' original program is introduced. Several aspects of water cooling in the part of coal bed affected by mine water recirculation are discussed.

INTRODUCTION

Mining activity causes several alterations of water relations:

- underground water table changes
- rock mass drainage caused by mine dewatering
- mineralized mine water discharge into surface basins
- mineralized and polluted mine water dumping into surface water-course

Caused by roof falls during mining and subsequent fracturing and destressing of rock mass, land subsidence occurs above exploited parts of the coal bed. Changes in bed geometry bring about changes of rock permeability, as well as changes of insulating properties of layers which separate aquifers. In such cases raising of subsurface water table is possible due to the contacts between surface water-courses and ground waters.

In some parts of Upper Silesian Coal Basin higher value of earth heat flux and relatively higher temperature of circulating mine waters are observed[(5)]. Thus heat recovery from utilized mine waters should be considered.

ENVIRONMENT POLLUTION BY MINE WATERS

Underground exploitation of useful minerals is often connected with mine water drainage. As the effect of the drainage rapid changes of circulation direction and velocity of subsurface waters occur which results in forming a cone of depression. The increased subsurface waters drainage causes gradual diminishing of water resources, water depletion of springs and wells or decreased productivity of cropland and forest.

Mine water discharge into surface water-courses and waste rock storage on the surface may result in subsurface waters pollution and have secondary effect on subsurface water flow. As big quantities of mine water are discharged, natural water flow of small water-courses adjacent to discharge point rapidly increases, resulting in water level raises due to the water-course's character inversion-from drainage to infiltrating. Discharged mine waters are usually highly mineralized or polluted with chemical substances, which causes underground water gradual pollution or degradation in the infiltration area. Similar impact on underground water is due to brine storing in retention reservoirs - a hydrotechnical solution to the mine waters problem. Subsurface waters pollution may also be affected by lixiviation of soluble mineral substances in spoil banks.

As the result of over 150 years of mining in the UCB, Carboniferous, Triassic and Tertiary aquifers were partially drained. Upper Carboniferous layers affected by mine drainage brought about by coal exploitation in 66 mines have an outcrop of estimated 1750 km^2 (6). Northern, western and central parts of the UCB include about 1300 km^2 of the above, south-western part (Rybnik Coal Region) include cca 330 km^2, the rest is due to individual activity of isolated coal mines. Mining related drainage has resulted in the lowering of the cone of depression. Changes in subsurface water flow directions and velocities reach 300 to 600 m deep, in some places even 1000 m. This has brought about the piezometric table depression of several dozen metres. The drained areas are usually delimited by the outcrops of aquifers directly drained by mining, and main tectonic faults. However areas around faults can be also hydrologically conductive which may lead to the expansion of drainage area beyond faults.

One of serious problems related to coal exploitation is surface waters degradation caused by mine waters discharge. Table 1 shows quantities of subsurface water inflow to coal mines in the UCB and mine water discharged to the rivers of the Vistula river basin.

It is to be stressed, that the majority of mine waters are discharged into surface water-courses which are already degraded. The biggest amounts of water are discharged by mine with the biggest water inflows. However, regarding that big inflow often provides low mineralization of inflowing water, big inflows don't necessarily cause biggest salt discharge (counted as the sum of chlorides and sulphates ions' masses).

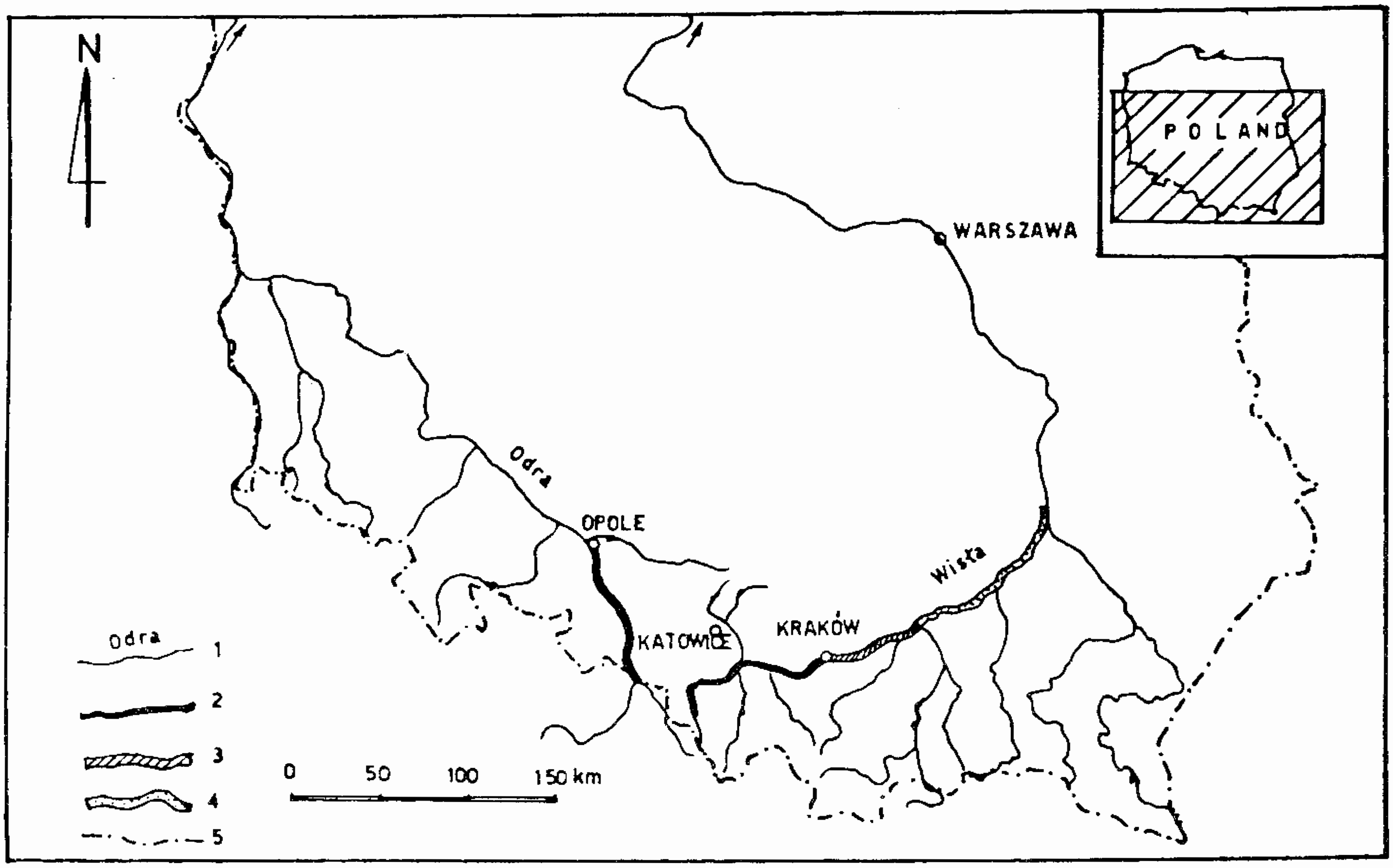
The main receivers of chemically polluted mine waters are the Vistula and Odra rivers. The load of chloride and sulphate ions brought to these rivers contributes to the fact, that in the 1st class of cleanness (less than 300 mg dm^{-3} mineralization) standard is not held in the whole course of the rivers. The Vistula river is polluted in this way from the Gostynia to the Dunajec estuaries during average middle river flow, up to Tyniec village during average high flow and up to Zawichost during average low flow (fig. 1). The Odra river is polluted by mine waters from the Olza estuary up to Opole during average middle flow.

In order to improve this disaster situation several measures are considered among them: water utilization, water recirculation into the rock mass, hydrotechnical methods consisting in controlled water drainage. These methods were described in an internal publication[8].

Table 1. Subsurface waters inflows to the mines of UCB and salt discharge into the Vistula river system

No	Name of mine	1985[6] Inflow $10^3m^3/d$	1985[6] Dumping t/d*	1990[7] Inflow $10^3m^3/d$	1990[7] Dumping t/d	forecast 1995[7] Inflow $10^3m^3/d$	forecast 1995[7] Dumping t/d
1	Andaluzja	0.3	0.4	2.0	3.7	1.4	2.0
2	Barbara	7.6	7.2	9.9	44.4	8.7	26.7
3	Bolesław Śmiały	0.9	0.3	30.6	28.3	30.7	16.9
4	Brzeszcze	10.2	97.2	14.2	254.1	14.4	245.3
5	Czeczott	10.0	459.6	17.7	1463.2	26.9	4002.6
6	Grodziec	4.2	8.9	7.1	7.5	7.6	13.8
7	Janina	30.7	27.3	38.2	69.4	35.5	53.0
8	Jaworzno	72.3	211.0	82.4	138.3	90.9	644.0
9	Jowisz	–	–	2.8	11.3	2.9	14.4
10	Julian	2.0	5.7	1.9	19.5	1.8	5.7
11	Katowice	10.9	38.4	10.3	24.4	12.2	36.8
12	Kazimierz-Juliusz	5.9	22.9	6.8	54.6	6.4	56.4
13	Kleofas	**	**	6.0	14.9	5.5	14.2
14	Komuna Par.	28.4	106.8	64.3	32.0	64.6	33.4
15	Murcki	29.5	7.8	39.3	16.0	35.6	19.6
16	Mysłowice	4.9	42.4	5.8	42.5	6.3	80.4
17	Niwka-Modrz.	21.3	167.2	20.9	409.2	19.1	354.9
18	Paryż	26.5	14.1	23.0	15.0	16.8	12.7
19	Piast	29.8	1699.4	32.7	2639.6	31.4	2498.4
20	Polska	6.6	10.2	9,8	29.2	11.3	34.6
21	Porąbka Kl.	7.3	5.5	9.5	12.9	7.7	11.9
22	Powstańców Śl.	5.6	7.2	4.4	11.2	4.3	15.0
23	Rozbark	8.0	17.7	10.5	58.5	10.0	52.9
24	Saturn	36.7	20.2	43.0	54.4	41.8	52.4
25	Siemianowice	20.0	29.1	37.5	82.9	37.6	76.0
26	Siersza	15.1	5.8	45.0	18.3	45.0	18.7
27	Silesia	10.7	329.2	9.2	532.1	9.0	540.9
28	Sosnowiec	14.7	8.4	13.9	11.0	9.3	13.9
29	Staszic	2.6	39.4	4.6	88.9	4.5	80.2
30	Wesoła	20.7	85.6	30.4	339.3	23.9	177.8
31	Wieczorek	14.1	40.6	13.6	85.2	12.9	149.0
32	Wujek	2.5	36.5	5.9	66.5	6.1	71.5
33	Ziemowit	34.6	1202.7	50.7	2398.4	45.2	2141.3
	Total:	495.5	4754.7	703.9	9076.7	696.0	11567.3

note:
* salt shown as sum of chlorides and sulfates ions' masses
** data not available



Legend: 1-rivers, 2-pollution at average high flow. 3-pollution at average middle flow. 4-pollution at average low flow, 5-state boundary

Figure 1. Rivers pollution caused by mine waters discharge

Mine brines utilization is based on mineral substances precipitation and their further utilization in solid state as well as recovering of water suitable for industrial and municipal purposes. The utilization process consists of several stages: concentrating (by means of reverse osmosis method), water conditioning before its bringing into the evaporating system, separation of solid, liquid and gaseous final products and terminal lye management. The recirculation method consists in brine injecting into drained aquifer complex, some of the recirculated water flowing back into mine heading while the rest migrates in the opposite direction decreasing water inflow from outer parts of rock mass.

Controlled discharge consists in delivering brines into water-courses during high water flow in rivers, with application of network of pipelines and water retention reservoirs.

INCREASED HEAT FLUX VALUE IN UPPER SILESIA

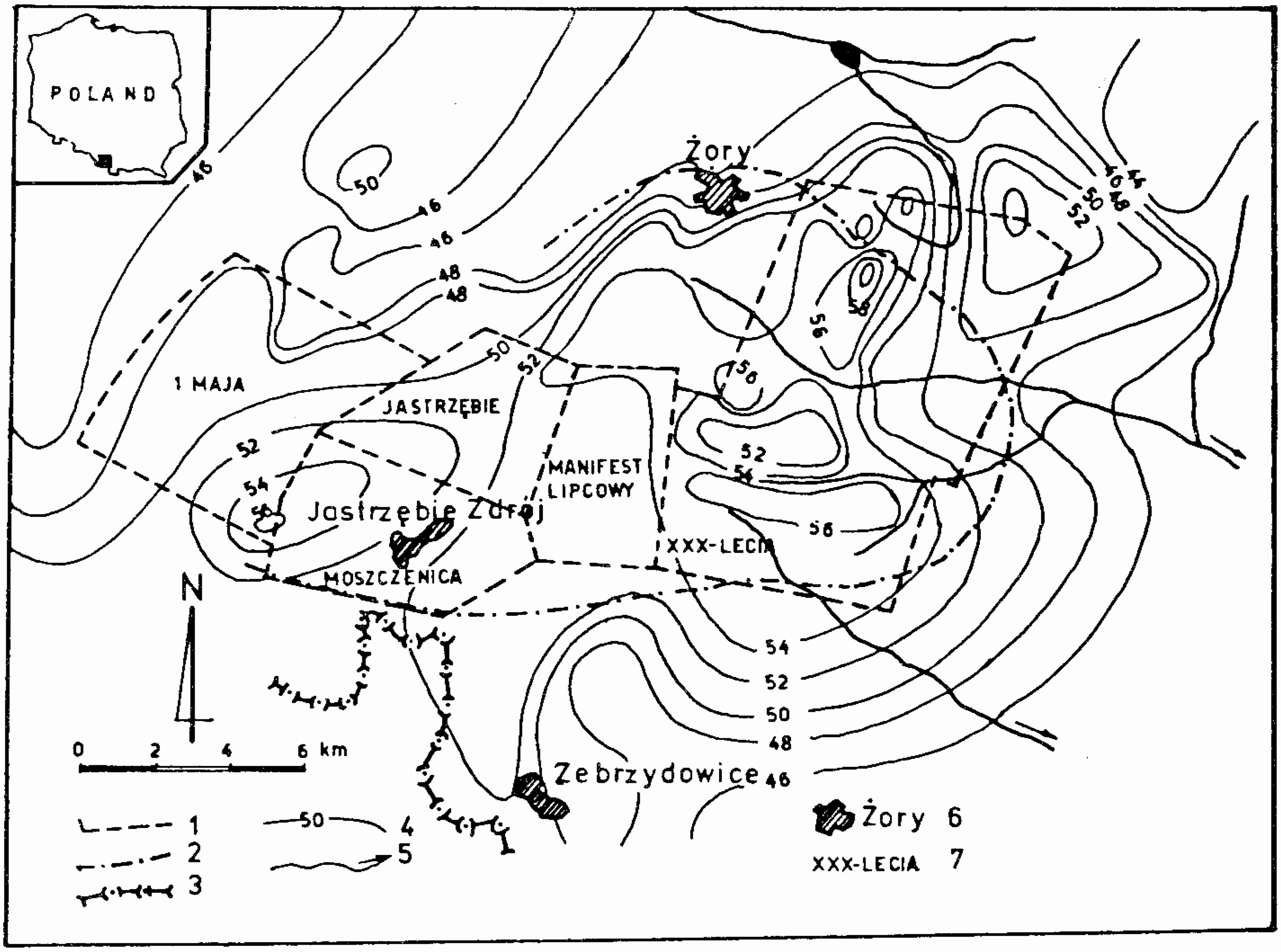
Upper Silesia is geologically reasonably well explored due to long-time intensive mining. Gravimetric and magnetometric maps of the area have been made, and researches concerning rock properties and subsurface water radioactivity have been carried out. Also detailed researches on the geothermal field have been made by means of temperature measurements at various depths(5). Measurements carried out in the southern part of the UCB have been used for establishing the thermal distribution model. Essential for defining the mechanisms of heat flow is determining the heat distribution along fault lines and along lines perpendicular to the faults. The heat transport model was based on two simultaneously occurring processes: one concerning radioactive material decay, the other connected with rock mass' thermal conductivity. Marcak H. & Lesnjak A. have introduced anticipated temperature distribution as a function of depth in their paper dealing with interpretation of geothermal field in Upper Silesia(5). This distribution was estimated on the basis of the simultaneous model mentioned above, processed by means of minimalization procedures. According to the authors(5), the heat distribution model has a geological explanation and can be related to very young tectonic motions, which are the most recent phase of the Apine orogenesis.

Fig.2 shows a schematic map of temperature distribution on depth of 1000 m in the area of "Jastrzebie", "Moszczenica", "Manifest Lipcowy", "1 Maja" and "XXX-lecia" coal mines. Mine waters have temperatures of about 50 °C to 60 °C on 1000 m depth in this area. Total thermal energy acquired from mine waters from these five mines should equal approximately E_t = 11.72 MW (assumed temperature drop in heat exchangers is T = 20 °C. The "XXX-lecia" coal mine appears to be the most promising regarding temperature distribution. It is possible to obtain E_t = 3 MW while ΔT = 30 °C due to three main thermal fields with temperatures >55 °C located in this area.

MODEL OF THERMAL ENERGY GAINED BY WATER RECIRCULATION

The southern part of the UCB features a mainly hydrogeologically restricted Carboniferous water-bearing system with local erosion windows shaped in the Tertiary cover in some places(6). Upper Carboniferous formations, where coal mining is situated, are composed of layers of sandstone, mudstone, clunch and hard coal beds. These strata form cyclotems with thickness between 10 and 20 m, where coal beds thicknesses ca 1 m. Carboniferous formations are covered with Tertiary clayey strata, impermeable to water with thickness up to 700 m. Thus meteoric and surface waters cannot infiltrate into Carboniferous bed-rock, one of the main aquifers in the Upper Silesian sandstone series. The amount of water contained within these strata is not very big. Water inflow in mines of the Rybnik Coal Region is between 1 m^3min^{-1} and 5 m^3min^{-1}.

The model of system of water circulation in a mining area is show in the Fig. 3. Water flows horizontally from fault areas limiting the mining field. Reinjection wells are situated in the fault areas. Water is taken from the mining area by the exploitation well in central part of the mining field. A cone of depression is created, enabling coal exploitation. Mine water drawn from the mining field is cooled in heat-exchangers on the surface and then sent back to the aquifer through the reinjection wells, which provides recirculation of mine waters. Particular water bearing systems are limited either by clastic cover of big thickness or by impermeable layers of clunch dividing cyclotems.



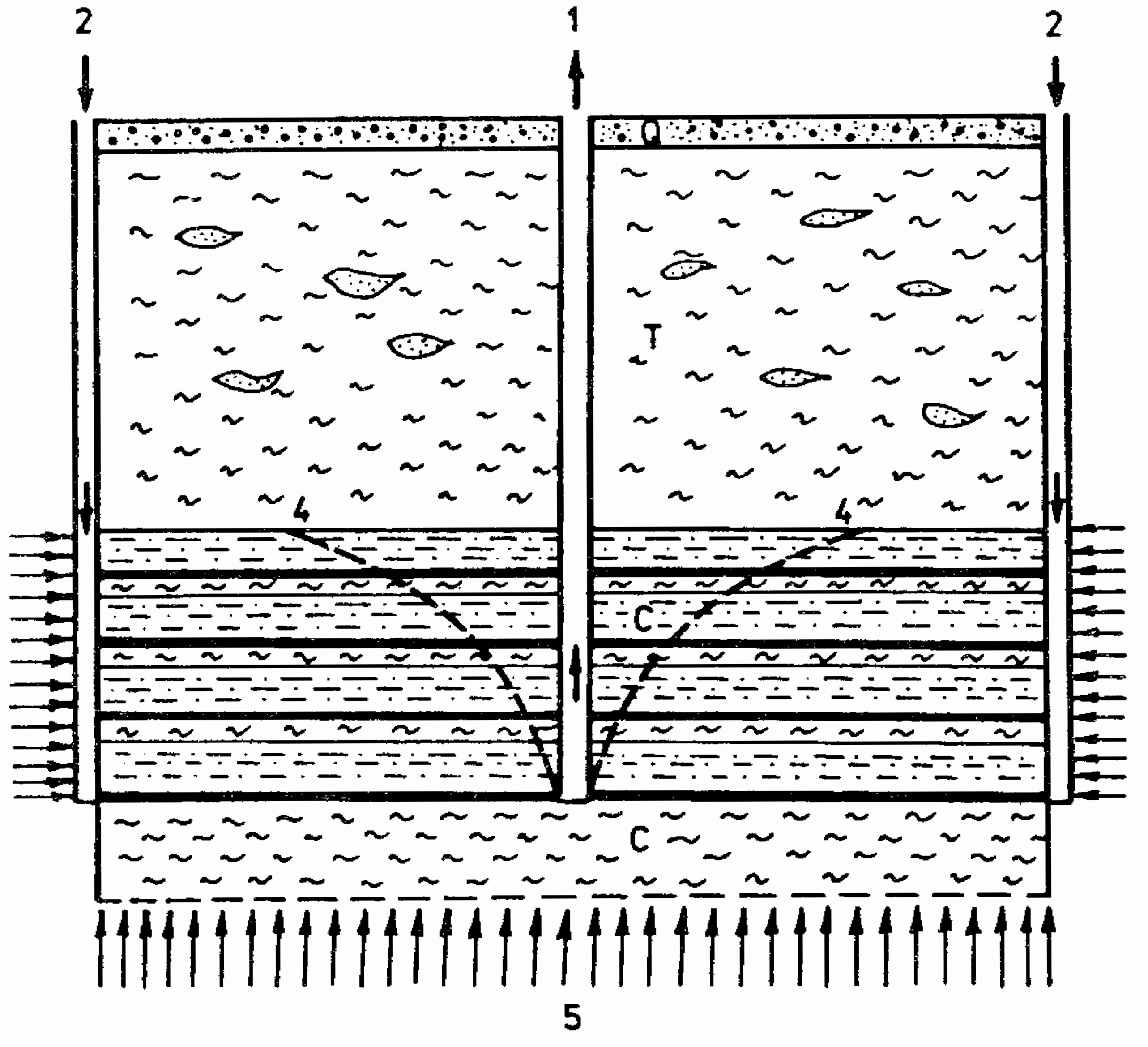
Legend:1-boundary of mine area, 2-probable limit of depression cone(6), 3-state boundary, 4-isotherm, 5-rivers, 6-cities, 7-name of mine

Figure 2. Map of isotherms at 1000 m depth(5)

Simplified models of temperature distributions in the drainage and recirculation field are shown in Fig. 4A and 4B. An unified water-bearing layer in the Fig. 4A represents the whole cyclotem consisting of coal beds, clunch, mudstone and sandstone, the latter being actual aquifer. Due to damaging of the hydraulic insulation between layers during mining, the whole cyclotem is assumed to be water permeable. The aquifer is limited from the roof and the floor by impermeable clunch. Fig.4B shows the aquifer as and individual layer of sandstone surrounded by two coal beds.

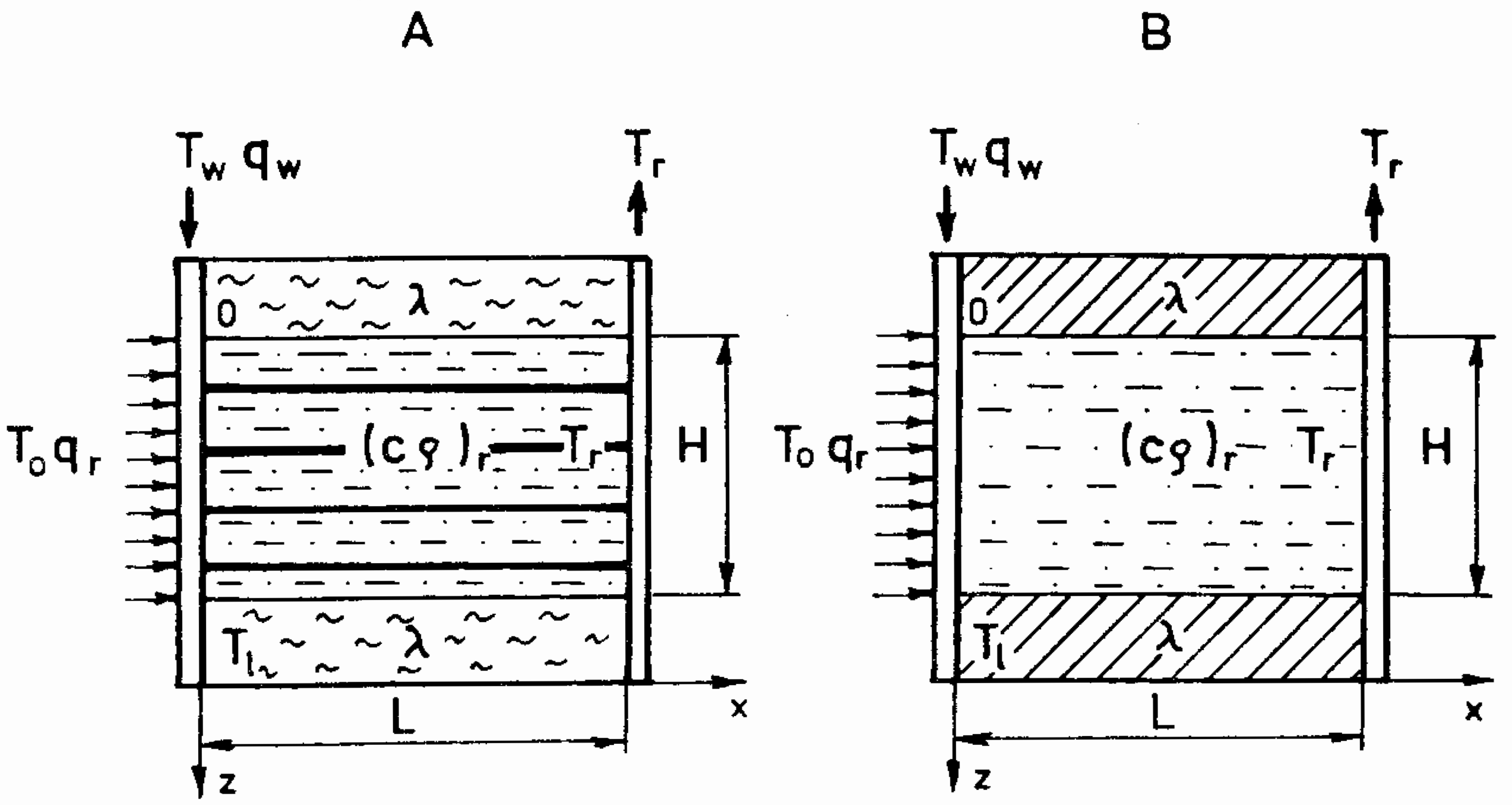
ESTIMATION OF TEMPERATURE FRONT MOVEMENT

Reinjection of cooled mine water back into the aquifer causes emergence of a moving temperature front brought about by the mass of cooled water. Following question has been considered: how long does it take for the expanding temperature front to reach the bottom of exploitation well and to change the temperature of water drained to the surface.



Legend: Q-Quaternary, T-Tertiary + Triassic, C-Carboniferous, 1-exploitation well, 2-reinjection well, 3-water inflow. 4-cone of drainage, 5-heat flux

Figure 3. Model of water circulation in a mining area



Explanation of symbols in the text

Figure 4. Mathematical model of geothermal doublet

Heat transport in a geothermal field is described by the general equation[4]:

$$div(\lambda.grad.T_r)-div(c_w\rho_w T_w v)=(c\rho)_r\frac{\partial T_r}{\partial\tau} \tag{1}$$

where: T_w - temperature of injected water, K
T_r - reservoir temperature, K
c_w - specific heat of water, $Jkg^{-1}K^{-1}$
ρ_w - density of water, kg m^{-1}
$(c\rho)_r$ - specific heat of reservoir, $Jm^{-3}K^{-1}$
v - liquid flow velocity, m s^{-1}
λ - thermal conductivity of rock, $Wm^{-1}K^{-1}$
τ - time, s

$(c\rho)_r$ in the above formula is defined as follows:

$$(c\rho)_r=\phi(c\rho)_w+(1-\phi)(c\rho)_s \tag{2}$$

where: $(c\rho)_w$ - specific heat of water
$(c\rho)_s$ - specific heat of rock forming the aquifer
Φ - porosity

Due to convective character of heat transport in the aquifer the above equation should be solved simultaneously with the flow equation:

$$div(kgrad\gamma)+Q_w=\beta\frac{\partial\gamma}{\partial\tau} \tag{3}$$

where: Q_w - water flow, m^3s^{-1}
k - filtration coefficient, m s^{-1}
Γ- hydraulic potential, m
β - elastic volume coefficient of reservoir, m^{-1}

The problem has no general analytic solution. However, when only an approximate solution is desired, a number of simplyfying assumptions can be introduced, which allows to obtain a simple analytic solution.

The model of geothermal field shown in Fig. 4A has been chosen for computations. A doublet of two wells (injection and exploitation) is standing for a fragment of the geothermal field. The following simplyfying assumptions were made:

- the reservoir is horizontal, homogenous, isotopic and equally thick in the whole of its extent
- the area of reservoir is infinite
- layers limiting the reservoir are impermeable
- horizontal heat conductivity is neglected, while vertical heat conductivity is assumed infinite: temperature in the whole thickness of the aquifer is constant
- viscosities of the reservoir and injected water are neglected and the boundary between the waters of different temperature is sharp

Assuming the above, the problem is reduced to one-dimensional and a simple formula is obtained:

$$\frac{T_r - T_w}{T_o - T_w} = erf\left(\frac{\sqrt{\lambda(c\rho)_2}}{\frac{Q_w}{A}(c\rho)_w\sqrt{\tau - \frac{H(c\rho)_r}{(c\rho)_w\frac{Q_w}{A}}}}\right) \tag{4}$$

where: T_o - initial reservoir temperature, K
T_w - cooled water temperature, K
T_r - reservoir temperature, K
λ heat conductivity of rocks limiting the aquifer, W $m^{-1}k^{-1}$
$(c\rho)_r$ - volume specific heat of reservoir, J $m^{-3}K^{-1}$
$(c\rho)_w$ volume specific heat of water, J $m^{-3}K^{-1}$
$(c\rho)_l$ - volume specific heat of the limiting rocks, J $m^{-3}K^{-1}$
Q_w - water inflow into the aquifer, m^3s^{-1}
A - area confined within the cool water front, m^2
H - thickness of the aquifer, m
τ - time, s

Further assumptions were made to comply with the specific conditions of the model:

- inflow Q_w is a sum of underground water inflow from outside of the aquifer (Q_o) and reinjected mine water; following values were assumed: Q_o=1.4 m^3min^{-3} (real value in the "XXX - lecia" mine), Q=1,5 Q_o
- temperature of cool water T_w is a weighted mean of the reinjected water and inflowing underground water temperatures
- $(c\rho)_r$is a weighted mean of specific heats of all rocks forming one cyclotem
- evaluating A - the area confined within the temperature front has been described in[3]: for computations A=1km^2 has been taken, which corresponds to distance between the two wells equal L=1100 m

Computations have been carried on a personal computer using an algorithm derived from formula (4). Following results have been obtained:

H (m)	t (years)
20	13
50	31
100	61

where: H - thickness of the aquifer
t - time after which the reservoir temperature at the bottom of exploitation well would drop

while: $(c\rho)_r$ = 2.643 J $m^{-3}K^{-1}$
$(c\rho)_l$ = 2.255 J $m^{-3}K^{-1}$
T_o = 50°C
T_w = 20°C
Q_w = 0.023 m^3s^{-1}
A = 1 km^2
λ = 2.219 W $m^{-1}K^{-1}$

Areas of mine fires (caused by self-ignition of coal) can be effectively cooled by the moving temperature front associated with recirculated mine water. Cooling can decrease the range of fires. Evaluating the time needed for the temperature front to move from the injection well to a fire area has been another question considered in the computations.

The model shown in Fig. 4B has been employed: a fire area is placed in one of the coal beds adjacent to the layer of sandstone which represents the aquifer. However, it appears that the simplyfying assumptions quoted in the above formula (4) can be hardly applied to this situation. Obtained results are therefore only a rough approximation and can give a general image of the process. The authors of paper(6) point out some problems connected with temperature distribution in vicinity of fire areas.

According to the computations, movement of the temperature front has step-like character, i.e. after the time in which the temperature front reaches the vicinity of a fire area, it is cooled by water of temperature T_w. Following results have been obtained:

L (m)	t (days)
50	5
100	17
200	63

where: L - distance between injection well and fire area
t - time needed for the temperature front to reach the fire area

while: $(c\rho)_r = 2.245 \ J \ m^{-3}K^{-1}$
$(c\rho)_l = 1.620 \ J \ m^{-3}K^{-1}$
$T_o = 50°C$
$T_w = 20°C$
$Q_w = 0.023 \ m^3s^{-1}$
$H = 10 \ m$
$\lambda = 0.327 \ W \ m^{-1}K^{-1}$
$\Phi = 0.1$ (Φ - porosity)

Subsequent process, i.e. temperature distribution in fire areas adjacent to cooled aquifer could be determined by means of numerical methods(e.g. a finite difference method(5).

CONCLUSIONS

Recirculation could be an useful method of protecting surface and underground water-courses from pollution caused by highly mineralized and/or chemically polluted mine waters. However, an application of this method is connected with a number of difficulties (avoiding colmatation etc.), primarily due to incomplete knowledge of aquifer's geometry and characteristics.

Together with recirculation, possibility of recovering heat energy from mine waters should be considered. This energy could be used on the spot in the mine, or even for heating nearby settlements.

Models of geothermal field applied in the paper are sufficient for an approximate evaluation of temperature front movement from places of injection towards exploitation well.

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