Protection of Ground Water from the Impact of Ash Depositories

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ABSTRACT

Low-caloric coals ash depositories of large thermal plants are considered. Several years of authors experience in environmental protection from the impact of ash depositories on alluvial sediments, with hydraulic ash transport, are condensed in the paper. Water protection, and particularily ground-water protection is emphasized. General principles of protection, as well as the results of field and numerical model investigations for a particular large thermal-power plant are given. Protection wells situated in the zone of downstream contour of the ash depository are far more efficient in the analized example.

In order to generalize the obtained results, the parameter analysis on a hypothetical model, containing fundamental features of some ash depositories in Yugoslavia, is carried out. Results are given in the form of the relations between optimum well location and technological and hydro-geological parameters of the depositories.

Some general considerations on constraints, criteria and alternative technological solutions for the design of ash depositories are also discussed in the paper.

INTRODUCTION

The paper deals with with the ash depositories of large thermal plants using low-caloric coal. Low-caloric coal is one of the most important thermal energetic resources in Yugoslavia (and particullarily in Serbia). Its exploitation requires that thermal electric power plant (TE) is near the mine. It is usually open pit exploitation. Coal combustion in big poweplant produces huge volumes of ash.

Author of this paper studied the problems of ash depositories for the most productive coal basin in Yugoslavia, the Kolubara coal basin, recently particullarily of one of them : the depository Obrenovac "B", formed by a thermal plant of $1230MW$, which produces more than 2 milions of cubic meters of ash per year. Its depository belongs to the external TE ash depositories (not in the coal excavation pit). The power plant is situated on the river of Sava, using the adventage of river water for plant cooling. Presently the active part of the ash depository covers more than $400ha$.

The hydrogeological section[1] in depository zone can be roughly simplified by a semipervious compressible surface layer of 8 to 10 m thicknees and an aquifer of sandy gravel of about 10 m thick. Both layers are alluvial deposits. The basement is practically impervious marl.

For ash transport from thermal power to the depository, hydraulic system is used , actually with rather low concentration of ash (ratio solid – water is about 1 to 10). This, for our conditions very economical transport system, has also the adventage of decreasing the air pollution. The disadvatage is water polution.

Principal macropollutant is sulphate[2]. Far the most important micropollutant is arsenic. Each tone of ash produces more than $3kg$ of sulphate, and about $0.5g$ of arsenic. Other information about pollutants will be given in the next chapter. A system of drainage wells is bored around the depository for the double sake (see chapter 3):

- to protect the ground water from pollution,
- to assure the stability of ash depository slopes.

The paper gives some information on the drainage wells, particullarily concerning the ground water protection, for the considered depository. An attempt is made, as well, to generalise our experience to other analogue depositories.

Some information concerning air pollution by the depositories of TE "Obrenovac A" and TE "Obrenovac B" can be found in [3].

ELEMENTS OF ASH DEPOSITORY. INFORMATION ON APPLIED EQUATIONS

A shematic cross section of ash depository for the above conditions is given in figure 1, with the necessary terms to explain the transport of water and pollutant through the depository and to form the balance equations. The following indices are used :

d – output from the depository to the aquifer (producing ground water pollution),

dr – drainage from the body of the depository. The drainage system is used for the stabilisation of depository slopes.

drc – drainage channel collecting water from drainage and wells

ev – evacuator . The level of the depository lake is controlled by the evacuator spillway.

in – ground water inflow into the considered area of the aquifer in the zone of the depository,

irr – sprinkler irrigation used to prevent air pollution for the peripheric part of the depository (depository beaches and embankments),

out – ground water outflow from the considered area of the aquifer,

s – surface water inflow from neighbouring terrain to drainage channel around the depository,

t – transport (water, pollutant) from thermal plant to the ash depository,

vert – vertical balance terms for aquifer flow due to evaporation from aquifer (index *evap*), or infiltration (index *inf*).

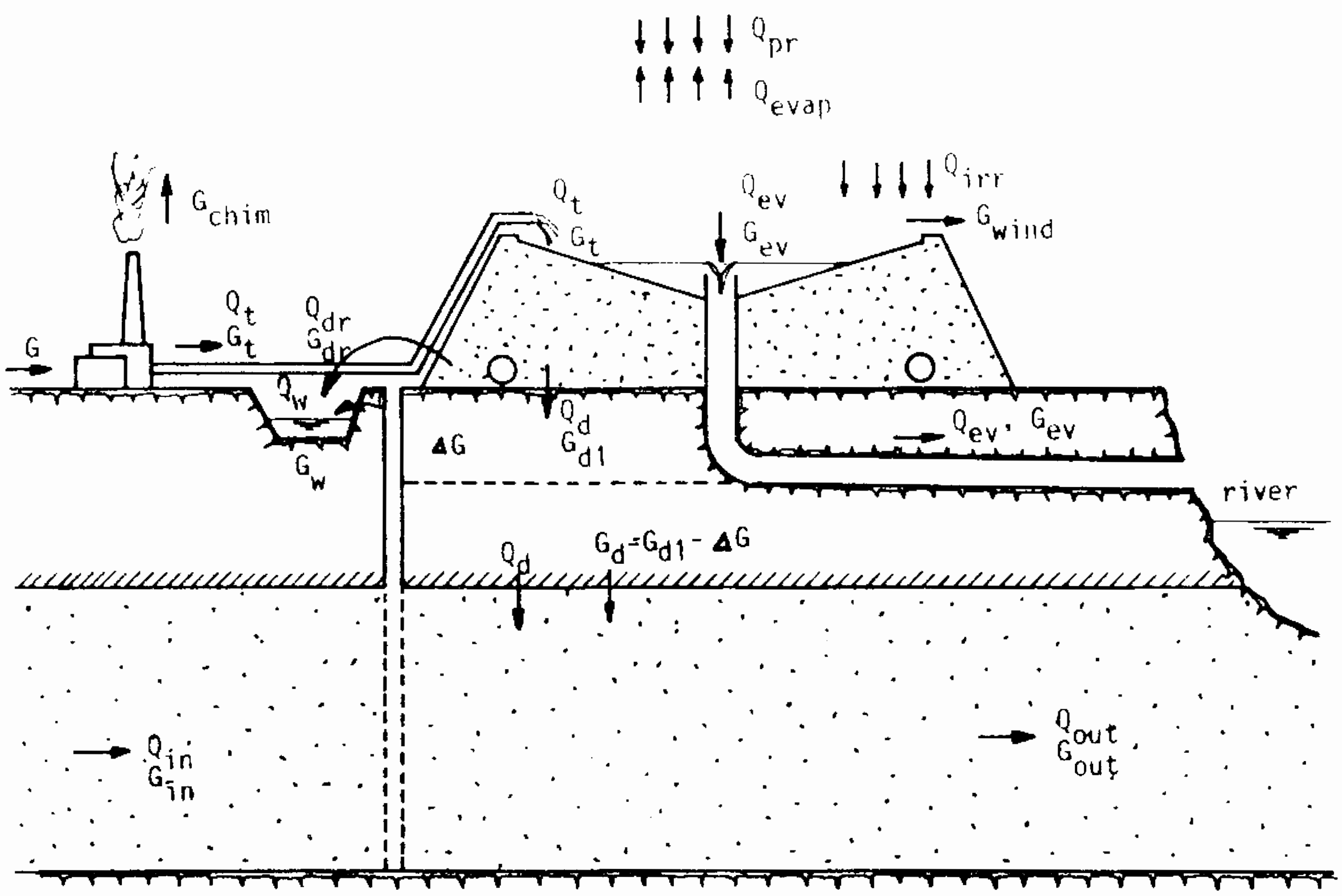

Figure 1: Transport of water and pollutant through the ash depository
Transport pipes, drainage channel and the wells are actually on both sides of the depository

Global balance equations for water and pollutants are used for a triple goal:
– to explain the transport of pollutants,
– to control the mesurements which last for years,
– in the framework of an alternative transport technology, recirculation, when the balance of water is of crucial interest (see chapter 6).

Some information, concerning the data about pollution of the depository Obrenovac "B" are the following:

- The water flowing through depository evacuator (Q_{ev}) contains $300mg/l$ of sulphate. Not very different is the concentration of sulphate in the drainage channel.
- Average concentration C of arsenic in Q_{ev} is about $0.27mg/l$ (maximum $1.2mg/l$). For drainage water C is as average $0.05mg/l$ (maximum $0.12mg/l$). We point out that the maximum permitted concentration for the river Sava (standard for second class river) is for As is $0.05mg/l$ and for sulphate $200mg/l$.

The following comments of the global balance equations seem intresting to us:

- For the nearfield zone of depository vertical balance factors for aquifer flow (evapotransporation Q_{et} and infiltration Q_{inf}) can be neclected. For larger area they can be important in some periods of years.
- When the balance equation for thermal plant is analysed, temperature of coal combustion seems to be of influence. This temperature defines the ratio $G_t/G_{chim(ney)}$ (figure 1).

- The effect of the purification by filtration due to ion exchange between water and soil can be neglected for sulphate. It is quite opposite for arsenic (and heavy metals in general). Here the arsenic ion is absorbed during the water filtration through the semipervious surface layer. (It means that the term ΔG represented in fig. 1 has to be included in the calculation). Altough this effect is temporary, it lasts for years and has to be included in the considerations.

Concerning the differential equation for ground water flow and pollutant transport, we emphasize that they were used in classical forms[4]. Far the most important term in pollutant transport equation is the convective one. This statement is involved in the analysis given in chapter 4 and 5.

CONSTRAINTS AND THE CRITERIA FOR THE DESIGN OF DRAINAGE WELL SYSTEM

Depositories are particular structures. Their construction lasts practically as long as their exploitation. Here the method "design as you go" can be used. This is valid for all the elements of the depository, including also the well system. Constraints and criteria also change with the growing of the depository. During the development of the depository the infiltration rate Q_d always increases due to the increase of piezometric head between lake level and the piezometric level in the aquifer, in spite of three counter effects:

– reduction of permeability of surface layer due to its compression (particular attention was payed to this problem),

– decreasing of permeabilty thanks to clogging effects,

– reduction of the area of the lake in the depository defined by the depository slope. These effects cause the increasing of Q_d to be much slower than increasing of the piezometric head. The increasing of Q_d makes the problem of water pollution more complicated. The slope stability is far more sensible to the hight of the depository than the pollution is. Both effects require the development of the system of protective wells during the growing of the depository.

Well system is defined by the number, position (dispositive) and characteristics (screen, diameter, etc.) of wells, as well as by the regime of their exploitation.

A well system must satisfy the following principal constraints:

- **Ground water protection criterium.** Q_{dout}, the outflow from the depository has to be eliminetcd

  $$Q_{dout} = 0$$

  This criterium obviously has to be satisfied for any point of the contour of the depository zone. It means that it is not allowed for any streamflow to leave this zone.

- **Slope stability criterium:**

  $$h < h_s$$

  h is the piezometric head, h_s is a limit piezometric head, when the stability is yet assured. It is obtained by geomechanical calculation (not analysed in the paper).

Both constraints are compatible. In the begining of depository development, ground water protection constraint is principal. It has to be controled during the period of low ground water level of surounding terrain when Q_d is maximal. The stability constraints define the characteristics of well system begining from a certain depository hight. It has to be controled for wett season (maximum ground water level).

All characteristics of well system should be found by **optimisation method** using the multicriteria optimisation aproach, based on economic and risk analysis. Many reasons didnt permit a rigorous application of this approach and we used a simplified matrix of criteria as follows:

- **Environment protection criteria**. We try to minimise:

    1. The area A_d influenced by the existence of the depository. A_d is defined by two fundamental state variables:

        (a) Concentration of pollutant which defines the criterium of pollution. There is a zone under and around the depository A_{dp} contaminated by the dissolved materials in ash. A_{dp} minimal, which satisfies this criterium, would be obtained whith an infinitely dense system of well all around the depository, and very close to it.

        (b) Drawdown criterium which defines a zone of influence of drainage wells A_{dd}. It can be shown by simple hydraulic considerations that Add, which satisfies this criterium, minimum would be obtained if the wells just pumped the quantity of water infiltrated from the depository.

        $$Q_w = Q_d$$

        It would be easy to understand why the ratio Q_w/Q_d is a very important indicator of the function of a well system. The closer this indicator is to unity the better is the system (in relation to the considered criterium)

    2. Impact on ground water resources. Drainage wells satisfying the constraints of ground water protection ($Q_{dout} = 0$), always pump a certain quantity of surronding aquifer water. The best solution would be (again), when $Q_w/Q_d = 1$. It confirms the importance of the indicator Q_w/Q_d.

- **Economic criteria** are given by:

    1. Minimum number of wells,
    2. Minimum drawdown in each well,
    3. Best policy of exploitation of well system satisfying both constrains. In the begining od depository development more water has to be pumped in dry period of year.

- **Reliability of well system**. It can be always expected that a well drops out of the system. The arangement of wells which minimise this event would give the best solution in relation to this criterium.

These simplified criteria with both above constraints were used do define the well system for TE Obrenovac "B" (Chapter 3), as well to analyse a hypothetical depository (Chapter 4).

REGIME OF THE SYSTEM OF WELLS AT THE ASH DEPOSITORY "OBRENOVAC B"

The number and the capacity of the protecting wells for the ash depository "Obrenovac B" were found by series of computations. Both aquifer protection and the stability criterion, explained in chapter 3, were checked, but the letter one was found much less important at this stage, since the depository is not very high yet. The conclusions of parameter analysis, presented in the next chapter were used in this study, as well.

The numerical model of ground-water flow comprises the zone of about 2500 ha, surrounding the depository. The surface of the model is small enough that vertical factor of water balance can be neglected outside the depository, compared to the infiltration from the depository. Boundary conditions of the model are given as piezometric levels, which were measured, and interpolated along the boundary.

The situation was analised when the active, upstream cassette (II in figure 2) is $9.5m$ high ($6m$ higher than presently), and the non-active, downstream cassette (I) is $3.5m$ high (same as now). The water level in the active cassette was evaluated (taking into accout flow towards drains), and in the non-active cassete it was measured.

The computations were carried out for two characteristical, staedy-state situations: minimum and maximum surrounding piezometric levels. Model calibration was oriented mainly to the leakage modulus (K_u/l) of the less permeable layer. The whole phenomenon is very sensitive to this parameter. It makes it easier to calibrate it, but on the other hand eventual error has larger influence. It should also be pointed out that the leakage modulus is likely to decrease as the depository develops, due to increased stresses. Therefore, it should be re-calibrated for each phase of the depository development. For the present situation, the leakage modulus, calibrated as a unique parameter (across the surface of the depository), has the value:

$$K_u/l = 1.5 * 10^{-9} s^{-1}$$

Only in the small zone (Zone 1 in figure 2) twice as big leakage modulus was obtained, because the upper layer is much thinner there.

Transmisivity of the aquifer is non-homogeneous across the model. Field data from pumping tests, made for 10 already constructed wells were available, as well as the transmisivity calibration results from previous studies, done for the natural conditions, without the depository. Contrary to the leakage modulus, transmisivity is not likely to change as the depository develops. Therefore, the available transmisivity data were taken for this model, without excessive further calibration.

From the point of view of aquifer protection, the situation with minimum surrounding piezometric levels defines the necessary number and capacity of the wells, since the infiltration from the depository is highest then. By series of "trial and error" computations it was found that the system of 15 wells protect the aquifer in the analised phase of the depository construction. Maximum capacity of the wells was evaluated on the basis of field pumping test, when the present 10 wells were operating simultaneously for 15 days. In the computation of necessary number of wells, 80% of this maximum capacity was supposed. The results of the computation, presented as izo-piezometric lines for the aquifer are shown in figure 2. The ratio between the quantity of water, captured by the wells and infiltrated from the depository, is for the computed situation:

$$C_Q = Q_w/Q_d = 2.42$$

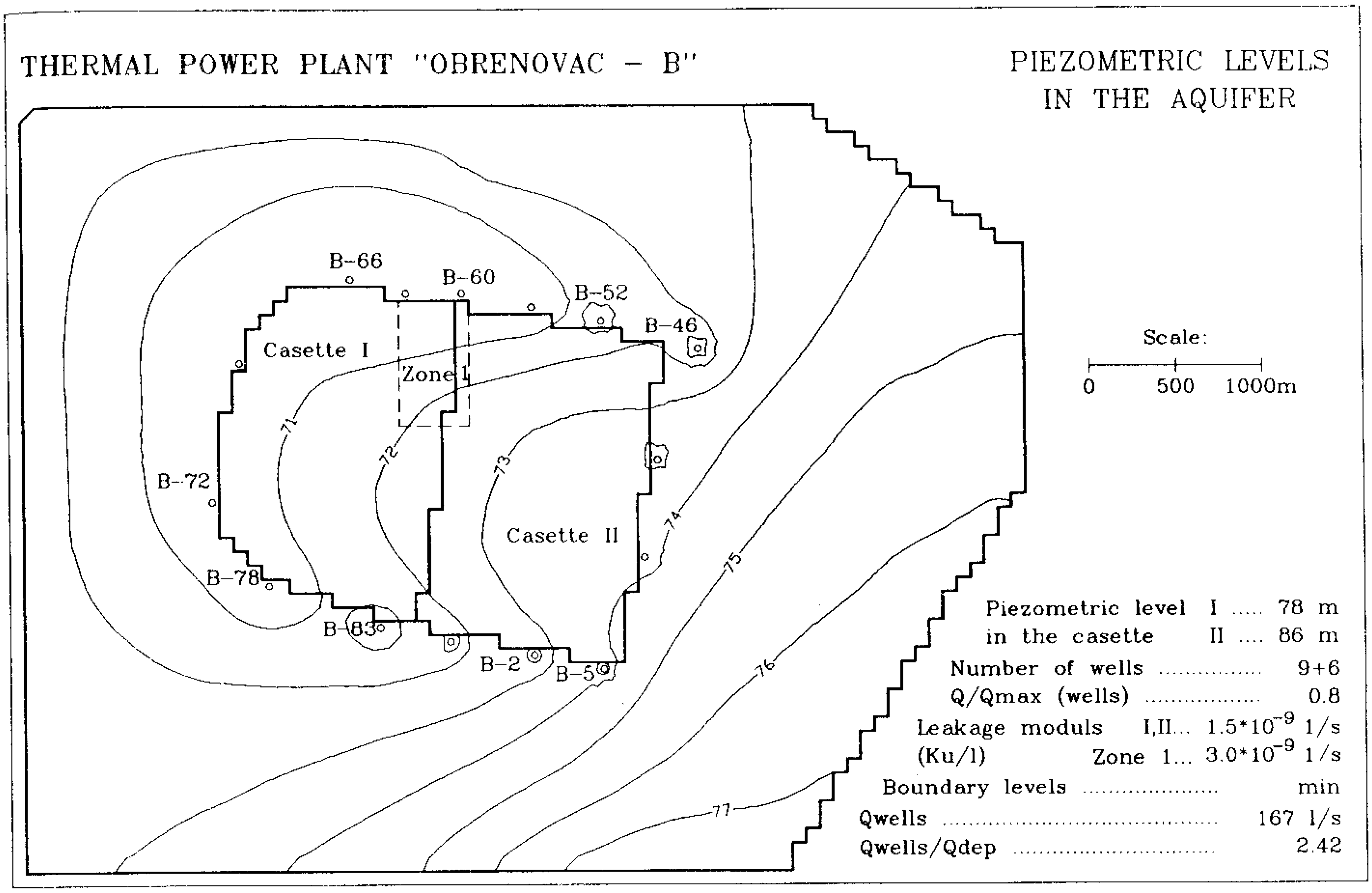

Figure 2:

This means that quite a large amount of well water consists of clean water from the surrounding aquifer, which is unneccessarily pumped. It is shown in the next chapter that this ratio is likely to decrease as the depository grows.

In the situation with maximum boundary piezometric levels, the piezometric head which causes infiltration is minimum. It is to be expected that aquifer protection is achieved with lower capacity of the well system, i.g. that maintaining the same capacity of the system all over the year would not be economical. Really, for the same situation as in figure 2, with the same capacity of the wells, but for maximum surrounding piezometric levels, the indicator C_Q increased to 3.15. Reducing the well capacity by 40% caused the reduction of C_Q to 2.58, while the protection of the aquifer was still obtained. Proper definition of the wells capacity can obviously save signifficant exploitation costs.

For the future steps of the analysis, more measurements, which will enable more rigorous control of the water balance are planned. In the re-calibration of the model for the conditions of further depository development, the data obtained for the operating well system will be of great help.

HYPOTHETICAL ASH DEPOSITORY

It was shown in chapter 4 that the solution of the aquifer protection from the pollution of the water infiltrated from the ash depository requires the ground-water flow simulation in complex natural conditions, in heterogeneous medium, with rather large uncertainties in parameters detection. The influence of a single parameter is sometimes difficult to evaluate with such a model, and it may be usefull to make a parameter analysis in advance, using somewhat simplified, hypothetical model. Such an analysis is described in this chapter. The purpose of the analysis was to evaluate the influence of the error in some parameters on the results of computation, and to clarify some basic relations which may be used in the complex model. Another reason was the need to generalize some conclusions, i.e. to prove that they are valid in series of possible situations. The whole following analysis considers only aquifer protection. Stability criterion was found to be too much dependant on local conditions to enable generalization.

Hydrogeological profile in the hypothetical model is two-layered – it corresponds to the conditions of the depository of "Obrenovac B". The depository is also made on the ground surface and surrounded with protection wells. The main simplification of the model is regular geometry and homogeneous aquifer. Flow domain is rectangular, with the following relations:

$$b/a = 2,\ B/b = 3,\ A/a = 7$$

where (fig. 3):

- a – length of the depository along the flow direction
- b – width of the depository
- A – length of the model
- B – width of the model

The model simulates two-dimensional flow in a horizontal confined aquifer, with vertical recharge from the depository, through less permeable layer. The water level in the body of the depository is supposed constant all over its area.

Undisturbed condition for the model, without depository and the wells, is the uniform ground-water flow along the longer side of the model, with constant piesometric slope of 1‰. The corresponding boundary conditions were kept constant through all the computations. Infiltration from the depository into the aquifer is caused by the difference between water level in the depository and the piesometric level in the aquifer (under the depository).

Computations were carried out using a numerical solution of steady ground-water flow equations, based on the integrated finite difference scheeme, with local analitical solutions for the flow near the wells. The porous medium is described as two-layered, with dominant vertical flow in upper, less permeable layer, and dominant horizontal flow in lower layer i.g. aquifer. The details of the model are presented elsewhere, and would not be repeated here.

Series of computations were carried out for the hypothetical model. Number and arrangement of the wells were given as input for each computation. For the sake of simplicity, wells were assumed to have equal discharges. The result of computation was the minimum capacity of the wells which guaranties protection of the aquifer. The protection of the aquifer was just achieved, in all the computations. (If the capacity of wells was sligthly lower, there would be a streamline starting in the depository, passing the boundary of the the polluted area A_{dp}, i.e. Q_{dout} would not be 0.) The results of computations are given in table 1, and, just as illustration of one computation, in figure 3. The following notation is used in the table:

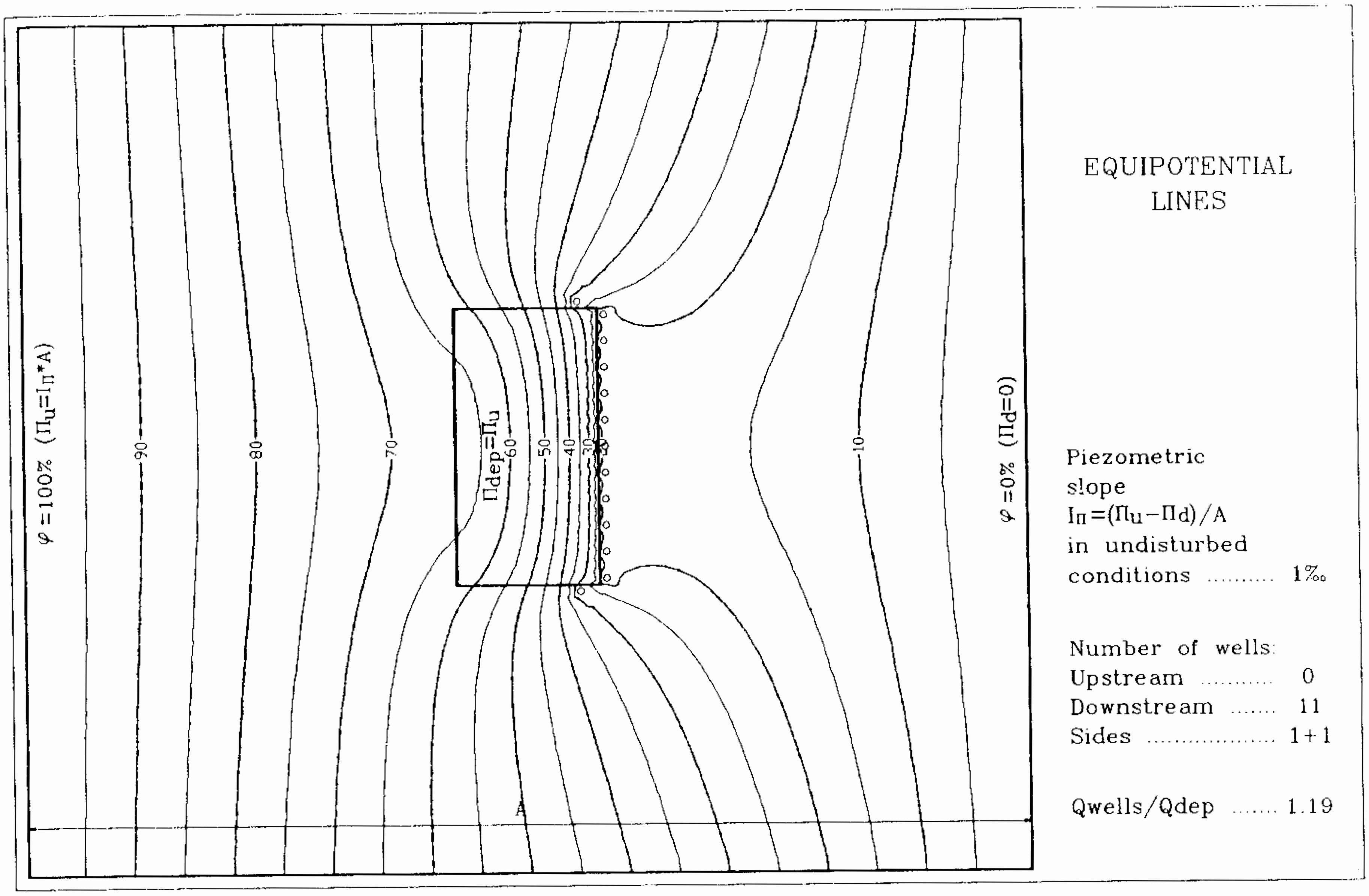

Figure 3:

T	–	transmisivity of the aquifer;
K_u	–	permeability coefficient of the upper, less permeable layer;
l	–	thickness of the upper layer;
K_u/l	–	leakage modulus of the upper layer;
Q_d	–	discharge infiltrated into the aquifer from the depository;
Q_w	–	total discharge of the wells;
S	–	maximum drawdown in the wells. (Drawdown is computed as the difference between piezometric level in the well when it does not function and when it does, while the depository is already constructed in both cases.)

The results in the dimensional form are valid for the width of the depository $b = 2000m$. The dimensionless results can be applied, using similarity rules, to the cases with different dimensions, but equal natural piezometric slope. Three basic cases are analized, differing in the relation between leekage modulus of upper layer (K_u/l) and aquifer permeability, defined similarily, which can be expressed by the dimensionless number:

$C_T = \frac{K_u a A}{l T}$

This number expresses the ratio between the discharge infiltrated into the aquifer from the depository and the discharge in the aquifer, through unit width, due to unit piezometric head. (For infiltration from the depository piezometric head is the difference between water level in the depository and piesometric level in the aquifer below the middle of the depository. For the flow in the aquifer, piezometric head is the difference between piezometric levels at the upstream and the downstream side of the model.) The factor $\frac{K_u}{lT}$ is commonly used in the analysis of flow in layered porous media.

In each of the three various cases several combinations of wells number and arrangement were analized, and for each of them, three different water levels in the depository. The results show the necessary wells capacity, which can be compared for various cases in order to find the most economical one. Total number of wells in the system defines investments. Exploitation cost is influenced by the total wells capacity, and the ratio:

$$C_Q = Q_w / Q_d$$

(chapter 3) which shows what part of the wells discharge is made of clear water from the surrounding aquifer, which should be captured as little as possible. If all other factors (i.e. number and capacity of the wells etc.) are equal, the larger C_Q requires larger unnecessary exploitation costs.

When comparing the results, the unit drawdown (ratio between the drawdown and the well discharge) should not be overlooked. For one well, the unit drawdown depends only on the transmisivity of the aquifer, and cannot be controlled. The lower unit drawdown requires the higher transmisivity. For a system of wells, unit drawdown depends also on the number and arrangement of the wells. Finding most economical solution is therefore a clasical optimization problem.

The influence of the arrangement of the wells on the parameter C_Q is obvious. By simple rearangement of the wells the amount of unnecessary pumping can be decreased by 50%. From the point of view of aquifer protection, the best position of the wells is, no dout, along the downstream side of the depository. Comparing to all other arrangements, it gives lower number and total capacity of the wells, as well as lower amount of pumped clear water (lower C_Q).

The discharge which is infiltrated from the depository Q_d depends on the number of wells. It is lowest without wells and increases as the well capacity increases. It follows that the capacity of the system of wells should not be increased beyond the limit which guaranties the protection of the aquifer.

The analised phenomenon depends on the dimensionless parameter C_T. It was shown[5] that literraly same flow pattern is obtained for the cases with the same C_T. It may be the cause of serious errors in model calibration which is based on the comparison of measured and computed piezometric levels at certain points. Overestimation of the aquifer transmisivity may cause the simultaneous overestimation of the leakage modulus of upper layer. This error can be avoided only if the transmisivity calibration is done before the depository was constructed, or by the separate calibration of leakage modulus (provided that the series of measurements of water level in the depository and piezometric levels in the aquifer are available).

T m^2/s	k/l s^{-1}	No of wells	H_d m	Q_w l/s	Q_d l/s	S m	S/Q_w m/ls^{-1}	Q_w/Q_d -
		→ 1	3.8	67.6	48.3	4.1	0.78	1.40
5.0	5.0	→ 0 ▯ 11	11.4	119.6	119.0	7.2	0.78	1.01
		→ 1	26.6	240.5	238.7	14.4	0.78	1.01
		→ 3	3.8	78.4	32.2	3.4	1.23	2.43
		→ 11 ▯ 11	11.4	120.4	73.7	5.2	1.21	1.63
		→ 3	26.6	187.6	136.9	8.1	1.21	1.37
		→ 3	3.8	70.4	30.4	3.5	1.08	2.32
		→ 5 ▯ 11	11.4	107.8	71.2	5.3	1.07	1.51
5.0	2.5	→ 3	26.6	167.2	132.9	8.1	1.07	1.26
		→ 3	3.8	94.6	35.4	3.8	0.89	2.67
		→ 11 ▯ 5	11.4	147.4	79.2	5.9	0.88	1.86
		→ 3	26.6	226.6	144.8	9.1	0.88	1.56
		→ 1	3.8	50.7	26.5	3.4	0.86	1.91
		→ 0 ▯ 11	11.4	78.0	65.4	5.2	0.86	1.19
		→ 1	26.6	126.1	125.1	8.3	0.85	1.01
		→ 1	3.8	41.6	14.0	2.9	0.92	2.97
5.0	1.25	→ 0 ▯ 11	11.4	55.9	34.6	3.9	0.92	1.62
		→ 1	26.6	78.0	65.6	5.5	0.92	1.19

Table 1

SOME ALTERNATIVE SOLUTIONS CONSIDERED TO IMPROVE THE ENVIRONMENTAL PROTECTION

Alternatives were considered with sometimes intensive laboratory and field investigations carried out by thre Institute for mine technology of Zemun. In the following text only some very short comments are given:

- **Recirculation of water** for hydraulic transport. In this case (fig. 1.) Q_{ev}, Q_w, and Q_{drc} returns to transport process. This solution increases the concentrantion of pollutant in the narow zone of the depository, but eliminates the river pollution. The ground water protection has to be done with higher reliability (less risk).

- **Recirculation with water treatement**. To obtain a economic solution only 5% of Qt has to be treated. That requires:

  - Good estimation of balance factors,

  - A developed monitoring system,

  - Tecnological solution permitting to overcome the problem resulting of a wrong estimation .

- **High concentration transport** (Ratio ash - water 1:1). In spite of the fact that in the case of Kolubara coals ashes this problem is technologically very difficult it seems that the real global impact on environment is unexpectedly slightly reduced. In fact the global impact on environement is given by the total dissolved pollutant quantity which does not change by this tecnology.

- **Prewashing of coals**[6]. This technology is very intresting for coal combustion and more economical utilization of the depository volume. Nevertheless, it has practically no influence on water pollution, as was shown by laboratory investigations.

- **Impermeable sheet**. This technology after some years would eliminate ground water pollution. Effect on stability is far more rapid. Without water treatement, it increases the pollution of the river, but simlifies the water treatement in case of recirculation.

  It is not expected that any of this alternative technology will be introduced before a period of 4 – 5 years. For the time being the protection of ground water will be by protection wells supported by a good monitoring system.

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