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Assessment of natural resources of thermal aquifers – formulation, test data, results

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Йотов, Ил. – Оценка естественных ресурсов термальных вод – формулировка, опытные данные, результаты. Разработан метод определения естественных (динамических) ресурсов Q_d относительно небольшого месторождения термальной воды. Месторождение является дренажной зоной гидротермальной системы. Гидрогеологические условия такой системы представлены схематично в виде вертикального водоносного горизонта с круговым сечением. Его латеральная граница – непроницаема, а нижняя и верхняя граничные поверхностьи (с площадями F_d) – проницаемы (фиг. 1). Водоносный горизонт получает естественное питание Q_d из глубины. Оно распределено равномерно по нижней поверхности F_d. Q_d дренируется на верхней поверхности при помощи естественных источников и (или) существующих самоизливающихся скважин. Часть питания однако остается скрытым, так как оно распределено незначительными количествами в различных зонах пласта или ввиду перетекания через перекривающие отложения речных террас, где обычно находится дренажная зона месторождения. Благодаря этой скрытой части пытания, его общая величина Q_d остается неизвестной. Для ее определения проводится опытная откачка из одной или нескольких скважин, расположенных приблизительно в центре водоносного горизонта. Откачка осуществляется в режиме двух постоянных дебитов Q_1 и Q_2. Каждый из них должен превишать величину естественных ресурсов месторождения Q_d. При этих условиях скорость понижения напора в данной наблюдательной скважины становится постоянной после некоторого времени с начала откачки. Значения этих постоянных скоростей v_1 и v_2 являются функцией дебита откачки. Величина Q_d определяется по формулам (8) и (9).

В статье даны некоторые дополнительные пояснения по приложению разработанной методики, в том числе и практическое определение естественного ресурса Q_d на примере конкретного месторождения термальных вод.

Abstract. A method is worked out for the assessment of natural (dynamic) resources Q_d of relatively small thermal deposits representing drainage zone of a hydrothermal system. The hydrogeological conditions in such a system are schematized by a vertical circular aquifer with impermeable lateral boundary and permeable upper and lower boundaries with surface F_d (fig. 1). The lower surface of the area is influenced by uniformly distributed constant recharge Q_d coming from the depth. Q_d is drained over the upper surface by natural springs and/or by existing flowing wells. Some part of recharge Q_d stay hidden because of its distribution as a small quantities in different parts of the aquifer and/or because of the leakage trough the materials of the river terrace, where the drainage zone normally is located. Because of this hidden part of the natural resource the total quantity of Q_d remains unknown. For determining its value a pumping test is carried out with two constant discharges Q_1 and Q_2. The pumping well or wells has to be located approximately in the middle of the aquifer. Each one of the two discharges must be greater than the total recharge Q_d. Under such condition the velocity of drawdoun of piezometric level in one observation well becomes constant after some time elapsed from the start of the pumping. The values of these constant velocities v_1 and v_2 are functions of the pumping rate.

The value of Q_d is determined according to formulas (8) and (9).

In the paper are given some complimentary explanations for application of the methodology including an example of determining the natural resources of one thermal deposit.

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Kew words: hydrothermal deposits, natural (dynamic) outflow, pumping test, piezometric level, storage coefficient.

Objective and its quantification

A subject of assessment are groundwaters of ***relatively small thermal deposits*** representing drainage zone of a hydrothermal system (Петров и др., 1998). The total outflow of the system Q_d is represented usually by natural springs (or by its catchment equipment) with discharge Q_n or by man made flowing wells having total rate of flow Q_a. In many cases part of Q_d stay hidden because of its distribution as a small quantities in different parts of the aquifer or because of the leakage into the materials of the river terrace, where the drainage zone is located. This hidden part of the resources is denoted by Q_h and it forms the unknown component of Q_d.

For steady state conditions the upper description can be summarized as

$$(1) \quad Q_d = Q_n + Q_a + Q_h.$$

In a particular case, when the flowing wells are absent, $Q_a = 0$ and then $Q_d = Q_n + Q_h$. If complimentary flowing wells are introduced in the deposit the component Q_a can be increased but the total natural resource Q_d redistributes between the components of (1). As a result the quantity Q_d stay constant but the discharges Q_n and/or Q_h diminish respectively on the account of the increased Q_a.

The quantities Q_n and Q_a can be measured during the hydrogeological prospection but the presence of a hidden component Q_h in (1) means that the total natural resource Q_d is unknown quantity. They are formed mainly in fissured intrusive rock massifs, in their metamorphic mantles or in volcanic rocks. Often the drainage zone is composed by carbonate materials.

Hydrogeological schematization

The relatively small thermal deposits are widely distributed in sought Bulgaria. They can be approximated as a vertical circular aquifer with cross section area F_d (F_d is the catchment or recharge area of the thermal deposit), with impermeable lateral boundary – $(\partial H/\partial n) = 0$; (H – piezometric head, n – direction, normal to the lateral boundary) and permeable upper and lower boundaries with surface F_d and radius R_d. The lower boundary is influenced by a constant recharge Q_d, which is uniformly distributed over the surface F_d – Fig. 1. A method for determining the water resources of the aquifer for such conditions is given by Yotov (2002, 2004). For applying the method the following data are needed:

– steady state drawdoun data in three observation wells, located at different distance from the pumping well. For some particular cases a variant of two wells is used where one of them is the pumping one;

– steady pumping test Q = f (s) under 4–5 different constant discharges Q with corresponding constant drawdoun s.

In the present paper this methodology is enlarged including nonsteady state drawdoun data from pumping tests.

Analytical formulation

It is known (Muskat, 1946, Бочевер, 1968, 1976) that during the pumping with constant discharge Q from a single well located in the center of the circular aquifer (Fig. 1) without any recharge ($Q_d = 0$), some time after the beginning of the pumping the draw-

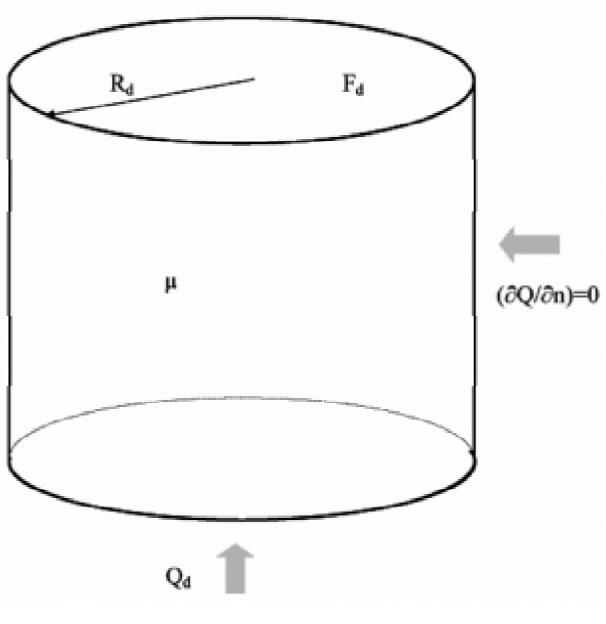

Fig. 1.

doun at each aquifer point increases with constant velocity v described by

$$(2)\quad v = \frac{1}{\mu F_d} Q,$$

where μ – storage coefficient of the aquifer.

Under the natural conditions the flow in thermal deposits is steady one in the frame of the corresponding season fluctuations of the recharge Q_d. In such a case when a pumping is applied two variant are possible:

1. *Variant I*

It satisfies the condition $Q < Q_d$. Then steady state flow arises, which is out of the scope of this paper.

2. *Variant II*

It refers to the condition

$$(3)\quad Q > Q_d$$

which is the case considered in the paper. Then the flow during all the period of pumping is nonsteady one. For such conditions on the basis of balance reasons instead of (2) we can write

$$(4)\quad v = \frac{1}{\mu F_d}(Q - Q_d).$$

Applying (4) for two different discharges Q_1 and Q_2 we receive

$$(5)\quad v_1 = \frac{1}{\mu F_d}(Q_1 - Q_d)$$

$$(6)\quad v_2 = \frac{1}{\mu F_d}(Q_2 - Q_d).$$

The dependences (5) and (6) show that the constant drawdoun velocities are produced by the corresponding parts of the two discharges Q_1 and Q_2, which exceeds Q_d. By analogy with the conditions for application of the basic formula (2), in this case the constant velocities v_1 and v_2 also appear some time after the beginning of the pumping.

The system (5)–(6) represents two equations with two unknown – Q_d and

$$(7)\quad D = \mu F_d.$$

After dividing the two equations we get

$$(8)\quad Q_d = \frac{CQ_2 - Q_1}{C - 1},$$

where

$$(9)\quad C = \frac{v_1}{v_2}.$$

Formula (8) represents the solution of our task, defined in the beginning, for the assessment of the natural resources of relatively small hydrothermal deposits.

After subtracting (5) from (6) we obtain

$$(10)\quad D = \frac{Q_2 - Q_1}{v_2 - v_1}.$$

When the complex parameter D is already known, we can use formula (7) to determine the surface of the aquifer area F_d if the storage coefficient is also known:

$$(11)\quad F_d = \frac{D}{\mu}.$$

Results

The method outlined here for determining the natural resources of thermal aquifer Q_d and the complex parameter D will be illustrated on the basis of the results from pumping test carried out in thermal deposit Erma reka, sought Bulgaria, in 1990. The thermal aquifer consists of karstifyed and cavernous marble body (cupola) distributed among Precambrian gneiss complex in a depth more than 450 m. In the border between the marbles and overlying gneisses a thick quartz-cavernous zone is formed. In this zone II Rudoupravlenie of "Gorubso", Madan with the participation of Geological Institute, Sofia, carried out a long pumping test from wells VPS-1, VPS-2 and VPS-3, drilled from underground horizon 300*. The wells penetrate the quartz-cavernous zone of the so cold "*I marble horizon*" of the deposit. The pumping test from the thermal aquifer consists of two flowing discharges: Q_1 = 104 l/s = 8985.6 m^3/d during about 36 days (from Mach 21 up to April 26, 1990) and Q_2 = 150 l/s = 12960 m^3/d (from July 11 up to August 8, 1990). In the mention periods the drawdoun of piezometric level is measured in a number of observation wells. For illustration we will use data from observation well DSH-1. Because of the close distance between the flowing wells compared to their distance from the observation well DSH-1, all three exploitation wells are assumed to work as one well, located at 863 m sought of the flowing wells.

On Fig. 2 is shown the drawdoun s_1 in well DSH-1, caused by the rate of flow Q_1 = 104 l/s. Only data from the last 9 days of the pumping are included because of the expectation of appearance of a linear relationship $s_1 = F(t)$ in this period. And indeed the regression equation in Fig. 2 shows practically such linear dependence. The last one indicates that the velocity of drawdoun is

$$(12)\quad v_1 = \frac{s_1}{t} = 0.1143 \text{ m/d}.$$

On Fig. 3 is shown the final stage of the drawdoun s_2 in well DSH-1, caused by the rate of flow Q_2 = 150 l/s. From the regression equation one can see that the

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* Йотов, Ил., Петров, П.Ст. 1991. Обработване на резултатите от I етап на опитнопромишленото осушаване на I-ви мраморен хоризонт (договор на ГИ-БАН с ГОРУБСО, Мадан от 1982 и 1987 г.). Архив ГОРУБСО, Мадан; Петров, П. Ст., Йотов, Ил., Бендерев, Ал., Христов, Вл., Гашаров, Ст. 1998. Преоценка на ресурсите на геотермална енергия в България (Договор на МОСВ с Геолог. инст. на БАН от 1998 г.). Архив МОСВ.

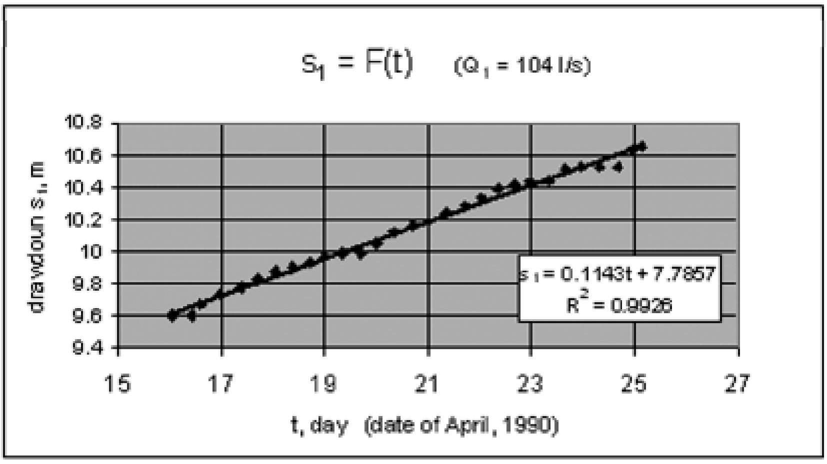

Fig. 2.

DSH-1

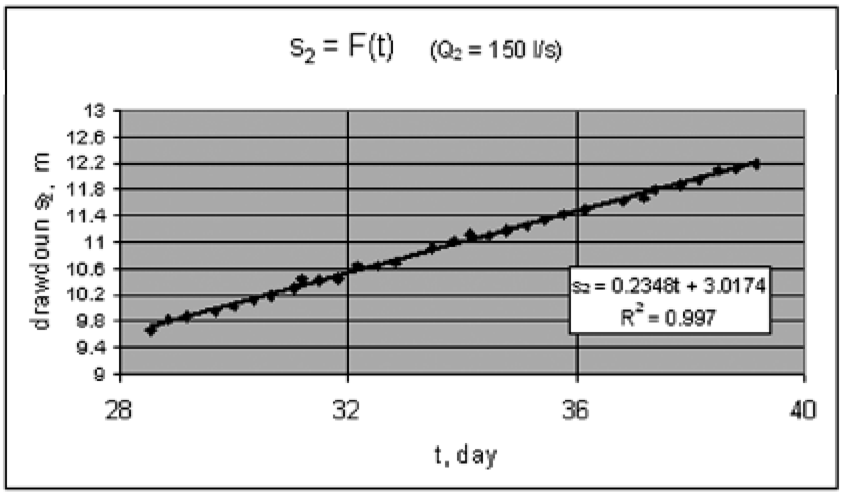

Fig. 3.

DSH-1

dependence $s_2 = F(t)$ practically is also linear one and consequently

$$(13)\quad v_2 = \frac{s_2}{t} = 0.2348 \text{ m/d}.$$

Then according to formula (9) we obtain

$$(14)\quad C = \frac{v_1}{v_2} = \frac{0.1143}{0.2348} = 0.487$$

and after that applying (8) –

$$(15)\quad Q_d = \frac{(0.487\text{x}150) - 104}{0.487 - 1} = 60.33 \text{ l/s} \approx 5200 \text{ m}^3\text{/d}.$$

The quantity $Q_d \approx 5200$ m^3/d ≈ 60 l/s represents the total natural resource of the thermal aquifer we are looking for.

Having in mind formula (4) and the hydrogeological conditions in the area we can say that the natural resource of Erma reka thermal deposit of about 5200 m^3/d is separated between the discharge of thermal springs Therme in the region of river Ilidza, Greece and the hidden drainage in the region of the deposit itself.

Determination of other quantities or parameters are not included as objectives of this paper. Anyhow, let us mention that applying the formulae (10) and (11) we can obtain the value of the complex parameter D:

$$(16)\, D = \mu F_d = \frac{12960 - 8985.6}{0.2348 - 0.1143} = 32982.57 \approx 33000 \text{ m}^2.$$

After that in order to determine F_d we have to know the storage coefficient μ. In connection with this assessment we want only to mention here that the value of μ is dependant of water temperature and therefore it specifies the storage property under the real aquifer temperature.

Requirements for applying the methodology

The most important requirements include:

1. Two wells have to be drilled in the deposit – pumping one and observation one. The pumping well has to be located approximately in the center of the aquifer and the observation one – in a place which is optimal for characterization the velocities v and the aquifer constants.

2. To carry out pumping test from the central well with two constant discharges Q_1 and Q_2. The duration of the pumping test has to ensure the appearance of at least 4–5 days long constant velocity of lowering of the piezometric level in the observation well.

3. Each of the two pumping discharges must be greater than the natural recharge Q_d of the thermal aquifer. This is required in order to realize the condition (3), which for the two discharges Q_1 and Q_2 can be written as $Q_{1,2} > Q_d$. If it is not fulfilled, some time after the pumping start steady state flow will take place and the period with constant velocities, needed for applying the methodology, will not appear. In practice the presence of such constant velocities means that in the corresponding periods there are not visible or hidden sources in the aquifer and as a result all the components of Q_d in (1) are already included in the pumping discharges Q_1 or Q_2. The absence of the real sources Q_n and Q_a can be seen by regime observations but these observations can not give any evidence of the case $Q_h = 0$. The only way to prove the absence of Q_h is through the total absence of Q_d as a necessary condition for receiving linear change of drawdoun some time after the start of the pumping. All the upper explanation means that the two discharges engage the total flow area with corresponding overall lowering of the piezometric level. Then during the periods of constant v_1 or v_2 the most probable water temperature will be the constant one and therefore the flow process can be assumed as isothermal one. This must be confirmed by the data of constant water temperature during the pumping with Q_1 as well as with Q_2.

In the drainage zone the thermal waters generally are in some contact with cold ground waters or surface waters. The interference between the worm and cold waters affects the determination of the thermal aquifer resources. However, as it was mention before, in the paper is examined the scheme of fig. 1, which is without the presence of cold aquifer and therefore it is accepted that interference with cold aquifer doesn't exist. Having this in mind for the present we will only mention that fig. 1 describes the real practical case when during the pumping with rate of flow Q_1 and Q_2 no change of water temperature is detected in the period of the constant velocities v_1 and v_2. If there is not such temperature changes, it can be assumed, that the quantity Q_d is representative for the natural resource of the thermal aquifer.

The interaction between worm and cold waters (worm and cold aquifers) requires to take into account a number of possible variants, which could be an object of further examination.

4. During the two regimes of pumping it is necessary to measure and correct (and register) the discharge in order to guarantee its constant values Q_1 and Q_2. The piezometric level in observation well (wells) and the temperature of the pumping water has to be also measured.

5. If in the deposit exist more than one observation wells they have to be object of the same observation like the first well. The obtained velocities v_1 and v_2 must be averaged in order to characterize more representatively the total flow area.

6. After stopping each one of two discharges or at least the last one, we have to measure the recovery of piezometric level. These data are not needed for determination of the resources according to the prepared here methodology, but they can be used eventually for determining the aquifer hydraulic constants taking into account the thermal impact of the aquifer over the water temperature in the well tubing.

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Yotov, I. G., 2002. About the Assessment of Exploitation Resources of Hydrothermal Deposits. – Geologica Balc., 32, 2–4; 103–106.

Ил. Йотов – Оценка на естествени хидротермални ресурси – постановка, опитни данни, резултати. Разработен е хидродинамичен метод за оценка на естествените (динамични) ресурси Q_d на ограничени по размер хидротермални находища. За тази цел хидрогеоложките условия се схематизират към вертикален кръгов пласт с непроницаема странична граница. Върху пласта от дълбочина въздейства постоянно подхранване Q_d, което се дренира в рамките на находището чрез естествени извори, чрез евентуален неизвестен (скрит) дебит, разтоварващ се в зоната на дрениране и(или) чрез самоизлив от прокарани експлоатационни или проучвателни сондажи. За определяне на Q_d се провежда опитно водочерпене от един или няколко сондажа, разположени приблизително в центъра на кръговия пласт. В един наблюдателен сондаж се проследява нестационарният процес на понижаване на пиезометричното ниво. Водочерпенето е с два постоянни дебита, като всеки от тях трябва да бъде по-голям от величината Q_d. При това условие известно време след началото на водочерпенето пиезометричното ниво в наблюдателния сондаж се понижава с постоянна скорост, зависеща от дебита на въздействие. Стойността на Q_d се определя от формула (8) и зависи от величините на двата постоянни дебита и предизвиканите от тях постоянни скорости на понижение на пиезометричното ниво на подземните води. В статията се дават и някои допълнителни пояснения, необходими за приложението на методиката, в това число и практическо определяне на естествения ресурс Q_d по данни от конкретно хидротермално находище.