MATHEMATICAL FLOW MODEL OF THE KRASNOVO THERMOMINERAL FIELD (SOUTHERN BULGARIA)

Nikolay Stoyanov[1], Stefan Zeinelov[1]

[1]*University of Mining and Geology "St. Ivan Rilski", 1700 Sofia, nts@mgu.bg*

ABSTRACT.A generalized conceptual scheme of the hydrogeological conditions in the region of the Krasnovo thermomineral field is developed. This concept is implemented in a three-dimensional model of the flow structure. The modeled area includes the upper part of the thermomineral reservoir to a depth of 400 m and covers a territory of about 72 km^2. Within these boundaries four hydrogeological units are determined: a fault-fissure conductive complex, a fractured poor water-bearing complex, a fault-drainage spring complex, and a Quaternary-Neogeneaquifer complex. The developed flow model is used to calculate the water balance revenue and expenditure elements for the fault-fissure complex and for the spring complex. The obtained model solutions are used as a base for the performed quantitative assessment of the Krasnovo field water resources. The boundaries of the sanitary protection zone around the existing facilities for extraction of thermal mineral waters are determined. The computer programs Modflow and Modpath are used.

Keywords: hydrogeological model, mineral water resources,thermomineral field, water budget

МАТЕМАТИЧЕСКИ ФИЛТРАЦИОНЕН МОДЕЛ НА ТЕРМОМИНЕРАЛНО НАХОДИЩЕ КРАСНОВО (ЮЖНА БЪЛГАРИЯ)

Николай Стоянов[1], Стефан Зейнелов[1]

[1]*Минно-геоложки университет "Св. Иван Рилски", София 1700;nts@mgu.bg*

РЕЗЮМЕ. Разработена е обща концепция за хидрогеоложките условия в района на термоминерално находище Красново. Концептуалната схема е имплементирана в тримерен математически модел на филтрационното поле. Моделната област обхваща подповърхностното пространство във водосбора на находището на територия с площ около 72 km^2 и до дълбочина около 400 m. В тези граници са детерминирани четири хидрогеоложки единици - разломно-пукнатинен проводящ комплекс; пукнатинен слабоводоносен комплекс; разломно-дренажен изворен комплекс и кватернер-неогенски водоносен комплекс. С филтрационния модел са изчислени приходните и разходните елементи от водния баланс на разломно-пукнатинния проводящ комплекс и разломно-дренажния изворенкомплекс. Въз основа на моделните решения е направена количествена оценка на водните ресурси на находище Красново.Определена е санитарно-охранителната зона около действащите съоръжения за добив на термоминерални води. Използвани са компютърните програми Modflow и Modpath.

Ключови думи: хидрогеоложки модел, ресурси на минерални води,термоминерално находище, воден баланс

Introduction

One of the areas rich in thermal mineral water in Bulgaria is the Sredna gora thermomineral water-bearing system, formed in the deep parts of the granite-gneiss massif of Sashtinska Sredna gora (Figure 1). Separate parts of this system are the thermal mineral fields Hissarya, Pesnopoy, Krasnovo, Strelcha and Banya (Panagyurishte), where some of the most famous national balneological centers are built. The listed fields have been known and used since ancient times, and in the last 100-150 years they have been increasingly exploited and thoroughly researched. Detailed data and different estimates of the genesis, water and heat resources, chemical composition, yield and use of the thermal mineral waters are presented in a large number of monographs, articles, scientific reports and notes. Systematic information on the thermal system and its composite fields is contained in a number of summary reports (Азманов, 1940; Щерев, 1964; Петров и др., 1970, 1998; Benderev et al., 2016; Pentcheva et al., 1997, and others).

The schemes and resource assessments, presented in various information sources for the Krasnovo field are too general, mainly based on data on the flow rate of the drainage water facilities, without taking into account, analyzing and assessing the characteristics of the composite and boundary hydrogeological units, the hydraulic connections and the water exchange between them, the influence of the boundary conditions and possible external impacts, the flow structure, the water budget, the boundaries of the sanitary-protection zones (SPZ), etc. In fact, there are similar deficiencies in the published data about most of the thermal fields and manifestations of the Sredna gora thermomineral water-bearing system.

For a detailed, well-grounded and more precise assessment of the water budget, a three-dimensional (3D) model of the Krasnovo field was developed using Modflow program. Based on the model solutions, the flow structure is determined, the elements of the water budget are calculated and the local and regional resources of the thermal-mineral waters are estimated. Using the Modpath program, the boundaries of the SPZ around the exploited water sources are defined. Publications and archive sources for the area of the thermomineral field (Христова, 1961; Щерев, 1964; Петров и др., 1970, 1998; Пенчев, 1999) were also used.

General information about the thermomineral field

Thermomineral field Krasnovo is located at the southern foot of Sashtinska Sredna gora Mountain, about 2 km east of the village of Krasnovo. The main reservoir is formed in the deep parts of a fissured and tectonically disturbed rock complex, including parts of the Matenica pluton (mtγ$_2$C), the Smilovene pluton (smγδ$_1$C) and the Arda group (ArPeC) (Figure 1). Thermomineral waters circulate by faults, and on the terrain they appear from the Quaternary-Neogene sediments, filling the Krasnovograben.

The warm springs have been used since ancient times, and documented studies and activities for more efficient utilization of the field began in the early 20th century. In 1928, Krasnovo capture was built, which captured two springs with a total flow rate of 2 l/s and a temperature of 53.5 °C. In the period 1958-1961, based on detailed geophysical and drilling studies, the main normal dip-slip faults which formed the Krasnovograben, tectonic disturbances and thermal anomalies in the spring zone were mapped (Христова, 1961). At a regional level, studies outline a stepped graben filled with clayey and sandy-clayey sediments. From the three deep boreholes (C-1, C-2 and C-3) drilled in the graben bedrock, the most perspective is C-1 (Figure 1). It is built in the spring area, at about 150 m from the existing capture. Its depth is 160 m. At 127 m below the ground, it enters the cracked and fissured granite bedrock, where it reveals a very conductive pressure zone hydraulically connected to the main reservoir. The other two deep boreholes (C-2 and C-3) have been identified as being without potential due to very low artesian flow rate (up to 0.3 l/s), insignificant relative flow rates at pump mode and temperature below 35 °C. The uncaptured spring Gyola located in the spring area with a flow rate of 0.2 l/s and a temperature of 21 °C is also of no significance. The water drained from these sources is not directly connected to the main reservoir but is a result of the mixing of thermal mineral water and fresh cold water.

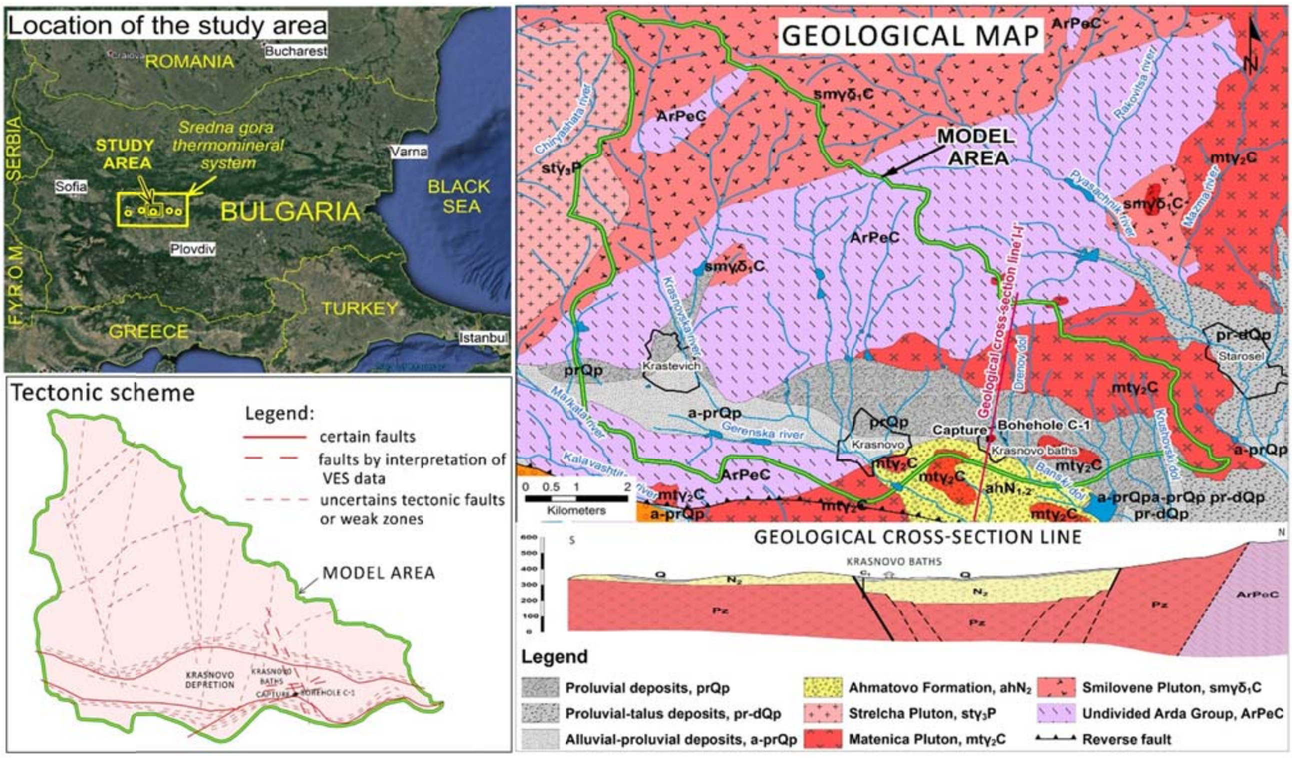


Fig. 1. Location of the studied area. Geological background

Note: The maps and the profile are compiled on the basis of the geological map of Bulgaria M 100000 – map sheet Panagyurishte and Karlovo (Илиев и Кацков, 1990; Русева и др., 1990) and unpublished materials (Христова, 1961)

The capture and C-1 borehole are the only existing water abstraction facilities in the Krasnovo thermomineral field. They are with artesian character, forming a complex drainage system very sensitive to external and internal impacts. Observations on the flow rate and the temperature of the drained waters also show that the exploitation resources of the field in the last six decades have been gradually decreasing, which is explicable for deep high pressured water-bearing structures. In the initial stage of the joint operation of the two facilities (1960), the outflow from C-1 was 24.5 l/s at 55 °C and the initial flow rate (2 l/s) decreased to 1.2 l/s. For ten months, the flow rate of C-1 decreased to 14 l/s at 55.2 °C, and the flow rate of the capture increased to its initial value of 2 l/s. In 1998/1999 the flow rate of C-1 was about 6-7 l/s at a temperature of 55.4 °C and the flow rate of the capture – 1.5 l/s at 52 °C. In the beginning of 2018, the outflow from C-1 was 5.5 l/s at a temperature of 53 °C, and the flow rate of the capture was 1.25 l/s at 49.6 °C. According to its chemical composition, the water from the Krasnovo field refers to the nitrogenous thermae, but besides N contains also H_2S. Its total dissolved solids (TDS) concentration is about 0.3 g/l, and the type of the water is HCO_3-SO_4-Na, with a neutral to alkaline pH. The microcomponents Li, Be, Ga, Ge, Se, Rb, Cs etc. are presented. The helium content is 234 Pa, and the radioactivity is 25 Em. Water is suitable for the treatment of kidneys, gallbladder, liver, digestive system and musculoskeletal apparatus. The resource assessments made so far, on the thermomineral field, are based on observations on its flow rate, chemical composition and temperature regime.

Conceptual model of the thermomineral field

On the basis of the current geo-tectonic knowledge of the region and the available information about the studied site (Христова, 1961, Кацков и Илиев, 1994, Русева и др., 1994), the following general conception for the hydrogeological settings in the range and the adjacent territories of the Krasnovothermomineral field was assumed (Figure 2).

Watershed area. The watershed area of the field covers an area of 72 km^2, including parts of the Gerenska River basins and its northern tributaries Krasnovska, Banskidol, Drenovdol etc. (Figures 1 and 2). The terrain is heavily intersected, with altitudes varying from 1273 m on the ridge of Sashtinksa Sredna gora to 320-350 m in the spring zone. The river network density is about 1.4 km/ km^2 and the average value of the surface runoff is 2 l/s/km^2.

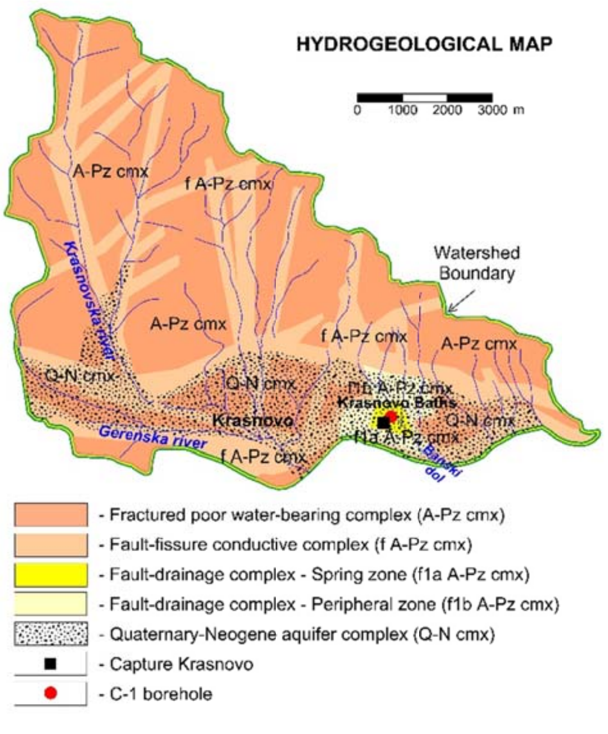


Fig. 2. Hydrogeological map of the watershed area of Krasnovo field

Basic hydrogeological units. According to the assumed working hypothesis, four main hydrogeological units are separated in the watershed area of the thermomineral field and its periphery, the surface outcrop and boundaries of which are illustrated in Figure 2.

- *Fault-fissure conductive complex (fA-Pz-cmx).* It is developed by the Krasnovo graben tectonic structures, and the associated river and deep gullies fault zones. It is built of faulted, fissured and secondary altered intrusive and metamorphic rocks. The Palaeozoic granites ($mt\gamma_2C$) dominate the graben and SE part of the watershed area, where the main thermomineral reservoir is formed at a depth of about 1000 m. In the central part of the watershed area, the fault-fissured complex is attached to the Precambrian gneisses (ArPeC) and in the N-NW – to the Paleozoic granites and granodiorites ($sm\gamma\delta_1C$). The hydraulic conductivity *k* is most often in the range of 0.01 to 0.1 m/d, with the high values being associated with the upper part of the cross-section – up to a depth of 100-200 m.
- *Fractured poor water-bearing complex (A-Pz-cmx).* Includes parts of the Paleozoic and Precambrian rocks that are not affected by the tectonic deformations. Up to a depth of 50-100 m, the rocks are very fractured and secondary altered, and below in the cross-section the open fissures gradually dwindle or are completely absent. The hydraulic conductivity varies widely from about 0.02 m/d in the upper part of the rock massif to 0.001 m/d and is lower in depth.
- *Fault-drainage spring complex (f1A-Pz-cmx).* It is formed in the most fractured parts of Paleozoic granites ($mt\gamma_2C$), where several sub-parallel and sub-meridian faults intersect. It covers a small territory in the SE part of the Krasnovo graben (the area of drainage of the thermomineral waters), which includes the Krasnovo capture, C-1borehole, the spring Gyola and other smaller scattered springs along the Banskidol River. Fault-drainage spring complex is the main path to the surface for the deep thermomineral flow and is a very important factor that determines the quantitative and qualitative parameters of the spring waters and partially limits the resources of the thermomineral field. The hydraulic conductivity in this zone ranges from 0.1 to1 m/d.
- *Quaternary-Neogene aquifer complex (Q-N-cmx).* It is formed in the sediments that fill the Krasnovski graben and is built of conglomerates, clayey sands, sandy clays and clays with a total thickness of 100-150 m. The predominant presence of the fine-dispersed fractions implies the low water permeability of the medium. The hydraulic conductivity is about 0.03 m/d, and in some parts it is up to 0.2-0.3 m/d.

Recharge and discharge. The main recharge is from infiltration of rainwater and river water. It occurs in the outcrop parts of the rock complexes. It is most intense in the outcrops of the fault-fissure conductive complex. The average infiltration rate *W* is between 3.0E-05 and 7.5E-05 m/d. It is determined by the assumption that between 2 and 5 % of the precipitations, whose annual sum in the area is 538 mm (Колева и Пенева, 1990), are infiltrated in the subsurface space. The cold water infiltrating by faults maintains the water budget and the high pressure in the main reservoir. In depth, their temperature reaches 55-60 °C under the influence of the geothermal anomaly in the deep parts of the Paleozoic plutons. The main direction of the thermomineral flow is S-SE and the average gradient is 0.015. The piezometric heads in the bedrock of the graben are very high, and at the lowest SE part of the catchment area are 10-15 m above the terrain, which generates the ascending thermomineral flow in the fault-drainage spring complex. Part of this stream is drained by the capture and C-1 borehole, and another part is discharged and mixed with the cold waters of the Quaternary-Neogene complex and emerging on the surface as scattered springs with low flow rate and low temperature (20-25 °C).

Composition of the flow 3D model

The flow model FM3D is a 3D simulation of the flow structure in the region of Krasnovo thermomineral field, taking into account the complex hydrogeological conditions and all external influences, including the activity of the capture and C-1 borehole. The basic points and input parameters in its composition are as follows:

- FM3D is compiled with Modflow computer program. The model area covers the subsurface in the watershed area of the thermomineral field with an area of 72 km^2 and up to a depth of about 400 m.
- Spatial discretization is made with an uneven orthogonal grid. FM3D includes two model layers - ML-1 and ML-2 (Figure 3). According to the differences of the hydrogeological parameters in the model layers, four model zones are defined (Tables 1 and 2), which simulate the spatial distribution of the hydrogeological units of different rank (Figure 3).
- The relief of the lower and upper boundaries of the model layers and zones are consistent with the morphological features of the terrain and the spatial forms of hydrogeological units. The ground surface is set as the upper boundary of the ML-1.
- The regional flow is modeled with a boundary condition of third kind under the *General Head Boundary (GHB)* scheme along parts of the outer boundaries of the model area.
- The Gerenska River and its tributaries are simulated as 3D objects with relevant geometry and hydraulic characteristics. They are defined as a boundary condition of third kind using the *River* program package.
- The infiltration recharge is set in all cells of the first model layer with the *Recharge* program package. According to the permeability of the surface layer, 3 model zones with different infiltration rates were introduced – MZ-W1, MZ-W2 and MZ-W3 (Figure 4), which respectively simulate the surface propagation of *fA-Pz-cmx*, *A-Pz-cmx* and *QN-cmx*. The introduced values of W in these zones are: W1 = 2.0E-04 m/d, W2 = 1.0E-04 m/d and W3 = 5.0E-05 m/d.
- The upstream flow from the main reservoir is set on the bottom of the ML-2 layer in the MZ-2.3a zone with a boundary condition of second kind by the *Specified Flow* program package. The initially accepted flow value was corrected for model calibration.
- The capture and C-1 borehole are modeled as 3D objects with corresponding coordinates and construction parameters. They are set to work with a constant level of drainage with a boundary condition of first kind by the *Specified Head* program package.
- The model calibration uses data from the long-term exploitation of the facilities and data on water levels in the rivers.

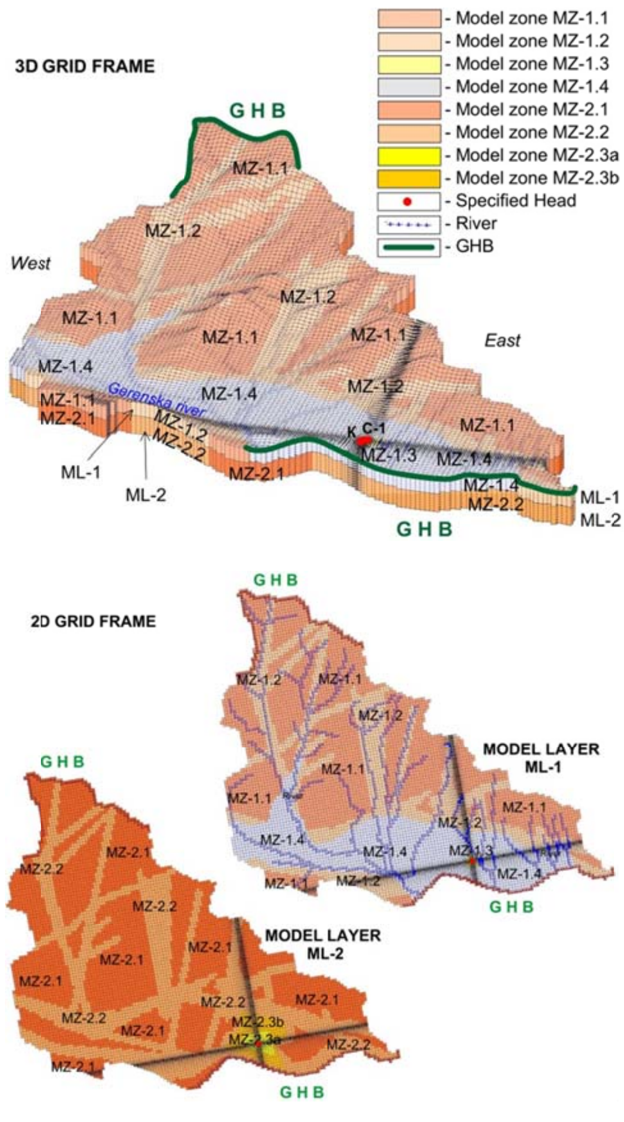
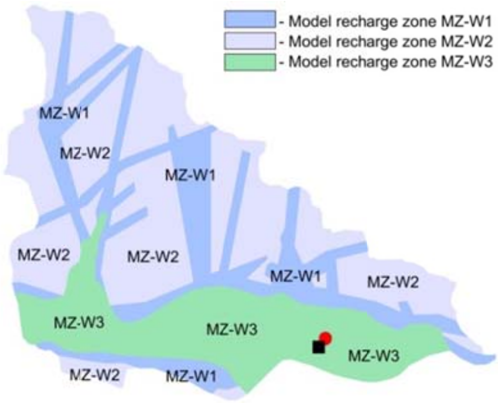


Fig. 3. Geometry of the model layers and zones. Boundary conditions.

Table 1.
Hydrogeological units, model layers and model zones

Hydrogeological unit		Geological unit	Lithographic characteristic	Geology index	Model layer	Model zone
1st rank	2nd rank					
Fractured poor water-bearing complex	Near-surface zone	Matenica pluton Smilovene pluton Arda group	granites, granodiorites, gneisses	γ_2C $sm\gamma\delta_1C$ ArPeC	ML-1	MZ-1.1
	Deep zone				ML-2	MZ-2.1
Fault-fissure conductive complex	Peripheral zone				ML-1	MZ-1.2
	Deep zone				ML-2	MZ-2.2
Fault-drainage spring complex	Spring zone	Matenica pluton	granites	γ_2C	ML-2	MZ-2.3a
	Peripheral zone					MZ-2.3b
Quaternary-Neogene aquifer complex	Spring zone	Prolluvialand alluvial-prolluvialdeposits Ahmatovo formation	clays, sandy clays, sands, conglomerates	prQp a-prQp ahN_{1-2}	ML-1	MZ-1.3
	-					MZ-1.4



Fig, 4. Model zones with different recharge rate in model layer ML-1.

Table 2.
Hydraulic conductivity k and active porosity n_0 of the model zones

Hydrogeological unit	Model zone	k, m/d	n_0, -
Fractured poor water-bearing complex	MZ-1.1	1.5E-02	2.0E-03
	MZ-2.1	7.0E-03	1.0E-03
Fault-fissure conductive complex	MZ-1.2	5.0E-02	3.0E-03
	MZ-2.2	2.5E-02	2.0E-03
Fault-drainage spring complex	MZ-2.3a	1.0E00	1.0E-02
	MZ-2.3b	1.5E-01	7.5E-03
Quaternary-Neogene aquifer complex	MZ-1.3	1.0E-01	5.0E-03
	MZ-1.4	3.0E-02	2.5E-03

Note: The values of k and n_0 are defined by literary data (Spitz and Moreno, 1996; Стоянов, 2015, and others).

Model solutions

Structure of the flow field. The model solution for the distribution of the hydraulic heads in the two model layers (Figure 5) presents the flow structure in the watershed area of the thermomineral field under the conditions of continuous exploitation of the capture and C-1 borehole.

Water budget. Groundwater resources. Using FM3D, the water budgets of the fault-fissure conductive complex (fA-Pz-cmx) and the fault-drainage spring complex (f1A-Pz-cmx) are composed, which are very closely related to the formation, circulation and drainage of the thermomineral waters (Tables 3 and 4). The presented results provide the basis for the following summaries and conclusions regarding the water resources of the thermomineral field.

- The total discharge of the circulating groundwater in the spring zone is 28.5 l/s.
- The regional water resource of the field is estimated at 26.4 l/s, assuming that it is formed from the upstream flow of the main thermomineral reservoir and the hot water entering the spring zone from the deep parts of the fault-fissure conductive complex and the fractured poor water-bearing complex.
- The local water resource of the water abstraction facilities (the capture and C-1 borehole) is 6.75 l/s, with guaranteed chemical composition and temperature of the abstracted thermomineral water and with a tendency for a slight decrease in the outflow in the near decades.

Table 3.
Water budget of the fault-fissure conductive complex (fA-Pz-cmx)

FLOW IN, Q_i^{IN}, l/s		FLOW OUT, Q_i^{OUT}, l/s	
Inflow from adjacent to the water catchment area complexes	24.45	Draining to adjacent to the water catchment area complexes	19.09
Inflow from rivers	6.48	Draining to rivers and gullies	52.39
Inflow from the Quaternary-Neogene aquifer complex	5.69	Draining to the Quaternary-Neogene aquifer complex	28.58
Inflow from the fractured poor water-bearing complex	81.37	Draining to the fractured poor water-bearing complex	27.61
Inflow from the fault-drainage zone and upstream flows by deep faults from the main reservoir	16.72	Draining to the fault-drainage zone and downstream flows by deep faults	24.81
Recharge from infiltration of precipitation	17.82		
Total flow in:	152.53	Total flow out:	152.48
Balance error 0.03 % (difference)			

Table 4.
Water budget of the fault-drainage spring complex (f1A-Pz-cmx)

FLOW IN, Q_i^{IN}, l/s		FLOW OUT, Q_i^{OUT}, l/s	
Inflow from the fault-fissure conductive complex and upstream flows by deep faults from the main reservoir	24.81	Draining to the fault-fissure conductive complex and by deep faults	16.72
Inflow from the fractured poor water-bearing complex	1.58	Draining to the Quaternary-Neogene aquifer complex	5.02
Inflow from the Quaternary-Neogene aquifer complex	2.12	Water intake facilities – capture and C-1 borehole	6.75
Total flow in:	28.51	Total flow out:	28.49
Balance error 0.07 % (difference)			

Models for determination of SPZ boundaries

The boundaries of subzone II and subzone III of the SPZ around the capture and C-1 borehole are calculated using the ModPath program. Two mass-transport models, MP3D-1 and MP3D-2 are compiled, taking into account the determined by FM3D flow structure. The values of the active porosity n_0 specified in the model zones are accepted according to the lithology and/or the secondary alterations in the water-bearing medium (Table 2). By MP3D-1, the boundaries of subzone II have been determined at a computing time of 400 days, and with MP3D-2 the boundaries of subzone III at a calculation time of 25 years (Figure 6). These periods have been chosen with accordance to the normative documents in Bulgaria.

Conclusion

A modern concept of the hydrogeological structure and the recharge conditions, circulation and drainage of the thermomineral and cold waters in the watershed area of Krasnovo field was implemented by the developed models. The model solutions determine the complex flow structure in the artesian aquifer system and quantify the water resources of the field as well as the parameters of the optimum yield and the boundaries of the SPZ around the water abstraction facilities. The obtained results enable a better understanding of the mechanisms of formation and movement of thermomineral waters and provide new data about their resources. These results have also an important practical significance for a more efficient exploitation of the field. The presented methodological approach can be successfully used in solving of other similar hydrogeological problems.

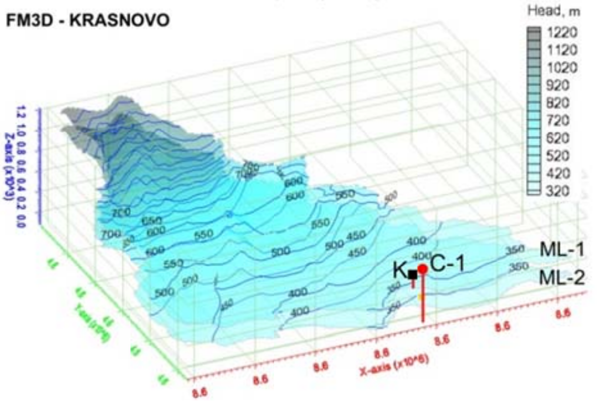
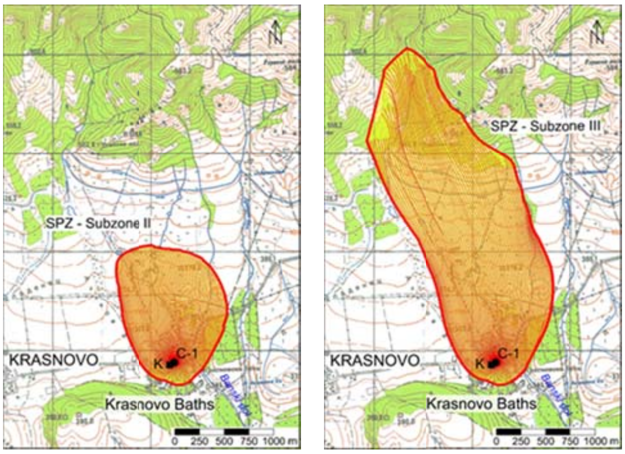


Fig. 5. Flow structure in model layers ML-1 and ML-2



(a) SPZ – Subzone II (b) SPZ – Subzone III

Fig. 6. Boundaries of SPZ around the capture and the C-1 borehole

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