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MODELING STUDIES OF THE PARATUNSKY GEOTHERMAL FIELD, KAMCHATKA, RUSSIA

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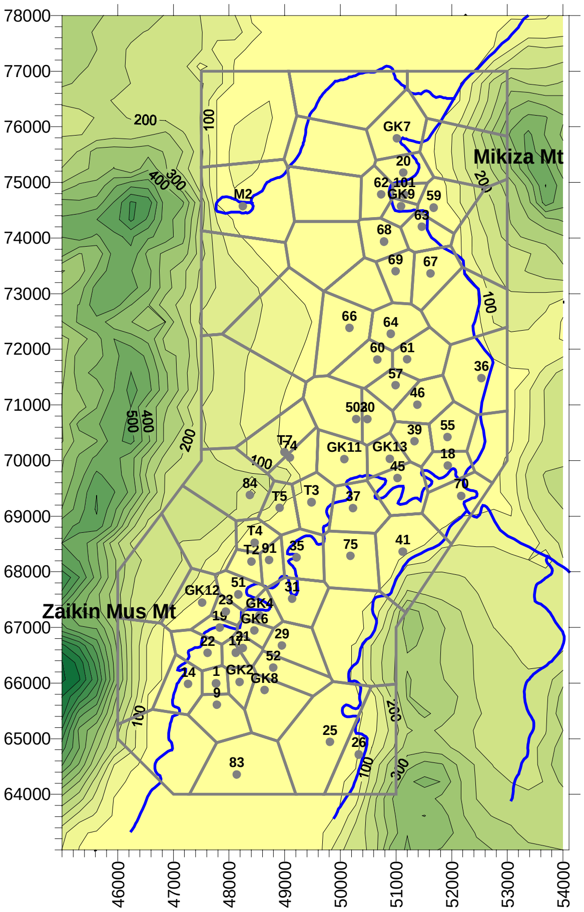
ABSTRACT

A numerical model of the low temperature Paratunsky geothermal field was developed. The model was used to understand heat and mass transfer conditions in the system, and to forecast exploitation scenarios.

INTRODUCTION

The Paratunsky Geothermal field is located 45 km south-west from Petropavlovsk-Kamchatsky city. It is a low temperature geothermal field with temperatures of 80 - 90 °C, which has been exploited since 1967 with extraction rates of 200 - 260 kg/s. Most production wells operate in free discharge conditions, but some wells have downhole pumps. The boundaries of the field are assumed to coincide with the boundaries of the Paratunka valley graben (Fig.1). The hydrothermal reservoir represents a subhorizontal structure in graben sediments that is charged with ascending hot fluid flows. Upflows occur in three main zones that are associated with magmatic stocks and hydrothermal eruption breccias, and are named the Sredne-Paratunsky, Nizhne-Paratunsky, and Severny sites of the Paratunka geothermal field. Recharge areas are associated with diorite outcrops at higher elevations (600 - 800 masl) outside of the Paratunka valley graben. A single-layer simulation model was developed to understand heat and mass transfer processes in the field under natural and exploitation conditions. The model uses an irregular grid generated with LBNL's AMESH grid generator and is implemented through the TOUGH2 reservoir simulation code. Calibration of the model against natural state and exploitation data revealed the following.

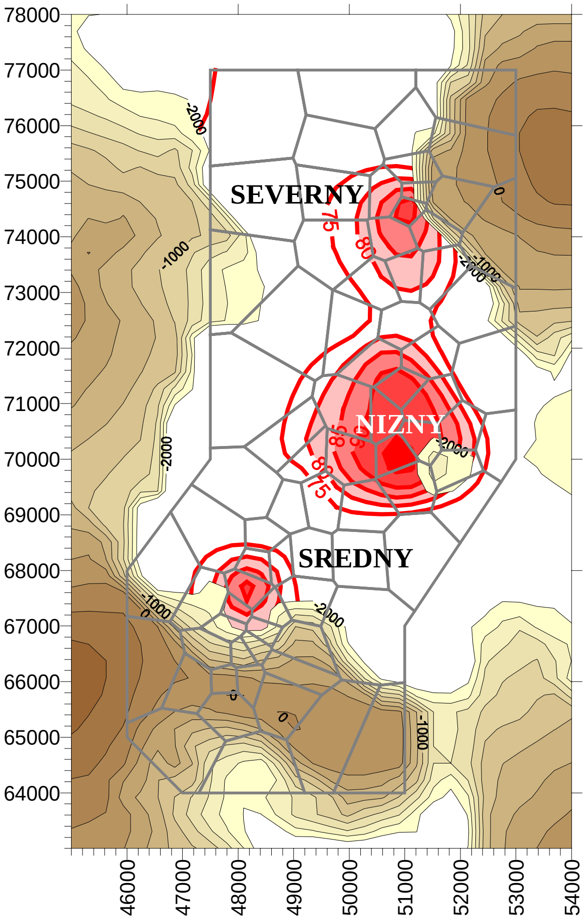
Fig.1 Schematic map of the Paratunsky geothermal field : topography features , and numerical grid geometry.



1. It was found that standard constant pressure boundary conditions cannot explain observed discharge variations during exploitation (declining flowrate while WHP is stable). Non-standards seepage faces boundary conditions were successfully implemented to represent discharge behavior it.

2. Specific to this field are seasonal variations in hot water demand (in the winter time, more hot water is needed than during summer), and seasonal variations of the hot fluid recharge (indicated by fluid pressure variations in the system). Cyclic variations were specified for the natural hot fluid inflow (mass sources) in the model.

Fig.2 Structure map of the Paratunsky geothermal field : surface map of the intrusive neogene rocks (by I.Delemen, 1999) overlay by temperature distributions at –1000 masl . Numerical grid shown too.



CONCEPTUAL MODEL OF THE PARATUNSKY GEOTHERMAL FIELD.

Fig.2 shows temperature distribution at –1000 masl. and intrusive complex of neogene age top surface distribution. At this elevation three roots of hot ascending flows associated with the boundaries of the intrusive diorites body are observed . These flows enter sub-horizontal layers at –1000 masl and are feeding Sredny , Nizhny and Severny geothermal reservoirs , which occur in andesite tuffs (so called “green tuffs” formation) . The elevation where ascending hot flow is diverted to lateral outflow (the bottom of the “green tuffs” reservoir) is detected by plotting normalized cumulative rate (e.g. total rate obtained at specified depth divided by number of wells drilled) of the well vs depth, based on data obtained during drilling. Fig.3 shows normalized rate is zero in the intervals from 0 to 100 – 150 m depth (upper caprock) , then increased from 0 up to 17-25 kg/s in the intervals from 100-150 m up to 1200 m depth (“green tuffs “ reservoir) , then slowly increased on 1-4 kg/s by 2500 m depth (relatively impermeable basement rocks) .

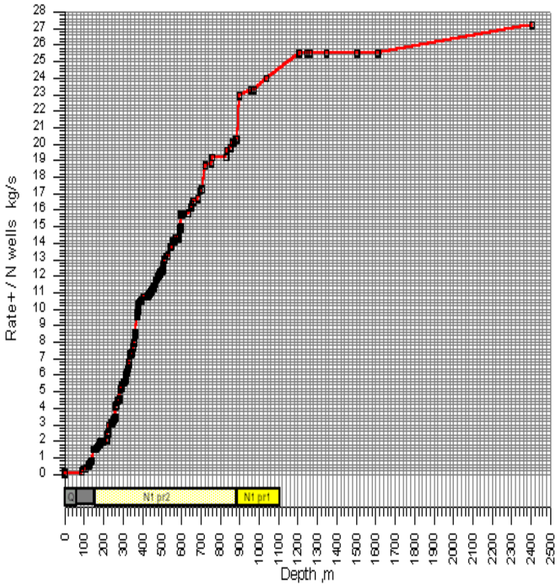
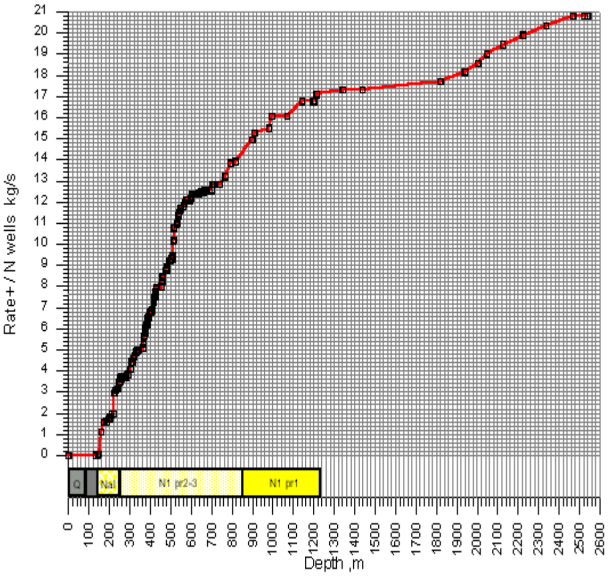


Fig.3 a Normalized wells flowrate of vs of depth , Sredny site Paratunsky geothermal field.

Fig.3 b Normalized wells flowrate of vs of depth , Nizhny and Severny site Paratunsky geothermal field.



Water recharge into the system assumed to be coincide with the outcrops of the intrusive complex mentioned above (Mt. Zaikin Mys in south-west and Mt. Mikiza in north-east) , these recharge assumed to be sub vertically downflows in the deeper hot parts of the geothermal/intrusive body system (4-5 km), where fluids heated due to water/rock heat exchange mechanism and finally forming hot water upflows . Note , this fluid recharge mechanism in the system is outside of the modeling boundaries (because we don't know exact geometry of the recharge system above) , so the one layer model of the reservoir fed by three hot water upflows (Sredny , Nizhny and Severny) assumed.

GRID GENERATION, SOURCES AND BOUNDARY CONDITIONS

1-Layer grid was used to represent numerical model of the Paratunsky field. AMESH grid generator used. The list of the elements included in the numerical grid consist of the main production wells (or groups of the production wells) , main observational wells , and boundary elements , associated with the reservoir boundary (Paratunsky graben boundaries). The total number of the elements used is 110 , including 78 non-zero volume elements , 31 inactive boundary condition elements , and one element representing heat exchange boundary conditions. The thickness of the 1-layer model assigned to be 1000 m. Fig.1 shows grid geometry used.

Sources were implemented as mass sources with specified enthalpies in the elements , corresponding to thermal anomalies areas Sredny (360 kJ/kg) , Nizhny (400 kJ/kg) and Severny (380 kJ/kg) .

Pressure boundary conditions assigned in inactive elements along lateral model boundary as a constant pressure and temperature 98.5 bars , 30 °C (around Nizhny and Severny) or 101.2 bars , 30 °C (around Sredny) , corresponding to -1000 m depth .

Heat exchange option through the caprock under the top surface of all elements was assigned through heat exchange coefficient 0.0042 W/m^2 °C with temperature 5 °C on the top of the caprock exist (corresponding implementation in QLOSS module of the TOUGH2 computer codes were made) .

MODELING OF THE NATURAL STATE CONDITIONS

Constant Mass Flowrate of Ascending Hot Fluids Approximation

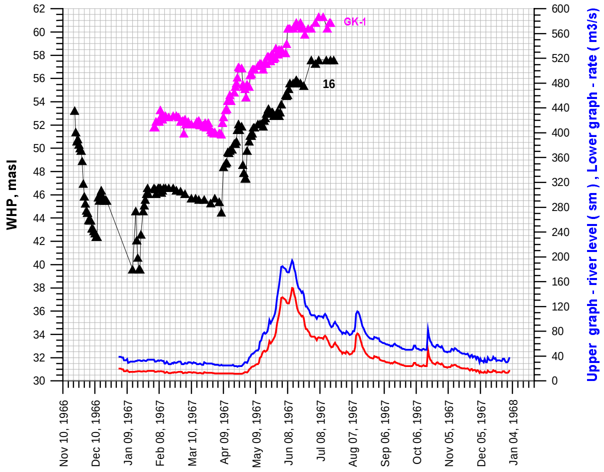
The target of the natural state modeling was to adjust mass flowrate of ascending hot fluids and reservoir permeability to reach satisfactory agreement of the real and calculated temperatures and pressures distributions , correspondingly . In this case preliminary estimations of the following characteristics were obtained :

Site / Region	Mass flowrate, kg/s	Permeability , mD
Sredny	80	30
Nizhny	75	60
Severny	40	60
Ambient reservoir		30

Seasonal Cycling of the Ascending Hot Fluids Mass Flowrate

Pressure monitoring data on the Paratunsky Field in the undisturbed conditions of the central parts of hot fluids ascending regions reveals seasonal pressure variations: in summer period pressure increase + 1.2 – 1.4 bars , while in winter period decrease(Fig.4) . These facts explained by seasonal change of recharge conditions of the system : in summer time recharge areas (outcrops of diorites on the flanks of the Paratunka river are open to meteoric water recharge in summer , while in winter time - recharge areas are frozen , so they are closed to penetration of meteoric waters in the deep parts of the system , where heat exchange and formation of the hot fluids ascending flows took place.

Fig.4 Seasonal variations of fluid pressure (masl) in geothermal reservoir (two upper graphs are WHP of two wells) , and flowrate and level of the Paratunka river (lower two graphs) . Data before exploitation started.



The problem of the model calibration is to introduce periodic variations of the mass flowrate in the source elements to match reservoir pressure variations in undisturbed conditions, so that :

Qmass = αQ , where $\alpha = \alpha_0$, when $0 < t < 90$ and $272 < t < 365.25$ ("winter") , $\alpha = \alpha_1$, when $90 < t < 272$ ("summer") , t = DMOD (TIME, 31557600.0) / 86400.0, where TIME - computer time in seconds.

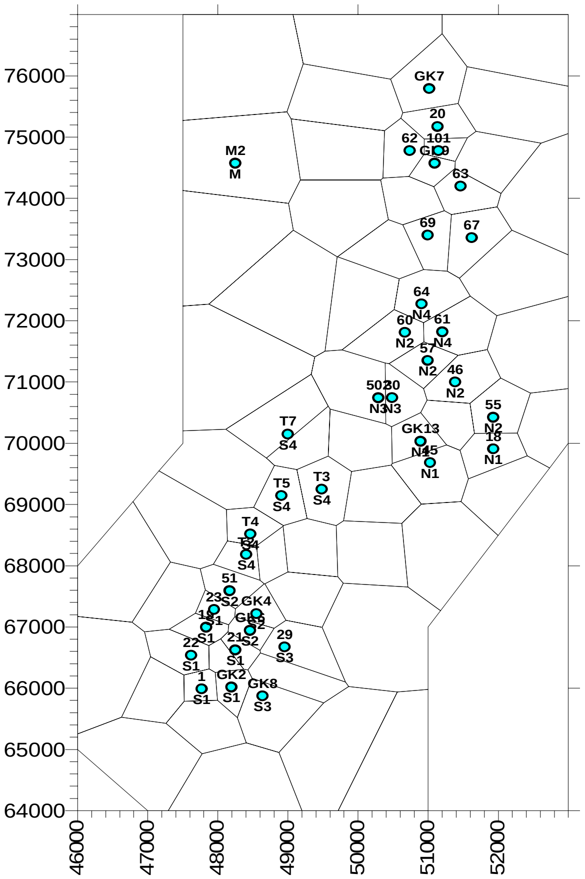
Reservoir compressibility coefficient c was also used to match modeled and observed pressure variations in undisturbed conditions . The following parameters estimations were obtained : $\alpha_0 = 0.75$, $\alpha_1 = 1.25$, $c = 5\ 10^{-9}$ Pa^{-1}.

MODELING OF THE EXPLOITATION

Flowrate Specified Runs

Flowrate specified runs were performed in the model as a first approach. All production wells were unified in groups , according to real conditions of hot water pumping system in the geothermal field , where flowrates measurements performed. The flowrates of well groups were divided on equal parts in the corresponding model elements , where additional mass sources were specified (Fig.5) .

Fig.5 Model Grid and Exploitation Wells Groups Position



Mass sources names	Group of the wells
N1	GK13,45,18,42
N2	55,46,57,60
N3	30,502,503
N4	61,64
S1	GK2,1,21,22,19,23,GK3, 3,4,5 ,6, 8 , 11, 15, GK1
S2	GK4 , GK6,51 , 53
S3	29, GK8
S4	Promezhutochny site wells

Fig.6 shows flowrates and well head pressure (WHP) transient data of the S1 group of wells , which deliver almost half of the Paratunsky field yield. Time period 1979 – 1984 years reveals flowrate decline, while WHP was almost constant. This is detected change of boundary conditions as a result of exploitation : when reservoir pressure drop below boundary specified pressure , boundary "constant pressure" conditions switch to "no flow " boundary conditions. This fact confirm assumption on seepage faces boundary conditions, which were implemented in the model.

Specified flowrate runs yield the transient pressures in source elements of the model , corresponding to groups of production wells positions (see table above). At this step a match of well head pressures WHP of production wells groups and reservoir pressures Pr was performed. To match the following inversion Pr to the corresponding well head pressure PPr used:

$$PPr = Pr - \int_{z0}^{z1} \rho(T)\ g\ dz$$

,where z1, z0 well bottom and head , correspondingly , ρ(T) - temperature dependent density of water , g – gravity acceleration.

An obvious PPr > WHP criteria (Fig.7) yield to ascending hot flow re-estimation in the model, so that :

Site / Region	Mass flowrate, kg/s	Permeability , mD
Sredny	138	90
Nizhny	95	60
Severny	60	60
Ambient reservoir		50-60

And seasonal variations coefficients α_0 =0.95 , α_1 = 1.05 .

Well on Deliverability Specified Runs

The following formulae (and corresponding implementation in TOUGH2 computer codes) used to specify well on deliverability option in the model:

$$Q = PI_i*(P-(1000+Z_i)\rho_i g-WHP_i)*10$$

,where Q – production rate , PI_i - production index of the group of wells (kg/s m) , P - reservoir pressure , Z_i - well group elevation , ρ_i - temperature dependent fluid density , WHP_i - well group WHP .

Production indexes were estimated to match real and model flowrates production wells groups. Fig.8 shows example of such matches. The following production indexes were obtained in the model: (4.0 , 0.9 , 1.2 , 0.8 , 3.0 , 1.0 , 0.3 kg/s m) for well groups (S1 , S2, N1 , N2, 20, 69 , GK9, GK7). Note , the flowrate option used for the rest of the wells.

Exploitation Forecast

Fig.9 shows two scenarios of the exploitation forecast. In case of "A" - WHP data of the 1997 year used to specify exploitation flowrates. Possibility of stable extraction of hot water yield in the Paratunsky geothermal field confirmed: average flowrate is 207 kg/s , maximum 248.8 kg/s (January , when demand is maximum) , minimum 179.8 kg/s (July , when demand is minimum). In case of "B" – minimum WHP specified in the model : a stable flowrate reach in 7-9 years with average flowrate 232 kg/s , maximum – 238.4 kg/s (September) , minimum – 224.2 kg/s (April).

CONCLUSIONS

The numerical model of the Paratunsky geothermal field was developed and used to understand heat and mass transfer conditions in geothermal system , and to forecast exploitation scenarios. The key points of these studies are :

1.Intrusive complex control of recharge/discharge conditions in the geothermal field , and sub-horizontal "green tuffs" formation control of geothermal reservoir location.

2.Cyclic natural ascending hot flowrate and cyclic demand for hot water extraction in the geothermal field.

3. Non-linear seepage faces reservoir boundary conditions.

REFERENCES

K.Pruess (1987) " TOUGH Users Guide" // LBL-20700.

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Fig.6 Investigation of the boundary conditions type (Sredny site S1 of the Paratunsky geothermal field). Lower red fill graph - flowrate , kg/s , triangles – WHP (converted in water level in masl) , upper solid lines are modeled pressure variations : upper red graph corresponding to P=const boundary conditions, lower black graph corresponding to seepage face boundary conditions. Straight lines are corresponding trends in the time intervals 1978 – 1984 yy. Left axes is flowrate , right axes – pressure (converted in water level in masl).

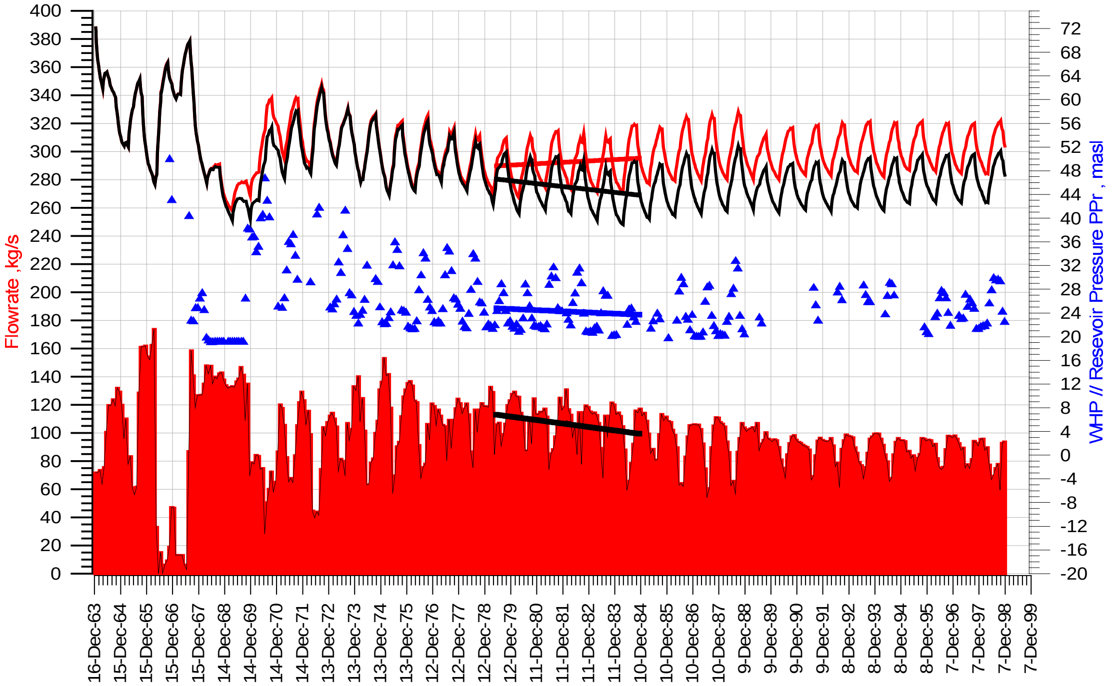

Fig.7 Sensitivity analysis of mass flowrate of ascending hot fluid inflow in the reservoir (Sredny site S1 of the Paratunsky geothermal field). Lower red fill graph – extracted hot water flowrate , kg/s , triangles – WHP (converted to water level in masl) , solid lines in upper part – reservoir pressure variations (converted in water level in masl) with different mass flowrate of ascending hot fluid inflow specified in the model (150 kg/s , 138 kg/s , 130 kg/s , 120 kg/s and 110 kg/s) , from upper to lower graphs , correspondingly . Left axes –extracted hot water flowrate , right axes – pressures.

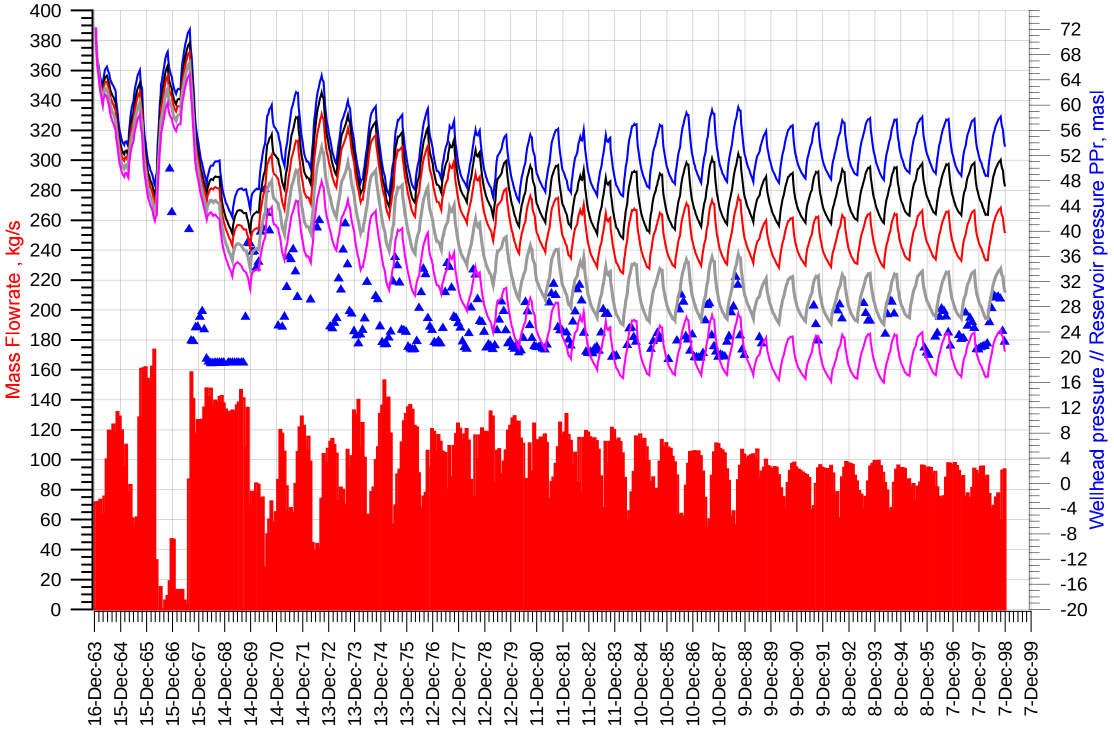

Fig.8 Flowrate match , Sredny site S1 of the Paratunsky geothermal field . Lower red fill graph – actual extracted flowrate of the hot water ,kg/s , black line – modeling flowrate (best match scenario) . Triangles and upper solid line - WHP and reservoir pressure in the model (converted to water levels in masl). Left axes - flowrate , right axes – pressures.

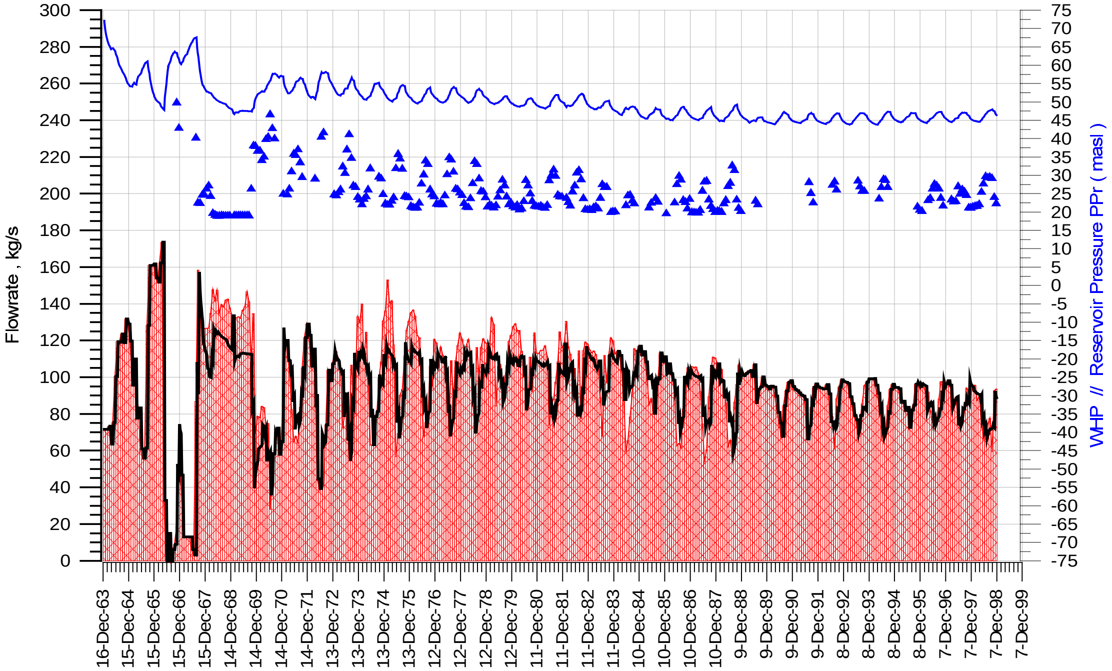

Fig.9 Modeling of the exploitation of the Paratunsky geothermal field . Red fill graph – actual total extracted flowrate, black line flowrate in the model (best match scenario) .Lower blue line in the right part is a forecast for “A” scenario of the exploitation ,upper black line in the right part is a forecast for “B” scenario of the exploitation .