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Distributed Parameter Model for the Laugarnes Geothermal Field - SW Iceland

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Abstract: The paper describes distributed parameter model of the Laugarnes geothermal field located inside Reykjavík, in south-western Iceland. The model was conceived after adopting the programme AQUA to process 30 years observation of the reservoir response to production. No cooling was observed in wells during the whole period of production. A good fit was achieved with the model for drawdown. The monthly average production of 16 wells measured between 1961 and 1991 was used to calibrate the model. The obtained reservoir parameters were used to predict the future behaviour of the reservoir at three different constant production rates until the year 2012. A constant decline of the water level and silica content has been observed. Based on the trend of the curve for the measured and calculated drawdown obtained from the distributed groundwater flow model it is quite obvious that with present production no steady-state condition in the reservoir will be reached before 2012.

Key words: Iceland, geothermal field, mathematical modelling, hydraulic parameters, prediction

1. Introduction

Iceland lies astride the N-S running Mid -Atlantic Ridge which spans the entire Atlantic Ocean. The surface expressions of the ridge are the so called neovolcanic zones, divided into several branches. In general, the structure of neovolcanic zone is dominated by fissure swarms and central volcanoes. Most fissure swarms are about 10 km wide and 30-100 km long. The rate of spreading of the divergent plates has averaged 2 cm/year over the last four million years (HAMMONS et al., 1991). The neovolcanic zone is flanked by Quaternary rocks characterised by sequences of subaerial lava flows, intercalated by hyaloclastics and morainic horizons, indicative of glacial conditions. The Quaternary formations are flanked by Tertiary floodbasalts (SAEMUNDSSON, 1978).

The thermal gradient is about 50 °C/km in the Tertiary basalts of Iceland farthest from active volcanic zone. It increases toward the volcanic zone and may be as high as 150° C/km near the edge of the volcanic zone (PÁLMASON et al., 1979). Geothermal activity is widespread in Iceland and most intense near, as well as inside, the volcanic zone. It falls into two main groups based on the temperature at depth in the geothermal systems (BÖDVARSSON, 1961). By definition the temperature is higher than 200 °C in high-temperature systems and lower than 150 °C in low-temperature systems. High-temperature fields are located inside the active volcanic zones and they can be used to generate electric power. Low-temperature fields are situated on both sides of these zones mostly in lowlands and valleys of the Quaternary and Tertiary strata. About 250 low-temperature fields and about 30 high-temperature are known at the present.

According to a hypothesis by Einarsson the geothermal water should be a part of the general groundwater flow from the highlands to the lowlands, heated due to flowing through hot rocks at depth in the Earth crust. The force driving the water through the crust was the hydrostatic pressure difference between the highlands and lowlands of Iceland (TÓMASSON, 1993). This model was based on the general hydrological considerations and assumed that the source of water supplied to the low-temperature systems was precipitation, infiltrated in the highlands interior. The ÅRNASON's (1977) interpretation of the deuterium content of the mean annual precipitation in Iceland supports Einarsson's model.

In the light of geological, geophysical and geochemical data compiled over the last few decades it is clear that the interpretation of any particular geothermal system has to take into account all available data from the area. This is especially true for the stable isotope interpretation of groundwater flow. It is considered questionable to use deuterium values in present-day precipitation to obtain information on the recharge areas to the various geothermal sites, without taking into account other available hydrogeological data from the area.

Data on permeability and temperature in deep wells in several low-temperature geothermal systems in Iceland indicate that these systems are transient and represent groundwater convection through young fractures. Thus, the heat source to the system is local and the hot rock is made permeable by active fracturing (SVEINBJÖRNSDÓTTIR et al., 1995). This contradicts the general model of the low-temperature geothermal systems described above.

One of the tools to study a geothermal field in detail is reservoir modelling by mathematical models. The optimal production strategy of a geothermal field cannot be obtained without using a good performing reservoir model. It should give a clear picture of all physical and chemical parameters of a reservoir and obtained results should be comparable to the field measurements. The past, present and future exploitation of the geothermal field must comply with the created model. All plans to change the production rate from a reservoir should be carefully confronted with it. The drilling of new boreholes, their situation and casing design, possible reinjection options for recovering the water level, changes in the chemical concentration and heat losses due to interaction with another aquifer should be taken into consideration, only after addressing the reservoir model. As a final result, it should reward its users giving them the best economical solution.

This paper is a summary of the author's results obtained during geothermal training programme at the United Nations University in Iceland in the field of reservoir engineering.

2. The main features of the Laugarnes geothermal field

2.1. Locality

The Laugarnes low-temperature field is located inside Reykjavík, in SW part of Iceland (Figure 1). The elevation of the area ranges from 15 to 40 m above sea level. It is one of the three major geothermal areas within a radius of 6 kilometres from the centre of Reykjavík. The others are the Ellidaár and Seltjarnarnes fields (Figure 1). Geothermal water from these areas is highly suitable for direct use because of low content of dissolved solids and, therefore, it can be piped directly into radiators for space heating. These three areas have been heavily exploited during the last 20-30 years (TÓMASSON, 1993). During 1991 the average production from the Seltjarnarnes area was about 35 l/s of 105 - 110 °C water, the average production from the Laugarnes area was 167 l/s of 127 °C water and the average production from the Ellidaár area was 113 l/s of 87 °C water. Since 1957 a total of 48 deep wells with depths ranging from 600 to 3 085 m have been drilled in the Reykjavík geothermal areas and in their neighbourhood, in addition to about 70 shallower wells.

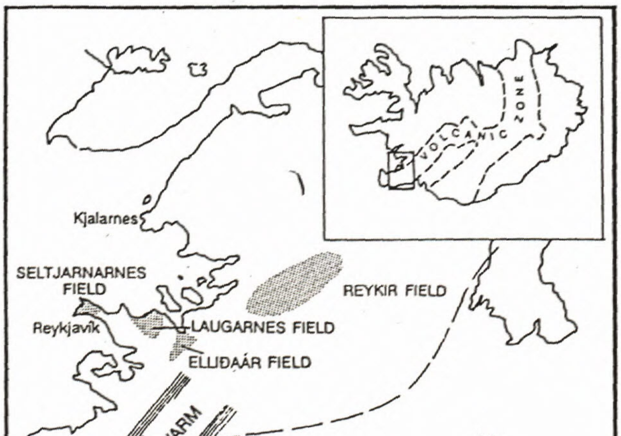

Fig. 1 General location of the Laugarnes geothermal field (KEPINSKA, 1994)

2.2. Hydrogeothermics

The Reykjavík area lies 8 -10 km N of the volcanically active Reykjanes rift zone. It is located in Plio-Pleistocene volcanics on the S outskirts of the Kjalarnes central volcano (FRIDLEIFSSON, 1973).

The Reykjavík area is covered by horizontal olivine tholeiite basalts of late interglacial age, down to a depth of 30-50 m (THORSTEINSSON - ELÍASSON, 1970).

Underneath this lava flow there are found up to 60 m thick, mostly marine sediments, overlaying a major discordance. Beneath, alternating lavas and hyaloclastites occur. This sequence is of Plio-Pleistocene age. Thick hyaloclastite formations are common in the upper 500 - 1 000 m, but basaltic lavas are predominant in the lower parts of the wells, which are commonly up to 2 km deep.

The Plio-Pleistocene strata in the Laugarnes area appear to dip at 3-12° to the SE (THORSTEINSSON - ELÍASSON, 1970). These strata occur at 250 - 300 m lower elevation in wells of the Ellidaár area.

Aquifers are predominantly found where lavas contact hyaloclastites. The Laugarnes geothermal field has been found to be fed by three aquifers (THORSTEINSSON - ELÍASSON, 1970). **Aquifer A** with water of 110 - 120 °C extends from 250 - 650 m, **aquifer B** with water of 135 °C from 730 - 1 250 m and **aquifer C** with water temperature of 146 °C, below 2 150 m. Tuffs and sediments act as aquicludes between the aquifers while scoriaceous and fractured contacts between individual lava flows are permeable. Because each lava flow is a lens between overlying and underlying flows, the permeable zones within each aquifer are not continuous but may merge with those of adjacent flows. Aquifer B is the main aquifer with a contribution of 80 %. Mixing of these waters yields an average **well discharge temperature of 125 - 130 °C.**

The recharge area of the Laugarnes field has been mapped by deuterium (ÅRNASSON, 1977). By comparing the deuterium content of the precipitation in Iceland to that of the geothermal water, the Langjökull area has been shown to provide the recharge for the Laugarnes geothermal field.

As in the Laugarnes field, aquifers in the Ellidaár field occur at contacts between hyaloclastites and lavas. The Ellidaár field is fed by at least two different groundwater systems. The N part of the Ellidaár field is probably fed by the same recharge area as the Laugarnes field. The other recharge area for the S part of this geothermal field is most likely E of Reykjavík, at a distance of less than 45 km (ÅRNASSON - TÓMASSON, 1970; TÓMASSON et al., 1975).

TÓMASSON et al. (1975) described the results from measured surface thermal gradients in shallow drillholes in Reykjavík. The high surface thermal gradients inside the thermal areas are due to localised transport of water from the thermal systems at depth to the surface. This is best demonstrated in the Laugarnes field, where the highest surface gradients are measured (400 °C/km). Prior to exploitation about 10 l/s of 88 °C water issued in free flow from thermal springs in that area, whereas, only minor natural thermal activity was found in the other areas in Reykjavík. There is very little, or no transport of water from depths in the rocks between the thermal areas, and the depth of the gradient drill holes (at least down to several hundred meters) has little influence on the measured gradient outside the thermal fields. The surface gradient of 0 °C/km to the SE of the thermal areas is due to cold groundwater penetrating young volcanic rocks. This cold groundwater zone has been found to reach down to 750 m (measured in a hole 986 m deep) in the volcanic zone 11 km S of the Ellidaár field (Pálmasson, 1967).

Outside the thermal fields the thermal gradient is about 100 °C/km. The reverse temperature gradients found in the Ellidaár and Reykir fields can only be accounted for by the circulation of cold water at depth. This cooling effect might be similar to the surface cooling effect observed SE of Reykjavík.

The Reykjavík geothermal fields appear to be separated by hydrogeological barriers. Production from one of the field does not effect the water level in the other two. In addition, the temperature, isotopic composition and the geochemistry of the water differ in the three fields. Shallow wells (less than 300 m deep) between the fields exhibit much lower temperature gradients than those measured within the Reykjavík geothermal fields. The geothermal fields therefore appear as thermal anomalies (Tómasson et al., 1975).

2.3. Production history and utilization

The Laugarnes field is the first geothermal field in Iceland utilized for public district heating. Up to 1958 the production was only by free flow from wells but after 1964 the production has been covered entirely by down-hole pumps. The rate of free flow from the field was some 20 - 40 l/s before pumping started but the average production in the years 1965 - 1993 has been about 167 l/s. An enhancement in production by a factor of 4 to 8 was, therefore, obtained by the introduction of down-hole pumps in the Laugarnes field. It should be noted that the production rate during the 30 years of pumping has been relatively constant and that the pressure (water level) in the reservoir has also been relatively stable during the pumping period (Stefánsson et al.,1995).

The exploitation of geothermal water in the Laugarnes field was begun in 1928 - 1930 by the drilling of 14 small diameter wells near the Thvottalaugar hot spring. The depth of the deepest well was 246 m; collectively, the wells yielded 15 - 20 l/s at a temperature of 95 °C, as compared to 5 - 10 l/s previously issuing from the spring.

Drilling was resumed, first in 1940 by drilling of two wells down to 650 and 760 m, respectively, at Thvottalaugar and at Raudará, and again in 1956 - 1959 by drilling of 16 wells, 260 - 696 m deep, 1 - 2 km W of the Thvottalaugar wells. The aggregate flow from these wells in 1959 was about 60 l/s, 90 - 98 °C. During the drilling phase of 1959 - 1963, 22 wells were drilled by the rotary method to depths of 650 - 2 198 m. The individual well flow rates ranged from 1 l/s to more than 50 l/s. Five additional deep wells have since been drilled, in 1968 and 1969, and 1978 - 1982, to depths ranging between 1 359 and 3 085 m, one of them, the RV-34, being the deepest well in Iceland.

The wells are of the open hole type. Casing is cemented in place to a depth required to prevent collapse of unconsolidated shallow formations and exclude surface waters and the hole left open below the casing point. Well data of supply wells and principal observation wells are given in Table 1.

Up to the year 1960, when deep-well turbine pumps were first installed, withdrawal of water from the wells was by flow on the head. Since 1967, however, it has been exclusively through deep-well turbine pumps from 11 supply wells. Prior to 1962, flow rates were estimated from periodic flow measurements but have since then been metered.

Withdrawal rates were relatively uniform during the period 1957-1962, when the withdrawal was predominantly by flow on the head but those subsequent to 1962 vary according to seasonal demand, being about three times as heavy in the winter season, October until March, than in the warmer season, April until September.

An investigation on the response of the piezometric surface in the area to increased pumping was begun in 1965 and continued through 1969. The investigation was conducted by automatic water stage records and by periodic measurements of water levels in non-pumping observation wells.

The oldest and by far the biggest district heating service in Iceland is Hitaveita Reykjavíkur (Municipal District Heating Service of Reykjavík), which supplies about 60 % of all geothermal water used in Iceland for district heating. Currently it supplies water for space heating and domestic use for Reykjavík and all neighbouring communities (150 000 inhabitants). Hitaveita Reykjavíkur uses three low-temperature fields: the Reykir field about 20 km NE of Reykjavík and two fields inside the town, those of Laugarnes and Ellidaár. Since 1990 Hitaveita Reykjavíkur also utilizes the Nesjavellir high-temperature field, 30 km E of Reykjavík, which currently provides about 18 % of the geothermal energy used by the district heating service.

The Laugarnes field has been exploited by the Hitaveita Reykjavíkur since 1928. Up to the present, more than 50 deep water wells have been drilled in the area producing hot water up to 130 °C. The wells are not all connected to the water supply system due to reasons such as: they are too shallow, the water temperature is too low or the water yield of the wells is too small. Besides, some of the production wells have been taken off-line as an increasing amount of dissolved salts (sea water) in the geothermal water has caused depositions in downhole pumps. The yearly average production from this area since 1962 is shown in Figure 2.

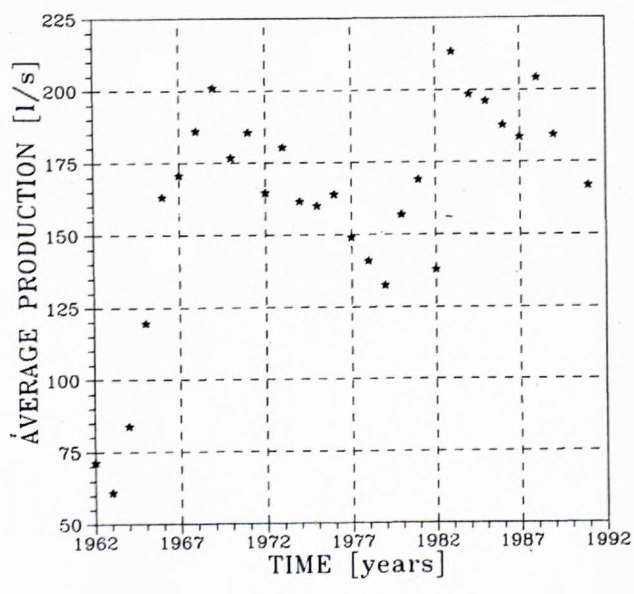

Fig. 2 The yearly average production from the Laugarnes geothermal field

3. Distributed parameter model for the Laugarnes geothermal field

In recent years, particularly during the last decade, the use of geothermal reservoir modelling has grown significantly. Modelling has turned out to be a very effective method for analysing data from geothermal reservoirs, as well as for estimating a geothermal field's future behaviour and its production potential. Numerous quantitative models have been developed for different geothermal fields all over the world (BÖDVARSSON et al., 1986).

In a broad sense, geothermal reservoir models can be divided into two categories:

1. **Simple models** are in many cases adequate idealisation of real situations (GRANT et al., 1982). They have a great advantage of being simple, they do not require the use of large computers and they are inexpensive to use. But simple models can neither consider spatial variation in the properties and parameters of a reservoir nor its internal structure. According to their methods of calculation, simple models can be further divided into two subcategories:

a. distributed analytical models in which, for example, the pressure response is given by an analytical function;

b. lumped parameter models that use very few blocks to represent the geothermal system. It does not consider the internal distribution of mass and energy. Usually, it is used as a first stage in a modelling process and for checking the results of more complex modelling. The main disadvantage of the lumped model is that it does not consider fluid flow within the reservoir, and does not consider spatial variations in reservoir properties and conditions. Usually, it is very useful for predicting the reservoir responses of single-phase geothermal fields.

2. **Numerical models** are very general mathematical models that can be used to simulate geothermal reservoirs in as much detail as desired. If only a few grid blocks are used, one has the equivalent of a lumped parameter model, but several hundred or thousand grid blocks can be used to simulate entire geothermal systems. But detailed numerical modelling of a geothermal reservoir is time consuming, costly and requires large amounts of field data. Numerical models can be further divided into two subcategories:

a. natural-state models developed for studies of the natural (unexploited) behaviour of geothermal systems;

b. exploitation models developed for studies of geothermal reservoirs under exploitation (BÖDVARSSON et al., 1986).

Numerical models allow a much more detailed description of a reservoir system and the different flow regimes that occur in the system. They can be used to simulate the entire geothermal system, including reservoir, caprock, bedrock, shallow cold aquifers, recharge areas, even tectonic structures. In general, it is necessary to use numerical models for a complete, realistic solution of geothermal problems. They are used in the case of two-phase reservoirs and in cases where large variations in temperature, or pressure conditions prevail.

Tab. 1: Well data in the Laugarnes field

Well no.	Year completed	Elevation [m a.s.l.]	Depth of well [m]	Depth of casing [m]	Temperature of water [°C]
RV-01	1962	12.04	1067	70	-
RV-02	1958	20.86	650	30	-
RV-03	1958	27.03	732	71	-
RV-04	1959	15.48	2198	69	135
RV-05	1959	15.07	741	68	130
RV-06	1959	27.63	765	99	-
RV-07	1959	16.90	752	94	-
RV-08	1960	11.01	1397	91	-
RV-09	1959	27.06	862	90	128
RV-10	1959	15.87	1306	92	130
RV-11	1962	25.72	928	112	130
RV-12	1962	17.74	1105	94	-
RV-13	1962	17.10	975	100	-
RV-14	1962	4.28	1026	101	-
RV-15	1962	24.72	1014	112	126
RV-16	1962	16.78	1300	256	-
RV-17	1963	21.59	634	93	122
RV-19	1963	28.09	1239	79	128
RV-20	1963	26.11	764	87	129
RV-21	1963	24.74	978	112	129
RV-22	1963	30.36	1583	83	-
RV-25	1968	29.50	1647	79	-
RV-32	1969	42.00	1359	100	-
RV-34	1978	33.00	3085	328	123
RV-35	1979	17.00	2857	276	119
RV-38	1982	16.50	1488	325	128
H-16	1943	12.36	770	17	-
H-18	1956	8.42	697	19	-
H-19	1956	10.20	471	-	-
H-27	1959	14.98	403	31	109
H-29	1959	19.82	249	33	-
H-32	1961	33.27	606	32	-
H-34	1961	7.00	399	-	-

In both cases, the models can only be as good as the data upon which they are based. Substantial monitoring programs are, therefore, essential.

3.1. Results from the calibration

Distributed parameter model for the Laugarnes geothermal field was created by AQUA programme package developed by Vatnaskil Consulting Engineers (1991) to solve the groundwater flow and mass transport by differential equations using the Galerkin finite element method with triangular elements. The model is two dimensional.

The total surface area covered by the mesh is about 67.95 km^2. The pumping area is located in the middle of the modelling area. The model was created with 1 356 nodes and 2 627 elements. Thus, the boundaries are taken far enough away to avoid their influence on the solution. Boundary conditions for the distributed groundwater flow model are established based on resistivity and water level measurements. The no-flow boundary was established around the whole Laugarnes area and only a small part in the SE area was used as boundary with constant potential. The boundary conditions which were used for the distributed model are shown in Figure 3. As for the initial state, prior to production it was assumed that the reservoir water head was constant.

The production rates are taken as a monthly average for each supply well from 1962 - 1991. The initial values for transmissivity and storage coefficient are taken from the results of well tests. A number of tests have been made in wells in the Laugarnes area in order to determine values of the aquifer constants, transmissivity and storativity, and to locate impervious boundaries believed to exist between the three hydrothermal systems. The tests were conducted by observations of water levels in observation wells after a supply well was turned off or on, correction being made for previous trends in water levels. Because of variation in demand, the tests are of short duration, usually less than 10 - 20

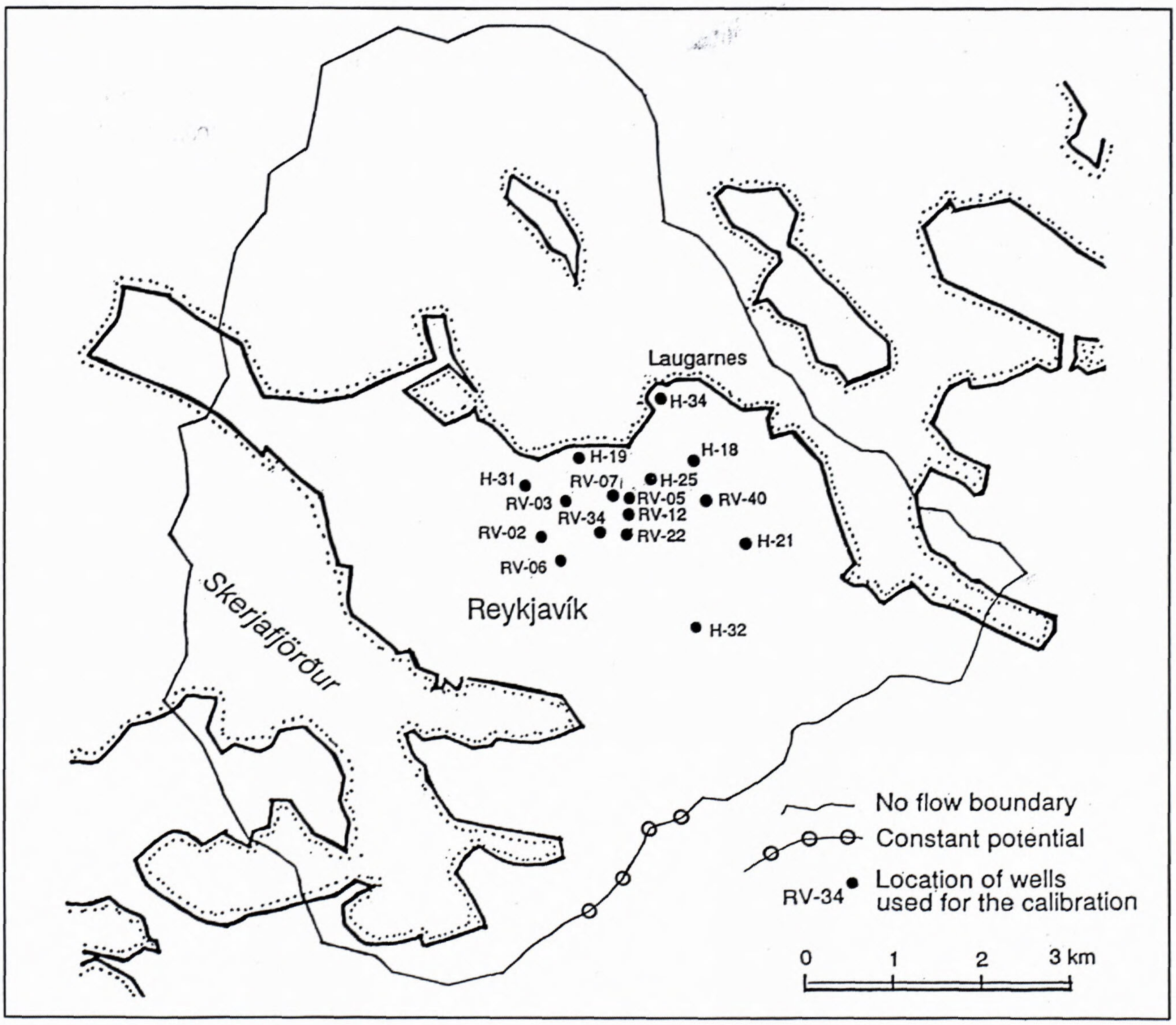

Figure 3: Boundary conditions of the model (FENDEK, 1992)

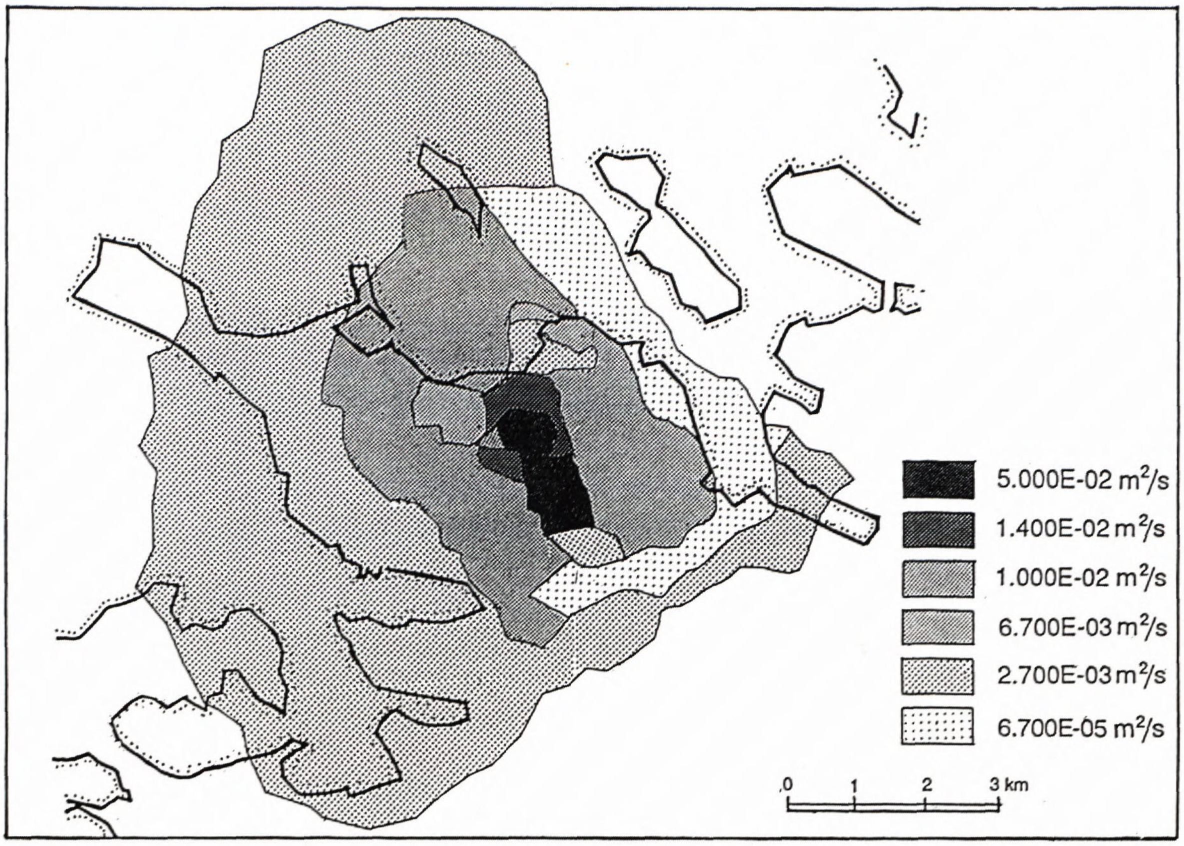

Figure 4: Map of transmissivity in the vicinity of wells (FENDEK, 1992)

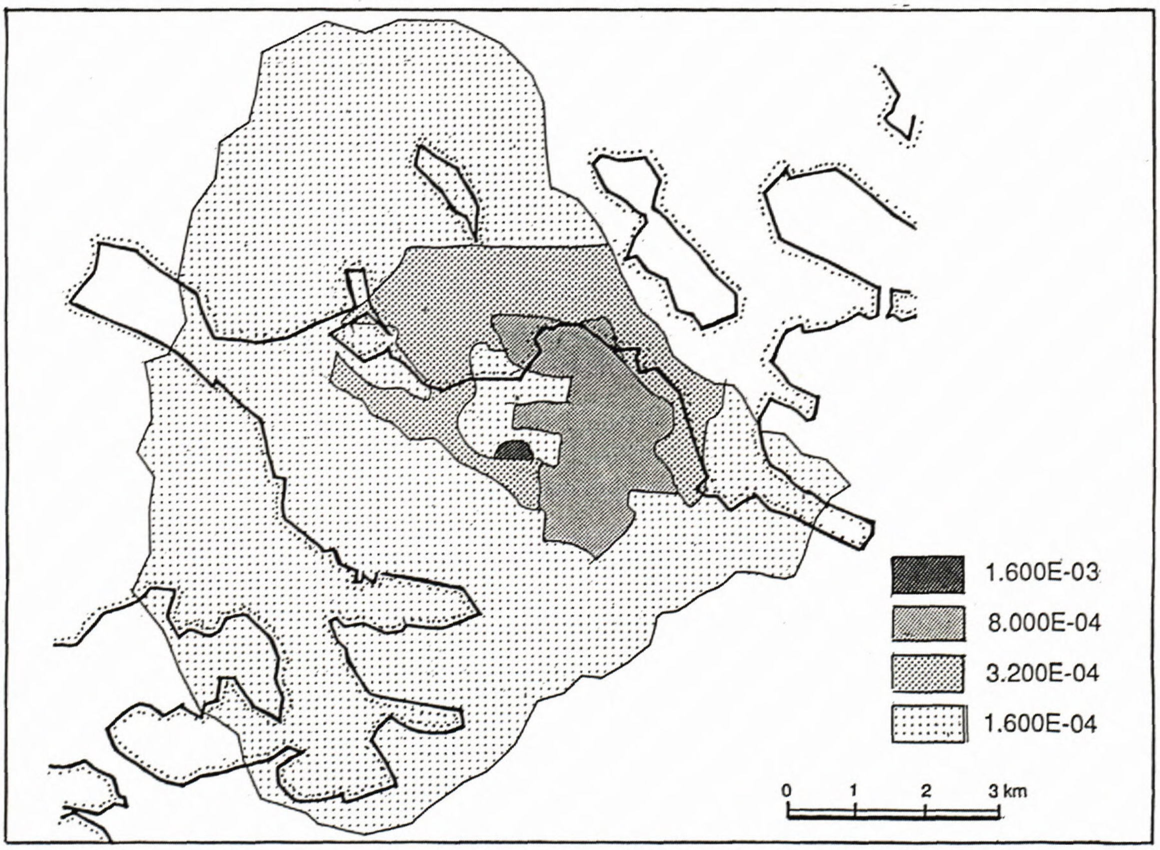

Figure 5: Map of storage coefficient (FENDEK, 1992)

hours and are interfered with by operating supply wells, the discharge of which varies somewhat by variations in water level. Analysed by the THEIS nonequilibrium method, the test data gave values ranging from **3.5×10^{-3}** to **8.8×10^{-3}** m^2/s for the **coefficient of transmissivity** and **3.9×10^{-5}** to **3.2×10^{-4}** for the **coefficient of storage** (THORSTEINSSON - ELÍASSON, 1970).

The transmissivity, storage coefficient, anisotropy and porosity are determined by matching observed and calculated reservoir response. The **transmissivity** in the area covered by the model varies from **5.0×10^{-2}** to **6.7×10^{-5}** m^2/s. The low value for transmissivity is obtained along the NE boundaries of Laugarnes area and the highest value is obtained in the centre of this area (Figure 4).

The calibration started with the value of the **storage coefficient** in the range of **1.6×10^{-3}** to **1.6×10^{-4}** (Figure 5).

The long term effect of the exploitation was analysed, so the elastic storage coefficient and the delayed yield effect were taken into account. It was assumed that **porosity** of the reservoir is in the range of **0.0111-0.0108** and the time constant 6 500 days.

The **leakage coefficient** in the centre area was taken to be in the range of **6×10^{-11}** to **9×10^{-12}** s^{-1} and around the main production area the value of zero (0) was used (Figure 6) because almost no influence on temperature from the cold water recharge from above was observed.

Anisotropy is determined by anisotropy angle and by the ratio between transmissivity in **x** (T_{xx}) and **y** (T_{yy}) directions equal to **0.0999**. **Anisotropy angles** range **from 50 degrees** in the W and S part of Laugarnes area **to 120 degrees** in the centre and NE part of the area (FENDEK, 1992).

For the calibration of the model the measured data from 16 wells were used. The areal distribution of these wells is shown in Figure 3. The example of results from the calibration is shown in Figure 7. The best results were obtained for observation well RV-07. A good fit between measured and calculated drawdown values was obtained with the model for wells which are inside the main production area (RV-05, RV-34, RV-11, RV-22, H-25, H-19, RV-03, RV-06 and RV-02). A slightly worse fit between measured and calculated drawdown values was obtained with the model for wells which are around this production area (H-34, H-18, RV-40, H-21, H-32, H-31) (Fendek, 1992). The depth of these wells ranges from 249 - 770 m (Table 1 refers), they are relatively shallow and produce geothermal water from the top of the reservoir. This can be the reason why better results are not obtained with the two-dimensional AQUA model for these wells.

Mass transport calculations can be used to estimate leakage coefficient and aquifer thickness. By fitting the calculated and measured values of silica concentration, the above-mentioned parameters can be calculated. Several measurements of silica concentration exist from each production well.

The silica content decreased due to the production (HETTLING, 1984) and the induced leakage from above. The model parameters used for solving the mass transport of silica are as follows:

average initial concentration: 160 mg/l
average concentration in the top aquifer: 22 mg/l
a_T/a_L: 0.16
longitudinal dispersivity (a_L): 80 m
molecular diffusion: 10^{-8} m^2/s
aquifer thickness: 800 m

The concentration calculated with the model shows the same decreasing trend (Figure 8).

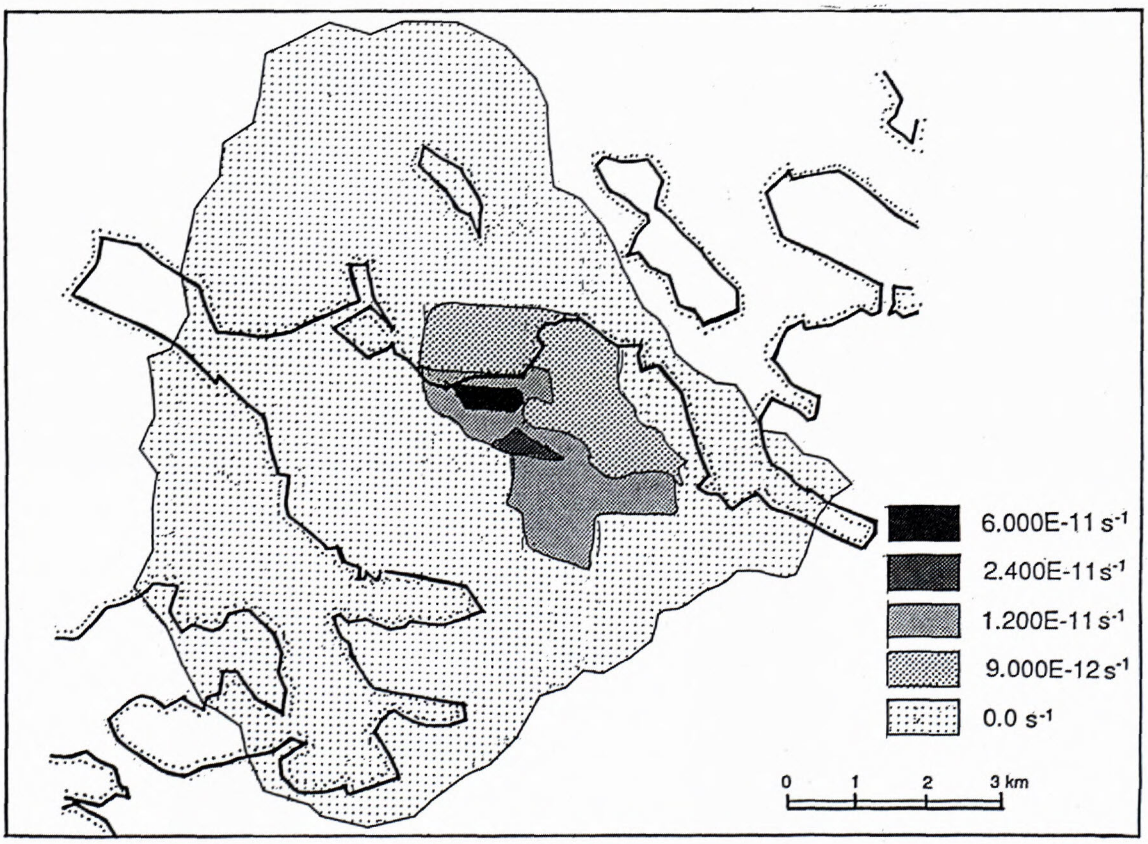

Figure 6: Areal distribution of leakage coefficient (FENDEK, 1992)

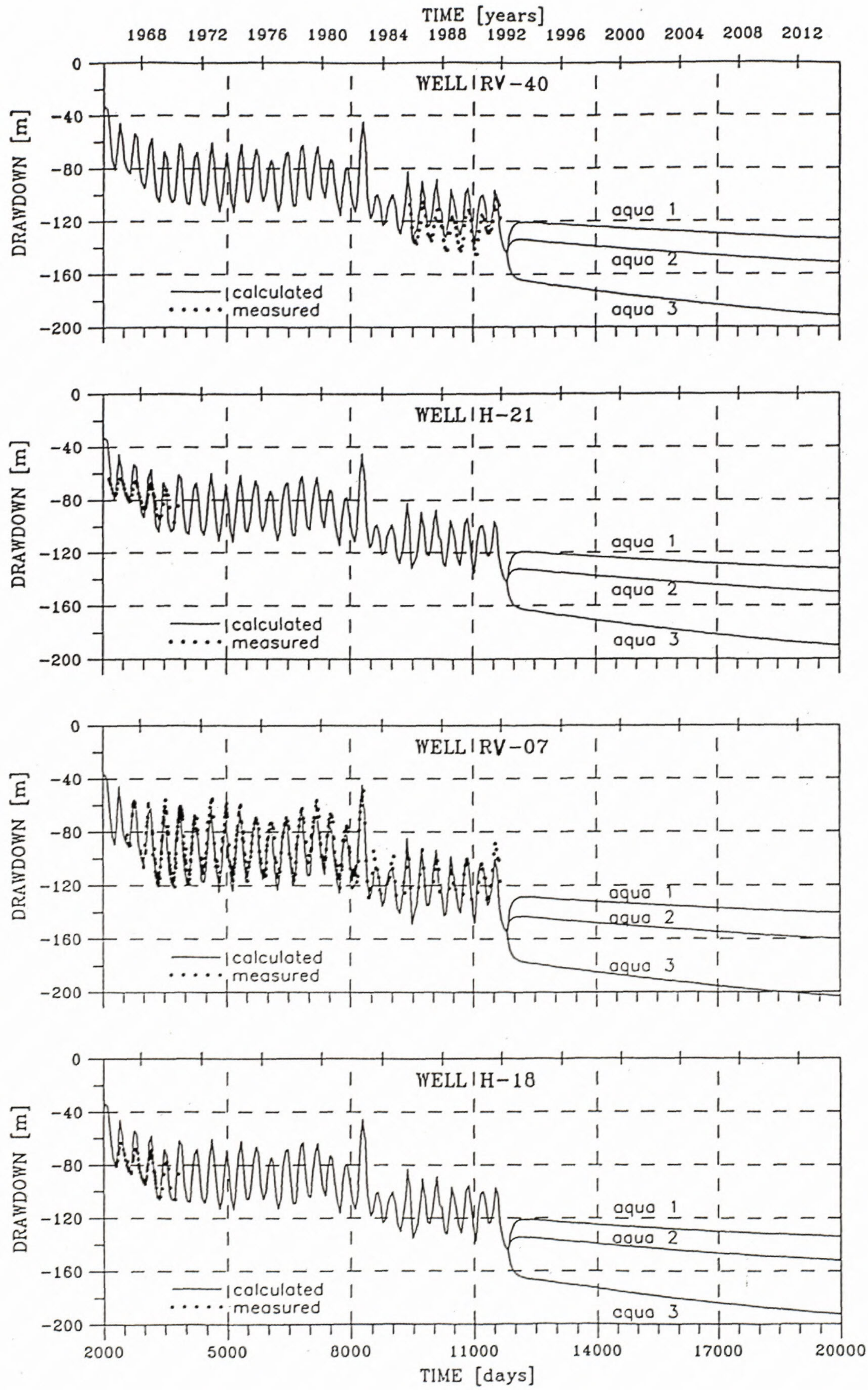

Figure 7: Measured, calculated and prediction drawdown for some wells (FENDEK, 1992)

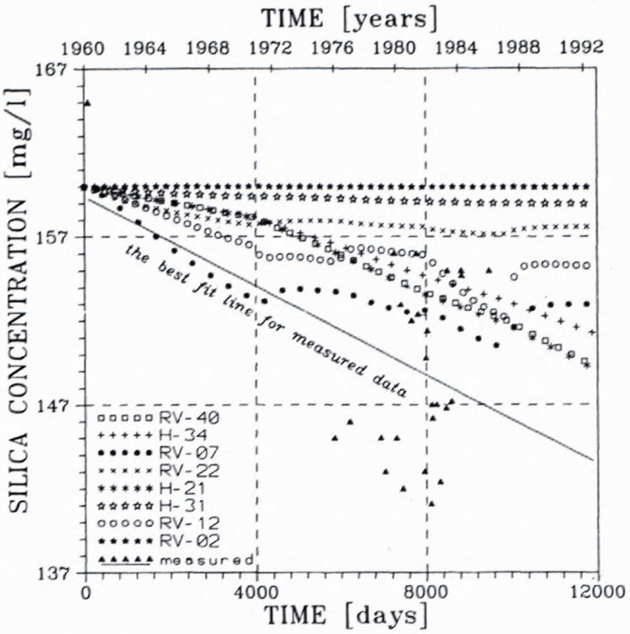

Figure 8: Example of silica concentration decline in some wells (FENDEK, 1992)

3.2. Future prediction of the reservoir response

After calibration, the model was used to calculate the drawdown until the end of the year 2012. As a starting point for future prediction the reservoir state as of 1992 is taken. The calculations were made with three different production rates which are shown in Table 2 for each supply well.

Table 2 : Future predictions for the yearly average production [l/s]

Well no.	aqua 1	aqua 2	aqua 3
RV-05	53.0	53.0	65.0
RV-09	4.4	7.0	10.0
RV-10	12.5	15.0	20.0
RV-11	20.6	25.0	30.0
RV-15	13.2	16.0	20.0
RV-17	10.9	12.0	15.0
RV-19	21.2	25.0	30.0
RV-20	15.6	24.0	33.3
RV-21	30.8	30.0	45.0
RV-35	7.1	7.0	11.0
RV-38	10.0	20.0	30.2
Total:	199.3	234.0	309.5

The production rates under column aqua 1 represent the average production for the last year (1991), which totals 199.3 l/s for all wells. The values under column aqua 2 indicate that the average production is increased by 17.4 % (total of 234 l/s) when compared to that of the actual values in the column under aqua 1. Furthermore, the values under column aqua 3 give the highest values for yearly average production rate and the total of 309.5 l/s is 55.5 % higher than the values in aqua 1. The calculation results for the future predictions are shown in Figure 7. All calculated curves of future drawdown show a lowering trend. The obtained **drawdown** is between **110 - 190 m** with a corresponding total yearly average production of **199.3 - 309.5 l/s** respectively. The results mentioned above are yearly average values and do not take into account the seasonal changes in production.

4. Results and conclusions

The prime objective of this paper was to create a model approximating the natural conditions of the Laugarnes geothermal field, using the field data for the last 30 years.

Through this model, the reservoir parameters and features of the field were described and some predictions of its future behaviour were made. All available geological, geophysical and geochemical information, along with field measurement data were collected and carefully studied to understand how all these factors contributed to the overall picture of the geothermal reservoir.

The study of the Laugarnes geothermal reservoir, applying the distributed model, presents results that are very close to the measured field data. This indicates a correct approach and that the model is reliable for similar reservoir modelling and future forecasting. However, as the methods use only linear functions in their mathematical models, the effects of turbulence and skin impact are not taken into account. This means that the drawdown values in close proximity to the pumping wells cannot always be considered accurate.

The measurements from the field indicate higher values of SiO_2 in 1962. Over the production period of 30 years, the effects of water discharge are observed very clearly with a lowering of the water level and decline of the SiO_2 content.

For the calibration of the model, the measured data from 16 wells were used. Good fit with the model for drawdown, using the equation for delayed yield, shows that the reservoir is controlled by two different storage mechanisms. At the start of production, storage is controlled by liquid/formation compressibility with characteristic values for the confined aquifers ranging from 1.6×10^{-3} to 1.6×10^{-4}. In later production, the storage coefficient is controlled by the mobility of the free surface with a value of approximately 0.011, which is near to the effective porosity. The transmissivity in the area covered by the model varies from 5.0×10^{-2} to 6.7×10^{-5} m^2/s. The leakage coefficient in the centre area was taken to be in the range of 6.0×10^{-11} to 9.0×10^{-12} s^{-1} and around the main production area the value of zero was used.

From the trend of the measured and calculated curves for the drawdown obtained from distributed groundwater flow model, it is quite obvious that with present production no steady-state conditions in the reservoir can be reached until the year 2012. The obtained drawdown is between 110 - 190 m with a corresponding total yearly average production of 199.3 - 309.5 l/s respectively. So, the recharge in the system is much less than production for the present drawdown.

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