Contribution to the Knowledge of Temperature and Reservoir Depth of Sulphurous Groundwater Aquifer Systems in the Dão River Basin, Portugal

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Abstract. The sulphurous groundwater aquifer systems of the Dão River basin in Portugal have been the subject of studies by some authors, as there are several Medical Spas, where over time there has been a need to increase their flow rates to guarantee more available mineral water and better quality. It is known that those waters resurface with anomalous temperatures, and that they are associated with very deep aquifer systems where the reservoir temperature is relatively high. Thus, the present work aims to contribute to the knowledge of the reservoir temperature and its depth, in the sense of taking to the planning of construction of deep wells, so that their results to be favourable, allow energy utilization, that function of the temperatures to be obtained, can allow from the production of electricity, to heating of buildings, heating of domestic water, to aqua-ludic uses in medical spas and leisure areas. After presenting the generic aspects of geomorphology, geology, climatic elements, and global conceptualization from the numerical models of the Dão River basin, the results of physical-chemical analyses of groundwater are presented. It should be noted that the groundwaters with the greatest geothermal potential are associated with deep aquifer systems, semi-confined to confined, fissured type (very localized), with sulphurous water, with pH values higher than 8.0, conductivity above 350 μS/cm, and surface temperatures between 15.7 and 50.9°C. It is important noting the occurrence of five main sectors with geothermal potential, which from upstream to downstream of the river basin are: Cavaca, Sezures, Alcafache, Sangemil and Granjal. By applying geothermal thermometers, in the results of physical-chemical analyses of the groundwaters of those sectors, the reservoir temperatures were obtained between 92 and 116°C and also reservoir depths generally greater than 2200m.

1. Introduction
The Dão River basin has an area of about 1370km², with an almost ellipsoidal plant shape contained in a rectangle of 62 km by 22 km (Figure 1). The river in the terminal zone represents a watercourse grade 3 according to the Strahler classification [1]. The altitude varies from 120m, the SW, in the zone of the mouth of the Dão River to the Mondego River (the largest river completely Portuguese), until about 900m, the NE, in the area where the main water lines of the whole basin begin; there is the particularity of locally to the west of the basin occur the highest elevation of the whole basin under study, which is...
1055 m. The average annual temperatures and annual precipitation of the entire basin vary between 17.5°C and 850 mm in the zones of lower elevation, and 10°C and 2200 mm in the zones of higher elevation (from SNIRH [1]).

After the calculation of the annual hydrologic balance, the water surpluses are of 232 to 523 mm/year, leading to recharges in depth of 81 to 183 mm/year [1]. Throughout the basin there are several hundreds of common water points, from springs, wells and boreholes, which currently correspond to bicarbonate-sodium groundwater, with electrical conductivity generally below 200 µS/cm, pH below 6.5 and average temperature of about 15°C. It should be noted that in the entire basin there are 5 sites where special sulphurous waters springs occur, which are the result of very long underground circuits with temperatures above 15°C, pH above 8.1 and electrical conductivity above 350 µS/cm. It is on these water points that this paper is dedicated, in the sense of knowing the depth of the reservoir, and also its temperatures in that depth, so that these elements contribute to the most rigorous possible knowledge of the geohydraulic model of such resources, in order to facilitate their exploration in the future, not only in medical spas but also in geothermal uses.

A global notion of how the geohydraulic model is developed taking into account several variables such, as altimetry, surface frontiers, water table position, natural flows rates, and resurgence site, was advanced by Gomes da Costa et al. [3], with software based on numerical modelling elements (Figure 2). From that image is evident the contribution of the morphology of the terrain and the discontinuity system, reflected in the flow model. The sulphurous water flow lines present a tendency in the NE-SW direction, although for the Granjal and Sangemil waters the flow projection also appears with a NS component, possibly resulting from the contribution of flows from higher elevations (Serra do Caramulo).
Figure 2. Graphical result of geohydraulic simulation based on numerical software for natural sulphurous water discharges of the Dão River Basin [3].

2. Geological Context
The Dão River Basin is developed in the Central Iberian Zone, consisting essentially of granitoids of the Hercynian age (Figure 3), in which sin-tectonic granitic massifs predominate in relation to F3 and in particular those of the Intermediate Series (γII2b) in the areas of confluence with the Mondego River, and also late to post-tectonic ones in relation to F3 and especially those of the Late Series (γII3b) in the upstream areas.

In the most downstream zone of the basin, there are also lithologies of the Schist-Greywacke Complex (Rosmaninhal formations - CBR), constituted by shale rocks resulting from fine turbidites and conglomerates of the Middle Series of Cambrian.

The granitic massif was subjected to hercynian and late-hercynian tectonic actions, resulting in folds, metamorphisms and faults (evidence of fractures with general NNE-SSW and NE-SW orientations, sometimes filled by veins).

Of the vast network of veins and linear structures that occur in the granitic massif, stand out the alignments of global direction NE-SW (Figure 3), which correspond to old fractures and were filled by veins of microgranites, quartz, and basic rocks. These linear structures reach more than ten meters in their thickness.

3. Geothermal Elements
Sulphurous water springs have higher emergency temperatures than other waters in their surroundings (normal groundwater), so, the maximum temperature that this resource reaches has always motivated the scientific community interest.

Over time, equations were developed and calibrated that relate the concentrations of elements of the chemical composition of water, as a way of estimating the maximum temperature at which a given resource reaches in its geohydraulic path.

In that sense, Table 1 presents the main chemical elements of the sulphurous waters of the Dão River basin, as well as three more non-sulphurous waters, which are also considered special and associated with classical fountains and have perennial flow rates.
The bibliography contains numerous equations, methodologies and respective limitations in estimating reservoir temperature ($T_r$). Several authors [5],[6],[7] presented some methodologies for various aquifer systems (including for some sulphurous springs). In this research, the procedure presented in Ferreira Gomes et al. [7] was used, in which equations based on silica content and the Na/K ratio were applied. Table 2 presents the equations that were applied to obtain the $T_r$, whose values obtained are shown in Table 3.

In a first analysis of the results of Table 3 it can be seen that there is a convergence of the results of the silica-based equations in detriment of the equations based on the Na/K ratio. On the other hand, the silica-based equations estimate the lowest and most consistent temperatures (with less variability between results).

The $T_r$ results generated by the Na/K ratio for non-sulphurous groundwater are incoherent with the expected (sometimes they generate negative temperatures or in the order of 400°C). In this sense, only the results of the equations using silica content as a base were considered, although in the certainty that the application of geothermometers generates more consistent results in groundwaters with more mineralization.

Figure 3. Geological situation of the Dão River Basin (adapted from SGP [4]).
Table 1. Physical-chemical analyses of groundwater in the Dão River Basin [2].

| Parameter                        | Cava | Sezures | Alcachete | Sange-mil | Granjal | Fail | Loreto | Bica |
|----------------------------------|------|---------|-----------|-----------|---------|------|--------|------|
| Temperature (°C)                 | 26.9 | 15.7    | 50.9      | 49.5      | 22.7    | 16.3 | 15.9   | 15.2 |
| pH                               | 8.28 | 8.17    | 8.44      | 8.11      | 9.07    | 6.02 | 6.41   | 5.63 |
| Electrical Conductivity (µS/cm)  | 357  | 542     | 458       | 528       | 634     | 150  | 224    | 158  |
| Alkalinity (mL/L)                | 27.5 | 45.0    | 30.0      | 30.7      | 32.7    | -    | 3.3    | 1.7  |
| Hardness water (p.p.10°CCaCO₃)   | 1.5  | 1.4     | 1.2       | 1.4       | 0.60    | -    | 3.40   | 4.60 |
| Silica (mg/L de SiO₂)            | 57.2 | 40.0    | 57.7      | 89.8      | 45.5    | -    | 7.9    | 16.9 |
| Sulphuration (mL/L de I₂; 0.01N)| 4.0  | <0.25   | 2.5       | 19.85     | 51.8    | -    | -      | -    |
| Dry residue a 180°C (mg/L)       | 261.0| 381.0   | 311.0     | 390.0     | 429.9   | -    | 155.1  | 129  |
| Total mineralization (mg/L)      | 336.7| 518.0   | 392.0     | 475.0     | 499.3   | 73.1 | 165    | 134  |

Table 2. Equations to estimate the reservoir temperature (Tr) based on the chemical composition of mineral waters (in Ferreira Gomes et al. [7].

| Geothermometer                  | Equation          | Limitations            | Author |
|---------------------------------|-------------------|------------------------|--------|
| Conductive quartz (silica)      | Tr = 1309 / (5.19 - log C) - 273.15 | Tr = 0 - 250°C         | [8], [9] |
|                                 | Tr = 1164 / (4.9 - log C) - 273.15 | Tr = 25 - 180°C        | [10]   |
| Adiabatic quartz (silica)       | Tr = 1522 / (5.75-log C) - 273.15 | Tr = 0 - 250°C         | [8], [9] |
|                                 | Tr = 1498 / (5.7-log C) - 273.15 | Tr = 25 - 180°C        | [10]   |
|                                 | Tr = 855.6 / (log D + 0.8573) - 273.15 | Tr = 100-275°C         | [11]   |
|                                 | Tr = 883 / (log D + 0.78) - 273.15 | -                      | [12]   |
|                                 | Tr = 933 / (log D + 0.993) - 273.15 | Tr = 25 - 250°C        | [10]   |
|                                 | Tr = 1217 / (log D + 1.483) - 273.15 | Tr > 150°C             | [8], [9] |
| Na/k                            | Tr = 1178 / (log D + 1.47) - 273.15 | Tr = 25 - 250°C        | [13]   |
|                                 | Tr = 1390 / (1,750 + log D) - 273.15 | -                      | [14]   |

C= silica in mg/L; D= Na/k, with Na= sodium, K = potassium, both in mg/L.

In association with the maximum temperature that a certain groundwater reaches, it is also important to reflect on how deep it is in the "maximum temperature" condition. To estimate the reservoir depth (Dr), equations 1 [15] and 2 [5] will be used assuming the temperature at 50 m is 20°C:

\[ P = \frac{(Tr - T₀)}{Δ} \] (1)

\[ P = (Tr - 20)/Δ + 50 \] (2)
being: Tr the reservoir temperature (°C), using the probable value, from the different methods (Table 2); T0 is the temperature (°C) that corresponds to the ordinate at the origin of the regressions obtained for each case of study, in terms of "Temperature versus depth", and that generically corresponds to the value of surface resurgence; ∆ is the geothermal gradient (°C/m).

Table 3. Reservoir temperatures (Tr), in °C, estimated from the chemical composition applied to the equations of Table 2.

| Geotermometer | Eq. | Sulphurous water | Not Sulphurous water |
|---------------|-----|------------------|----------------------|
|               |     | Cavaca | Sezures | Alcafache | Sangem | Granjal | Fail | Loreto | Bica |
| Conductive quartz (silica) | 1  | 107.6  | 91.8    | 109.0    | 125.6  | 97.5    | 59.5  | 31.8   | 57.2  |
|                  | 2  | 96.6   | 79.8    | 98.0     | 115.7  | 85.9    | 46.2  | 17.7   | 43.8  |
| Adiabatic quartz (silica) | 3  | 107.6  | 93.8    | 108.7    | 122.9  | 98.8    | 65.5  | 40.5   | 63.4  |
|                  | 4  | 101.6  | 88.0    | 102.7    | 116.6  | 92.9    | 60.1  | 35.6   | 58.1  |

| Na/K | Tr- average (°C) | 124 | 92 | 105 | 124 | 91 | 58 | 31 | 56 |
|      | Tr- probable reservoir (°C) | 106 | 92 | 108 | 116 | 98 | 60 | 35 | 57 |

Table 4 presents the results of the reservoir depth (Dr) for the various groundwaters under analysis using the average geothermal gradient, ∆ = 0.033°C/m [16].

Table 4. Geothermal elements calculated for the sulphurous and non-sulphurous waters of the Dão River basin, assuming the average geothermal gradient (∆ = 0.033°C/m).

| Sulfurous water | Not Sulphurous water |
|---------------|----------------------|
|               | Cavaca | Sezures | Alcafache | Sangem | Granjal | Fail | Loreto | Bica |
| surface elevation (m) | 580 | 420 | 230 | 195 | 180 | 380 | 180 | 175 |
| surface groundwater temperature (°C) | 29.7 | 15.7 | 50.0 | 49.0 | 22.7 | 16.3 | 15.9 | 15.2 |
| spontaneous flow rate (L/s) | 0.20 | 0.05 | 1.40 | 1.00 | 1.40 | 0.15 | 0.03 | 0.25 |
| reservoir temperature - Tr (°C) | 106 | 92 | 108 | 116 | 98 | 60 | 35 | 57 |
| depth of reservoir - Dr (m), (Eq.11) | 2312 | 2312 | 1758 | 2030 | 2282 | 1324 | 579 | 1267 |
| depth of reservoir - Dr (m), (Eq.12) | 2656 | 2232 | 2717 | 2959 | 2414 | 1262 | 505 | 1171 |
| depth of reservoir - Dr (m), Average | 2484 | 2272 | 2237 | 2495 | 2348 | 1293 | 542 | 1219 |

The results presented in Table 4 show that the estimated reservoir temperatures for sulphurous groundwaters are higher than for non-sulphurous groundwaters, as well as the respective reservoir depths are higher in sulphurous groundwaters than in non-sulphurous groundwaters, directing ao that sulphurous groundwaters are subject to a deeper geohydraulic circuit.

Another method used to estimate the depth of the reservoir is through the Rybach models [17], which will be applied as comparative quantities in sulphurous groundwaters to the previous procedure. Thus, according to that author, situations of groundwaters of deep circulation, such as the cases concerned, require models that explain the heat loss of the groundwater from the reservoir to the surface where it ascends with the heat being transferred to the adjacent rock. The models take into account the reservoir temperature (Tr), the discharge temperature (Ts), the discharge flow rate (Q) and maximum depth (Dr) of the groundwater circuit. The loss of heat is estimated based on one expression of the type: Tr-Ts = f (Q, Dr, Geometry). Introducing a dimensionless variable, θ simplifies the mathematical calculation according to the expression [17]:

\[ Tr - Ts = f(Q, Dr, Geometry) \]
\[ \theta = \frac{(T_s - T_e)}{(T_r - T_e)} = f(Q, Dr, Geometry) \]  

(3)

where \( T_e \) is the average annual surface temperature.

The method seeks to make an analogy to the physical architecture of the discharge circuit of the aquifer system, which can be simplified and translated according to the vertical discharge pipe (cylindrical conduit) model and plane fracture (plan conduit) model. Table 5 shows the previous elements necessary for the application of Rybach's experimental methods [17]. Subsequently, the data are projected in the abacuses, on which the maximum depths are estimated through the proximity of the normalized curves presented in Figure 4.

**Table 5. Elements of maximum depth estimation (Dr) from the Rybach method [17].**

| Sulphurous water | \( Q \) (L/s) | \( T_s \) (°C) | \( T_e \) (°C) | \( T_r \) (°C) | \( \theta \) | Dr (m) |
|------------------|--------------|----------------|---------------|---------------|-------------|--------|
| Cavaca           | 0.2          | 29.6           | 12.0          | 106           | 0.18        | 900    |
| Sezures          | 0.05         | 15.7           | 12.0          | 92            | 0.05        | 2000   |
| Alcafache        | 1.4          | 50.9           | 12.9          | 108           | 0.40        | 2900   |
| Sangemil         | 1.0          | 49.5           | 12.3          | 116           | 0.35        | 2800   |
| Granjal          | 1.4          | 22.7           | 13.2          | 98            | 0.11        | 1100/5000 |

![Figure 4](image-url)  

**Figure 4.** Projections of the results of the Rybach method for sulphurous groundwaters in study.
From the analysis of Figure 4, it can be seen that the projection of most sulphurous groundwaters fits into the circulation in the form of "cylindrical conduit" (Cavaca, Alcafache, Sangemil and Sezures); the case of Granjal, the projection that apparently best represents the model is the "plane conduit", however, by the actual data obtained, as presented below, is also understood to be of the type "cylindrical conduit".

In the Granjal case, a hole with a depth of 670.6m (Well AQ1) was recently made, having been drilled from 0-160m, in broken percussion, and from 160-670.6m in rotation with core drilling; the final result allows obtaining sulphurous groundwater with a flow rate of 1.4 L/s in artesianism and 13.0 L/s in pumping, with a water temperature at the well head of 22.4°C [18]. From the measurements of temperature in the rotation section, the results presented in Figure 5 were obtained, and the evolution of the temperature in depth, according to the following:

\[ T = 18.685 + 0.0157 P \]  

with \( P \) the depth in meters, and \( T \) the temperature in °C.

From equation 14, the local geothermal gradient is 0.0157 °C/m, which is lower than the average geothermal gradient 0.033 °C/m attributed to the continental crust [16]; even so, that value is close to what is considered normal in granitic massifs (0.0125 °C/m) by Pomerol and Ricour [19]. However, these results indicate that there are still many investigations to be carried out in this field, since this geothermal gradient leads to the reservoir temperature (\( T_r = 98^\circ C \)) being obtained at about 5022m, a situation that guides that the Rybach's model applied to Granjal is in fact of the "cylindrical conduit" type.

![Graph showing temperature evolution](image)

**Figure 5.** Evolution of temperature in depth in the granitic massif in the Granjal area, from records in AQ1 Well [18].

Table 6 presents the synthesis of the main geothermal elements of the various sulphurous groundwater sectors of the Dão River basin. From these results it is worth noting that the reservoir depth (\( D_r \)) evaluated on the basis of the theoretical evolution of the mean gradient, the results are all very close (\( D_r = 2237 - 2495 \)m), a situation that is no longer observed when applying the Rybach method, that according to the cylindrical conduit model (which is considered more suitable for the present case studies), is oriented to \( D_r \) between 900 and 5000m. The Granjal case, on the basis of actual records, does in fact point to a \( D_r \) of the order of 5000m.
Table 6. Synthesis of geothermal elements of the sulphurous groundwater sectors of the Dão River Basin.

| Local   | Ts (ºC) | Tr (ºC) | Dr (m) with Δ = 0.033°C/m by Rybach method | real records: Δ = 0.0157°C/m |
|---------|---------|---------|------------------------------------------|-----------------------------|
| Cavaca  | 29.6    | 106     | 2484                                    | 900 (*)                     | -                          |
| Sezures | 15.7    | 92      | 2272                                    | 2000 (*)                    | -                          |
| Alcafache | 50.9  | 108     | 2237                                    | 2900 (*)                    | -                          |
| Sangemil | 49.5   | 116     | 2495                                    | 2800 (*)                    | -                          |
| Granjal | 22.7    | 98      | 2348                                    | 5000 (*),1100 (**)          | 5022                       |

Ts - discharge temperature; Tr - reservoir temperature; Dr - Reservoir depth; Δ - geothermal gradient.
(*) cylindrical conduit; (**) plane conduit.

4. Conclusions

Of the studies presented, the following should be highlighted:

i) the Dão River basin in Portugal (Figure 1) is relatively extensive, and in geological terms it is mainly occupied by granite rocks of Hercynian age;

ii) along of the Dão River surround there are several sulphurous groundwater sprangings, which due to their singularities have potential for use in the Medical Spa and also potential for geothermal applications; from upstream to downstream of the basin there are the following sectors: Cavaca, Sezures, Alcafache, Sangemil and Granjal;

iii) of the sectors mentioned above, the cases of Cavaca, Alcafache and Sangemil are already active such as medical spas; the case of Alcafache also uses hot sulphurous groundwater (Ts=50.9ºC) to support the heating of buildings and heating of domestic water; the case of Granjal has recently been under study with the main objective of installing new medical spa; the case of Sezures, corresponds to a spring but currently abandoned;

iv) it is therefore important to know the geohydraulic model of the various sectors, and possible relationships between them, in order to increase larger and better explorations in the future, and consequently to plan an appropriate management and exploitation of the various aquifer systems in the region;

v) that the reservoir temperature, Tr, of the sulphurous groundwaters of the various sectors, are between 92 and 116ºC;

vi) the reservoir depths (Dr), by the various calculation methods, are oriented to depths between 900 and 5000 m approximately, and it should be noted that in fixing the various parameters there are still many doubts, either about the true local geothermal gradients, or whether the most appropriate models in the calculations follow the model of cylindrical or plan conduit, among others;

(vii) the result of the drilling of the recent AQ1 Well in the Granjal, leads to a geothermal gradient of Δ = 0.0157°C/m, which leads to Tr (98ºC) at a depth of 5022m; this gradient is lower than the average geothermal gradient of continental crust (Δ = 0.033°C/m); there is the understanding that the geothermal gradients of the other sectors are higher than those observed in the Granjal, because they are more in the interior of the granitoids, which are generally more recent, since the Granjal is in the periphery and very close to the rocks of the Schist-Greywacke Complex of Cambrian.

viii) it would be desirable that new studies of mechanical prospection be verified in the various sectors, because there is a need to evaluate not only the true geothermal gradient, but also to forecast new groundwater abstractions, their costs and risks, since it is pointed out, that it is currently possible to perform electricity with water temperatures above 70ºC [20], [21].

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