Assessment of geothermal reservoir temperature and energy fields based on resistivity data

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Abstract. Geothermal is a consistent and reliable source of renewable energy for various scale exploitation. However, harnessing geothermal energy is limited to small-scale direct heat applications in many countries, primarily due to various technical and economic reasons. One among the many reasons is a meager amount of field studies available for the reliable prediction of reservoir potential, especially in India. Assessment of temperature field depends on proper information of subsurface field properties. The assessed temperature field further determines the stored heat energy. The accurate assessment of reservoir potential depends on temperature field. Reasonable reservoir potential information would encourage policymakers to plan developmental works at various scales. Since the information on subsurface characteristics is limited in the absence of deep exploration data, assessment of reservoir potential is associated with uncertainties. In this regard, this study presents a methodology for preliminary assessment of reservoir potential in terms of temperature and thermo-hydro-geological features, which also predicts the stored heat energy. The study considers the geothermal status of India, where the developmental activities and exploration are still at nascent stages, and predicts the temperature and energy distribution of Puga geothermal reservoir based on the available resistivity data.

1. Introduction

The demand for energy has been increasing with the progress of civilization. This situation is in conflict with the availability of conventional sources for the generation of electricity. This posed formidable pressure on available conventional sources. Under this scenario, many countries have emphasized the development of renewable energy. In the late circumstances, hydro, wind, solar, biomass, and geothermal energy turned out as alternatives sources. The potential of renewable energy often depends on its source. Hydro generators require a continuous flow of water as its source, wind turbines depend on the velocity of wind for its motion in blades, and the solar receivers requires clear skies and irradiation for the generation of electricity. The supply of these resources fluctuates with time. Therefore, the energy generation depending on these fluctuating sources is unpredictable and inconsistent. On the contrary, geothermal energy uses the heat stored in the earth’s crust. The rate at which the heat is continuously replenished from the higher temperature regimes below the 3-5 km depth is about 65 mW/m\textsuperscript{2} that corresponds to an average thermal energy recharge rate of about 315 EJ/year [1]. Because of its continuous availability, geothermal energy is considered to be a promising option among available renewable energy alternatives. The locations that are close to tectonic boundaries, where the geothermal activity is indicated by the existence of hot springs, fumaroles, steam vents, and geysers are best suitable to extract the energy for electricity generation. However, the
Heat energy associated with these thermal waters is being used for direct heat applications that include space heating, cooking, greenhouse cultivation and fish farming from ancient civilization [2,3], in various parts of the globe as shown in figure 1.

![Figure 1](Image)

**Figure 1.** Countries utilizing geothermal energy for direct heat applications as of 2015 (modified from [2,3])

2. **Conceptualization of geothermal reservoir**

Developing a conceptual model of a geothermal field is one of the substantial criteria, which would aid in further reservoir exploration and developmental activities. The observations of various field investigations conducted at a geothermal field are put together to develop the conceptual model. These studies contain information corresponding to geological properties of reservoir rocks, geochemical properties of thermal fluids, and reservoir temperature distribution. Typically, a conceptual model provides the information on the areal extent of geothermal field, thickness, depth of the reservoir, location, and nature of heat source. The inclusion of this information depends on the stage of developmental activities and field studies conducted at the considered geothermal site. However, the precision of the conceptual model increases with deep exploration and detailed field studies conducted at the geothermal site. In view of the available conceptual models [4–9], it is observed that if a detailed distribution of lithology and temperature is available for the geothermal fields, it is more convenient to delineate the aquifer region, which is further considered for exploitation with an appropriate extraction scheme. In situations where geothermal exploration is still in the nascent stage, i.e., restricted to the shallow depth, the limited database of thermo-hydro-geological parameters corresponding to the subsurface hinders the proper assessment of the reservoir. Under these circumstances, the geothermal field is conceptualized as homogenous [10], which may not reflect the real field situation. This infers that the field representations of these parameters till deeper zones are essential to develop a conceptual model that reflects the reality.

3. **Methodology**

The approach discussed by Jha and Puppala [11] helps to estimate the thermo-hydro-geological fields of a geothermal reservoir using resistivity data. This approach uses the database of resistivity maps corresponding to the geothermal field and estimates the thermo-hydro-geological and temperature features of a reservoir. Each rock exhibits a range of resistivity values, which often overlap with another type of rock. To address this uncertainty in determining the rock type corresponding to a particular value of resistivity, the possibility of a block being a combination of all possible types of rocks within a range is considered with a proper weightage to all [11]. This is mathematically represented as equation (1).
\[ E_{p(i,j)} = \sum_{l=1}^{n} w_l p_l \]  

Equation (1)  

\[ E_{p(i,j)} \] is the effective parameter of each pixel; \( p_i \) is the parameter of interest, which is a thermo-hydro-geological parameter, i.e. porosity, thermal conductivity, specific heat, radioactive heat capacity, and density; \( w_l \) is the weight allotted to each rock type among the multiple rocks whose range contains \( R_{(i,j)} \) within it. The weight allotted to each type of rock is mathematically expressed as equation (2)  

\[ w_l = \frac{\alpha_i}{\sum_{i=1}^{n} \alpha_i} \]  

Equation (2)  

\( \alpha_i \) is the absolute inverse distance between the mean resistance value of each type of rock, and \( R_{(i,j)} \), which is mathematically expressed as equation (3).  

\[ \alpha_i = \frac{1}{R_{(i,j)} - R_n} \]  

Equation (3)  

"\( R_n \)" is an average resistivity value of each rock type, which is derived by considering the lower and upper limit of the resistivity values.

Considering the thermo-hydro-geological fields, which are evaluated using equations (1) to (3), the geothermal field can be conceptualized as a homogenous or heterogeneous reservoir. To convert the pixel-wise information to either a representative value or effective value corresponding to homogenous and heterogeneous value respectively, a methodology termed as shifting window algorithm is proposed by Jha and Puppala, 2018 [11]. The evaluated thermo-hydro-geological fields are used in estimating the temperature field from the heat conduction equation as shown in equation (4).  

\[ T_z = T_s + \left( \frac{Q}{k} \times z \right) - \left( \frac{A_s}{2k} \times z^2 \right) \]  

Equation (4)  

where, \( T_z \) is the temperature at a depth of \( z \) km; \( T_s \) is the surface temperature; \( Q \) is the average heat flow of the region; \( A_s \) is the radioactive heat capacity of the rock (\( \mu W/m^3 \)) and \( k \) is the thermal conductivity of rock (W/mK). Subsequently, thermo-hydro-geological fields are the inputs to determine total heat energy stored in the reservoir as shown in equation (5) [12].  

\[ E_R = \sum_{l=1}^{n}[ (1 - \phi_r) \rho_r c_r V_r \times (T_R - T_{ref}) \] + \[ \phi_c \rho_{gf} c_{gf} V_r (T_R - T_{Ref}) \]  

Equation (5)  

where \( E_R \) is the total heat energy stored within the reservoir (kJ); \( \phi \) is the porosity of rock, \( \rho_r \) and \( \rho_{gf} \) is the density of rock and geothermal fluid in kg/m\(^3\) respectively, \( c_r \) and \( c_{gf} \) is the specific heat of rock and geothermal fluid in (kJ/kg K), respectively, \( V_r \) is the volume of reservoir rock, \( T_R \) is the reservoir temperature as obtained from equation (4), \( T_{ref} \) is surface temperature, \( n \) is the total number of blocks representing the reservoir domain.

4. Geothermal status in India

From the literature, it is evident that Puga, Chhumathang, Parbati, Sutlej, Beas, Tapoban and Manikaran, are prominent locations in the orogenic belt, distributed over Trans Himalayan, Central Himalayan and Outer Himalayan locations. Cambay Garben, Son-Narmada-Tapi, West Coast geothermal province, Damodar Valley, and Mahanadi are identified as the most promising locations in non-orogenic provinces as shown in figure 2. The geographical locations of these geothermal provinces along with the locations of hot springs are evident from the geothermal atlas of India [13].
From the available information base, it is observed that although Puga, Chhumathang, and Manikaran are in the Himalayan geothermal province, the regional geology is found to be different at these locations. The conducted geophysical studies at Puga geothermal field demarcated a low resistive zone between 2 and 8 kilometers. Additionally, these studies helped to map the thermal manifestation zone and the areal extent of heat source, which has been presented in the literature [14,15].

At Chhumathang geothermal field, between 15 and 100 m depth it was observed unconsolidated material filling the valley, and a low resistivity zone (13-30 ohm-m) up to the depth of 300 m. This low resistivity zone is interpreted in terms of vigorous geothermal activity within the shallow depths of Chhumathang geothermal field. However, from the literature [14–17] it is observed that Puga is explored in great detail relative to Chhumathang. Studies at Manikaran and Tapoban demarcated the zone of lower resistivity in each one, which is in the order of 30-100 ohm-m and 100 ohm-m, respectively. Besides geophysical studies, shallow exploration wells have been drilled at all promising fields to study the temperature variation with depth.

From literature [16–18], it is found that the number of hot springs in each of these fields is different. In Puga 120 hot springs have been found, followed by Manikaran, Chhumathang, Tapoban and West Coast with 35, 10, 12 and 3 hot springs, respectively. The temperatures of the hot springs of Tattapani geothermal field are relatively higher, according to the reported measurements. The maximum temperatures of the thermal waters at Puga, Chhumathang, Manikaran, Tapoban, Tattapani and Unhavre-Khed are 84°C, 87°C, 96°C, 65°C, 98°C and 71°C respectively [16]. As per the classification of thermal waters based on temperature [16], it can be interpreted that the thermal water of Puga, Chhumathang, Manikaran, and Tattapani could be used for binary-cycle electric power generation, in addition to domestic purposes. The thermal logs of the wells at all the promising fields, compiled from the Geothermal Atlas of India [17] are presented in figure 3 (a-f).

The plausible cause of high thermal gradients within shallow depths may be interpreted either as the fact that the heat source is close to the surface, or the thermal waters in the subsurface have gone to deep zones through faults or other structures where they interacted with the rocks and were heated.

From the thermal logs shown in figure 3 (a-f), it is noted that the deepest wells have been drilled in Manikaran (figure c, up to more than 650 m). However, the measured temperature is low. From literature [17] the most productive wells in terms of cumulative discharge are Puga (250 tons/hour), Tapoban (150 tons/hour), Tattapani (120 tons/hour), Manikaran (100 tons/hour), Chhumathang (50...
tons/hour) and Unhavre Khed (5 tons/hour). As per the present geothermal database, the heat flow of the Puga geothermal field is estimated in the range of 180-540 mW/m² [15]. Based on the highest significance level associated [19], Puga geothermal field is considered in this study for the assessment of potential in terms of thermo-hydro-geological properties and reservoir temperature distribution.

Figure 3. Variation of temperature with depth at the identified geothermal fields of: (a) Puga, (b) Chhumathang, (c) Manikaran, (d) Tapoban, (e) Tattapani, and (f) Unhavre Khed. (Figure modified from [16] and [17])

5. Results and Discussion
The conceptual model in the present study considers a block size of 100 m x 50 m, resulting into block heterogeneity model of the geothermal field. The representative value of resistivity for a homogenous model is 271.40 ohm-m. Using the effective resistivity value, the thermo-hydro-geological parameters are estimated. The distribution of the parameters is shown in figure 4 for layered heterogeneity. The estimated parameters for homogenous, block and layered heterogeneity approaches are provided in table 1.

Considering the estimated thermo-hydro-geological parameters and by adopting heat flow at Puga as 180 μW/m² [16], the temperature distribution is estimated for the homogenous, block, and layered heterogeneity approaches as shown in figure 5. It is evident that the temperature distribution shows different results with a different approach. Therefore, it can be conceived that a proper conceptual model of reservoir plays a significant role in the assessment of reservoir potential. Finally, the evaluated thermo-hydro-geological parameters and temperature fields are used to determine the total stored heat energy within a reservoir as discussed in subsequent sections.
**Figure 4.** Distribution of thermo-hydro-geological parameter (layered heterogeneity model).

**Table 1:** Thermo-hydro-geological parameters for homogenous and heterogeneous cases.

| Type of conceptualization | Porosity | Thermal conductivity [W/m K] | Specific heat [kJ/kg K] | Radioactive heat capacity [μW/m³] | Density [g/cm³] | Permeability [mD] |
|---------------------------|----------|-------------------------------|-------------------------|----------------------------------|----------------|-----------------|
| Homogenous                | 0.23     | 1.56                          | 0.81                    | 0.98                             | 2.23           | 392.07          |
| Block heterogeneity       | L -0.09  | L -0.76                       | L -0.71                 | L -0.05                          | L -1.64        | L -0.04         |
|                           | H -0.37  | H -2.7                        | H -0.94                 | H -2.16                          | H -2.68        | H -1546.9       |
|                           | M -0.24  | M -1.74                       | M -0.82                 | M -1.20                          | M -2.30        | M -349.2        |
| Layered heterogeneity     | L -0.14  | L -0.76                       | L -0.71                 | L -0.05                          | L -1.65        | L -14.8         |
|                           | H -0.37  | H -2.7                        | H -0.94                 | H -2.16                          | H -2.68        | H -1546.0       |
|                           | M -0.25  | M -1.69                       | M -0.80                 | M -1.12                          | M -2.25        | M -263.17       |

Note: L-lowest observed, H- Highest observed, M-mean value
Figure 5. Temperature distribution with homogenous, block, and layered heterogeneity approaches.

The estimation of extractable energy from the reservoir under various extraction schemes and operating conditions can be studied by simulation of reservoir dynamics. The simulation studies of reservoir dynamics yield the production temperature over the operation period of the reservoir, which is further used to estimate the extractable power from a reservoir under a chosen extraction scheme that is part of a future study.

The stored heat energy of the reservoir is estimated using equation (5) by considering homogenous, layered heterogeneity and block heterogeneity approaches. The estimations are shown in figure 6. For a better understanding of energy distribution, the stored energy map is shown at depths of 275 m, 725 m, 1450 m, and 1925 m as shown in figure 7. These depths are identified as some plausible depths for injection/extraction operations [20]. The estimated stored heat energy is used for finding the recovery factor under reservoir operating condition.

Figure 6. Theoretical heat energy stored within the reservoir.
Figure 7. Energy distribution estimated at various depths for Puga geothermal field.

From figure 7, the energy distribution is found to be non-uniform at a considered depth. It is concentrated along the central zone trending in E-W direction and a decreasing trend is observed while navigating along N-S direction from the central zone. This observation satisfies the fact that the temperature along the central section is relatively higher than at the surroundings. These finding are also in line with the comments made by Azeez and Harinarayana [14], i.e. lower resistivity is associated with higher temperature zones. Since the low resistivity zone is identified along central profile C after magneto-telluric studies, which is trending along E-W direction and through the center of the valley, the estimated temperatures and heat energy are higher along the central profile.

6. Conclusions
The ever-growing energy demand enforces to give thrust on renewable energy development, especially in a country like India. The present state of the art indicates that geothermal energy is a promising alternative. Although there are some geothermal fields already identified, they have not been developed due to the technical difficulties and lack of expertise. In this study a correlation between resistivity data and thermo-hydro-geological parameters is discussed, which is further extended to estimate the temperature distribution in the most promising geothermal field. Although it is a preliminary estimate, it serves as a predrilling estimate and gives an insight of the probable stored heat of the reservoir. The
estimated stored heat energy would be helpful in determining the recovery factor of the reservoir while considering the reservoir life under heat extraction. The assessment of the temperature field varies based on the type of conceptualization. Homogenous and layered field consideration overestimates the reservoir potential. Since the estimation of extractable energy from a reservoir would very much depend on the proper assessment of reservoir parameters, it is very important to consider the proper field conditions and conceptualization for a safe estimation of the reservoir potential.

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