Distribution and Characterization of Thermal Springs in Northern Oman

Fahad Al Shidi, Reginald Victor

***Abstract*—This study was conducted in Northern Oman to assess the physical and chemical characteristics of 40 thermal springs distributed in Al Hajar Mountains in northern Oman. Physical measurements of water samples were carried out in two main seasons in Oman (winter and summer 2019). Studied springs were classified into three groups based on water temperature, four groups based on water pH values and two groups based on conductivity. Ten thermal alkaline springs that originated in Ophiolite (Samail Napp) were dominated by high pH (> 11), elevated concentration of Cl- and Na+ ions, relatively low temperature and discharge ratio. Other springs in the Hajar Super Group massif recorded high concentrations of Ca^2+ and SO^{2-}_4 ions controlled by rock dominance, geochemistry processes, and mineralization. There was only one spring which has brackish water with very high conductivity (5500 µs/cm) and Total Dissolved Solids and it is not suitable for irrigation purposes because of the high abundance of Na+, Cl−, and Ca^2+ ions.

***Keywords*—Alkaline springs, geothermal, Hajar Super Group, Northern Oman, ophiolite.

I. Introduction

GEOTHERMAL zone formations worldwide are controlled by geological settings, geophysical properties and hydrological processes. This system is usually associated with geologic features such as faults, fractures, stress fields and active tectonics ultimately determine the chemical composition and flow path of the water [1], [2].

Classification of thermal springs based on geothermal characteristics and water chemistry is a priority, because these springs affect the surrounding ecosystems and can be used to assess the effect of heated wastewater from power plants or predict the effects of climate change. These inputs from thermal springs include geochemical behavior, physicochemical parameters, trace element concentrations and biological life [3], [4].

Mountainous areas in North of Oman have large number of springs varying in their temperature, discharge and water quality. These springs are used for water supply, irrigation, therapies, and recreation purposes. Most of them are connected to ancient man-made channel systems (*aflaj*) and supply water for domestic use. The origin of these meteoric waters are in two major geologic systems; (i) the Al Hajar limestone conventionally called Hajar Super Group (HSG) massif and (ii) the Ophiolite massif, a section of the oceanic lithosphere with an area of ~30,000 km^2- [5]. HSG, intensely fractured by joints and faults, yields good, stable supply with reliable water quality. The Ophiolites are less permeable and yield alkaline water (pH ≈ 11.9). Springs in this category have relatively low temperature because of short pathways [6].

The aim of this study is to map the number of thermal springs in Northern Oman and create a comprehensive database of their physical properties, chemical composition and other environmental factors representing their thermal regime.

II. Study Area

The study area located in Northern part of Sultanate of Oman including seven governorates and is lying between N 23° 53' 45.672 and E 59° 22' 59.376’. 40 springs scattered within the mountain areas and piedmont – foothills are shown in Fig. 1.

III. Field Sampling and Laboratory Processing

Samples were collected twice a year on January 2019 and on September 2019 to represent two different seasons (winter and summer). Water quality characteristics (T ºC, pH, E.C µs/cm, Total Dissolved Solids (TDS) ppm) were measured in the field using HANNA HI 991301.USA. Concentration of dissolved oxygen (DO, mg/l) was determined by a dissolved oxygen meter probe YSI DO200, Turbidity in Nephelometric Turbidity Units (NTU) and alkalinity as ppm were measured using a turbidity meter EXTECH TB400 Taiwan, and a handheld Colorimeter HANNA HI755. USA.

The collection, physical measurements and analysis of water samples in the study area were performed according to standard protocols recommended for the environmental analysis of water samples [7].

Water samples for chemical analysis were taken directly from the source of each spring in 60 ml plastic bottles for anions (Cl- - SO^{2-}_4 - NO^{3-}) and cations (Na+ - Ca^{2+} - Mg^{2+} - K+). An Ion Chromatograph (IC) located in the Central Analytical and Applied Research Unit (CAARU), Sultan Qaboos University was used for measuring the ionic composition.

IV. Data Analysis

The classification of studied springs was conducted based on geologic origin [6], water temperature [8], pH values [9] and conductivity indicative of geothermal discharges [10].

Statistical analyses were performed by MS Excel and PAST 4.03 software. The Principal Component Analysis (PCA) was used to determine relationships between sites and

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environmental variables.

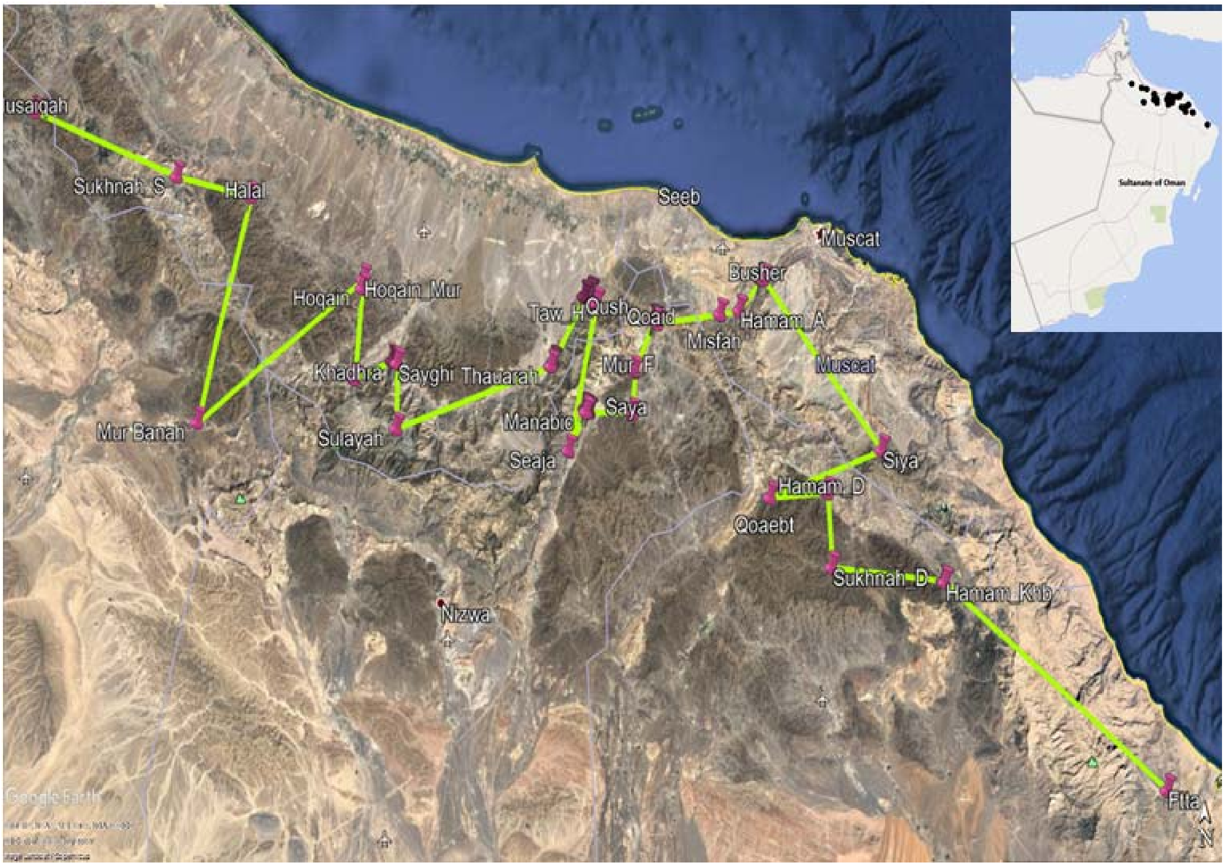

Fig. 1 Location of 40 thermal springs in Northern Oman [15]

V. Results

Geological Classification

The geological characterization of the study area has two main origins. Therefore, the study springs were classified spatially based on these two geological formations. Thirty springs are situated within HSG with sedimentary origin (HSG) and ten are within the Ophiolite formation (Semail Nappe) (Fig. 2).

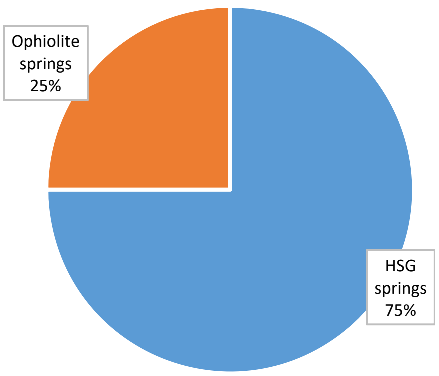

Fig. 2 Classification of studied springs based on geology origin

Water Temperature Classification

The studied springs were divided into three categories based on the water temperature standard as shown in Table I.

TABLE I
Classification of Studied Springs Based on Water Temperature (Liao's system [8])

	Spring class	Criteria of spring water temperature	Spring water temperature °C	Number of springs in study area
1	Tepid Spring	Higher than air annual average temperature of 8 °C and lower than earth annual average maximum air temperature (35 °C)	27 °C - 35 °C	2
2	Worm/thermal Spring	Higher than 35 °C and less than 45 °C	> 35 °C ≤ 45 °C	30
3	Hot/hyper thermal Spring	Higher than 45 °C and lower than boiling point of local elevation.	> 45 °C ≤ boiling point	8
4	Boiling Spring	Reached the boiling point of local elevation.	Boiling point	-
5	Fumaroles Spring	Spring discharge boiling water and steam.	1-2 °C higher than boiling point	-
6	Steaming ground	Only steam emit from the ground.		-

pH Classification

Based on pH values following [9] the studied springs categorized in four classes are given in Table II.

TABLE II
CLASSIFICATION OF THERMAL SPRINGS PASSED ON PH VALUES

	Springs class	pH values	Number of springs in study area
1	Neutral	6 -7.5	21
2	Weak alkaline	7.5 - 9	9
3	Alkaline	9-10	1
4	Hyper-alkaline	>10	9

Geothermal Discharges Based on Conductivity

Studied springs were classified in three categories based on electric conductivity values. 39 springs were categorized as high conductivity (≥ 600 µS/cm) and only one was moderate (301 - 600 µS/cm) Low conductivity (≤ 150 µS/cm) springs were absent (Fig. 3).

PCA

Fig. 4 summarizes the relationships of studied springs and variation of environmental variables. The majority of the variance was accounted for by PC1 and PC2. First axis explained 49.1% and second one represented 28.9 % of the total variance.

Electric conductivity and TDS were positively correlated with PC1 while DO showed a negative correlation. In contrast, water temperature had positive correlation with PC2 and the pH correlated negatively with PC1. The plot shows that the two main groups of studied springs distributed within two axes. First group (red dots) which represents HSG formation springs correlated positively with water temperature and DO and negatively with pH except one spring (Sukhnah in Saham City) which showed high association with E.C and TDS. The second group (green dots) which represents Ophiolite origin springs showed highly positive correlation with pH, E.C and TDS but negative association with DO and water temperature.

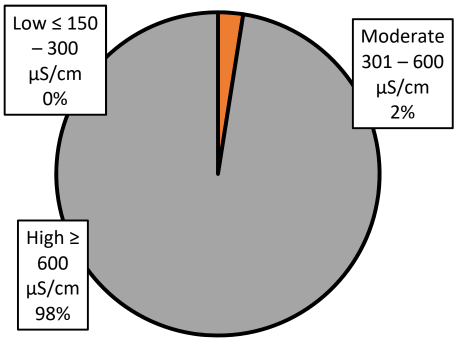

Fig. 3 Classification of studied springs based on conductivity values (µS/cm)

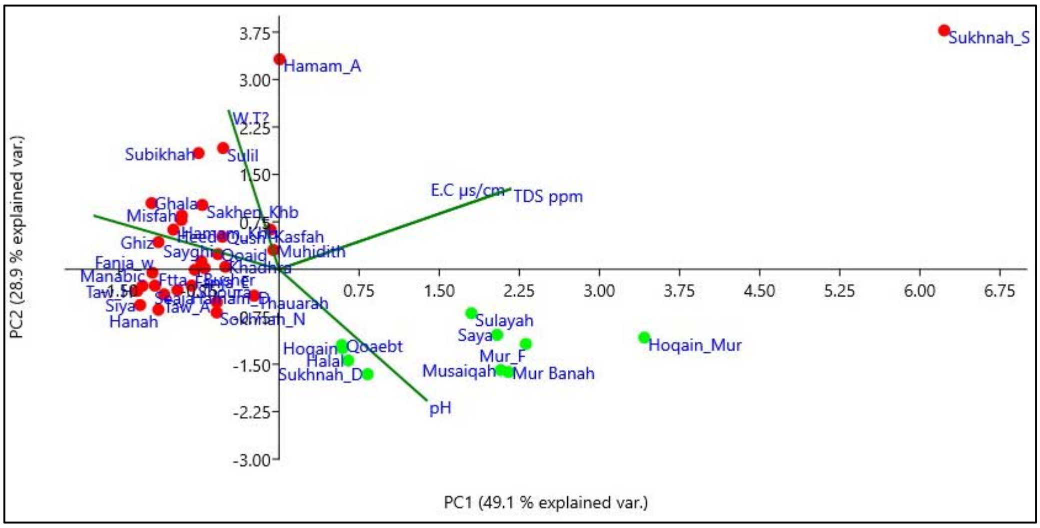

Fig. 4 PCA of five environmental water quality parameters (W.T, pH, DO, TDS and E.C)

Fig. 5 shows the PCA analysis for the concentrations of anions and cations. The two axes PC1 and PC2 explained the cumulative variance. The first component (PC1) explained 91.1% of the variance and the second axes (PC2) contributed only to 7.9%. Accordingly, Cl- and Na+ were correlated positively with PC1 (r = 0.79, r = 0.56 respectively) while SO_4^{2-} and Ca^{2+} were associated with PC2 (r = 0.89, r = 0.38 respectively). In contrast, NO^{3-} and K+ had weak negative association with PC2 (r = - 0.001, r = - 0.01 respectively). Both Cl- and Na+ were influencing water composition of springs (green dots) which occurred in Ophiolite formations while the HSG springs (red dots) were weak affected by NO^{3-} and K+ concentrations; they showed negative association with Na+ and Cl- concentrations. The other (HSG) springs were associated with SO_4^{2-} , Ca^{2+}, and Mg^{2+} concentrations.

VI. DISCUSSION

The high number of hot/thermal springs in carbonate massif (HSG) in the study area is ascribed to the geological characterizations and aquifer properties. The existence of deep faults, the highly fractured flow paths with intensive joints, folds, porosities and large deep cave systems are the reasons for the occurrence of this type of springs. The high altitude groundwater aquifer is the most important source of water in the northern areas of Oman. This aquifer occurred from a simple anticline in Jabel Akhder toward both northern spring line and southern spring line in foothills areas [6].

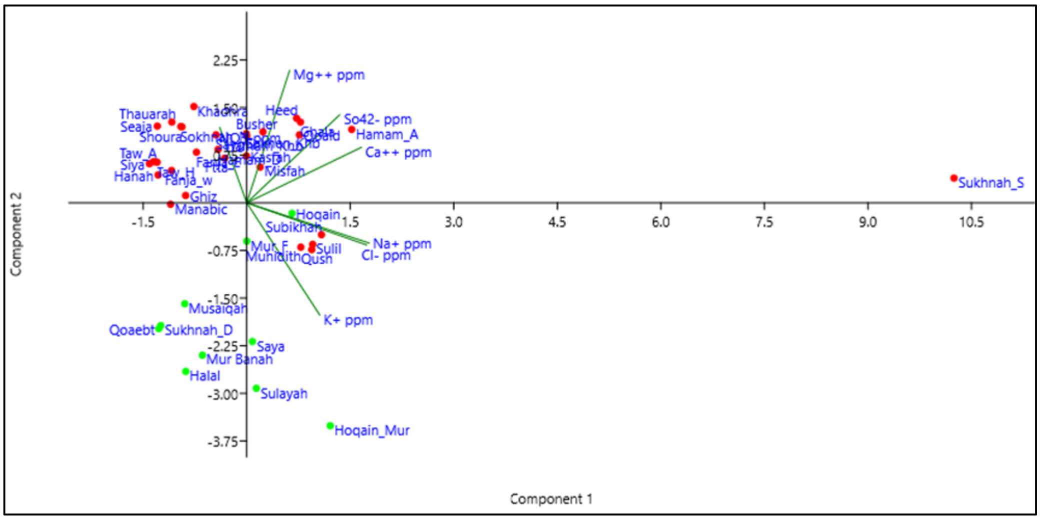

Fig. 5 PCA of anions and cations of the study springs

Limestone and Ophiolite springs vary in water temperature based on its location within the fault zones. Historically, within a degree or two, spring temperatures have been stable for over 150 years indicating a permanent equilibrium of thermal conditions; nothing was lost within vapor phase, and there were no mixing points between thermal and surface waters [11], [1]. The hot springs are heated through the geothermal process from the deep faults which allow intensive heat to flow into surrounding rock and then to the aquifers of the hot springs [2].

The possible reason of spring's heat in northern Oman is estimated from the thermal gradient tests of boreholes within the thermal spring and the investigation of trace element (SI-Mn-Fe-Ni-As) mineralization associated with the thrust zone [6]. The results indicated that the heat source appears to be from normal upward thermal diffusion of radioactive decay in the lower crust. There is no evidence of residual heat of either magmatic or tectonic origin from the base of the nappe sequence [6], [12]. The existence of exceptionally high values of most anions and cations from the Sukhnah spring in Saham city, in addition to strong association between EC and TDS (Fig. 4), and between Na+ and Cl- concentration (Fig. 5) may be related to the geological section of saline aquifer in Haousnah formation. This formation promotes the dissolution of inter crystalline halite or mixing with Na+, Cl- waters that are saturated by halite minerals [6], [13]. However, the short arrows of Ca2+, Mg2+ and K+ (Fig. 5) may suggest low solubility contribution in the HSG springs aquifer and also indicate relatively low or little total dissolved solids and EC [14].

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