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THE APPLICATION OF FUZZY LOGIC IN EXPLORING FOR A GEOTHERMAL RESOURCE (PHILIPPINE SETTING)

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ABSTRACT

Fuzzy logic technique is applied in pre-evaluating the North Davao Geothermal Prospect in the Philippines. A decision support system is developed where sets of classes are collated and compared using the assigned fuzzy membership values. Specific grid points are evaluated using established knowledge-based criteria. Based on qualitative and subjective judgement, fuzzy membership values for each point are assigned to reflect its degree of membership. These values are then processed using a variety of operators like Fuzzy AND, Fuzzy OR, Fuzzy Algebraic SUM/PRODUCT, and Fuzzy Gamma operation). The outputs of these operators are the likely locations of prospective geothermal areas. The technique is applied to an area of about 476 km^2 within the North Davao Geothermal Prospect (NDGP) located in Compostela Valley province in southeastern Mindanao, Philippines. The case study delineated an arbitrary high potential area of about 45 km^2 where focused and additional geoscientific studies are recommended. This area of interest includes the vicinities of Mt. Dasuran, Amacan-Gopod, NW to Teresa-Mainit, Lake Leonard, Paloc and further north to Kinasing-Tandic.

1.0 INTRODUCTION

Fuzzy logic has been used extensively in creating decision support systems (Brule, 2000). It is popular among management and financial decision modeling experts and other workers in data analysis as well as pattern recognition among geologists that involves complex issues and high level of uncertainty. Geographic Information System (GIS) modeling also employs fuzzy logic in mineral potential evaluation and land suitability analyses (Bonham-Carter, 1994).

Geothermal exploration could use this technique because mathematical modeling of a geothermal system is too complex and, analytical calculations involve various assumptions that are often not true in the real world. Real world problems always constitute vague, imprecise or incomplete information so that proper weighing of available evidences and their integration requires the knowledge of an expert. A knowledge-based decision support system using fuzzy logic may therefore be employed to analyze exploration field data so that decision for further study may be streamlined. The aim of this paper is to demonstrate the application of fuzzy logic technique in arbitrarily delineating a prospective geothermal area in the North Davao Geothermal Prospect (NDGP), Philippines.

2.0 METHODOLOGY

2.1 What Is Fuzzy Logic?

Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth – truth values between "completely true" and "completely false". According to Lotfi Zadeh (2000), its founder, it is the logic of approximate reasoning wherein the membership of a set is expressed on a continuous scale from I (full membership) to 0 (non-membership). This is in contrast to Boolean logic which abruptly defines the membership of a set into just 1 (member) and 0 (non-member). Fuzzy logic or fuzzy sets were introduced by Zadeh to handle vagueness, uncertainty and in particular, linguistic variables. For any fuzzy set A the function μ_A represents the membership function for which μ_A (x) indicates the degree of membership that x of the universal set X belongs to set A and is, usually expressed as a number between 0 and 1 (Abdul-aziz and Parthiban, 2000):

$$\mu_A(x): X \rightarrow [0,1] \quad (1)$$

2.2 How Does Fuzzy Logic Works?

The use of fuzzy logic in solving problems is akin to how a computer works with a CPU and RAM (Fig. 1). The sets of rules are stored in a RAM or memory while in the CPU, fuzzy arithmetic operations and decisions are undertaken. Attached to the CPU and RAM however, is a database which is constantly updated, revised and improved to have more effective decisions.

In the case of geothermal exploration, model parameters that include geological, geochemical, hydrological and geophysical exploration data are used to come up with the proper weighting of evidences. The field data are assigned specific membership values based on subjective judgement and chosen to reflect the degree of membership of a set. All these available information with fuzzy values are then processed using fuzzy logic operators. Five samples of operators are described in the following section:

a. Fuzzy AND

This is the intersection operation in fuzzy set theory where the membership functions of μ_A, μ_B, μ_C and so on is defined as the minimum of all the functions included in the set (Bonham-Carter, 1994).

$$\mu_{combination} = MIN(\mu_A, \mu_B, \mu_C, ...) \quad (2)$$

b. Fuzzy OR

On the other hand, is the union operation of membership functions μ_A, μ_B, etc. It is the maximum of all the membership function values put together (Bonham-Carter, 1994).

$$\mu_{combination} = MAX(\mu_A, \mu_B, \mu_C, ...) \quad (3)$$

c. Fuzzy Algebraic Product

Here, the combined membership function is defined as

$$\mu_{combination} = \prod_{i=1}^{n} \mu_i \quad (4)$$

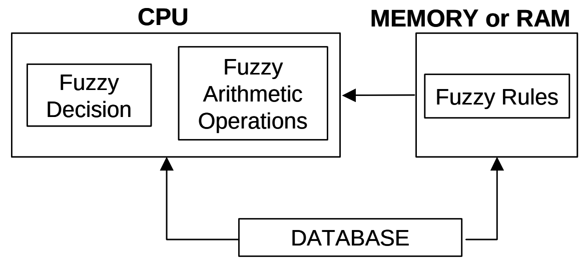

Figure 1. Diagram of how fuzzy logic works.

Where μ_i is the membership function for the ith set, and i=1,2 … n sets are to be combined (Bonham-Carter, 1994).

d. Fuzzy Algebraic Sum

This is the complement operation where the membership function μ_A is defined as the negation of the fuzzy membership function (Parthiban and Abdul-Aziz, 2000).

$$\mu_A = 1 - \mu_A \quad (5)$$

Hence for the combined membership function $\mu_{combination}$ (Bonham-Carter, 1994), this is defined by

$$\mu_{combination} = 1 - \prod_{i=1}^{n} (1 - \mu_i) \quad (6)$$

e. Fuzzy Gamma

This is defined in terms of the fuzzy algebraic product and the fuzzy algebraic sum by

$$\mu_{combination} = (FuzSUM)^{\lambda} \times (FuzProduct)^{1-\lambda} \quad (7)$$

Where λ is a parameter chosen in the range (0,1). The discrete use of λ will ensure a flexible compromise between the “increasive” tendencies of the fuzzy sum and the “decreasive” effect of the fuzzy algebraic product (Bonham-Carter, 1994).

After carrying out fuzzy logic operations in stages, the ultimate product is a predictive map that will indicate the relative favorability of an area for a geothermal resource to occur that can be recommended for further geoscientific investigations.

3.0 CASE STUDY

The applicability of fuzzy logic method is demonstrated in the North Davao Geothermal Prospect (NDGP), Mindanao, Philippines that is one of the geothermal prospect of the Philippine National Oil Company – Energy Development Corporation (PNOC-EDC). Reconnaissance field data include geological, geochemical as well as geophysical (AB/2=500m) results (PNOC-EDC, 1985; Maturgo, 1997, Pioquinto *et al.*,1997), and thermoluminiscence dating of rocks (Ramos *et al.*, 2000). These were incorporated to generate a database in this study.

3.1 Overview of the North Davao Geothermal Prospect (NDGP)

The prospect is located in the province of Compostela Valley in southeastern Mindanao with an approximate area of 476 km^2 bounded by the following coordinates: a) 125°58'E; 7°30'N, b) 126°8'E; 7°30'N, c) 126°8'E; 7°16'N, d) 125°58'E; 7°16'N (Fig. 2). The updated maps of surface lithology, major structures and thermal features are shown in Figures 3, 4 and 5, respectively.

Quaternary pyroclastics, volcanics, domes and plugs are common in the area. ^{14}C dating of pyroclastics yielded ages ranging from ~25,144 to 1,800 years BP (Sajjad, 1998 and Wood, 1980 in Ramos *et al.*, 2000). Thermoluminiscence (TL) dating of the domes suggests three age groups, these are: young domes (<10 ka), intermediate (10-100 ka) and old (>100 ka) (Ramos *et. al.*, 2000). These rocks are dominantly underlain by Miocene batholithic intrusives, volcanics and minor Pre-Tertiary metavolcanics and metasediments. Tertiary clastics are found in the western margins which is unconformably overlain by Miocene limestone. The Pliocene sediments also are in unconformable contact with the Miocene intrusives and volcanics in the southeastern side of the prospect. Ultramafic rocks outcropped on the other hand in the southwestern periphery of NDGP and are inferred as tectonic slices rifted along fault zones in the region (Pioquinto *et al.*, 1997).

Two major N-S trending faults that form part of the Philippine Fault serve as structural boundaries of NDGP. NE-SW and NW-SE fault network also intersect the area. Several collapse features are mapped including Lake Leonard Kniazeff caldera structure, the most prominent feature in the center of the prospect. Thermal manifestations such as hotsprings, warm springs, bubbling pools, solfataras and fumaroles are common and are interpreted to be channeled by the existing geological structures (PNOC-EDC, 1985 and Maturgo, 1997).

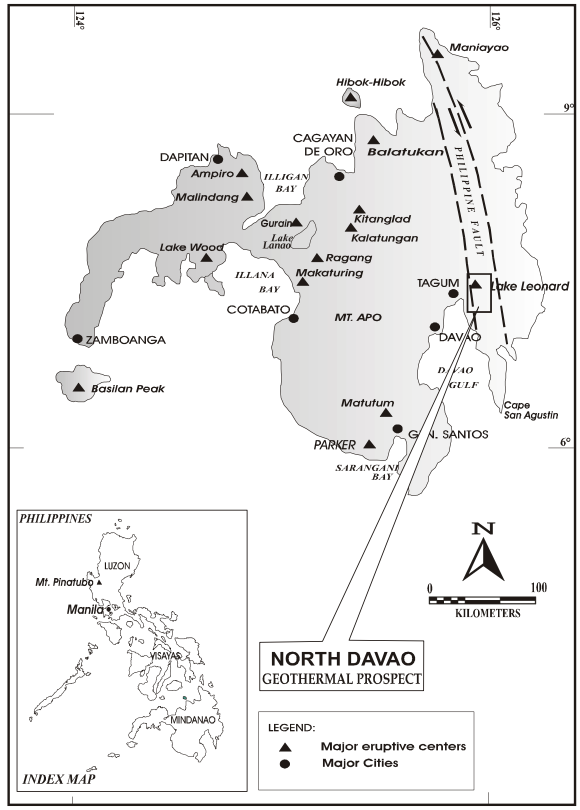

Figure 2. Location map of North Davao Geothermal Prospect (NDGP) showing relative distribution of eruptive centers and trace of Philippine Fault.

3.2 Assessment of the Prospect

In order to come up with the assessment using fuzzy logic method, the prospect area is subdivided initially into 19 x 24 km^2 grids. The procedure of this evaluation scheme is illustrated in Figure 6.

Available informations at each grid point are qualitatively assessed using the parameters presented in Table 1. The factors include geology, like the presence of volcanic centers, in the premise that these features relate to subvolcanic magma bodies that would host a hydrothermal system. Another is geochemistry, which pertains to the chemistry of the thermal

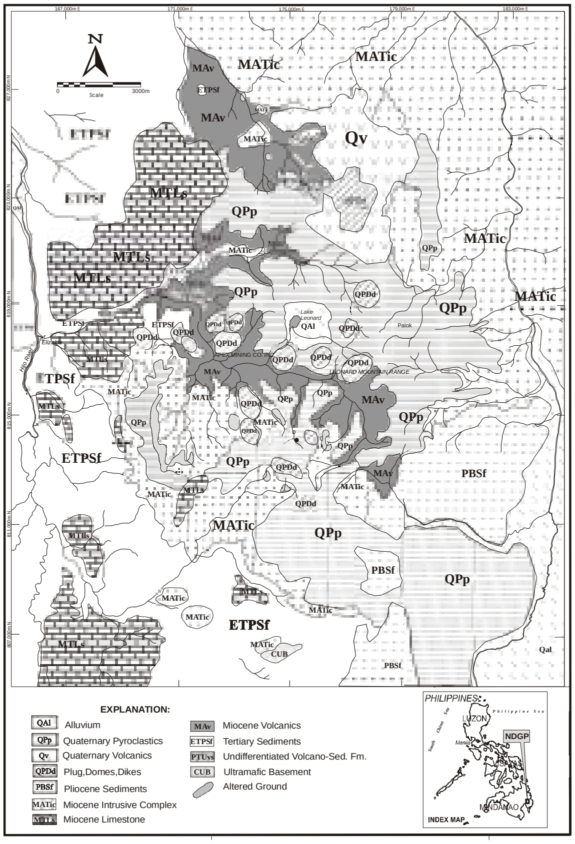

Figure 3. Surface lithologic distribution (modified after Pioquinto *et al.*,1997)

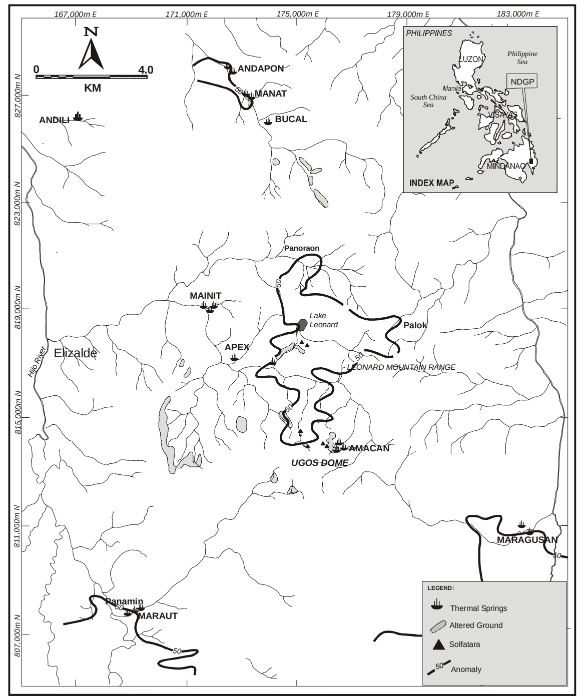

Figure 5. Map showing thermal manifestations including 50 Ω-meter anomaly and major drainage system (after Maturgo, 1997 and PNOC-EDC, 1985).

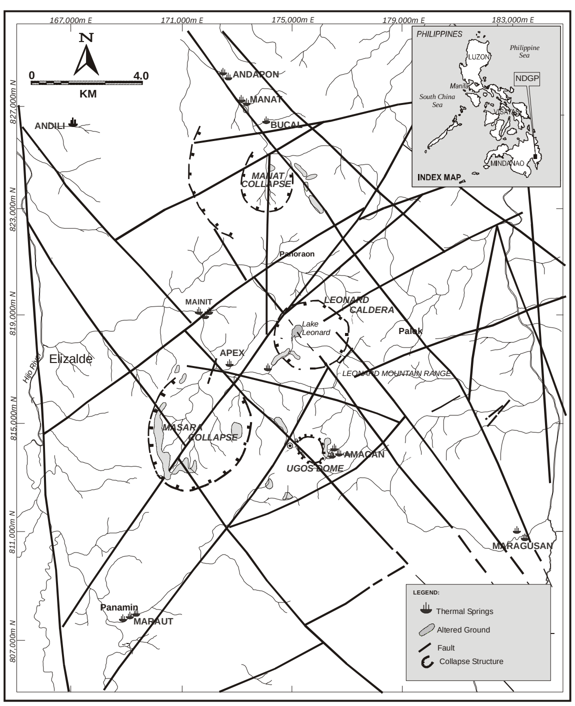

Figure 4. Map showing major structures, thermal features, and main drainage system.

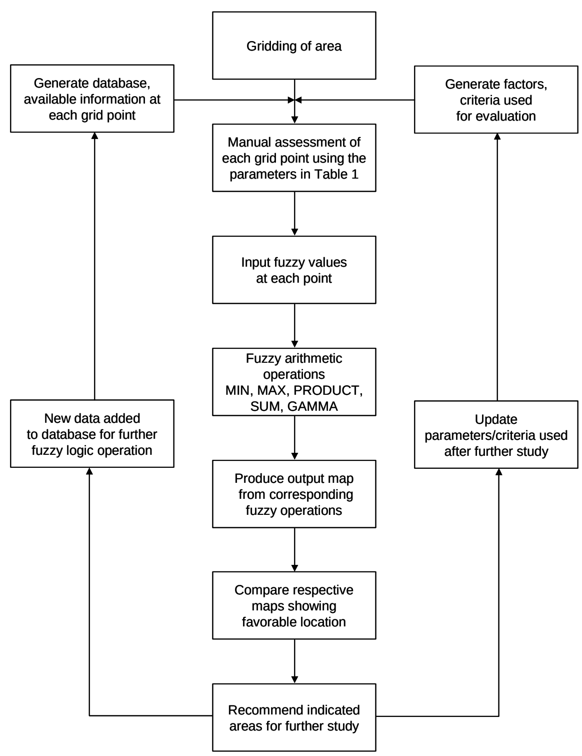

Figure 6. Diagram of fuzzy logic assessment of NDGP.

Table 1. Factors and parameters with fuzzy values used in the assessment.

Factors/Parameters	Range of fuzzy values assigned to membership sets
A. Geology	
1. Proximity to volcanic centers, caldera, collapse structures	0.8, 0.75, 0.6, 0.45, 0.2
2. Proximity to solfataras, fumaroles	0.8, 0.7, 0.5, 0.35, 0.2
3. Relative location to thermal springs	0.8, 0.75, 0.7, 0.6, 0.5, 0.4, 0.2
4. Presence of mineralization	0.9, 0.7, 0.5, 0.3
5. Proximity to major faults	0.7, 0.5, 0.2
6. Presence of domes, plugs and effusive products	0.8, 0.4, 0.2
7. Age of nearby volcanics, pyroclastics, domes	0.9, 0.7
8. Dominant country rock	0.8, 0.7, 0.5, 0.4, 0.3
9. Thickness of nearby pyroclastic rocks	0.65, 0.5, 0.4, 0.1
10. Presence of altered grounds nearby	0.8, 0.75, 0.4, 0.25
11. Thickness of volcanic sequence	0.85, 0.7, 0.4, 0.2
B. Geochemical	
1. Characteristics of thermal springs nearby (neutral pH, high Cl, high flow rate, etc.)	0.85,0.8,0.7,0.6,0.5,0.4,0.2,0.1
C. Geophysical	
1. Proximity to an anomaly (50 Ω-m)	0.8,0.75,0.6,0.5,0.4,0.3,0.2,0.1

springs (Sanchez *pers. comm.*, 2004) and geophysical factor in which the 50 ohm-meter low resistivity anomaly is considered (Layugan, *pers. comm.*, 2004). Only the major structures with traces of >3 km. were chosen during this assessment. Other parameters such as presence of altered ground, mineralized zones, thermal manifestations were also taken into account, as these are common features in Philippine geothermal fields.

After fuzzy values are inputted, fuzzy arithmetic operations followed. Each grid point with corresponding value of a certain membership set was comparatively assessed with other membership set or parameters using Fuzzy AND, Fuzzy OR, Fuzzy Algebraic Product, Fuzzy Algebraic Sum and Fuzzy Gamma operators.

An output map is generated for each corresponding fuzzy operator. The resulting predictive maps are further compared together to achieve a fusion of their relative indications of a prospective area or areas. The fuzzy logic operation is repeated as new data is generated and if further studies are undertaken for that particular prospective area.

4.0 RESULTS AND DISCUSSION

The relative favorabilities indicated by each fuzzy logic operator are shown in Figures 7 to 12.

4.1 Fuzzy AND

By getting the minimum value of the fuzzy membership values at each grid point, the map produced by this operator is somewhat conservative due to the effect of the smallest value occurring at each grid point (Fig. 7). The relatively favorable areas indicated in the map are in the vicinity of Amacan-Gopod going to the Lake Leonard in the north and slightly south of Amacan going to Mt. Dasuran. Peak values are also noted in Teresa vicinity and just above median values are also observed north of Panoraon vicinity west of Kinasing-Tandic cluster of domes. Low values are given in the margins of NDGP.

4.2 Fuzzy OR

This operator is the opposite of fuzzy AND and is controlled by the maximum fuzzy values given at each grid point. The predictive map it produced therefore is relatively broader in scope compared to the above operator. The indicated favorable areas almost encompass the N-S length of the central region of the prospect. It included the vicinities of Gopod-Amacan, APEX then going to the north in Bucal vicinity. Even slightly above median values are also noted in the margins of NDGP (Fig. 8).

4.3 Fuzzy Product

The result of multiplying values <1 tend to make the output “decreasive”, so that this opeator

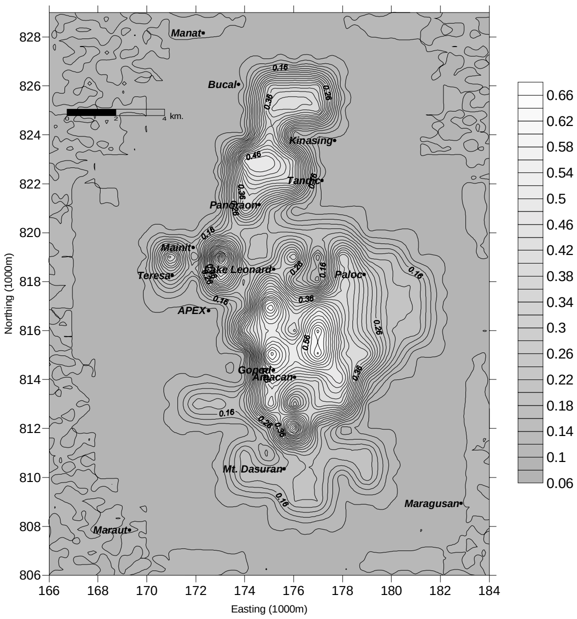

Figure 7. Relatively favorable areas indicated by fuzzy AND.

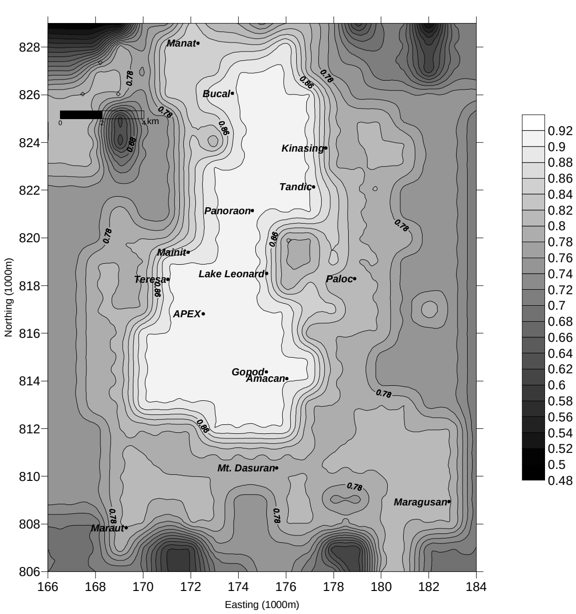

Figure 8. Relatively favorable areas indicated by fuzzy OR.

tends to reflect rather conservative indications of relatively favorable areas (Fig. 9). The peak values noted are in the vicinity between Mt. Dasuran and Gopo-Amacan, between Lake Leonard and Gopod-Amacan as well as the area between Teresa and Lake Leonard. Further north, average values ($\mu_{comb.} = 0.016 - 0.018$) are determined for the Kinasing-Tandic sector.

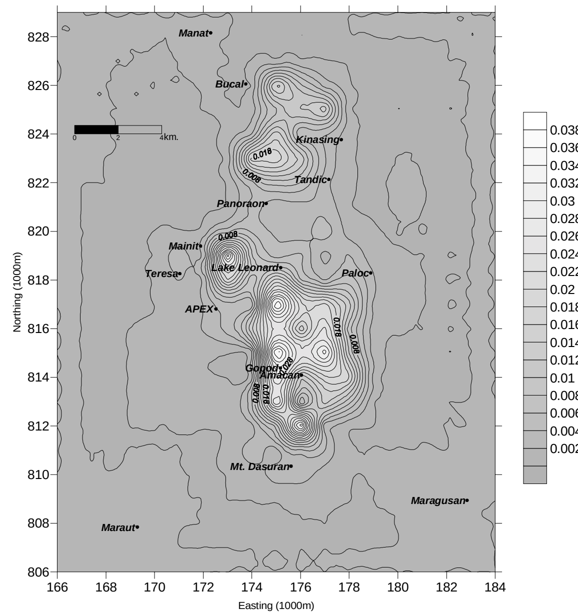

Figure 9. Relatively favorable areas indicated by fuzzy PRODUCT.

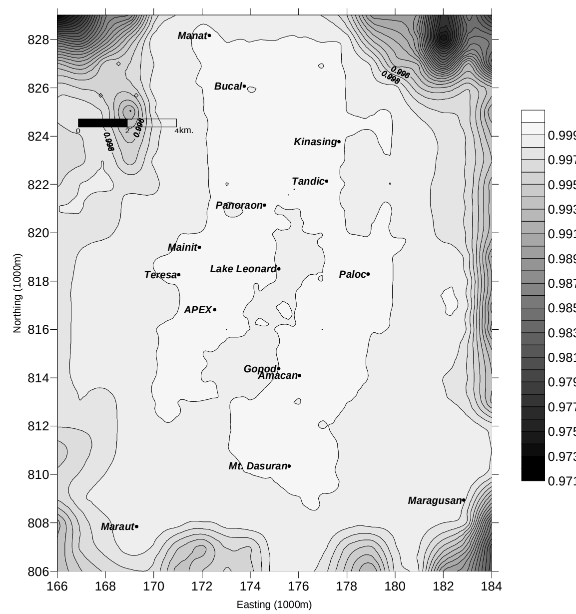

Figure 10. Relatively favorable areas indicated by fuzzy SUM.

4.4 Fuzzy Sum

In contrast to fuzzy product, this operator produces output with larger values due to the “increasive” tendency of subtracting 1 by very small numbers (Fig. 10). A bigger favorable area is therefore obtained more than what the fuzzy OR operator has defined previously. The area now includes Mt. Dasuran in the south central

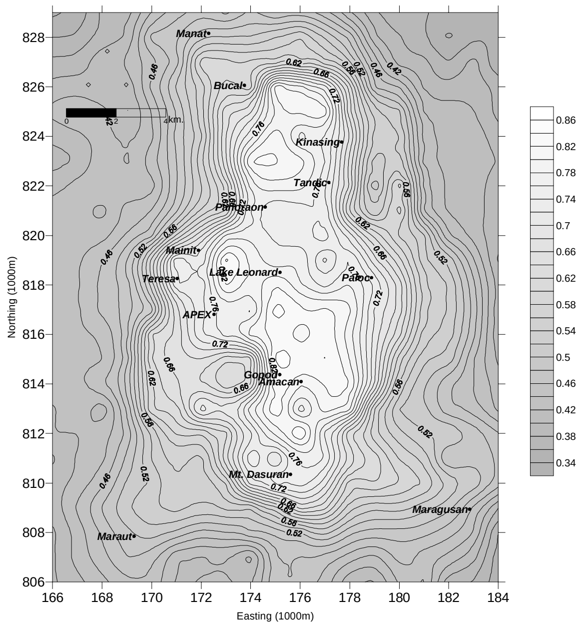

Figure 11. Relatively favorable areas indicated by fuzzy gamma (0.95).

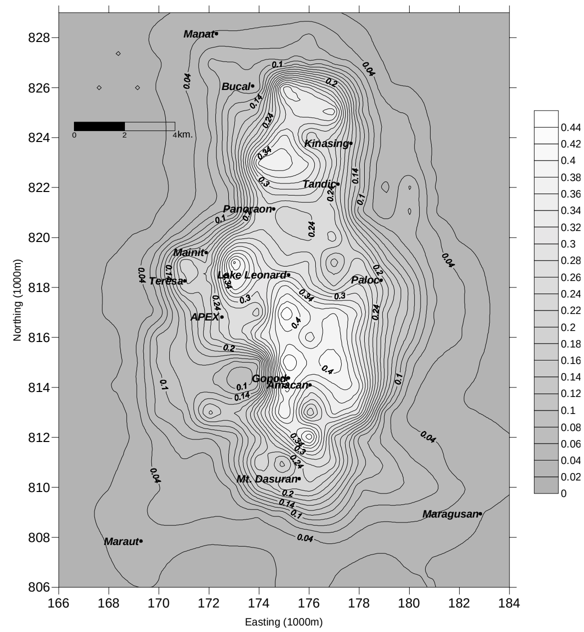

Figure 12. Relatively favorable areas indicated by fuzzy gamma (0.75).

sector, Paloc in the east, and even Manat in the northernmost part of the prospect along with Kinasing and Tandic cluster of domes.

4.5 Fuzzy Gamma

Two fuzzy gamma values of 0.95 and 0.75 were used in this work to give contrasting values. The 0.95 value was used in order to reflect the subjective decision-making during an exploration (An *et al.*, 1991 in Bonham-Carter, 1994). Meanwhile, the 0.75 value was used to give a conservative estimate of the rating of fuzzy membership values assigned to each grid point. The maps produced by the two gamma values are similar in terms of indicating the relatively prospective areas (Figs. 11 and 12). These areas are the vicinity between Mt. Dasuran and Amacan-Gopod, the central part of the prospect that includes Teresa, Mainit, Lake Leonard and Paloc vicinities. The northern sector is also indicated near Kinasing-Tandic area.

In summary, all the fuzzy logic operators consistently define the central part of the North Davao Geothermal Prospect (NDGP) as relatively favorable in terms of exploration potential. The central part includes the vicinity of Amacan-Gopod going to Lake Leonard and going south near Mt. Dasuran (the highest peak in NDGP). This indicated area corroborates the current interpretation wherein a geothermal system was postulated to be upflowing in the Ugos-Amacan-Leonard sector (Pioquinto *et al.*, 1997; PNOC-EDC, 1985). A deep (2695m) exploratory well AM-1 was previously drilled in Amacan tapped neutral, hot fluids (~265°C) but encountered highly impermeable intrusive complex (PNOC-EDC, 1985).

Other areas indicated favorably by the predictive maps include the eastern and western central margins of Paloc and Teresa-Mainit sides respectively as well as the sector north going to Bucal near Kinasing-Tandic dome structures.

The predictive maps obtained from fuzzy logic technique may be used as an initial guide for further geoscientific studies to evaluate the resource potential of the North Davao Geothermal Prospect. This is to reinforce the present interpretation and the existing database so that parameters can be generated to attain a more refined model. Additional geophysical investigations may be undertaken especially magneto-telluric (MT) surveys to outline the possible geothermal resource delineated in the study. Also, gravity surveys with additional stratigraphic correlation can be done to supplement the result of the MT surveys. This is to effectively map out the subsurface extent of the lithological assemblages in the area and to better characterize the potential reservoir rocks hosting the inferred system.

Based on the areas identified by the predictive maps, we therefore recommend additional studies in the following locations: (1) the vicinity of Mt. Dasuran going to Gopod-Amacan, (2) from Amacan NW towards Teresa-Mainit, (3) N towards Lake Leonard, (4) NE towards Paloc, and (5) further north towards Kinasing-Tandic area.

5.0 CONCLUSIONS

The fuzzy logic technique presented in this paper can be used in pre-evaluating a geothermal prospect using fuzzy operators. This technique produces predictive maps that comparatively define the geothermal potential of an area or areas for further studies. The output maps can either be 'restrictive' or 'liberal' in defining the relatively favorable area. However, the discrete use of a gamma value balances the 'restrictive' or 'liberal' effects resulting to a more reasonable output map.

The case study in the North Davao Geothermal Prospect (NDGP) demonstrates the application of fuzzy logic method that defines potential areas for further studies. These prospective areas are in the vicinity of Gopod-Amacan, south going to Mt. Dasuran, also north toward Lake Leonard area, to the west near Teresa-Mainit locality, and Paloc to the east. The Kinasing-Tandic area to the north is also included as potential area for geothermal exploration. All in all, the total aggregate potential area is approximately 45 km^2.

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