Multi-method Geophysical Observations in Governing Sustainable Development of a Volcano-Hosted Geothermal Area in Cangar, Indonesia

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Abstract: Volcano-hosted geothermal area holds great potential to be developed in a sustainable development concept. This research aimed to explore the potential of geothermal resources and the threats from potentially eruption of dormant volcano in Cangar, Indonesia. The geophysical approach was utilized to assess both exploration and mitigation aspect in this area. The geothermal system was estimated by gravity method, while the volcanic activity of Mt. Arjuno-Welirang was estimated by LST analysis. As the result, the emergence the geothermal manifestation is the associated with 5 secondary faults structure, where the fluid flows in the western direction through the secondary structures near the main fault. Meanwhile, from the analysis of Landsat 8 satellite data, it is evidenced that there was an increasing volcanic activity in 2018 at Arjuno-Welirang crater, signaling that there are magma movement in the shallow depth, which may become threat of eruption in the future.

Keywords: multi-method; geophysics; volcano-hosted geothermal; Cangar; Arjuno-Welirang

1. INTRODUCTION

Cangar is located in the Arjuno-Welirang Volcano complex, one of the quaternary volcanoes that hosted geothermal potentials at three districts in East Java (Malang, Mojokerto, and Pasuruan) (Fig. 1). The temperature of geothermal reservoir at Cangar was estimated at around 190° to 230°C, determined by using a Na-K-Ca geothermometer [1]. The Directorate of Geothermal [2] estimated that geothermal reserves in Arjuno-Welirang complex is about 280 MWe. Reservoir rocks in this area were suspected to be the old Arjuno-Welirang volcanic products (lava, pyroclastic) that had been deformed in the late Pleistocene period. Due to the fault structure activities around the complex area, hence its rocks have permeable properties.

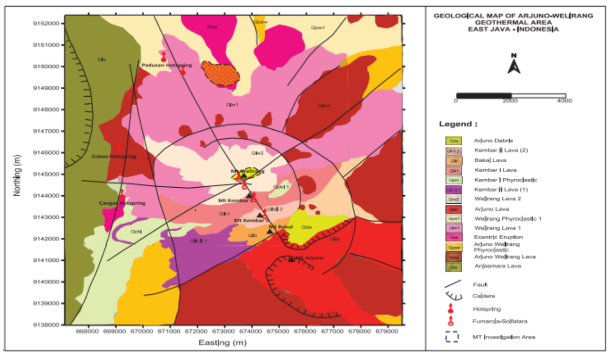

Fig. 1. Geological map of the Cangar, Indonesia with Mt. Arjuno-Welirang in the East side of the geothermal field [3].

The geological structures in Arjuno-Welirang are dominated by faults, which were formed by volcanic and tectonic activities [4]. The faults structure in the North-South direction is represented by Cangar, Pucung, and Claket faults. The faults structure in the Northwest-Southeast direction is represented by the Padusan, Kemiri, and Bakal faults. In the Southwest-Northeast direction, there are Welirang, Kembar, and Bulak as well as Ledug and Ringgit faults in the East-West direction, which influence the formation of the Arjuno-Welirang volcanic complex [5]. Main faults generally have very low primary permeability as they were formed in the volcanic rock formation. Meanwhile, the secondary structures (fracture, crack, etc.) near the main faults precisely become the biggest trigger for the emergence of geothermal manifestations on the surface. This is very important to note because secondary structures near igneous rocks with low primary permeability will produce greater secondary permeability [6,7].

The complexity of Cangar area possesses a great potential for exploration and research purposes. Many researches aimed to identify the subsurface structures and geothermal potential had been carried out by employing various geophysical methods [3,8-11]. Based on this research, it is known that the emergence of hot springs in Arjuno-Welirang area was mainly triggered by main faults trending in the North-South (Cangar, Pucung, and Claket faults) and Northwest-Southeast direction (Padusan, Kemiri, and Bakal faults).

In another hand, researches concerning the volcanic activities of Mt. Arjuno-Welirang are not explored much. This because this volcano is currently in dormancy since its last eruption in 1952. The activity of Mt. Arjuno-Welirang is indicated by the emergence fumarole and solfatara, mainly in Welirang summit. However, on February 7, 2018, there are an increasing seismic activity in this volcano [12]. This served as a warning of an impending volcanic eruption in Indonesia, as to not repeating the case of Mt. Sinabung eruption. This approach is also crucial as consideration for developing volcanic hosted geothermal area when mitigation aspect cannot be neglected.

This research mainly aimed to explore the potential geothermal system in the Cangar area and the threat of volcanic activities of Mount Arjuno-Welirang by integrating various geophysical observation. It is expected that by identifying the potential and disaster threat, governing a volcano-hosted geothermal area in Cangar, Indonesia in a sustainable development project can be assessed, both in exploration and mitigation aspects.

2. GEOPHYSCAL OBSERVATION

2.1 Gravity observation

The gravity method is frequently used to predict subsurface structures. In geothermal areas, this method could identify abnormal geological features based on variations in density values [21]. Gravity data was directly collected at 115 points (see Fig. 2) in the looping method by using LaCoste and Romberg gravitymeter model G-1053 in the area of 600 x 800 meters. Gravity data correction including tidal correction, drift correction, latitude correction, free air correction, Bouguer correction, curvature correction, and terrain correction was applied to obtain the total Bouguer anomaly (Fig. 7). The regional and residual anomalies were then separated by using spectrum analysis.

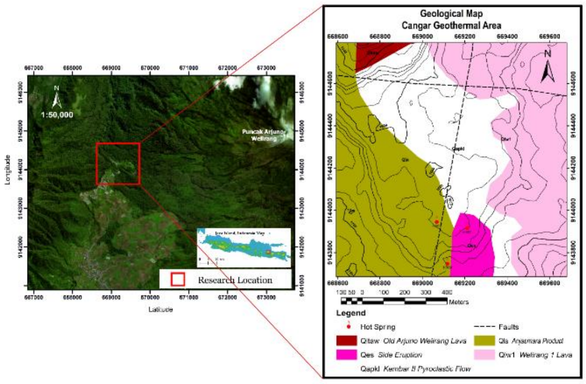

Fig. 2. The coverage area for estimating the geothermal system in Cangar by gravity method.

The Second Vertical Derivative (SVD) analysis [13] was carried out to determine the location of secondary faults structures (Fig. 9). SVD was applied after correcting the observed gravity data and separating regional and residual anomalies. SVD is capable to brought up shallow anomalies and determining the structure boundaries in the study area. It is expected that by identifying secondary structures in the Cangar area of the Arjuno-Welirang complex, the complexity of hydrothermal activity can be estimated. The results obtained was then correlated with the emergence of manifestations and seismicity around the study area.

2.2 LST analysis to observe the evolution of Mt. Arjuno-Welirang

Mt. Arjuno-Welirang is a dormant volcano with last eruption occurred in 1952. Since the last eruption, the volcanic activities are indicated by the emergence of fumarole and solfatara, mainly in the Welirang summit. However, A-type volcanic earthquake was recorded at February 2018 and followed by B-type volcanic earthquakes, signalling the magma movement towards the conduit in the shallow depth [12]. Unfortunately, seismic observation in this volcano is very limited, unlike the research interests on geothermal resources. Thus, land surface temperature (LST) analysis is proposed to monitor the volcanic activity development of Mt. Arjuno-Welirang.

The implementation of thermal remote sensing technology was realized through the analysis of Landsat 8 satellite imagery in the Mt. Arjuno-Welirang area (Fig. 3) from 2016 to 2021. To determine the values and distribution LST, the free access data of Landsat 8 satellite imagery is used. The analysis of Landsat 8 imagery was carried out using Google Earth Engine (GEE) platform. Landsat 8 imagery was obtained from the USGS database via GEE cloud computing, where Landsat satellite imagery is the most frequently used satellite imagery on this platform [15].

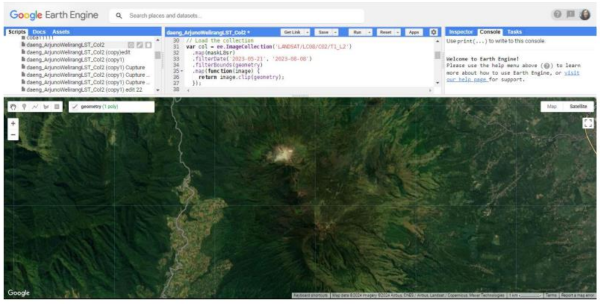

Fig. 3. The coverage area of LST analysis

Researchers have employed the LST algorithms for various purposes, including analysis of LST and NDVI using geospatial techniques [16], LST extraction from LANDSAT TM5 [17], and analysis of LST in the geothermal hot spot of Arjuno-Welirang using multitemporal Thermal Infrared (TIR) data [18]. Landsat 8 imagery from acquisition was processed to extract the surface thermal anomaly map in Arjuno-Welirang crater. The change of LST distribution from each imaging represent the volcanic activities in the volcano. The calculation of LST is based on TOA radiation, while thermal shade of satellite imagery is based on NDVI values to determine the emissivity in the surface [19].

LST data was then analysed to obtain the correlation of satellite imaging and the temperature disturbances caused by the El Niño phenomenon. This to affirm if the result of LST imagery was representing the volcanic activities in the research area. Thus, the seismic event recorded by Magma Indonesia [23] occurred during May 23 – August 19, 2023 (Fig. 4) was correlated to the fluctuation of LST.

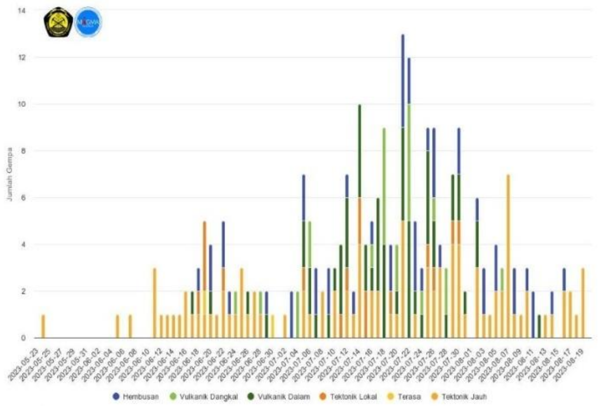

Fig. 4. Seismic events recorded at May 23 – August 19, 2023 to confirm the occurrence of thermal anomaly in research area.

2.3 MAGDAS (MAGnetic Data Acquisition System)

A MAGDAS station [24] had been installed in Cangar area, Indonesia at March 2024 and named CNG station (Fig. 5). The installation is purposed to improve the monitoring of magnetic field fluctuation activities in Java Island, especially in Cangar and Mt. Arjuno-Welirang complex. The magnetic data are available for near real-time monitoring (Fig. 6) and can be accessed at MAGDAS homepage [25]. The change of magnetic field in Cangar area may be correlated with geological phenomenon, such as magma movement beneath Mt. Arjuno-Welirang, fault structures at Cangar geothermal system and tectonic earthquake. However, the analysis of MAGDAS data in Cangar area have not been researched further, as the station was newly installed.

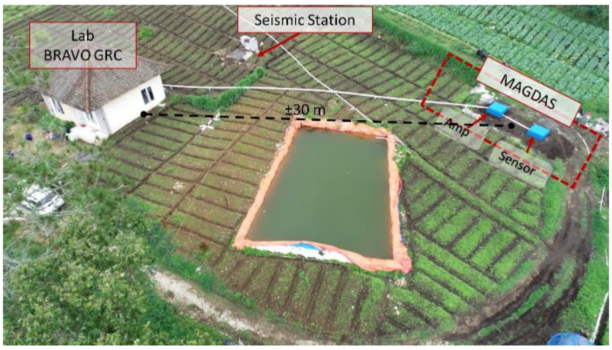

Fig. 5. MAGDAS Station as a tool for geophysical research in Cangar area.

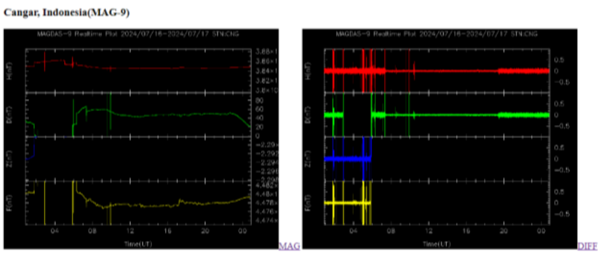

Fig. 6. MAGDAS near real time plot at Station Cangar (CNG) in July 17, 2024 00:58:09 GMT, accessed at MAGDAS homepage [25]

3. ANALYSIS AND DISCUSSION

3.1 Geothermal system in Cangar Area based on Gravity observation

Total Bouguer anomaly provides information on the lateral gravity anomalies in the study area. The map of the total Bouguer anomaly is shown in Fig. 7. The high anomaly in the Northwest part of the research area is regarded as less representative since there is only 1 data point due to a steep research area, in which the data acquirement in that area was not possible. The complete Bouguer anomaly map shows the high anomaly in the ranges of 30.7 to 37.7 mGal, expanding from the Southeast to the Northwest of the study area. Meanwhile, low anomalies are shown in the East and Southwest with values ranging from 24.7 to 30.7 mGal.

Based on the geology map in Fig. 1, the high Bouguer anomaly values in this area are predicted caused by the presence of igneous and lava rocks as the result of the old Arjuno-Welirang volcanic activity and Anjasmara volcanic products. Meanwhile, the low anomalies are associated with rocks produced by Kembar II pyroclastic flows and Welirang lava flow I. The low anomaly could also appear because of the secondary faults in those areas, thus the hydrothermal activity tends to be high. This is proven by the presence of hot springs that appear in the Southern part of the study area near the main fault oriented in a North-South direction.

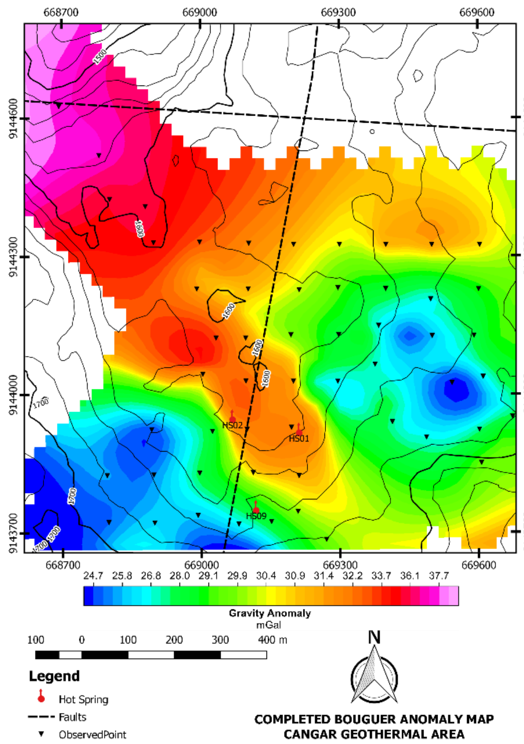

Fig. 7. The map of Complete Bouguer Anomaly obtained from gravity data processing

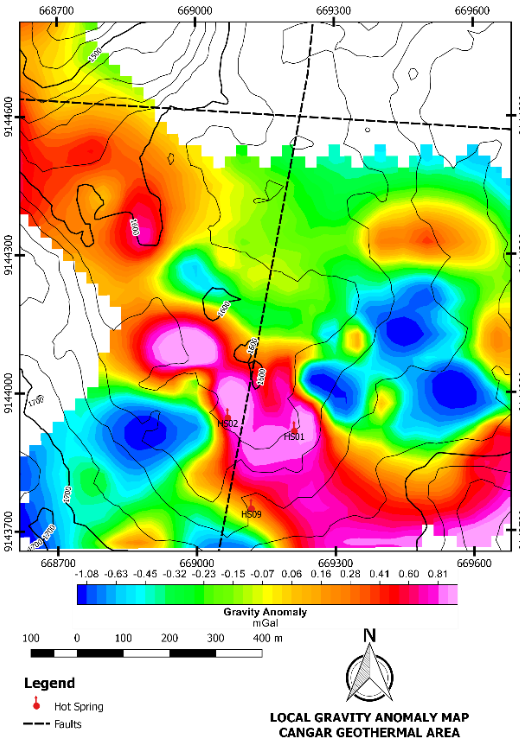

Fig. 8. The residual anomaly of the researched area.

The gravity study in this research focused on the identification of the smaller-scale structure; hence the residual anomaly map (Fig. 8) was used for further analysis. The residual anomaly map shows the distribution of low anomalous values in the Southwest and Southeast with the ranges of -1.08 mGal to -0.32 mGal. Low value commences on residual anomaly shows a clearer structure than that if provided by the regional anomaly. But this value is inadequate to determine the secondary structures because these structures are usually indicated by anomaly values with very high and very low contrast which are close together at very tight contours.

The secondary structures are presented in the SVD anomaly map as shown in Fig. 9. Secondary structures are distributed around the main fault oriented in North-South and their circumscription was determined based on maximum and minimum values on the SVD curve. The value of 0 mGal/m2 in yellow color represents the boundary of local geological features [22]. As illustrated in Fig. 7, the gravity anomaly shows a very high value at of approximately 0.13 mGal/m^2 to 0.22 mGal/m^2 adjoin with very low anomaly values of -0.67 mGal/m^2 to -0.26 mGal/m^2. The very tight contour (0 mGal/m^2) between these very high and very low anomalous values indicated the presence of secondary structures (faults) which triggered hot water to come out toward the surface.

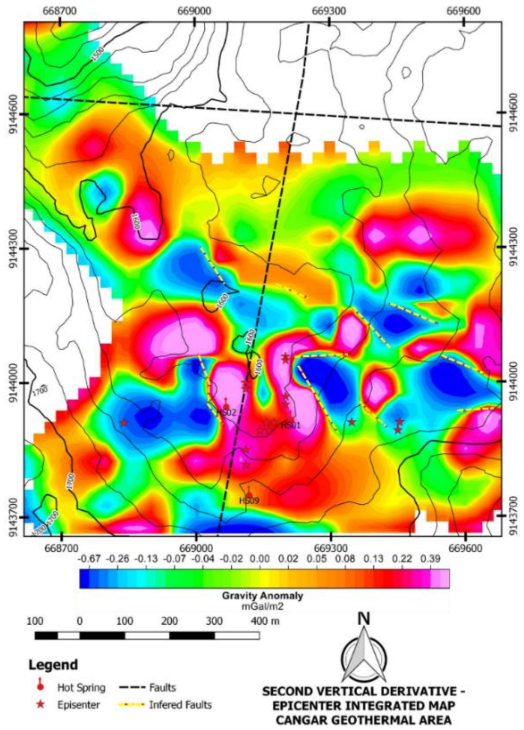

Fig. 9. The map of Second Vertical Derivatives to estimate the geological structure in the study area.

The geothermal system of Cangar area based on gravity data is illustrated at Fig. 10. The results obtained from the SVD map were correlated with earthquakes sources location data from Maryanto (2019) [12] regarding the Peak Ground Acceleration (PGA) values around Arjuno-Welirang and the research area. The earthquake's epicenters were found to be around the emergence of hot water HS01, HS02, and HS09. There are at least 4 (four) secondary structures oriented in North-West and East-West, likewise 1 (one) North-South oriented main fault adjacent to the HS01, HS02, and HS09 hot springs. These 5 structures indicate the cause of hot water discharges to the surface.

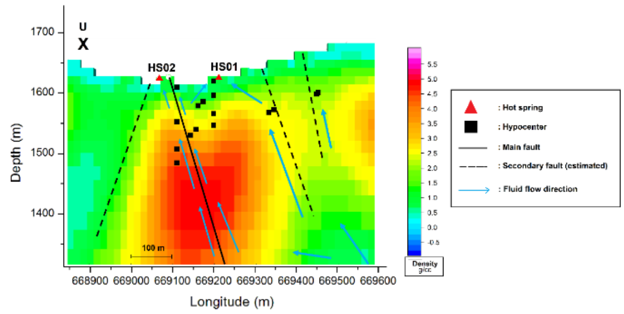

Fig. 10. The West-East cross-section after the residual gravity anomaly inversion and correlated with seismic analysis. The blue arrows indicate the direction of the hot fluid flow to the surface through high-density rocks due to secondary structures near the main fault. This fluid movement is also associated with the appearance of seismicity near hot springs.

Based on the geological information, the study area was dominated by igneous rock as a result of Arjuno-Welirang lava and Anjasmara products in the Quaternary period. These rocks are indicated as clay caps from argillic alteration types [5] which have a high-density value (2-5 gr/cc; Fig. 10), thus they are categorized as compact rocks and impermeable. The emergence of geothermal manifestations on the surface is more controlled by the secondary structures (fracture, joint, etc) which make these compact rocks have high permeability.

The result of the residual anomaly inversion in Fig. 10, shows the estimated movement of the hot fluid in the Cangar outflow zone according to the conceptual model of the Arjuno-Welirang geothermal Field by Wardana et al (2016) [14] which leads to the West towards the Cangar hot spring. The movement of fluid that passes through secondary structures is also proved by the high permeability value of 100 md. In the Western part of the research area, characterized by low-density values (around 0 - 2 g/cc) is part of the Anjasmara product and meteoric water recharge zone from the surface to the reservoir. High-density values in areas with many secondary structures are also indicated as a result of the flow of hot fluids into rock crevices. This hot fluid tends to have high pressure thus it increases the value of its density. Research by Maryanto [3] also revealed that hot spring in Cangar area possibly caused by the heating process of groundwater by igneous lava and basalt rock, which is the main constituent of Arjuno-Welirang volcanic rock.

Cangar Fault is the main vessel of hot water rising towards the surface and manifested as hot spring HS02. The active Cangar fault leads to the secondary faults establishment that affects hydrothermal activity in the study area. This activity results in HS01 hot spring and HS09 hot spring manifestations.Cangar Fault is the main vessel of hot water rising towards the surface and manifested as hot spring HS02. The active Cangar fault leads the secondary faults establishment that affects hydrothermal activity in the study area. This activity results in HS01 hot spring and HS09 hot spring manifestations.

3.2 Volcanic Activity of Mt. Arjuno-Welirang

Based on the LST analysis results obtained during the period of 2016-2018, surface temperatures in the Arjuno-Welirang crater area experienced their highest increase in 2018, reaching 33.94°C, with larger contours of thermal distribution compared to other periods (see Fig. 11). This thermal-based increase in volcanic activity correlates with the seismic activity increase monitored by the Volcanological Survey of Indonesia (VSI). Other researchers have analyzed LST in volcanic studies, such as the analysis of the Geothermal Prospects in the Arjuno-Welirang Region using Multitemporal Thermal Infrared (TIR) data [20].

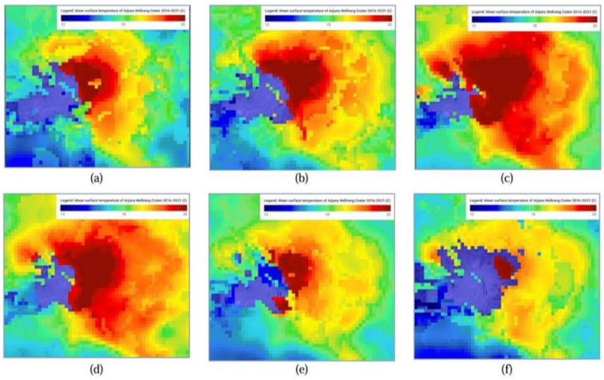

Fig. 11. LST contour imagery at the crater of Mt. Arjuno-Welirang at (a) 2016, (b) 2017, (c) 2018, (d) 2019, (e) 2020, and (f) 2021. Highest activities occurred at 2018 [26].

Furthermore, this study demonstrates the performance of LST detection for monitoring normal volcanic activity changes at Mount Arjuno-Welirang, affected by temperature disturbances caused by the El Niño phenomenon (Fig. 12 and Fig. 13). LST analysis was conducted on Landsat 8 imagery for the period of May-August 2023. The selection of this time period was based on the daily volcanic activity reports released by Magma Indonesia coinciding with notifications from the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) regarding the El Niño phenomenon. The results of this research include an LST curve over time, indicating a trend of increasing surface temperatures in the Arjuno-Welirang crater in July. This trend aligns with the reported increase in seismic activity on the Magma Indonesia website (see Fig. 4) and contrasts with the anticipated temperature increase due to the El Niño effect predicted by BMKG. The highest temperature increase occurred on July 24, 2023, reaching 31.78°C, followed by a subsequent decrease in temperature.

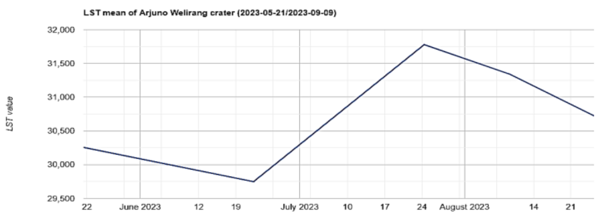

Fig. 12. LST fluctuation in Mt. Arjuno-Welirang is correlated to the increasing volcanic activity reported by Magma Indonesia website [23] but not correlated to the thermal factor of El Niño as reported by BMKG.

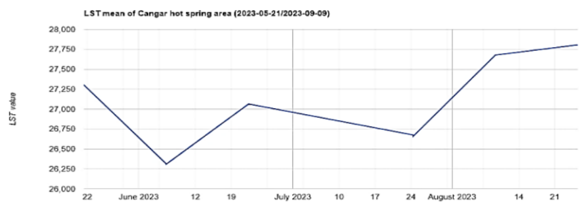

Fig. 13. Trend of LST fluctuation in Cangar geothermal area affected by El Niño as predicted by BMKG. Surface temperature at August 2023 was 27°C and above.

3.3 Sustainable development in Cangar, Indonesia

The potential of geothermal resources in Cangar, Indonesia had been widely researched by various geophysical observation. Geothermal exploration hold a big role in achieving the Sustainable Development Goals (SDGs) in term of green and sustainable energy sources. Nevertheless, the exploration purposes often neglect the mitigation aspect. Thus, a sustainable development project is proposed in Cangar, Indonesia. This project was planned to integrate the tourism, research and mitigation aspect, as illustrated in Fig. 14. The research facility has been improved by installing seismic station, MAGDAS station and visual camera monitoring system. The research facility is focused on exploring the geothermal resources in Cangar area and monitoring the geological hazards, especially the volcanic activity of Mt. Arjuno-Welirang. An education center is also planned as part of the facilities to provide knowledge on disaster heritage in Indonesia, especially East Java, which is beneficial for community-based hazard mitigation.

Fig. 14. The planned zonation of Cangar, Indonesia for sustainable development project.

To attain sustainable development in Cangar Area, Indonesia, geophysical researches are planned to be conducted continuously, involving different geophysical approach alongside the integration of geological and environmental studies. Various aspects related to geothermal exploration and hazard mitigation are still required to be studied from various perspectives. For example, the implementation of geo-electricity method is beneficial for research on groundwater resources and landslide potential, another hazard threat in a highland area. Analysis on MAGDAS data will provide information on subsurface change on geothermal and volcanic system in Cangar Area, based on fluctuation of magnetic field. Furthermore, aspect concerning the impact of the project to the environment are also important to be considered.

4. SUMMARY

The multi method of geophysical observation is significant to planning a sustainable development of a volcano-hosted geothermal area, such as Cangar, Indonesia. This area is known for its geothermal resources, with the presence of a dormant volcano called Mt. Arjuno-Welirang. Thus combining various geophysical method for detailed identification and determination of geothermal system and resources is beneficial. The gravity method conducted in this research was aimed to identify the secondary fault structure that associated with geothermal manifestation. The result SVD analysis shows that there are at least 5 secondary structures in the study area that trigger the emergence of hot water, especially in hot water HS01, HS02, and HS09. The fluid flows to the West of the study area through the secondary faults near the main fault, as evidenced by the indication of fluid movement from the recorded microearthquake around the study area.

Another geophysical approach was employed to assess the hazard potential of a dormant volcanic eruption. Although Mt. Arjuno-Welirang is currently in dormancy since its last eruption in 1952, there were a record of increasing volcanic activity in 2018. This activity signaled that there were a magma movement in the shallow depth, which may lead to an eruption. The LST analysis is capable of detecting changes in normal volcanic activity at the Arjuno-Welirang crater despite thermal disturbances caused by the El Niño influence. LST values are predominantly influenced by volcanic activity rather than extreme El Niño weather conditions.

Gravity and LST analysis in this research indeed provide useful information in geothermal exploration and volcanic threat information in the planned sustainable development area. Assessing both the potential resources and hazard threat are necessary to attain sustainable development in Cangar. The conducted research provides preliminary information and in-depth research are subsequently needed. Thus, integrated studies geophysical research alongside with geological and environmental perspectives are planned for future work in this area. Furthermore, analysis on MAGDAS data is planned to be conducted in the near future as initial stage of magnetic field monitoring in Cangar area.

5. ACKNOWLEDGEMENTS

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