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The Chemistry of Thermal Manifestations at the Recent Exploitation Stage of Wayang Windu Geothermal Field

Alyssa Saumi Juta[1]* and Dwiyogarani Malik[1]
Star Energy Geothermal (Wayang Windu) Limited, Jakarta, Indonesia[1]*
*Alyssa.Saumi@starenergy.co.id

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ABSTRACT

The Wayang Windu Geothermal Field, operated by Star Energy Geothermal, has been in continuous operation for 25 years and has an installed capacity of 230.5 MWe. This paper investigates the physical and chemical evolution of key surface features during this sustained production period. Among 11 thermal manifestations identified, five are emphasized for their representativeness: Wayang and Burung Craters, and the Cibolang, Sukaratu, and MBA Springs. While no significant physical changes were observed across the broader thermal area, minor chemical changes were noted in specific location. At Burung Crater, a drop in reservoir pressure led to more steam and less gas, while Cibolang Hot Spring remained geochemically stable with only slight surface oxidation. Stable isotope analysis ($\delta^{18}O$ and δD) confirmed these localized differences, showing marked changes at Burung Crater but consistent values elsewhere. Despite these localized chemical shifts, the overall thermal manifestations across the Wayang Windu Geothermal Field demonstrate remarkable resilience, indicating minimal long-term impact from geothermal development. These findings support improved management of mature geothermal fields by enhancing the interpretation of surface manifestations as indicators of subsurface changes.

1 INTRODUCTION

The Wayang Windu Geothermal Field (WWGF) is a high-temperature geothermal system located in West Java, Indonesia. It hosts a two-phase reservoir and lies along a chain of Quaternary Volcanoes, including Mt. Malabar, Puncak Besar, Gambung, Bedil, Wayang, and Windu (Figure 1). Initial exploration began in 1980 with geochemical surveys of thermal manifestations. Full-scale development commenced in the late 1990s, leading to commercial production in 2000 (Bogie et al., 2008).

After 25 years of continuous production, variations in subsurface conditions are expected and may be reflected in surface thermal manifestations. This study explores the physical and chemical evolution of key surface manifestations, focusing on the most active fumaroles and thermal springs. Among the 11 thermal manifestations identified, this paper emphasizes Wayang and Burung Craters, and the Cibolang, Sukaratu, and MBA Springs (Figure 1). By analyzing monitoring data from 1980 to 2024, changes in the physical and chemical characteristics of these features are evaluated.

2 PHYSICAL DESCRIPTION OF THERMAL MANIFESTATION

The surface thermal manifestations in WWGF are distributed along the slopes of the Bedil-Wayang-Windu andesitic dome and the southern flank of Puncak Besar. These thermal manifestations consist of fumarolic fields and thermal springs. In general, fumarole temperatures range from 93 to 98°C, accompanied by acidic steam condensate (pH ≤ 4). Meanwhile the thermal springs have temperatures range from 38 to 69°C, with pH values between 2.7 and 7.5.

a. Burung Crater

Located in the Gambung area at 2,037 masl, Burung Crater comprises a mud pool and a fumarolic field (Figure 2). The mud pool has a temperature ranging from 90 to 93°C, with a highly acidic pH of 1–2. It exhibits active bubbling and reaches boiling conditions. Meanwhile, the fumaroles have temperatures ranging from 92 to 97°C, with steam condensate pH around 2. The total surface area of the thermal feature is approximately 304 m^2, with no significant changes in surface extent observed over time.

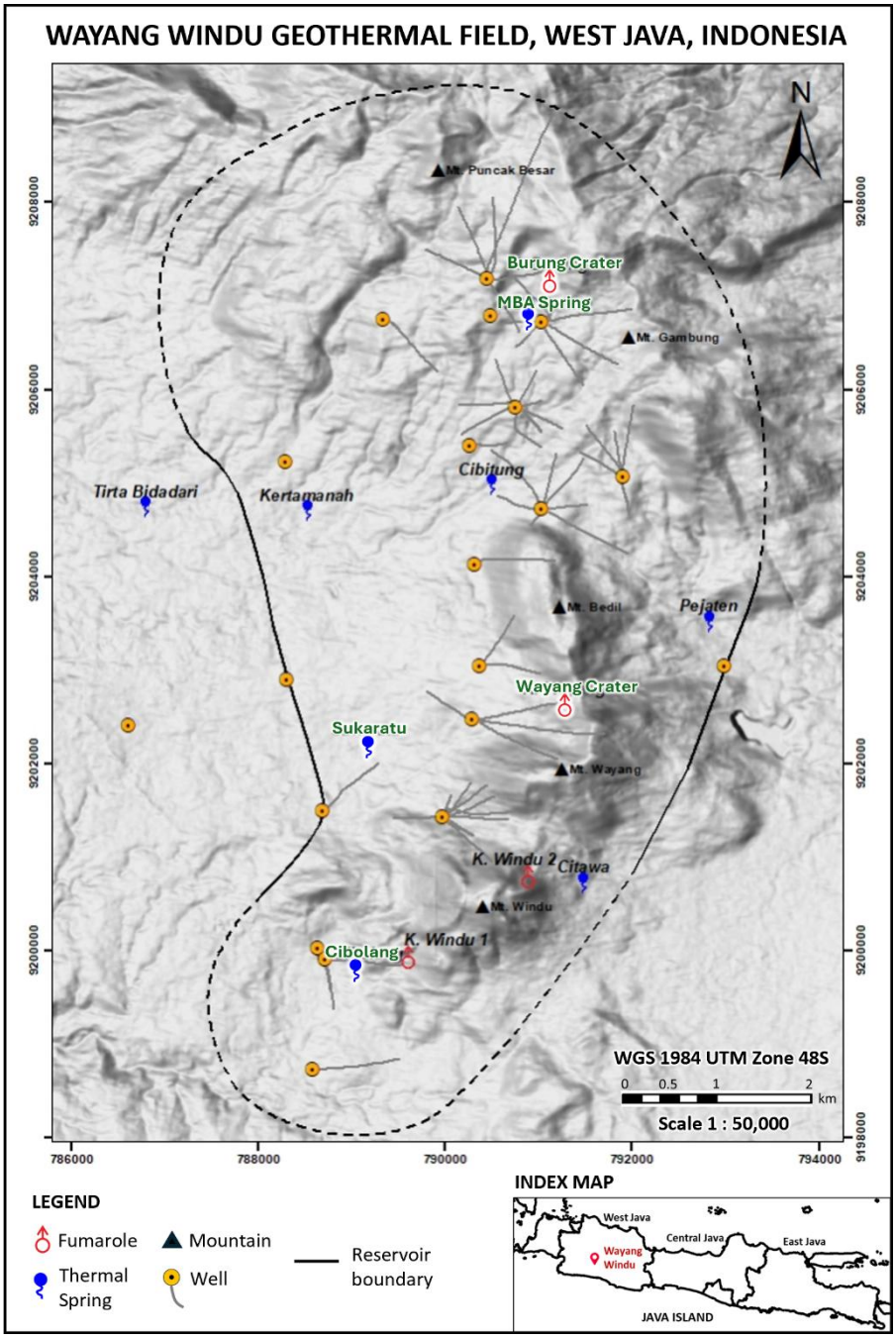


Figure 1. Location map of the Wayang Windu Geothermal Field within a series of Quaternary Volcanoes, showing 11 thermal manifestations. Five analyzed manifestations labeled in green.



Figure 2. Burung Crater consists of a mud pool and a fumarolic field. The mud pool exhibits active bubbling.

b. Wayang Crater

Situated in the Wayang area at approximately 1,919 masl, Wayang Crater includes a fumarolic field with altered ground composed mainly of clay, sulfur, and iron oxides (Figure 3). The altered ground is predominantly located on the western flank of Mt. Wayang, while the eastern flank retains fresh rock outcrops. Fumarole temperatures range from 93 to 98°C, with steam condensate pH between 1.5 and 2. The total surface area of the thermal feature is approximately 22,117 m^2, with no significant changes in surface extent observed over time.



Figure 3. Fumarolic field at Wayang Crater, with altered ground mainly on the western flank of Mt. Wayang.

c. Cibolang Spring

Cibolang Spring is located at 1,527 masl and exhibits temperatures ranging from 56 to 68°C with a near-neutral pH of 6.3 to 7. The water is clear, and travertine deposits around the pool indicate a high bicarbonate concentration (Figure 4). The spring has been developed as a public hot spring bath, and no significant physical changes have been observed at the site.



Figure 4. Cibolang Hot Spring, characterized by clear water and travertine deposits around the area.

d. MBA Spring

MBA Spring, the highest-elevation spring in WWGF at 1,813 masl, is the only acid-sulfate hot spring in the area. It maintains a stable pH between 2.7 and 3, with temperatures ranging from 44 to 61°C. The water appears slightly turbid, likely due to low pH dissolving surrounding rock material, and no significant physical changes have been observed at the site (Figure 5).



Figure 5. MBA Spring is an acidic hot spring with turbid water from surrounding rock dissolution.

e. Sukaratu Spring

Sukaratu Spring is classified as a warm spring, located at 1,590 masl. It has a stable temperature ranging from 38 to 42°C and a neutral pH of 6.5 to 7. The water is clear and shows bubbling activity, indicating a high concentration of CO_2 gas (Figure 6). No significant physical changes have been observed at the site.



Figure 6. Sukaratu Warm Spring has clear water and exhibits bubbling activity, indicating high gas.

3 CHEMICAL CHANGES OF THERMAL MANIFESTATION

3.1 Fumarole

The most significant chemical changes in fumarolic activity have been observed at Burung Crater. Since the onset of geothermal production in 2000, the CO_2/H_2S ratio has gradually decreased from approximately 18 to 12, while the non-condensable gas (NCG) content has significantly decreased from 8.8 to 1.1 wt% (Figure 7). The steep decline in NCG primarily reflects a significant decrease in CO_2 concentration, which constitutes over 90% of NCG, whereas the more gradual decrease in the CO_2/H_2S ratio is due to the relatively smaller increase in H_2S. These trends indicate intensified boiling, which enhances steam dominance and reduces gas concentrations.

In 2015, an unplanned production shutdown of several nearby steam production wells occurred across the field. During this period, the CO_2/H_2S ratio increased significantly from around 14 to 56 and the NCG content rose to 9.5 wt% (Figure 7). These variations are attributed to steam condensation resulting from changes in pressure and fluid flow due to the well shut-in. These changes also reduced steam discharge to Burung Crater, causing localized condensation. Once production resumed, all parameters returned to their previous levels.

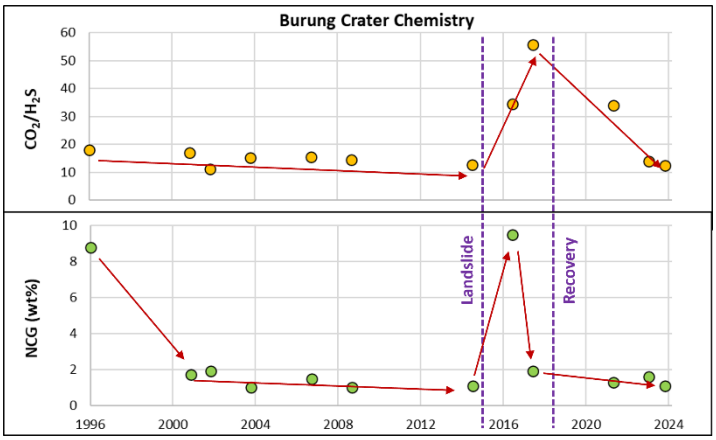


Figure 7. Burung Crater shows decreasing CO_2/H_2S and NCG, indicating intensified boiling and greater steam contribution. The increase observed during an unplanned production shutdown likely reflects steam condensation.

In contrast, Wayang Crater has remained relatively stable. Although the NCG content show a gradual decline, the CO_2/H_2S ratio has remained within a narrow range of 17 to 20 (Figure 8). During the 2015 unplanned production shutdown, Wayang Crater showed temporary chemical changes: the CO_2/H_2S ratio rose to about 27, with slight increase in NCG content, indicating short-term steam condensation during the shutdown (Figure 8). This relative stability is likely because Wayang Crater is more directly connected to the deep reservoir, making it less sensitive to short-term disturbances in the shallow zone.

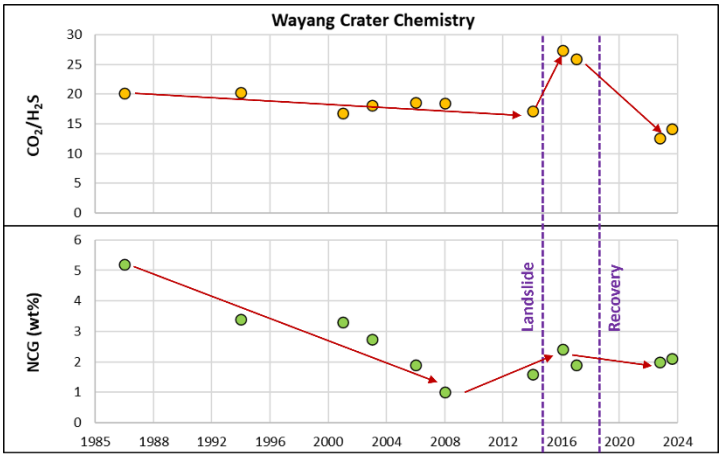


Figure 8. Wayang Crater shows relatively stable CO_2/H_2S, while NCG shows a decreasing trend. A temporary increase in all parameters occurred during an unplanned production shutdown.

Gas geothermometers, particularly the H_2S-based geothermometer were used to estimate deep reservoir temperatures. This method correlates well with downhole temperature logging. Overall, the estimated reservoir temperatures at both Burung and Wayang Craters remain relatively stable at around 280°C. A slight and temporary temperature decrease was observed following the 2015 unplanned production shutdown, likely as a result of condensation. Over time, reservoir temperatures gradually recovered, possibly indicating reestablished or enhanced boiling activity at both Burung and Wayang Craters (Table 1).

Table 1. H_2S-geothermometer results indicating a slight increase in deep reservoir temperature at both craters.

Burung Crater	Year	H_2S-Geothermometer (°C)		Wayang Crater	Year	H_2S-Geothermometer (°C)
KB-96	1996	279		KW-87	1987	276
KB-01	2001	280		KW-95	1995	276
KB-02	2002	287		KW-02	2002	280
KB-04	2004	282		KW-04	2004	278
KB-07	2007	282		KW-07	2007	278
KB-09	2009	282		KW-09	2009	278
KB-15	2015	285		KW-15	2015	280
KB-17	2017	267		KW-17	2017	271
KB-18	2018	257		KW-18	2018	272
KB-22	2022	266		KW-23	2023	282
KB-23	2023	283		KW-24	2024	282
KB-24	2024	285				

3.2 Thermal Spring

Chemical changes in thermal springs were assessed using water type classification and equilibration analysis. These parameters provide insights into subsurface geochemical processes and water-rock interaction. Based on the ternary diagram of $Cl–SO_4–HCO_3$, Cibolang and Sukaratu Springs are classified as bicarbonate waters (Figure 9a), formed by the condensation of steam and CO_2-rich gases into poorly oxygenated subsurface groundwater (Nicholson, 1993). Meanwhile, MBA Spring is categorized as acid sulfate water (Figure 9a), resulting

from the condensation of H_2S-rich gas into near-surface, oxygenated groundwater. Water equilibration analysis using the Na-K-Mg ternary diagram indicates that all thermal springs fall within the immature zone, suggesting mixing with shallow groundwater or near-surface water-rock interactions (Figure 9b).

While the water types and equilibration zones have remained consistent since initial measurements, chemical compositions have evolved—most notably at Cibolang Spring. Its temperature increased from 59°C to approximately 69°C, indicating enhanced boiling. Initially characterized by a neutral pH of 7 and SO_4 concentration of ~180 ppm, Cibolang Spring now shows SO_4 levels of 250–280 ppm and a slightly reduced pH of 6.3–6.5. Chloride content decreased from ~19 to 13 ppm, and bicarbonate dropped from ~420 to 300–370 ppm. These changes suggest increased surface oxidation of H_2S gas, likely triggered by higher water temperatures which promote the conversion of H_2S to sulfate near the surface.

In contrast, Sukaratu and MBA Springs have shown minimal chemical variation. Sukaratu Spring maintains stable HCO_3 concentrations (530–570 ppm), Cl levels (4–5 ppm), and SO_4 levels (100–140 ppm). MBA Spring remains enriched in SO_4 (160-200 ppm), with consistently low Cl and HCO_3 levels, and stable acidic pH.

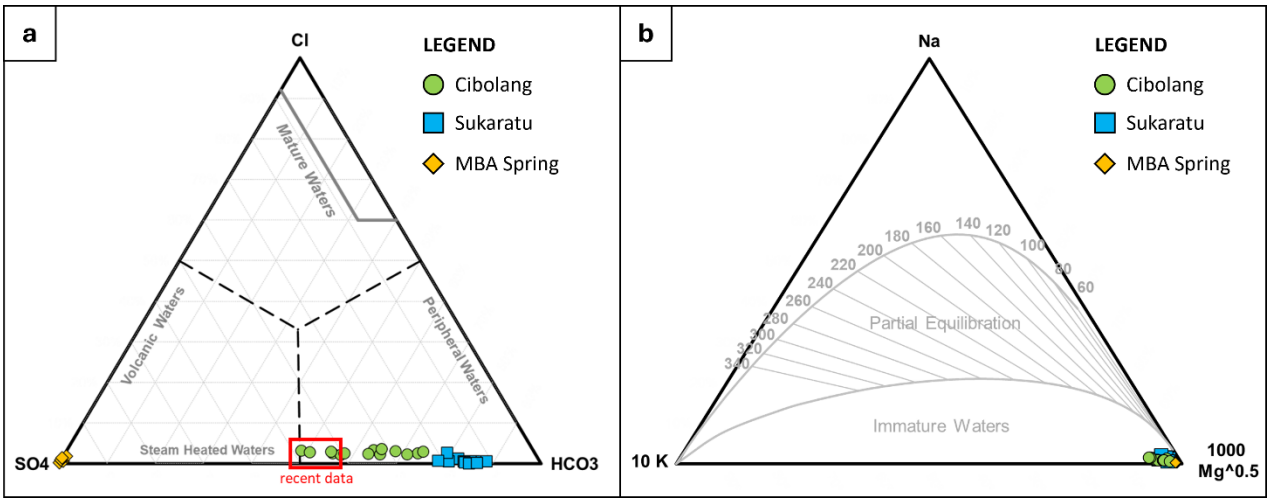


Figure 9. (a) Cl-SO_4-HCO_3 diagram shows Cibolang and Sukaratu as bicarbonate waters, MBA Spring as sulfate water. Cibolang shows a slight increase in SO_4. (b) Na-K-Mg diagram shows all springs are immature.

4 STABLE ISOTOPE COMPOSITION

Stable isotopes of oxygen-18 ($\delta^{18}O$) and deuterium (δD) are valuable indicators of subsurface processes such as boiling, mixing, and water-rock interaction (Arnorsson, 2000). The correlation between $\delta^{18}O$ and δD values of thermal manifestations and the parent fluid of the WWGF is illustrated in Figure 10.

Most thermal manifestations plot near the local meteoric water line (LMWL), suggesting limited contribution from deep reservoir fluids and dominant influence of surface water or shallow processes. Among these, Burung Crater exhibits the most depleted $\delta^{18}O$ values, consistent with secondary steam formation. According to Giggenbach and Stewart (1982), the isotopic composition of secondary steam tends to shift $\delta^{18}O$ values toward more negative levels due to fractionation during boiling. This implies that the fumarolic steam at Burung Crater likely originates from shallow steam-heated waters or prediluted waters.

In contrast, Wayang Crater shows more enriched $\delta^{18}O$ and δD values, closely aligning with the parent fluid, indicating a direct connection to deeper reservoir fluids. These interpretations are consistent with previous stable isotope studies conducted at WWGF (Prasetio et al., 2015).

Among thermal manifestations, only Burung Crater demonstrates significant temporal variation in stable isotope composition linked to geothermal production. Over time, $\delta^{18}O$ and δD values at Burung Crater have decreased, reflecting enhanced boiling in shallow aquifers (Figure 10). As lighter isotopes preferentially partition into the vapor phase, this leads to isotopic depletion in the steam (Giggenbach and Stewart, 1982). During the 2015 unplanned production shutdown, the equilibrium state of the liquid phase was disrupted, leading to temporary condensation followed by a re-boiling process (Figure 7). This resulted in a temporary shift toward heavier isotopes due to slight re-boiling, and a return to lighter isotopes when production resumed normal conditions (Figure 10).

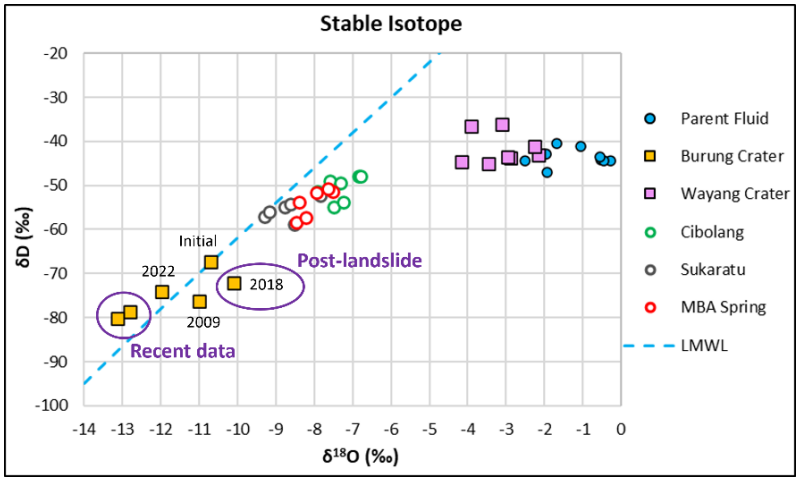


Figure 10. Stable isotopes show variation only in Burung Crater, indicating depletion over time due to intensified boiling, with a temporary increase during the 2015 unplanned production shutdown. Annotated years indicate the sampling year of the respective data points.

5 DISCUSSION

As geothermal production continued at the WWGF, some changes in fumarolic activity have been observed at Burung Crater. While these changes are noticeable, they remain within a moderate range and do not suggest a major transformation. One of the natural consequence of long-term geothermal production is a gradual reservoir pressure drawdown, which can enhance boiling activity and expanded the steam zone (Glover, 1970). This has led to a modest increase in steam output and fumarole temperatures at the Burung Crater fumarole. As steam separated from water, early steam tends to be enriched in gas content, while later steam—originating from residual liquid—contains lower gas concentrations (Nicholson, 1993). Over time, this process has contributed to a slight reduction in overall gas concentration in the vapor phase. Additionally, the CO_2/H_2S ratio decreased with continued boiling, as early steam was relatively CO_2-rich, whereas later steam from the residual liquid became proportionally enriched in H_2S due to its higher solubility in the liquid phase. These processes led to observable chemical changes at Burung Crater, including reductions in CO_2/H_2S ratio and non-condensable gas (NCG) content.

The connection between Burung Crater and the shallow reservoir became more apparent during the 2015 unplanned production shutdown. This brief reduction in steam extraction led to increased condensation within the system, resulting in a higher proportion of gas relative to steam in the remaining vapor. As steam condensed, soluble gases such as H_2S were removed from the vapor phase, resulting in a temporary increase in CO_2/H_2S ratio and NCG content. These variations were short-lived and returned to baseline levels once production resumed, highlighting the dynamic response of the fumarole to operational conditions.

In contrast, the thermal springs across WWGF remained stable, with only Cibolang Spring showing minor geochemical shifts. The increase in SO_4 concentration over time is attributed to intensified surface oxidation of H_2S gas, a process accelerated by rising temperatures. Despite these changes, the water type at Cibolang Spring remains dominated by bicarbonate, indicating that deeper geochemical processes have not significantly altered the spring's character.

These chemical and isotopic changes are also reflected in the stable isotope composition of the thermal manifestations. At Burung Crater, a gradual depletion in $\delta^{18}O$ and δD values was observed over time, consistent with isotopic fractionation caused by boiling. During the unplanned production shutdown in 2015, transient condensation followed by a re-boiling process resulted in a temporary enrichment of $\delta^{18}O$ and δD values. In contrast, other manifestations across the field maintained relatively stable isotopic profiles, suggesting limited influence from deep reservoir dynamics.

Overall, the observed variations at Burung Crater reflect localized responses to subsurface changes associated with geothermal operations, while the consistency of other surface manifestations suggests that the broader geothermal system remains stable and resilience.

6 CONCLUSION

Over 25 years of geothermal development at the Wayang Windu Geothermal Field, the system has exhibited localized geochemical and thermal variations, particularly at Burung Crater. These changes—such as increased fumarole temperatures, reduced gas concentrations, and isotopic shifts—are consistent with natural responses to evolving subsurface conditions, including pressure drawdown and steam zone expansion. Temporary fluctuations observed during the 2015 unplanned production shutdown further illustrate the system's responsiveness to operational dynamics, with parameters returning to baseline once production resumed.

Stable isotope data support these observations, showing trends aligned with boiling-induced fractionation and transient enrichment during reduced extraction periods. In contrast, other surface features such as Cibolang Spring and additional fumaroles have remained largely stable, with only minor geochemical adjustments.

Overall, the geothermal system has demonstrated strong resilience, reflecting effective and well-balanced resource management practices. The limited and reversible nature of changes in surface thermal manifestations indicates that production and reinjection strategies have been carefully designed and executed to maintain reservoir pressure and thermal balance. This equilibrium between subsurface extraction and reinjection has allowed sustainable production without compromising the integrity of surface thermal manifestations.

At Wayang Windu Geothermal Field, such stability suggests that the field management has successfully optimized energy recovery while safeguarding the natural geothermal manifestations that serve as indicators of the system's health. The consistency of these manifestations over time highlights the effectiveness of the monitoring and management framework that has been implemented in this mature geothermal field. These findings provide valuable insight into how responsible reservoir management can ensure both long-term resource sustainability and environmental preservation.

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REFERENCES

Arnorsson, S.: *Isotopic and Chemical Techniques in Geothermal Exploration, Development, and Use*, International Atomic Energy Agency, Vienna, Austria (2000), 351 pp.

Bogie, I., Kusumah, Y.I., Wisnandary, M. C.: Overview of the Wayang Windu Geothermal Field, West Java, Indonesia, *Geothermics*, **37**, (2008), 347-365.

Giggenbach, W.F., and Stewart, M.K.: Process Controlling the Isotopic Composition of Steam and Water Discharges from Steam Vents and Steam-Heated Pools in Geothermal Areas, *Geothermics*, **11**, (1982), 71-80.

Glover, R.B.: Interpretation of Gas Compositions from the Wairakei Field over Ten Years, *Geothermics Special Issue*, **2**, (1970), 1355-1366.

Nicholson, K.: *Geothermal Fluids: Chemistry and Exploration Techniques*, Springer-Verlag, Berlin Heidelberg, Germany (1993), 345 pp.

Prasetio, R., Wiegand, B. A., Malik, D., Sauter, M.: Stable Isotopes Study of Wayang Windu Geothermal Field, Indonesia, *Proceedings,* 5th World Geothermal Congress, Melbourne, Australia (2015).