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Geochemical Study of Water and Gas in The Wayang Windu Geothermal System

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Abstract - This study presents a comprehensive geochemical and hydrogeological characterization of the Wayang Windu Geothermal System in West Java, Indonesia. The research aims to identify water and gas chemistry patterns, to determine fluid origins, and to estimate reservoir temperatures to support conceptual modeling of the geothermal field. Field sampling was conducted on hot and cold springs and fumarolic gases, complemented by laboratory analyses of major ions (Cl^-, SO_4^{2-}, HCO_3^-; Na^+, K^+, Mg^{2+}), stable isotopes (δ^2H, $\delta^{18}O$), and gas compositions (CO_2, N_2, Ar). Data interpretation employed standard geochemical tools, including Cl-SO_4-HCO_3 and Na-K-Mg diagrams for water classification, δ^2H-$\delta^{18}O$ plots for recharge source identification, and N_2-CO_2-Ar ternary diagrams for gas origin assessment. The results indicate that sulphate-type hot springs mark upflow zones, while bicarbonate-type warm and cold springs reflect lateral outflow and mixing processes. The isotopic signatures confirm predominantly meteoric recharge with localized steam-heated and magmatic influences. The gas geothermometers estimate reservoir temperatures between 225° and 286° C, and Cl-Li-B relationships reveal three distinct reservoir clusters: Gambung, Wayang, and Windu. These findings provide critical insights into fluid pathways, reservoir structure, and recharge dynamics, forming a robust basis for sustainable geothermal resource management in volcanic settings.

Keywords: volcanology, geothermal system, water and gas geochemistry, water and rock interactions, environmental hydrogeochemistry, contaminant hydrogeology

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Introduction

Background

Geothermal systems are one of the renewable energy sources with significant potential for development in Indonesia. One of the commercially exploited geothermal systems is the Wayang Windu Geothermal Field, located south of Bandung (Figure 1) (Bogie *et al*., 2008). This field exhibits complex geological and geochemical characteristics, necessitating in-depth studies to understand the dynamics of subsurface hydrothermal fluids. This research aims to characterize hydrothermal fluids, including their type, origin, and reservoir temperature, and to determine the subsurface fluid flow patterns. Using a geochemical approach, analyses were conducted on hot spring water, cold spring water, and fumarolic gases collected from various locations across the field. This study is expected to contribute to a better understanding of the Wayang Windu Geothermal System and to support the sustain-

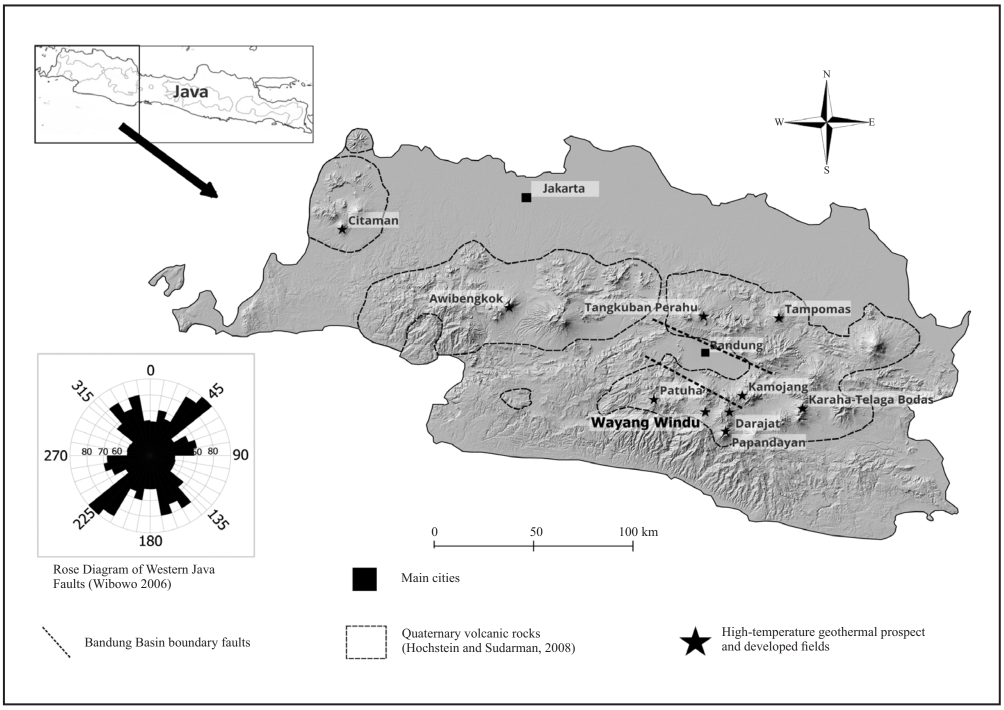

Figure 1. Distribution of Quaternary volcanic rocks and high-temperature geothermal fields in West Java (Bogie *et al*., 2008).

able development of geothermal energy (Bogie and Mackenzie, 1998).

A comprehensive literature search was conducted using the Scopus database with the keywords “geothermal” and “Wayang Windu", which yielded forty-three articles. Among these, thirty-seven were identified as relevant to the scope of this study, and twenty of them are cited in this manuscript. This indicates that the geothermal field has attracted substantial scientific attention due to its exceptional thermal characteristics and complex structural features. Foundational geological mapping by previous researchers provided detailed stratigraphic and lithological frameworks for the Garut-Pameungpeuk region and southern Bandung, respectively (Alzwar *et al*., 1992; Bronto *et al*., 2006). These comprehensive studies meticulously documented the volcanic succession, structural elements, and lithological variations across the region, establishing a robust geological foundation that continues to underpin subsequent geothermal exploration initiatives and sophisticated reservoir modeling efforts throughout the Wayang Windu area.

The application of volcanic facies models to stratovolcano-hosted geothermal systems, using Wayang Windu as a case study, has been demonstrated effectively (Bogie and Mackenzie, 1998). This work, together with the comprehensive field overview, established the conceptual basis for understanding the dual-phase reservoir system and the spatial distribution of upflow zones (Bogie *et al*., 2008). These insights were further supported by studies that contextualized the Wayang Windu within the broader evolution of geothermal exploration in Indonesia and the characteristics of volcanic geothermal systems (Hochstein and Browne, 2000; Hochstein and Sudarman, 2015).

Regional tectonic reconstructions and volcanic rock distribution studies provide essential context for understanding the geodynamic setting of West Java Geothermal Systems (Hall, 2012). Additionally, structural assessments and fracture analyses have refined the understanding of permeability architecture in Wayang Windu (Sugiono and Rusitadi, 2012; Ramadhan and Masri, 2014).

Comprehensive hydrogeological investigations and detailed isotopic analyses have significantly illuminated the critical importance of well-defined recharge zones and the extensive network of fracture-controlled permeability systems in maintaining the long-term sustainability and productivity of the geothermal system (Hendrasto and Hutasoit, 2007; Hendrasto, 2014). Their meticulous research demonstrated how precipitation infiltration patterns and groundwater movement through fractured volcanic media directly influence reservoir replenishment rates and thermal equilibrium. These fundamental hydrogeological insights were substantially enhanced and corroborated through sophisticated analytical approaches, including high-resolution gravity surveys, density contrast modeling, and advanced 3D geomechanical simulations to precisely map and characterise the complex network of structurally controlled fluid pathways, permeable fault zones, and discrete reservoir compartments throughout the geothermal field (Kusumah *et al.*, 2010; Masri *et al*., 2015). This integrated methodology enabled the identification of preferential fluid migration routes and hydraulically isolated reservoir sections, providing crucial information for optimizing well placement and production strategies.

Geochemical methodologies have been foundational and instrumental in comprehensive geothermal characterization efforts. Robust theoretical frameworks and meticulous empirical methodologies continue to serve as cornerstones for modern geochemical applications in geothermal science (Giggenbach, 1980). These pioneering researchers systematically developed sophisticated techniques for geothermometry calculations, quantitative modeling of solute equilibrium relationships, and high-precision isotopic tracing protocols that collectively revolutionized the understanding of hydrothermal fluid dynamics and water-rock interactions at elevated temperatures and pressures. Their comprehensive analytical approaches enabled researchers to reliably estimate subsurface reservoir temperatures, to characterize fluid mixing processes, to determine residence times, and to identify primary water sources within complex geothermal systems. These established methodological frameworks have been specifically adapted and rigorously applied in the Wayang Windu Geothermal context through detailed time-series analyses that meticulously documented the progressive chemical evolution patterns in reservoir fluids throughout the pre-production baseline period and subsequent production phases (Fahrurrozie, 2014). Similarly, advanced mineralogical and geochemical techniques have been employed to systematically investigate and to characterize the complex hydrothermal alteration patterns and mineral paragenesis sequences observed in the northern sector of the field, providing crucial information about historical fluid-rock interaction processes and thermal regime evolution within the geothermal system.

Geothermal geochemistry is a branch of science that investigates the chemical composition of hydrothermal fluids and their interactions with reservoir rocks. Previous studies have shown that analyses of anions, cations, and stable isotopes can be used to identify water types, fluid origins, and reservoir temperatures (Bogie *et al*., 2008). Ternary diagrams such as Cl-SO_4-HCO_3 and Na-K-Mg are commonly used to classify geothermal water types, while stable isotopes δ^2H and $\delta^{18}O$ are employed to determine groundwater origins. Additionally, gas analyses involving CO_2, N_2, and Ar provide insights into magmatic degassing processes and fluid-atmosphere interactions. These interpretations are based on foundational studies in geothermal geochemistry (Giggenbach, 1980). Although the Wayang Windu Field has been the subject of various geological and geophysical investigations, comprehensive geochemical studies remain limited. Therefore, this research seeks to fill that gap through a systematic and thorough geochemical approach.

A critical assessment of the existing literature reveals several significant knowledge gaps in the geochemical understanding of the Wayang Windu Geothermal Field. First, there is limited integration of fluid geochemistry with structural controls on fluid flow, particularly regarding how fault and fracture systems influence the spatial distribution of distinct geochemical signatures. Second, temporal variations in fluid chemistry across seasonal cycles remain poorly documented, potentially obscuring important recharge dynamics. Third, detailed isotopic fingerprinting of different water sources (meteoric, magmatic, connate) has not been comprehensively mapped across the field's extent. Addressing these specific gaps would significantly enhance conceptual models of this geothermal system and improve long-term resource management strategies.

This research is supported by multiple references specifically focused on Wayang Windu (Bogie and Mackenzie, 1998; Bogie *et al*., 2008; Kusumah *et al*., 2010; Sugiono and Rusitadi, 2012; Fahrurrozie, 2014; Hendrasto, 2014; Ramadhan and Masri, 2014; Masri *et al.*, 2015). The main topic of this research is geothermal system characterisation, with emphasis on geochemistry of geothermal fluids (water and gas); reservoir modeling and structure; hydrothermal alteration; geothermometry and isotopic analysis; fracture and fault systems; and volcanostratigraphy and geological mapping.

This is evident from references on geochemical techniques, structural geology, and geothermal exploration methods (Figure 2) (Giggenbach, 1980; Nemcok *et al*., 2004; Nukman, 2014; Hochstein and Sudarman, 2015; Masri *et al*., 2015).

Methods and Materials

The methods consist of collecting both primary and secondary data. Primary data were obtained through field sampling of hot springs, cold springs, and fumarolic gases. Samples were analyzed for physical parameters such as temperature and pH and chemical parameters including anion content (Cl^-, SO_4^{2-}, HCO_3^-), cation content (Na^+, K^+, Mg^{2+}), and stable isotopes (δ^2H and $\delta^{18}O$). Laboratory analyses were conducted using standard methods such as titration, mass spec-

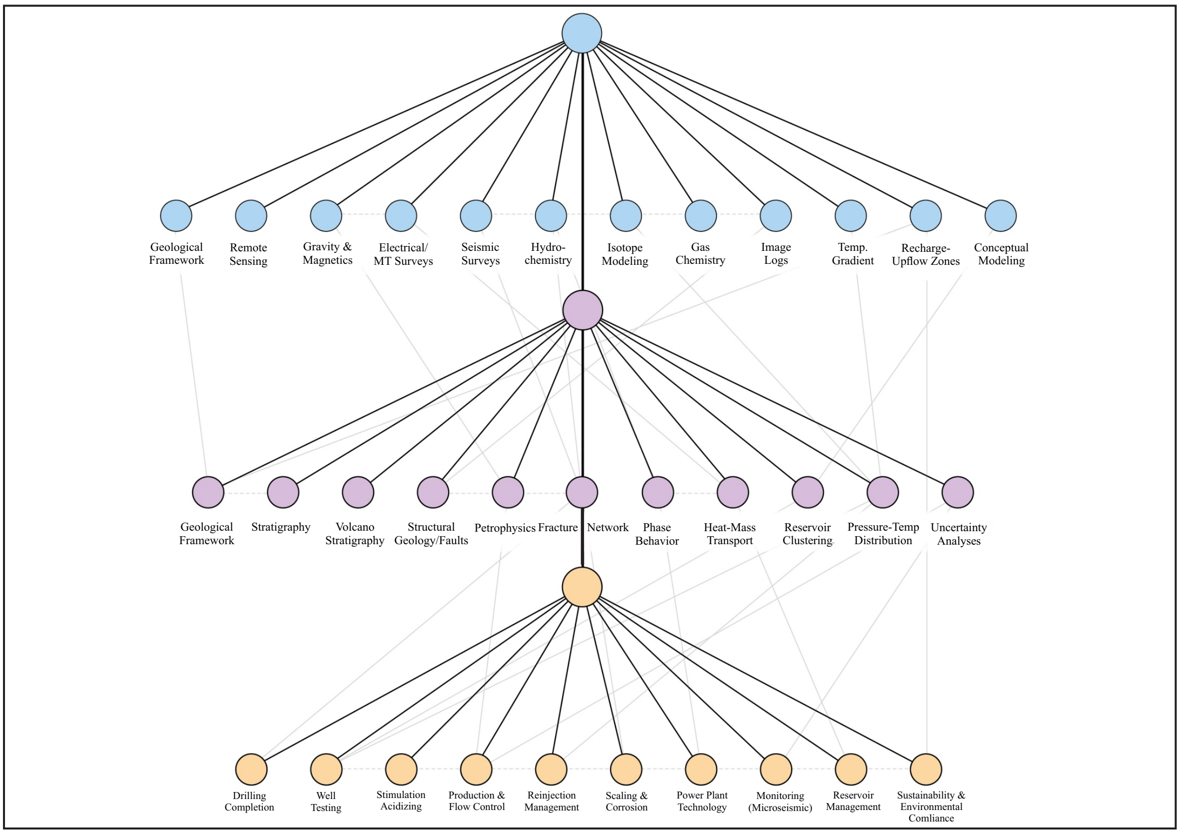

Figure 2. Concept map of geothermal studies in the Wayang Windu area, summarizing research branches based on forty-three Scopus articles.

trometry, and ion chromatography. Secondary data were sourced from literature and previous exploration reports. Interpretation was carried out using ternary diagrams Cl-SO_4-HCO_3, Na-K-Mg, Cl-Li-B, and N_2-CO_2-Ar to determine water types, fluid maturity, and gas origins. The CO_2 gas geothermometer was used to estimate reservoir temperatures. Data validation was performed by comparing analytical results with historical data and existing geological models.

Data

Data for this study were obtained through both indirect and direct methods. Indirect data acquisition involved a comprehensive literature review, including previous research reports, existing maps, and scientific publications.

Direct data collection was conducted at surface levels. Surface investigations included volcanostratigraphic mapping; mapping of thermal manifestations; and sampling of rocks, hot and cold spring waters, as well as gas samples from solfataras. The overall research workflow is illustrated in Figure 3.

The initial dataset comprised geothermal study reports conducted by SEGWL and scientific papers discussing geothermal systems in and around the Wayang Windu area. These data served as the foundation for mapping thermal manifestations and guiding the collection of water and gas samples. The mapping data represent primary data collected systematically based on the distribution of thermal manifestations and cold springs in the Wayang Windu region (Table 1).

The geochemical investigation examined nine thermal springs and forty-one cold springs within the Wayang Windu Geothermal Field. Table 2 presents the sampling locations and observation codes, with their spatial distribution illustrated in Figures 4, 5, and 6. Secondary rainwater data appear in Table 3 (Hendrasto and Hutasoit, 2007; Matahelumual and Wahyudin, 2009).

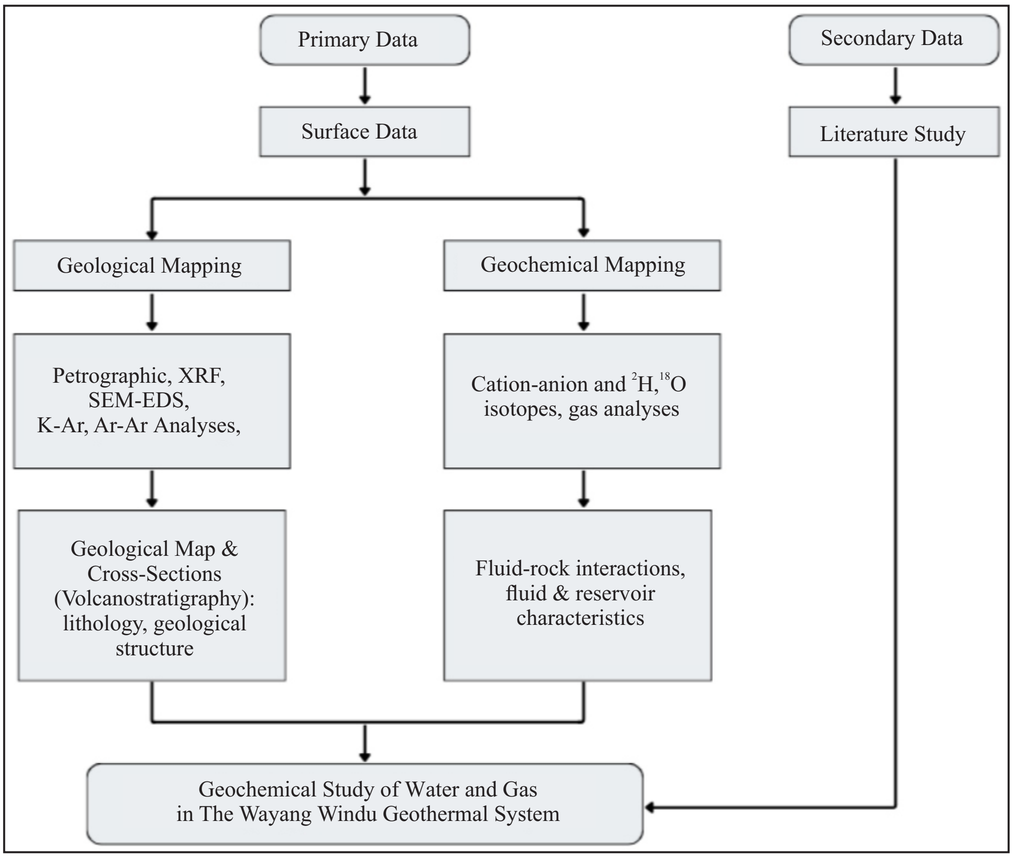

Figure 3. Overall research workflow.

Table 1. Types of Data Used in The Water and Gas Geochemistry Study

No.	Water and Gas Sample Data	Data Source	Data Type	Quantity
1	Physical parameters (hot water)	Field	Primary	8
2	Water chemistry cation-anion (hot water)	Laboratory	Primary	8
3	Stable isotopes (hot water)	Laboratory	Primary	8
4	Tritium (hot water)	Laboratory	Primary	7
5	Physical parameters (cold water)	Field	Primary	42
6	Cation-anion (cold water)	Laboratory	Primary	30
7	Stable isotopes (cold water)	Laboratory	Primary	34
8	Tritium (cold water)	Laboratory	Primary	12
9	Gas chemistry (solfatara)	Laboratory	Primary	4
10	Stable isotopes (solfatara)	Laboratory	Primary	4

Water and Gas Geochemistry

The methodology employed in this study includes the following steps:

- Literature Review: Indirect data collection through a review of previous research reports, existing maps, and scientific publications

Table 2. Sampling Locations and Observation Codes

Location	Spring Type	Code	Coordinates (UTM)		Elevation (masl)
			Easting (mT)	*Northing* (mU)	
Kawah Wayang	Hot/warm	KWA	791248	9202594	1930
Cibolang	Hot/warm	CBB	789076	9199758	1518
Malabar	Hot/warm	MBA	790885	9206762	1867
Kertamanah	Hot/warm	KM	788537	9204712	1524
Tirta Bidadari	Hot/warm	TB	786791	9204735	1587
Pejaten	Hot/warm	PJ	792831	9203520	1610
Cilaki	Hot/warm	CLK	784751	9198893	1343
Citawa	Hot/warm	CT	791450	9200711	1625
Sukaratu	Hot/warm	SR	789174	9202179	1566
Ciseupan*	Cold	AD-BD	792131	9203650	1703
Situ Kinceu	Cold	AD-SK	788842	9203792	1528
Citawa	Cold	CTW1	791649	9199991	1686
Cisanti	Cold	CST-1	793299	9202440	1593
Cisanti	Cold	CST-2	793224	9202194	1615
Cinyiruan	Cold	MAD-1 CNY	787670	9206418	1635
Curug Panganten	Cold	CP4	789902	9207742	2026
Curug Panganten	Cold	CP5	789915	9207690	2010
Curug Panganten	Cold	CP6	789644	9207607	1960
Curug Panganten	Cold	CP7	789893	9207380	1951
MBB1	Cold	MAD MBB1	790475	9207834	2114
Munjul	Cold	MAD MJ1	787679	9206922	1690
Munjul	Cold	MAD MJ2	788289	9207460	1862
Sukaratu	Cold	MAD SR1	788663	9202137	1578
Sukaratu	Cold	MAD SR2	788673	9202144	1577
Ciliang	Cold	MAD CLG	786234	9204707	1496
Cigoong*	Cold	AD-01	794880	9202999	1496
Pejaten	Cold	MAD-PJ	793793	9203669	1496
Cikoleberes	Cold	AD-03	793271	9202152	1593
Ciblegblegan	Cold	AD-04	793353	9201330	1593
Citawa	Cold	AD-05	791649	9199991	1593
Santosa	Cold	MAD STS	791012	9199131	1639

Table 2. Contiued ...

Location	Spring Type	Code	Coordinates (UTM)		Elevation (masl)
			Easting (mT)	*Northing* (mU)	
Banjarsari	Cold	MAD BNJ	786903	9201664	1534
Cisaladah	Cold	MAD CS	787681	9200924	1553
Cisemen	Cold	MAD CSM	789279	9198517	1511
Hong Bou	Cold	MAD-HB	787400	9203166	1539
Cilíouk	Cold	MAD-CL	788163	9199770	1502
Ciliweung	Cold	MAD-CLW	788379	9199865	1505
Ciseng	Cold	MAD-CSG	788245	9199876	1508
Babakanranca	Cold	MAD-BBR	792824	9199826	1648
Cianjing	Cold	MAD CNJ	795102	9204269	1525
Kebon Dua	Cold	MAD KB2	793563	9206978	1757
Berecek	Cold	MAD BRC	795177	9207640	1543
Sukapa	Cold	MAD SKP	796416	9206659	1389
Cibeureumeumpe	Cold	MAD-01	783854	9205318	1413
Cikakapa	Cold	MAD-02	788950	9205306	1627
Banjarsari	Cold	MAD-03	786561	9202021	1541
Sukaratu	Cold	MAD-05	789195	9201422	1583
Sukaratu	Cold	MAD-06	789429	9201940	1614
Cinyiruan	Cold	MAD-07	787408	9206275	1581
Tirtasari	Cold	MAD-08	786362	9207489	1519

Figure 4. Water sampling procedure: a. Measurement of water physical parameters; b. Data recording/documentation; c. Water sample collection; d. Filtration for chemical analysis.

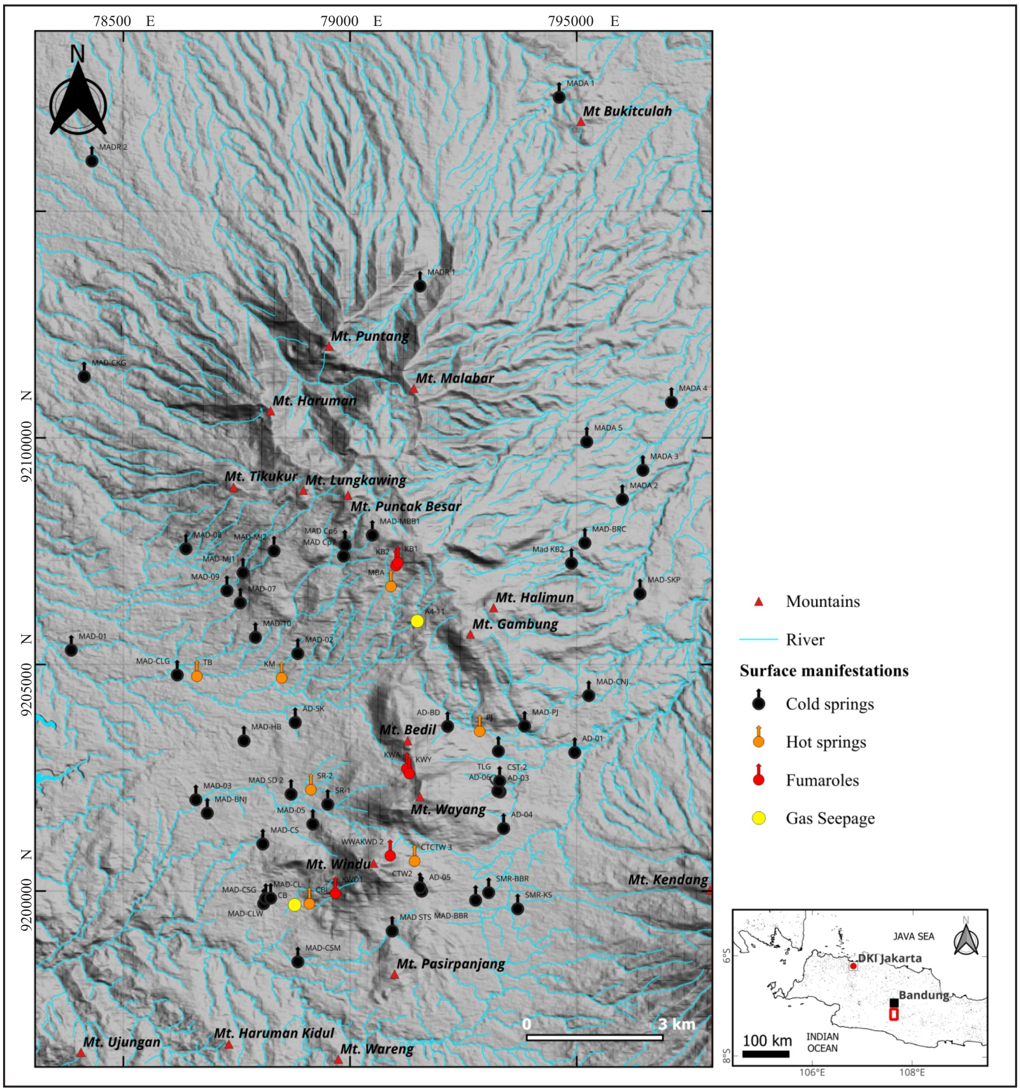

Figure 5. Map of surface manifestations and water and gas sampling locations.

relevant to water and gas geochemistry in geothermal fields.

- Field Measurements: Physical parameters measured at each hot, warm, and cold spring manifestation. These included air and water temperature, pH, total dissolved solids (TDS), redox potential, dimensions of the manifestation, and discharge rate. Water samples were collected when necessary.
- Laboratory Analysis: Chemical analyses to determine the concentrations of dissolved ions such as Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, CO_3^{2-}, NH_4^+, and Fe^{3+}, as well as stable isotopes ^2H and ^{18}O. Similar analyses were conducted on selected hot and warm springs to support hydrogeological interpretations of the studied area.
- Geochemical Data Processing: Water geochemistry data were processed using ternary diagrams, including Cl-SO_4-HCO_3, Na-K-Mg, and Cl-Li-B. Gas geochemistry data were analyzed using the N_2-CO_2-Ar ternary diagram. Secondary data from literature, such as local rainwater hydrochemistry, were also incorporated to assess the initial composition and physical characteristics of groundwater.

Through the integration of physical parameters, chemical composition changes, and geological data, further analysis and interpre-

Figure 6. Water sampling locations:a. Kertamanah hot spring (KM); b. MBA hot spring (MBA); c. Citawa warm spring (CT), d. Tirta Bidadari warm spring (TB); e. Situ Kinceu cold spring (AD-SK); f. Ciblegblegan cold spring (AD-04).

Table 3. Secondary Rainwater Data

Location	Rain Station	Coordinates (UTM)		Elevation (m.asl)
		Easting (mT)	*Northing* (mU)	
Soreang	1	780209	9222534	727
Desa Tribaktimulya	2	782747	9209717	1173
Perkebunan Malabar	3	787505	9200221	1544
Perkebunan Talun-Santosa	4	791510	9197392	1662

tation were conducted. The outcomes include a comprehensive assessment and conceptual model of the Wayang Windu Geothermal System.

Analytical Procedures

Water Sample Analysis

Water samples were analyzed for physical and chemical parameters to determine ion balance and to classify water types and facies using discriminant diagrams. Water samples were categorized into two types: those for isotope analysis and those for dissolved ion analysis. Before sampling, ambient air temperature and spring-specific physical parameters were measured, including water temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS). Where possible, spring dimensions, discharge rates, and qualitative descriptions of spring characteristics were also recorded.

The sampling procedure followed a standardized methodology. For anion-cation analysis, water was collected in two 250 mL plastic bottles after filtration through micropore filter paper with an 8 µm pore size. The sample designated for cation analysis was acidified with HNO_3 to prevent silica precipitation and unwanted cation-anion reactions. Anion concentrations were determined using ion chromatography, while cation concentrations were measured via Atomic Absorption Spectroscopy (AAS). These analyses were conducted at The Centre for Mineral, Coal, and Geothermal Resources (PSDMBP), Geological Agency, Ministry of Energy and Mineral Resources (KESDM).

Isotope samples were collected in 50 ml plastic bottles with careful handling to exclude air bubbles. Isotope analysis was performed using the Cavity Ring-Down Spectroscopy (CRDS) method at the Testing Laboratory of the Centre for Isotope and Radiation Applications, National Nuclear Energy Agency (BATAN).

Gas Sample Analysis

Geothermal gas parameters were examined to estimate reservoir temperatures using gas geothermometers. These geothermometers rely on the chemical equilibrium of specific gas species, such as CO_2, H_2S, and CH_4, to infer subsurface thermal conditions. The geochemical data obtained from both water and gas analyses were integrated with volcanostratigraphic mapping data to construct a comprehensive geochemical model of the Wayang Windu Geothermal System. This integration allowed for a more accurate delineation of subsurface thermal anomalies and fluid pathways, enhancing the reliability of the geothermal resource assessment.

Gas sampling protocols in geothermal surveys are essential to ensure the accuracy and reliability of geochemical data. Sampling begins with careful site selection, targeting geothermal features such as fumaroles, hot springs, steaming ground, and well discharges. These sites are chosen based on temperature, flow stability, accessibility, and their representativeness of the geothermal system. Prior to sampling, all equipment, including evacuated flasks, gas-tight syringes, and Tedlar bags, was sterilized and flushed with inert gas or vacuumed to prevent contamination. Instruments used for field measurements, such as thermocouples and pH meters, were calibrated to ensure precision.

Various sampling techniques are employed depending on the source and type of geothermal feature. For steam vents and fumaroles, direct condensate sampling was used, where condensers separate steam from noncondensable gases. The alkaline absorption method is commonly applied to trap acidic gases like CO_2 and H_2S in sodium hydroxide solutions for later analysis. In the case of well discharges, isobaric samplers were used to maintain pressure and prevent degassing during collection. Gas-tight syringes and flasks were also utilized to collect dry gas samples, ensuring minimal atmospheric contamination.

Field measurements were recorded alongside gas sampling to support geothermometric calculations and to provide context for geochemical interpretations. These included temperature, pressure, flow rate, pH, and conductivity, particularly for associated water samples. Each sample was carefully labeled with site information, including date, time, and environmental conditions, and stored in cool, dark containers to preserve chemical integrity during transport to the laboratory.

To maintain data quality and traceability, strict quality control measures were implemented throughout the sampling process. Replicate samples were collected to assess reproducibility, while blanks and standards were used to detect contamination and calibrate analytical instruments. A chain of custody was maintained to track sample handling from field collection to laboratory analysis. These protocols collectively ensure that the gas samples accurately reflect the subsurface conditions of the geothermal system and contribute meaningfully to the overall geochemical model.

Results and Discussions

Results

Hydrothermal Fluid Characteristics and Flow Patterns

The geochemical investigation of the Wayang Windu Geothermal Field successfully identified the characteristics of hydrothermal fluids and subsurface flow patterns. Three main reservoir clusters were identified, indicating zones of upflow and lateral flow. Sulfate-type hot springs mark upflow zones, while bicarbonate-type warm and cold springs indicate lateral flow and thermal fluid contamination. Isotopic analysis shows that most groundwater originates from meteoric sources, with some influenced by steam heating or magmatic water. Gas composition analysis confirms CO_2 dominance and magmatic degassing processes, with reservoir temperatures ranging from 225°C to 286°C. These findings provide valuable insights into the Wayang Windu Geothermal System and serve as a foundation for sustainable geothermal energy development.

Spring Classification And Geochemical Signatures

The analysis revealed that hot springs such as MBA, KWA, and CT exhibit a sulphate-type composition, indicating zones of hydrothermal upflow. In contrast, warm springs such as CB, TB, PJ, KM, CLK, and SR show bicarbonate-type characteristics, reflecting lateral flow. Most cold springs are also bicarbonate-type, although some show signs of thermal fluid contamination. Isotopic analysis of δ^2H and $\delta^{18}O$ indicates that KWA originates from magmatic water and MBA from local meteoric water, and others have undergone steam heating. Gas composition analysis shows a dominance of CO_2, with Non-Condensable Gas (NCG) levels ranging from 1.62% to 8.94%. Low O_2 concentrations indicate excellent sample quality, while low HCl and HF levels suggest that the magma has cooled. Gas geo-indicators show that KWD1 and KWD2 are associated with magmatic degassing, whereas KWY and KWB are influenced by atmospheric gases. Reservoir temperatures estimated using the CO_2 geothermometer range from 225°C to 286°C. Overall, The Wayang Windu Geothermal System comprises three main reservoir clusters: Gambung, Wayang, and Windu, with complex fluid flow patterns.

The MBA, KWA, and CT hot springs are characterized by high sulfate concentrations, indicating magmatic gas condensation processes. In contrast, CB, TB, PJ, KM, CLK, and SR springs exhibit bicarbonate-type thermal waters, typically associated with lateral outflow zones in geothermal systems. Most cold springs in the studied area is classified as bicarbonate-type, with the exception of MAD-1, MAD BRC, and MAD SR2, which show elevated sulfate levels—likely due to agricultural contamination. Springs such as AD-SK, MAD-8, MAD CSM, MAD CLG, CHR, and AD-01 contain bicarbonate waters with relatively high sulfate content, while MAD-3 and MAD HB exhibit bicarbonate waters enriched in chloride, resembling the chemical composition of local rainwater.

Reservoir Clustering and Temperature Estimation

Based on Cl/B and Cl/Li ratios and the Cl–Li–B ternary diagram, three distinct clusters were identified, corresponding to three separate geothermal reservoirs: Gambung, Wayang, and Windu. Additionally, Na/K ratios below 15 suggest that the sampled fluids originate from upflow zones or zones with high permeability.

Isotopic Analysis of Water Sources

The δ^2H versus $\delta^{18}O$ isotopic plot shows that the KWA hot spring is derived from magmatic water, representing condensate in an upflow zone. The MBA thermal spring plots near the global meteoric water line, suggesting its origin from local meteoric groundwater. Warm springs TB, SR, CT, CB, CLK, and KM follow a trend consistent with steam-heated or evaporative processes, indicating subsurface heating by steam—a hallmark of lateral-flow zones. Most cold springs align with the local meteoric water line, confirming their precipitation origin. However, slight isotopic shifts in MAD SR2, CP5, and MAD-CNJ suggest minor thermal fluid contamination.

Gas Composition and Geo-indicators

Gas composition analysis revealed noncondensable gas (NCG) contents ranging from 1.62% to 8.94%, predominantly composed of CO_2. The low oxygen concentrations confirm high sample integrity. The low levels of volatile components such as HCl and HF suggest that the heat source in the Wayang Windu Geothermal System is a cooling magma body. Geo-indicator analysis using the N_2–He–Ar ternary diagram indicates that gases from Kawah Windu 1 (KWD1) and Kawah Windu 2 (KWD2) are magmatic in origin, while those from Kawah Wayang (KWY) and Kawah Burung (KWB) are atmospheric. Gas geothermometry, based on the H_2/Ar and CO_2/Ar ratio grid, estimates reservoir temperatures between 225° and 275°C under equilibrated vapour conditions, consistent with a high-temperature geothermal system.

Discussions of Conceptual Model

Multidisciplinary Approaches in Geothermal Exploration

The integration of structural geology and hydrochemistry in geothermal exploration has been demonstrated in other Indonesian settings, offering comparative insights into fracture development and fluid migration in volcanic arcs (Nemcok *et al*., 2004; Nukman, 2014). Remote sensing approaches have also proven valuable for mapping volcanic hazards and geothermal potential (Saepuloh *et al*., 2017). Geospatial and geostatistical tools for geothermal prospectivity mapping, along with sustainability assessments, highlight the importance of integrating multidisciplinary data for long-term resource management (Energy, 2011).

Geological Framework of The Wayang Windu Geothermal System

The Wayang Windu Geothermal Field is classified as a hydrothermal geothermal system associated with a young stratovolcano. Hydrothermal systems linked to stratovolcanoes typically comprise four principal components: a heat source, a reservoir, a recharge area, and a discharge area, the latter of which is expressed at the surface through thermal manifestations (Hochstein and Browne, 2000; Hochstein and Sudarman, 2015).

The discharge area may result from either vertical (upflow) or lateral (outflow) fluid movement within the geothermal system. In upflow zones, the surface manifestations are typically characterized by sulfate-rich thermal fluids and are commonly located near the summits of stratovolcanoes. In contrast, the peripheral zones of such systems often exhibit chloride-type thermal springs with neutral pH values (Figure 7). Additionally, bicarbonate-type thermal springs, sometimes mixed with sulfate or chloride waters, may occur in lateral flow zones.

The heat source in the Wayang Windu Geothermal Field is primarily associated with a complex of volcanic eruptive centres strategically positioned south of Mount Malabar, specifically including Mount Windu, Mount Wayang, and Mount Gambung. These volcanic edifices are believed to contribute significant thermal energy to the underlying geothermal system through magmatic intrusions and residual heat transfer processes. This interpretation is substantiated by comprehensive analyses of fluid geochemistry from production wells and detailed characterization of surface manifestations, both of which consistently indicate pronounced fluid upwelling phenomena concentrated in the immediate vicinity of these volcanic structures (Hendrasto, 2014). The spatial correlation between these eruptive centres and zones of intensified hydrothermal activity strongly suggests

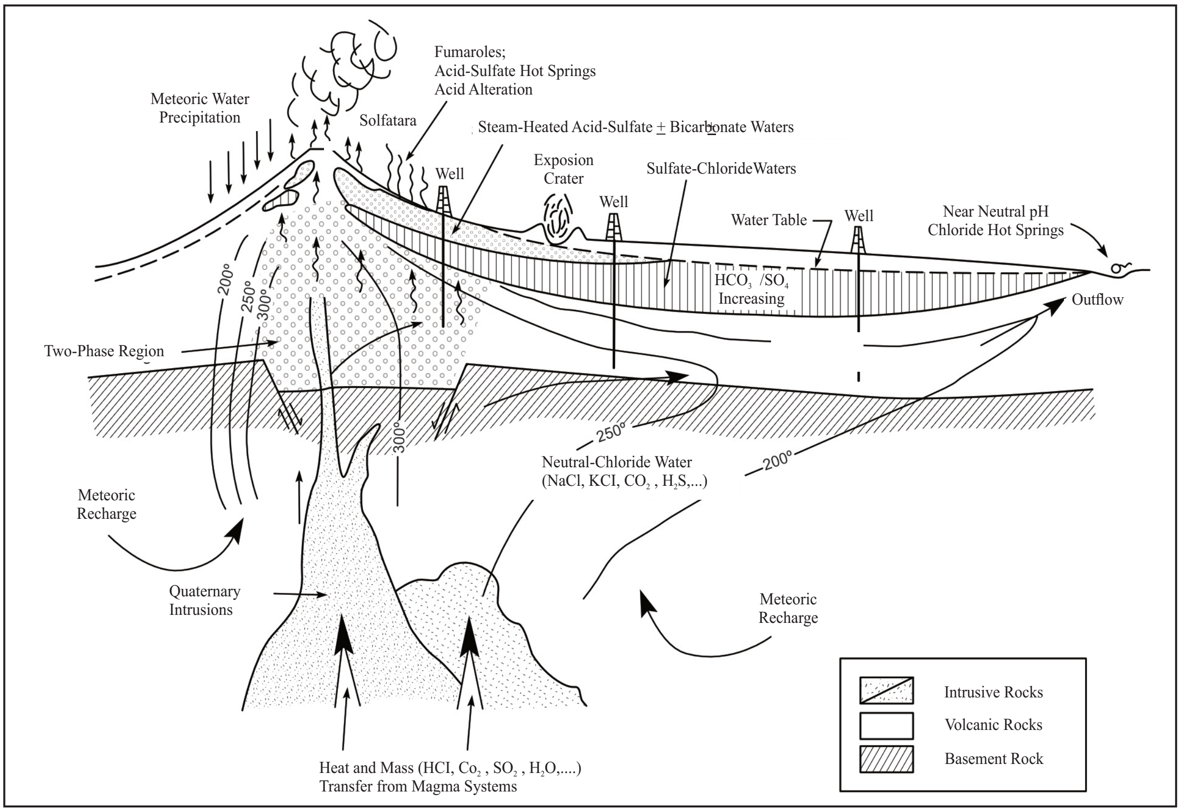

Figure 7. Conceptual model of a stratovolcano-hosted geothermal system (Goff and Janik, 2000).

that this particular area constitutes the primary zone of enhanced thermal convection within the broader geothermal field, where heat transfer from deep magmatic sources to circulating groundwater reaches its maximum efficiency.

Reservoir Characteristics and Vapour-Dominated Zone

The northern sector of the Wayang Windu reservoir is characterized by a complex two-phase hydrothermal system, with a distinctive vapour-dominated zone occupying the elevation interval between 500 and 1,330 m asl. This vapour-rich region is precisely delineated by multiple geological and geophysical indicators, most notably the presence of epidote mineral assemblages that mark its upper boundary. Additional confirmation of this zone's extent comes from detailed well temperature profiles collected during drilling operations and subsequent production testing. The distribution of these diagnostic mineralogical markers, combined with the thermal gradient patterns observed in exploration wells, provides strong evidence for the spatial configuration of this vapour-dominated portion of the reservoir system.

Comprehensive geochemical analyses of reservoir fluids from production wells reveal distinctive physicochemical properties throughout this northern reservoir section. Fluid temperatures consistently range between 250° C and 260° C, placing this system in the high-enthalpy category of geothermal resources. Chemical characterization shows that these geothermal waters maintain near-neutral pH values and exhibit a predominantly chloride-type composition, suggesting minimal interaction with acidic magmatic volatiles and prolonged water-rock equilibration at elevated temperatures. These geochemical signatures are consistent with mature hydrothermal systems where fluid compositions have reached relative equilibrium with the surrounding host rocks, providing valuable insights into the reservoir evolution and potential production characteristics (Bogie *et al*., 2008).

The caprock structure within the Wayang Windu Geothermal Field is distinctly characterized through detailed geophysical investigations that have identified a well-defined conductive layer with a resistivity measurement of approximately 5 Ohm·m. This low-resistivity zone represents the impermeable barrier that effectively contains the geothermal fluids within the reservoir system below. Comprehensive magnetotelluric surveys conducted across the field have revealed that this cap rock formation exhibits considerable variability in its vertical dimension, with an average thickness of approximately 500 m across most of the field. Notably, the cap rock layer displays significant thinning in specific locations that have been interpreted as upflow zones, where hot fluids from deeper portions of the reservoir ascend toward the surface through zones of enhanced permeability, often associated with structural features such as faults or fracture networks.

Subsurface Structure and Recharge Dynamics

Spatial analysis of the geophysical data has enabled precise delineation of this conductive layer's horizontal extent, revealing that it covers an expansive area of approximately 40 km² within the broader geological context of the Wayang Windu region. This areal extent is considered highly significant from a resource assessment perspective, as it effectively defines the spatial boundaries of the potential geothermal reservoir beneath. The correlation between the cap rock distribution and underlying reservoir characteristics has been further validated through multiple exploratory wells that have successfully intercepted productive reservoir zones precisely predicted by the geophysical model. This integration of surface geophysical data with subsurface well information has substantially enhanced the accuracy of reservoir volumetric calculations and resource potential estimates, providing critical parameters for sustainable development planning and optimal production strategies for the Wayang Windu Geothermal Field.

Recharge zones within the Wayang Windu Geothermal Field are distributed across two distinct elevation bands, with the lower zone ranging from 1,317 to 1,606 m asl and the higher zone extending from 1,987 to 2,837 m asl, as documented by Hendrasto and Hutasoit, (2007). This vertical distribution significantly influences the hydrogeological dynamics of the geothermal system, as it creates differential hydraulic gradients that drive groundwater circulation through the subsurface fracture networks. The substantial elevation differential between these recharge zones (approximately 670 m between the upper boundary of the lower zone and the lower boundary of the higher zone) establishes considerable hydrostatic pressure that facilitates the deep percolation of meteoric water into the geothermal reservoir system, providing the necessary fluid component for sustained hydrothermal circulation and heat transfer processes.

From a morphological perspective, the higher elevation recharge areas (1,987–2,837 m) constitute integral components of an extensive mountainous complex that encircles the Wayang Windu Geothermal Field, creating a natural watershed that channels precipitation toward the geothermal system. The northern section of this mountainous recharge system is prominently defined by the impressive elevations of Mount Puncak Besar and Mount Malabar, which serve as principal precipitation collection zones during the wet season. Conversely, the southern recharge areas are concentrated around Mount Karancang, which functions as an additional significant catchment zone that contributes substantially to the hydrogeological budget of the geothermal system. This spatial arrangement of elevated recharge zones surrounding the geothermal field creates an ideal hydrogeological configuration that ensures consistent groundwater replenishment to maintain the long-term sustainability and productivity of the Wayang Windu geothermal resource.

Surface Manifestations and Hydrothermal Activity

Numerous surface manifestations are observed in the Wayang Windu Geothermal Field, including five solfataras (Kawah Burung 1, Kawah Burung 2, Kawah Wayang, Kawah Windu 1, and Kawah Windu 2), ten hot springs (MBA or Kawah Burung 3, Tirta Bidadari, Kertamanah, Kawah Wayang, Pejaten, Sukaratu, Citawa, Cilaki, Cibolang 1, and Cibolang 2), one gas emission site, and areas of hydrothermal alteration. These features indicate the presence of an active hydrothermal fluid circulation system.

In addition to hot and warm springs, dozens of cold springs are also found near the thermal manifestations (Figures 8 and 9). The spatial closeness of geothermal manifestations and cold springs suggests the potential for groundwater mixing, which may influence the chemical composition and quality of the groundwater. Active manifestations are predominantly located in the southern part of Mount Malabar, particularly around the MBA and Kawah Wayang hot springs, which are sulfate-rich. The presence of five solfataras in this area further supports the interpretation that this zone represents the upflow region of the Wayang Windu Geothermal System (Fahrurrozie, 2014).

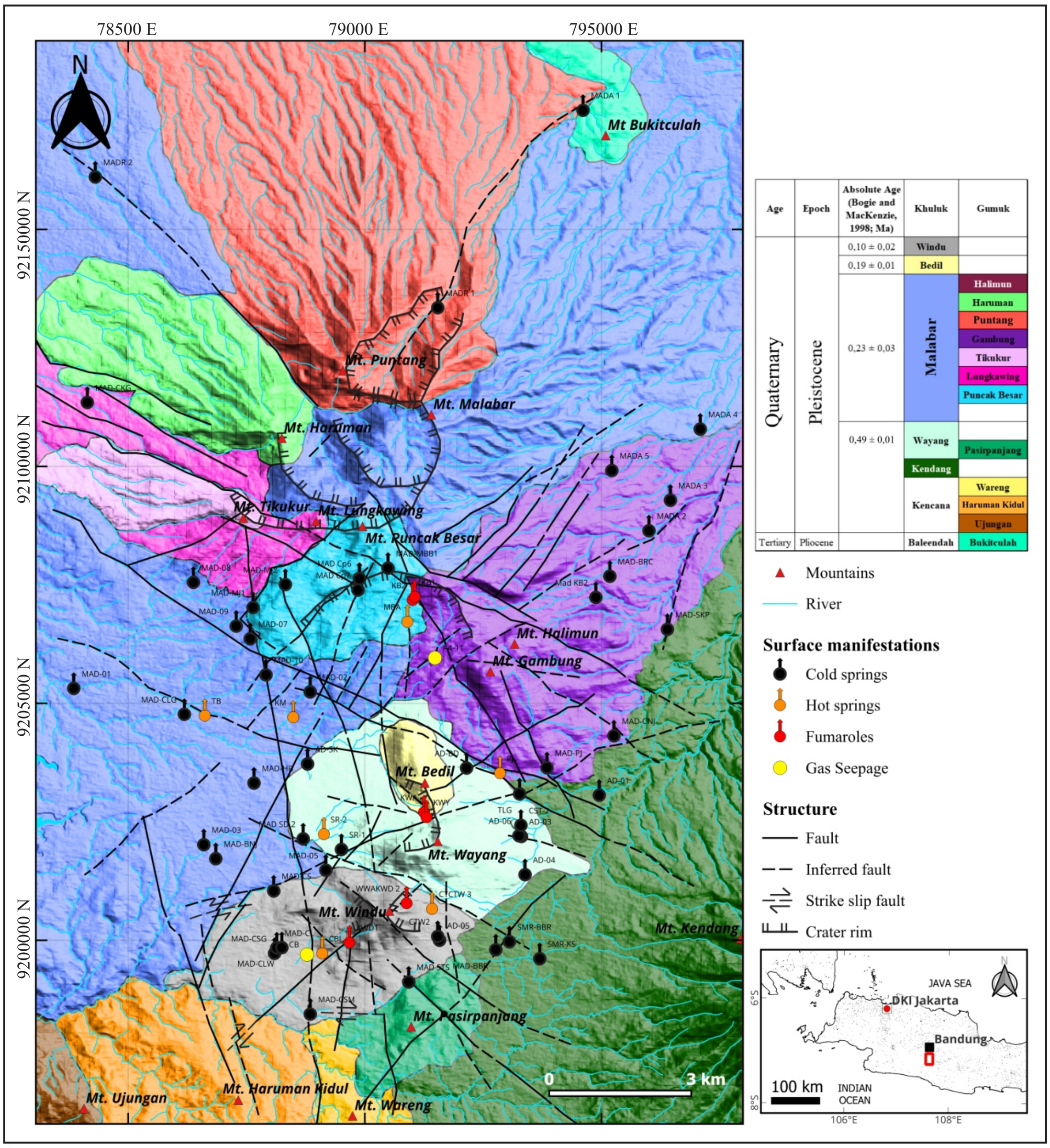

Figure 8. Volcanostratigraphic map of the *studied area* showing the distribution of volcanic domes and cones, geological structures, surface manifestations, and SEGWL drilling wells.

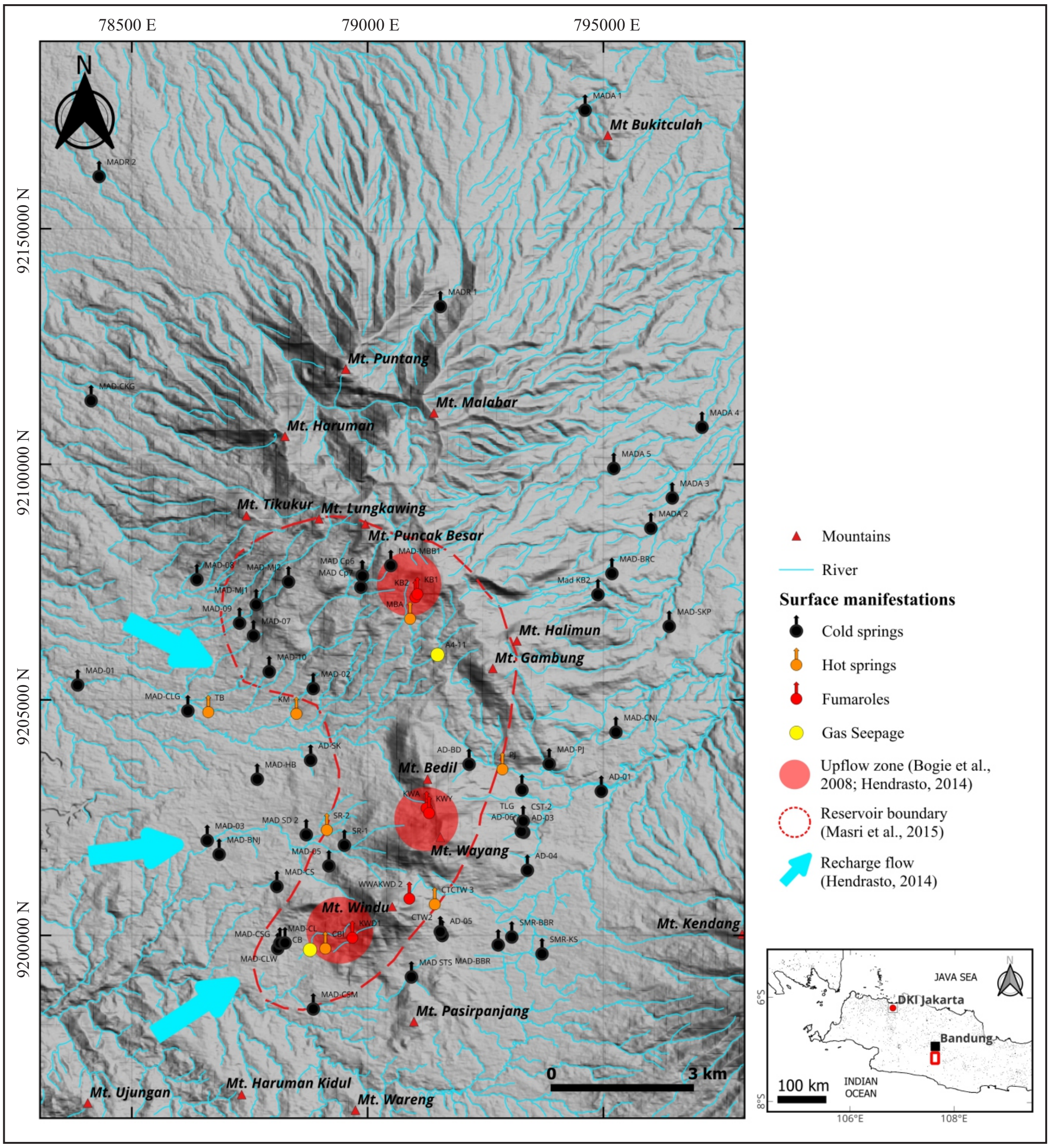

Figure 9. Map of surface manifestation distribution.

Conclusions

This study provides a detailed geochemical and hydrogeological characterization of the Wayang Windu Geothermal System, integrating field observations, laboratory analyses, and conceptual modeling. Through systematic sampling and analyses of hot and cold springs, as well as fumarolic gases, three distinct reservoir clusters – Gambung, Wayang, and Windu – were identified, each exhibiting unique hydrothermal fluid signatures and flow dynamics. Sulfate-type hot springs were found to mark upflow zones, whereas bicarbonate-type warm and cold springs indicate lateral outflow and mixing processes. Isotopic analyses (δ^2H and $\delta^{18}O$) confirm that meteoric water is the dominant recharge source, with localized magmatic and steam-heated influences contributing to fluid evolution.

Gas geochemistry revealed CO_2-dominated compositions and magmatic degassing processes, with noncondensable gas contents ranging from 1.62% to 8.94%. Reservoir temperatures estimated using gas geothermometers fall within

225° C to 286° C, consistent with a high-enthalpy geothermal system. The presence of vapour-dominated zones and well-defined cap rock structures further supports this classification. Integration of geochemical data with volcanostratigraphic and structural mapping delineates fluid pathways and recharge zones, highlighting the critical role of fracture-controlled permeability in sustaining reservoir productivity.

These findings not only advance the understanding of fluid chemistry and subsurface dynamics in volcanic geothermal systems but also provide practical insights for resource management. The identification of reservoir clusters and recharge mechanisms offers a quantitative basis for optimizing well placement, monitoring strategies, and long-term sustainability planning. Additionally, this research fills significant knowledge gaps regarding seasonal variations in fluid chemistry and isotopic fingerprinting, establishing a foundation for future studies on the resilience of geothermal systems in the face of changing climatic conditions. Overall, the multidisciplinary approach adopted here emphasises the necessity of integrating geochemistry, geology, and geophysics to ensure efficient and sustainable development of geothermal energy resources in tropical volcanic settings.

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