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IDENTIFICATION OF DEEP AQUIFER DEPTH IN LAVA FAN AREA, HARUMAN PEAK, MALABAR MOUNTAINS BASED ON AUDIO MAGNETOTELLURIC SOUNDING

ASEP HARJA[1]*, SHOFIE DZAKIA HANIFAH[2], NABILAH RAHMAWATI[2], NABILA PUTRI KUSUMA[2], G. M. LUCKI JUNURSYA[3]

[1]Department of Geophysics, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, Jl. Raya Bandung-Sumedang Km. 21, Jatinangor, 45363
[2]Program Study of Geophysics, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, Jl. Raya Bandung-Sumedang Km. 21, Jatinangor, 45363
[3]Center for Geological Survey, Ministry of Energy and Mineral Resources, Jl. Diponegoro No.57, Bandung, Jawa Barat 40115, Indonesia

*Corresponding author
Email: a.harja@unpad.ac.id

Abstract. Haruman Peak, located in the southern region of the Bandung Basin, is one of the summits of the Malabar Mountains. This mountain range functions as a significant recharge area for the Bandung-Soreang Groundwater Basin, a role supported by its dense vegetation cover, high precipitation, and slopes that facilitate direct runoff into the basin. Previous studies have identified the presence of shallow aquifers in the Haruman Peak area at depths of less than 40 meters. This study aims to investigate the existence of deeper aquifer systems in the Haruman Peak area using the Audio-Magnetotelluric (AMT) method. AMT data were acquired at three measurement points located on the northern side of a suspected fault zone. The inversion of the AMT data yielded one-dimensional (1D) resistivity models that provide insight into the subsurface structure. These models were used to interpret the lithological composition and to delineate potential aquifer zones. The subsurface stratigraphy in the study area is interpreted to consist of soil, Malabar–Tilu Volcanics (Qmt), and the Waringin–Bedil Andesite Formation, also referred to as Old Malabar (Qwb). The results indicate the presence of deep aquifers at measurement points MB-01 and MB-02, at estimated depths of approximately 1,322 meters and 804 meters, respectively. At point MB-03, a shallow aquifer was identified within a soil layer at a depth of less than 100 meters.

Keywords: Aquifer, Audio Magnetotelluric, Resistivity,Groundwater, Haruman Peak

Abstrak. *Puncak Haruman, yang terletak di wilayah selatan Cekungan Bandung, merupakan salah satu puncak Pegunungan Malabar. Pegunungan ini berfungsi sebagai daerah imbuhan yang signifikan bagi Cekungan Air Tanah Bandung-Soreang, peran yang didukung oleh tutupan vegetasinya yang rapat, curah hujan yang tinggi, dan lereng yang memudahkan limpasan langsung ke cekungan tersebut. Penelitian sebelumnya telah mengidentifikasi keberadaan akuifer dangkal di wilayah Puncak Haruman pada kedalaman kurang dari 40 meter. Penelitian ini bertujuan untuk menyelidiki keberadaan sistem akuifer yang lebih dalam di wilayah Puncak Haruman menggunakan metode Audio-Magnetotelluric (AMT). Data AMT diperoleh di tiga titik pengukuran yang terletak di sisi utara zona sesar yang diduga. Inversi*

data AMT menghasilkan model resistivitas satu dimensi (1D) yang memberikan wawasan tentang struktur bawah permukaan. Model-model ini digunakan untuk menafsirkan komposisi litologi dan untuk menggambarkan zona akuifer potensial. Stratigrafi bawah permukaan di daerah penelitian diinterpretasikan terdiri dari tanah, Gunungapi Malabar–Tilu (Qmt), dan Formasi Andesit Waringin–Bedil, yang juga disebut sebagai Malabar Tua (Qwb). Hasil penelitian menunjukkan keberadaan akuifer dalam di titik pengukuran MB-01 dan MB-02, dengan perkiraan kedalaman masing-masing sekitar 1.322 meter dan 804 meter. Di titik MB-03, akuifer dangkal teridentifikasi di dalam lapisan tanah pada kedalaman kurang dari 100 meter.

Kata Kunci: *Akuifer, Audio Magnetotellurik, Resistivitas, Air Tanah, Puncak Haruman*

1. Introduction

Malabar Mountains are the highest mountains located in the southern area of Bandung and thus serve as the main recharge area that fills the Bandung-Soreang Groundwater Basin (CAT) [1]. This is supported by the morphology of the mountain slope as it is surrounded by complex alluvial systems and mostly leads to the Bandung Basin [2], along with its densely vegetated area with high annual rainfall, which is around 1.5 - 4.0 mm/year [3].

Based on previous research using the 2D resistivity method in the Puncak Haruman area that included in the western Malabar Mountains range, the shallow aquifer zone is known to be at a depth of less than 40 meters [4]. Considering its morphology and high rainfall, there are assumed to be deeper aquifer systems. Therefore, a geophysical method of deep investigation, such as Audio Magnetotelluric (AMT) method is required.

The AMT method can be applied to subsurface investigations with target depths ranging from 0.03 to 1 kilometers. Another advantage of this method is that its measurement can be carried out on steep slopes. The AMT method research successfully identified the aquifer layer at a depth of up to one kilometer in Tarshich-Lebanon [5]. The results of the 1D AMT method are expected to interpret the deep aquifer zone in the Haruman Peak area based on the contrast of resistivity values.

The Malabar Mountains, the highest range located in the southern part of Bandung, function as the primary recharge area for the Bandung–Soreang Groundwater Basin (CAT) [1]. This role is supported by the mountain's morphology, which features slopes that are part of a complex alluvial system and predominantly drain toward the Bandung Basin.

Previous studies using the 2D resistivity method in the Puncak Haruman region part of the western Malabar Mountain range identified a shallow aquifer zone at depths of less than 40 meters [4]. Given the favorable morphological characteristics and high precipitation, it is hypothesized that deeper aquifer systems may also be present. To explore this possibility, a geophysical method capable of deeper subsurface investigation, such as the Audio-Magnetotelluric (AMT) method, is required.

The AMT method is suitable for imaging subsurface structures at depths ranging from approximately 30 meters to 1 kilometer. One of its key advantages is its applicability in areas with steep topography. A notable example includes successful identification of aquifer layers at depths approaching 1 kilometer in Iwo, Nigeria using the AMT method [5]. In the present study, the 1D inversion results derived from AMT measurements are

used to interpret the presence of deep aquifer zones in the Haruman Peak area, based on resistivity contrasts indicative of lithological changes.

2. Geology of Research Area

This research was conducted in the Puncak Haruman area, located in the western part of the Malabar Mountains, specifically in Warjabakti Village, Cimaung District, Bandung Regency. The Malabar Mountain range is a Quaternary volcanic system characterized by fingered valleys and ridges, forming a distinctive morphology. Volcanic fans provide valuable information about past volcanic activity, including the nature and frequency of eruptions. These landforms are created by the deposition of volcanic materials (such as ash and lava) as they flow downhill, allowing geologists to reconstruct the history of eruptions and understand the dynamics of ancient volcanic systems. The topography of volcanic fans can affect local hydrological patterns. They may serve as natural catchments for rainfall, influencing groundwater recharge and surfacewater flow. This has implications for water resource management in volcanic regions. This landscape was shaped by volcanic materials flowing downslope toward lower elevations, resulting in fan-shaped deposits, commonly referred to as volcanic fans [6].

According to the Geological Map of the Garut and Pameungpeuk Quadrangle (Figure 1), a minor fault is suspected to exist within the study area. This fault appears to align with the slope of Puncak Haruman, trending southeast to northwest. This faults and fractures often create zones of increased secondary porosity and permeability by breaking and shifting the surrounding rock. This allows water to flow more easily through the faulted area compared to the unfractured host rock

The stratigraphic successionof the study area, arranged from the oldest to the youngest geological units, is as follows:

1. Beser Formation (Tmb) – Late Miocene. Composed of tuffaceous breccia and andesitic to basaltic lava flows. This unit is unconformably overlain by Pliocene volcanic rocks.
2. Tuffaceous Breccia (Tpv) – Pliocene. Composed of breccia, tuff, and pumice. This formation unconformably overlies older, undecomposed volcanic units.
3. Undifferentiated Old Volcanics (QTv) – Plio-Pleistocene. Consisting of tuff, tuff breccia, and lava. This unit is unconformably overlain by Quaternary volcanic rocks.
4. Undifferentiated Efflata Deposits of Old Volcanics (Qopu)–Pleistocene. Comprised of crystalline tuff, tuff breccia, and old laharic deposits.
5. Malabar–Tilu Volcanics (Qmt) – Pleistocene. Composed of tuff, laharic breccia containing minor pumice, and lava flows.
6. Mt. Tilu Lavas (Qml) – Pleistocene. Comprising andesitic and basaltic–andesitic lava flows.
7. Andesitic lava and basaltic-andesitic lavas of Mt. Tilu (Qml) of Pleistocene age.
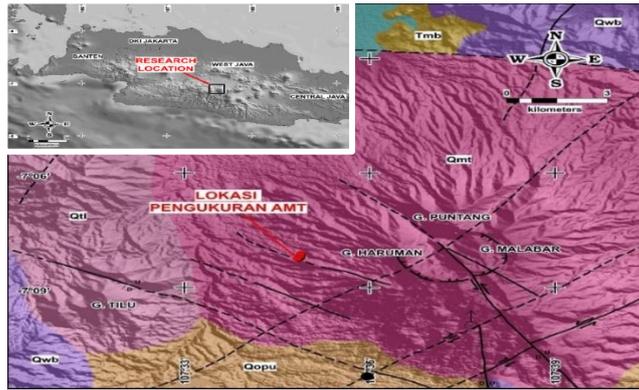
Figure 1. Geological map of Audio Magnetotelluric (AMT) method measurement point locations, modified from [2]
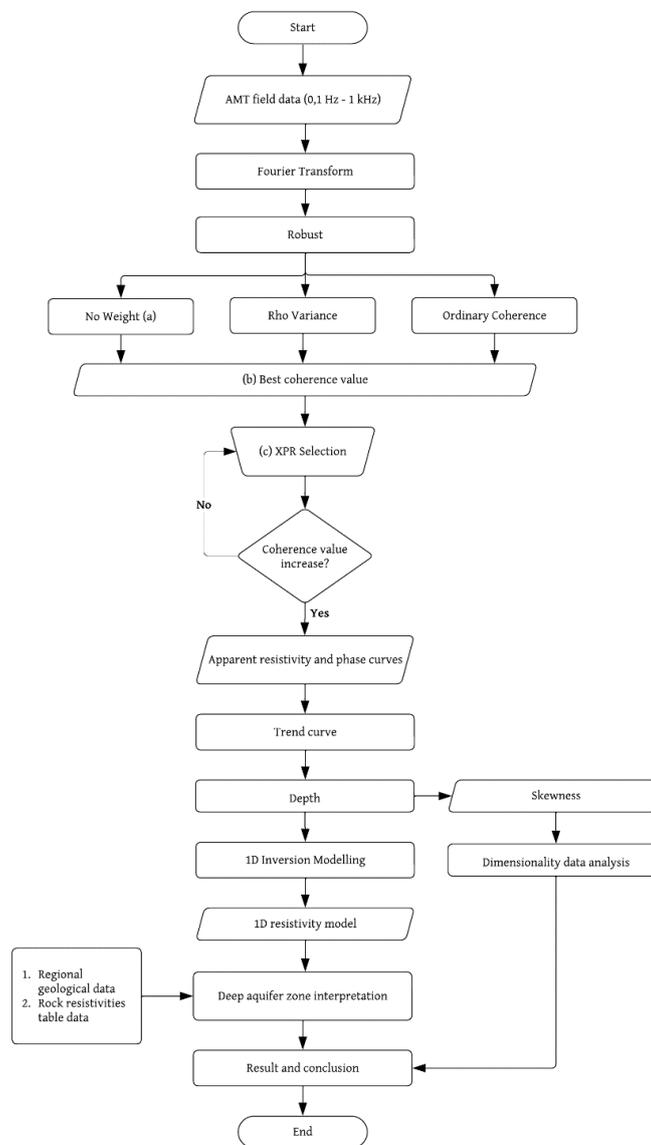

Figure 2. Flowchart of AMT data processing and analysis in the Haruman Peak area consisting of three measurement points, modified from [7]

Data processing involved a robust estimation approach using three types of weighting: No Weight, Rho Variance, and Ordinary Coherence. The optimal weighting method was selected based on the highest coherence value at each site. Measurement points MB-01 and MB-03 were processed using Ordinary Coherence, while MB-02 was processed using Rho Variance. To improve data quality, XPR (Cross-Power Residual) selection was applied to the apparent resistivity and phase curves, retaining only the highly weighted XPR values and discarding the low-weighted ones at each frequency. This step produced smoother curves and enhanced coherence [10]. A trend curve analysis was subsequently applied to reduce noise associated with outliers [11]. Skewness (S) was used to assess the dimensionality of the regional electrical structure, based on Equation 1, where where Zxx, Zxy, Zyx, and Zyy are the components of the impedance tensor [7]:

$$S = \frac{|Z_{xx} + Z_{yy}|}{|Z_{xx} + Z_{yy}|}$$ 1

In practice, the skewness value calculated using Equation (1) may still be affected by distortions in the impedance tensor. To account for these distortions, a modified skewness parameter (η) was introduced, as expressed in Equation (2), which incorporates both the real (Re) and imaginary (Im) components of the complex impedance elements.. The formulation is as follows:

$$\eta = \frac{\sqrt{2|ReZxx \cdot ImZyx - ReZyy \cdot ImZxy + ReZxy \cdot ImZyy - ReZyx \cdot ImZxx|}}{|Z_{xy} + Z_{yx}|}$$ 2

Values of η provide insight into the dimensionality of the subsurface electrical structure [10]:

$\eta > 0.3$ suggests a 3D structure,
$\eta < 0.3$ indicates a 2D structure, and
$\eta \approx 0$ corresponds to an ideal 1D or 2D condition.

The depth of investigation associated with the skewness analysis is defined by the skin depth, calculated using Equation (3), where ρ represents the resistivity ($\Omega \cdot m$) and f is the frequency (Hz):

$$\delta = \sqrt{\frac{\rho}{f}}$$ 3

The 1D resistivity model was generated through an Occam inversion scheme, which minimizes model roughness while preserving geologically plausible features [5]. The resulting model divides the subsurface into eight layers of varying thicknesses (Figure 2). Interpretation was performed by correlating inversion results with regional geological information and standard resistivity values for various rock types, as summarized in Table 1.

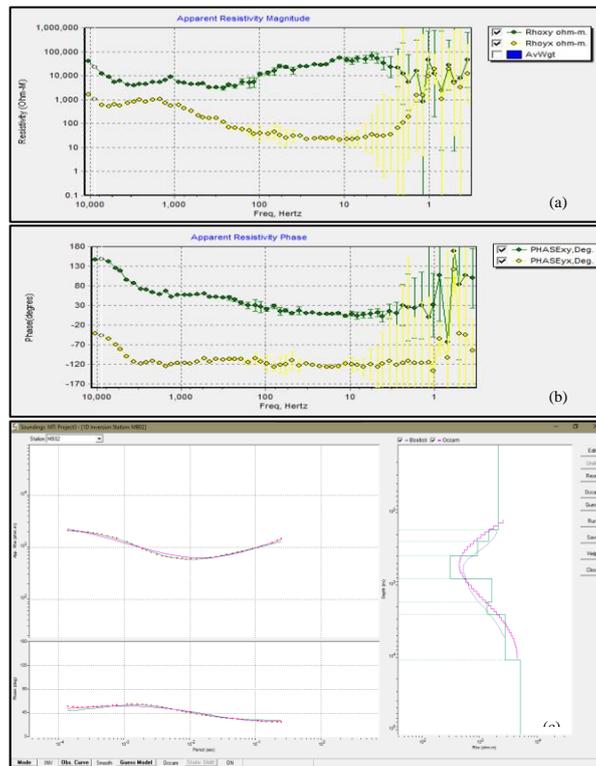**Table 1.** Typical resistivity ranges for various rock types [12].

Figure 3. Example of AMT data processing results at measurement point MB-02: (a) and (b) show the apparent resistivity and phase curves over a frequency range of 0.1 Hz to 1 kHz; (c) presents the result of 1D inversion modeling, indicating resistivity variations across eight subsurface layers.

3. Result and Discussion

Audio-Magnetotelluric (AMT) data acquisition in the Haruman Peak area yielded three measurement points, all located north of the suspected fault zone (Figure 4). The results of 1D inversion modeling for all three points are presented in Figure 3.Lithological and aquifer zone interpretation was conducted by correlating the 1D resistivity models with the stratigraphic framework provided in Table 2. This stratigraphic model was

developed using resistivity ranges from Table 1 and geological information derived from the Geological Map of the Garut and Pameungpeuk Quadrangle (Figure 1)
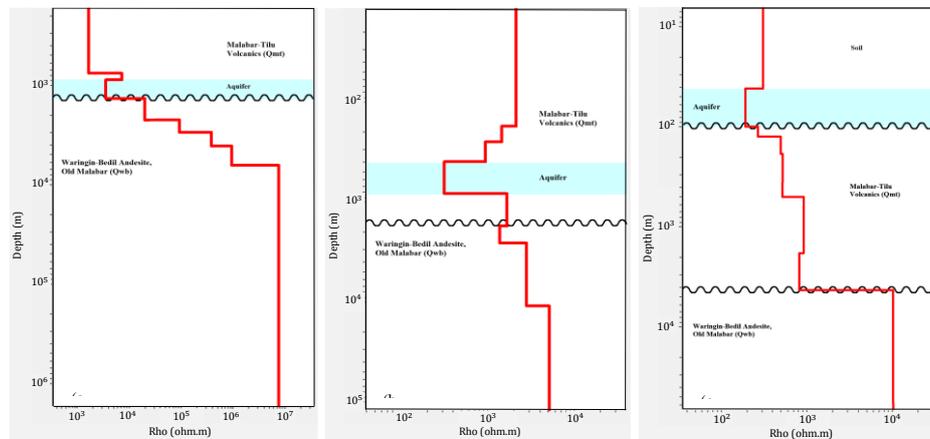

Figure 3. 1D resistivity models derived from Occam inversion of AMT data at: (a) point MB-01, (b) point MB-02, and (c) point MB-03.

Table 2. Stratigraphic model based on rock resistivity values in the Haruman Peak area and its surrounding areas

DESCRIPTION		AGES	THICK (m)	COMPONENT	AVERAGE (Ωm)	AVERAGE (Ωm)	1D MODEL (Ωm)
Qmt	Malabar-Tilu Volcanics	Pleistocene	±1400 m	Andesitic lithic tuffs / Laharic breccia / Andesitic lavas	709	21,500	11,105
Qopu	Undifferentiated Efflata Deposits of Old Volcanic	Pleistocene	± 400 m	Crystalline tuff / Tuffaceous breccia / Old laharic deposit	1,014	7,250	4,132
Qwb	Waringin-Bedil Andesite, Old Malabar	Pleistocene	± 600 m	Lavas / Breccia / Tuff	709	21,500	11,105
QTv	Undifferentiated Old Volcanics	Plio-Pleistocene	± 500 - 800 m	Fine crystalline tuff / Tuff breccia / Lavas	372	19,750	8,579
Tpv	Tuffaceous Breccia	Pliocene	600 - 700 m	Breccia / Crystalline tuff / Lithic tuff / Sandstone	1,146	5,875	3,511
Tmb	Beser Formation	Late Miocene	± 500 - 1000 m	Tuffaceous breccia / Lithic tuff / Lavas	405	20,583	8,904

The 1D resistivity model at point MB-01 shows a vertical resistivity distribution extending to depths exceeding 6,264.24 m (Figure 3a). Layers 1 to 3 exhibit resistivity values of 1,563 Ω·m, 6,934 Ω·m, and 3,358 Ω·m, respectively. The decrease in resistivity in the third layer compared to the second may indicate fluid saturation, suggesting the potential presence of an aquifer. Based on the stratigraphic resistivity classification (Table 2) and surface geological data from the Haruman Peak area (Figure 1), these layers are interpreted as belonging to the Malabar–Tilu Volcanics (Qmt), consisting of tuff, laharic breccia, and lava. This Qmt sequence unconformably overlies a high-resistivity layer (>19,365 Ω·m), interpreted as the Waringin–Bedil Andesite, Old Malabar (Qwb). The high resistivity of this layer suggests it is massive, compact, and impermeable, thus acting as a confining layer.

The 1D inversion results for point MB-02 (Figure 3b) reveal eight subsurface layers with resistivity values ranging from 308.09 Ω·m to 5,014.29 Ω·m. Correlation with Table 2 and the regional geological data (Figure 1) indicates that layers 1 to 5belong to the Qmt formation, while layers 6 to 8correspond to the Qwb formation. A particularly

low resistivity in layer 4 (308.09 Ω·m is interpreted as a deep aquifer, likely composed of tuff with minor pumice content.

Figure 3c shows the 1D resistivity model for point MB-03, with investigation depths exceeding 4,210.78 m. Layers 1 and 2 have resistivity values of 298.98 Ω·m and 188.74 Ω·m, respectively values that are relatively low compared to deeper layers. These are interpreted as soil layers that contain shallow aquifers, likely formed through weathering of underlying volcanic rocks. The second layer is interpreted as an unconfined aquifer, with an impermeable layer below and direct exposure to the surface above, allowing for groundwater discharge [13]. Layers 3 to 7are interpreted as Qmt formation, while layer 8 is attributed to the Qwb formation.

The aquifers identified at points MB-01 and MB-02are interpreted as confined aquifersbounded above and below by impermeable layers. In contrast, the aquifer at point MB-03is interpreted as an unconfined aquifer. The aquifer at MB-03 is located at an elevation of 1,317 m, while the southern Bandung Basin (e.g., Banjaran and Soreang) lies at elevations of approximately 700 m. This elevation difference enables groundwater flow from MB-03 toward the Bandung Basin, driven by gravitational potential.

The resistivity layering at all measurement points reveals a typical volcanic resistivity structure. A similar study using the same method around Kelud Volcano reported surface resistivity values ranging from 1 to 100 ohm-m at depths of up to 1000 meters, which were interpreted as indicative of a clay-rich cap layer [14]. Below this layer, resistivity values increase, suggesting underlying volcanic features. A comparable study conducted on Ulleung Island, East Sea (Sea of Japan) [15] provided a geological interpretation of shallow volcanic structures and indicated the possibility of an active magma reservoir as a potential heat source beneath the volcanic edifice..

The distribution of skewness values from the AMT data is shown in Figure 4, with values ranging from 0.004 to 0.192. These low skewness values indicate an insignificant dimensionality effect across the dataset. However, a minor influence is observed near the western portion of the survey area, possibly due to the presence of a fault. Importantly, the aquifer zones identified in the 1D models exhibit consistently low skewness values, suggesting that these layers are not significantly affected by 3D distortion and can be reliably interpreted within a 1D or 2D framewor
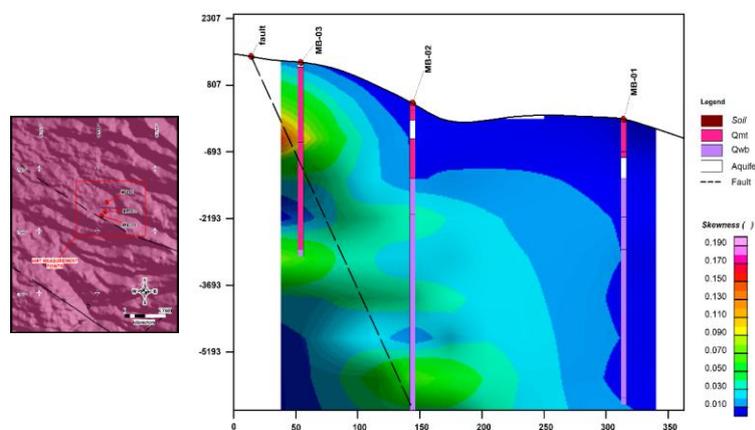

Figure 3. 1D resistivity models derived from Occam inversion of AMT data at: (a) MB-01, (b) MB-02, and (c) MB-03.

4. Conclusion

Interpretation of the 1D AMT models indicates the presence of aquifer zones at all three measurement points. At MB-01 and MB-02, the aquifers are classified as deep aquifers, located at depths of approximately 1,322 meters and 804 meters, respectively. These aquifers are confined by overlying and underlying layers of impermeable volcanic rock. In contrast, the aquifer identified at MB-03 is a shallow, unconfined aquifer, situated at a depth of less than 100 meters, where the upper boundary is directly in contact with soil layers.The presence of deep aquifers at MB-01 and MB-02 is further supported by low skewness values, indicating minimal influence from dimensionality effects and confirming the reliability of the 1D interpretation.

Acknowledgment

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