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HYDROGEOLOGICAL INTERPRETATION USING ELECTRICAL RESISTIVITY TOMOGRAPHY: METHODOLOGY AND CONCEPTUAL MODEL IN ANDESITIC VOLCANIC CONTEXT

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ABSTRACT: This paper aims to propose a methodology to interpret electrical resistivity tomography (ERT) in an andesitic volcanic context and to feed hydrogeological conceptual model of the structure of the aquifers in volcanic context. The study takes place in Pandaan, in the northeastern part of Arjuno Welirang volcano, Indonesia. The district relies on the groundwater supply to sustain its needs (industries, agriculture, domestics). Therefore, characterizing the aquifers boundaries and functioning is important to apply sustainable groundwater management. The methodology is in two steps, first geological and hydrogeological mapping, leading to the ERT location identifications. And second, interpretation of electrical resistivity tomography profiles with the subsurface hydrogeological dataset. In this paper, the relationships between volcanic facies and aquifer properties are well described through 15 ERT profiles, calibrated with geological outcrops, borehole logs, and hydrogeological data. The geophysical signature shows that, in the proximal–medial zone of the Arjuno Welirang volcano, major springs are located where the lava flows end (lava tip) and are in contact with a clayey layer/lahars. In the medial zone, below and above the clayey/lahars layer, the volcanic sandstone and tuff breccia respectively support unconfined and confined aquifers, with the evidence of artesian boreholes for the latter and dug wells for the former. These results lead to an improved hydrogeological conceptual model for this research area.

Keywords: Groundwater, Electrical Resistivity Tomography, Hydrogeological conceptual model, Andesitic stratovolcanoes, sustainability

1. INTRODUCTION

In volcanic settings, water resources depend on accurate and sustainable groundwater management which becomes an important global policy element under global changes [1]. To achieve sustainable groundwater development, it is important to have scientific-based knowledge of aquifers and to adapt groundwater management to their characteristics.

Java Island, Indonesia, is in the subduction area of the Indo-Australian plate under the Eurasian plate, where volcanic activity is a common geological feature. Therefore, volcanic aquifers with volcanic facies associated with andesitic stratovolcanoes are common on Java Island, for example, the Bromo-Tengger volcanic aquifer system in east Java [2]. Another andesitic volcanic aquifer system in east Java is located on the northeast slope of the Arjuno Welirang volcano. Indeed, aquifers in this area provide a large amount of high-quality groundwater and can be accessed, depending on the type of aquifer and hydrogeological features, through springs or drilled artesian or pumped wells. The groundwater use evolution was identified from an unpublished report of a previous preliminary study conducted between Danone Aqua, Universitas Gadjah Mada, and the University of Montpellier. It stated that deep groundwater abstraction in this area has been increasing by around 1,000 L/s for the last decade due to land use change and water demand.

The apparent similarity between the two volcanic bodies may lead local stakeholders/regulators to miscalculate when applying groundwater management. The recharge and discharge area delineated on the Pasuruan watershed map [3] for Arjuno–Welirang volcano is almost the same compared to the Bromo-Tengger volcano, the limit between recharge and discharge areas is only limited by a topographical limit whereas the geological structure of both volcanoes is far to be the same.

Some studies showed that andesitic stratovolcanoes display lateral and vertical geological/lithological variability depending on the distance to central volcanic vents [4, 5]. Commonly, in andesitic settings, each volcano is characterized by groups of lithological units: volcanic central facies (0 – 2 kilometers from the vent) marked by lava dome(s), dikes, sills, and autobrecciated lava. Proximal facies (5 – 10 km) are dominated by lavas, autobrecciated lavas, interspersed with pyroclastic

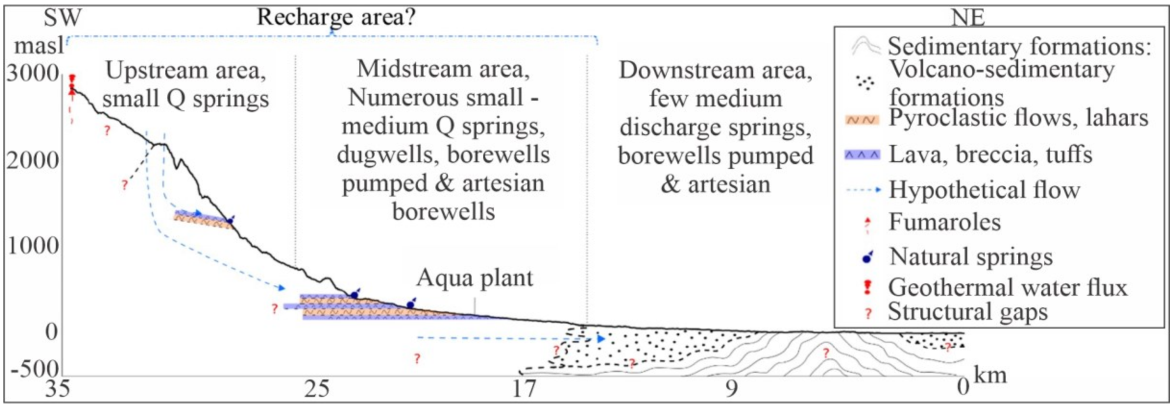

Fig.1 Preliminary hydrogeological conceptual model of Mt. Arjuno Welirang, from [10]

flows, and pyroclastic falls. Medial facies (10 – 15 km) is composed of debris pyroclastics (lahars), and fluvial conglomerates, also interstratified with pyroclastics/pyroclastic breccias. Finally, distal facies (15 – 40 km) are only composed of weathering/erosion of geological units such as fluvial sand, breccia, conglomerates, and interlayered fine–coarse sediments. In the andesitic volcanic context as the aquifer structure is controlled by the geological facies, it should be investigated with multi-disciplinary in-depth data, such as geology, hydrogeology, and geophysical data [6].

In volcanic settings, electrical tomography is a common and Electrical tomography is a common and well-suited method in volcanic settings well-suited method because it can reflect resistivity contrasts between a few and several thousand Ω meters [7]. However, the application of ERT in an andesitic volcanic context is still limited by the method itself (depth of investigation, and the need for well logs to be calibrated). For example, detailed characterization from Toulier [2] is not able to delineate the boundaries of the aquifer.

To explain the artesian aquifer spring system in Salak volcano, West Java, Indonesia, [8] used ERT to identify the resistive substratum, ranging between 100 – 165 Ω m, as an artesian aquifer that lies beneath a low resistivity layer (impervious lahar deposits) ranging between 0 – 60 Ω m, that is acting as an impermeable, clayed confining roof.

On the northeast of the Arjuno Welirang area, a multiple 1D resistivity correlation was performed in the midstream part of the watershed [9]. The resistivity value distribution range started to the lowest from 1 – 10 Ω m, interpreted as soil and clay, 10.1 – 100 Ω m as sandy tuff, lahars, and pyroclastics, 100.1 – 300 Ω m as sand, gravels, volcanic breccia, and > 300 Ω m as massifs breccia, andesitic and basaltic lavas. This interpretation leaves some gaps in the highest resistivity values. Moreover, it cannot distinguish between massive breccias and lavas. However, even if the authors do not describe whether the geological interpretation is based on outcrops, boreholes, or regional geological maps, they manage to summarize the average thickness for each geological unit, 10 m for tuff and clay unit, 10 – 80 m for volcanic breccia unit interstratified with clay and lavas, and 15 m for fractured lava.

To summarize, the link between resistivity values and geology is not straightforward. Various rocks may have different responses/wide resistivity ranges from site to site depending on the grain size, porosity, water saturation, and even secondary porosity. So, an ERT survey must first be carried out in areas where the geology and/or the hydrogeology settings are at least known locally to correctly calibrate resistivity values on outcrops or borehole logs for instance. Additional profiles can then be extended from this starting point in the direction of the identified objects of interest. This methodical technique must be reviewed based on daily data collection analysis to adapt to the next line acquisition.

The first preliminary conceptual model of Arjuno Welirang was defined [10] by using a remote sensing/satellite-based approach to map geological and hydrogeological conditions. The authors proposed that the midstream area (Fig.1), where numerous small to medium discharge springs are located, along with dug wells, pumped borewells, and artesian borewells, is composed of repetition between two main volcanic deposits, on one hand, pyroclastic flows, lahars, cooked paleo-soils (impervious) and, on the other hand, lavas, breccias, tuffs, considered as aquifers, either fractured or porous media. Our research will develop this preliminary conceptual model, especially on the structure and aquifer functioning. We completed it with extensive geological data (surface & sub-surface), especially in the midstream area, to precisely describe the geological facies and their correlation with the aquifers, to improve the previous conceptual model.

Our paper mainly discusses the hydrogeological interpretation using electrical resistivity tomography (ERT), divided into four

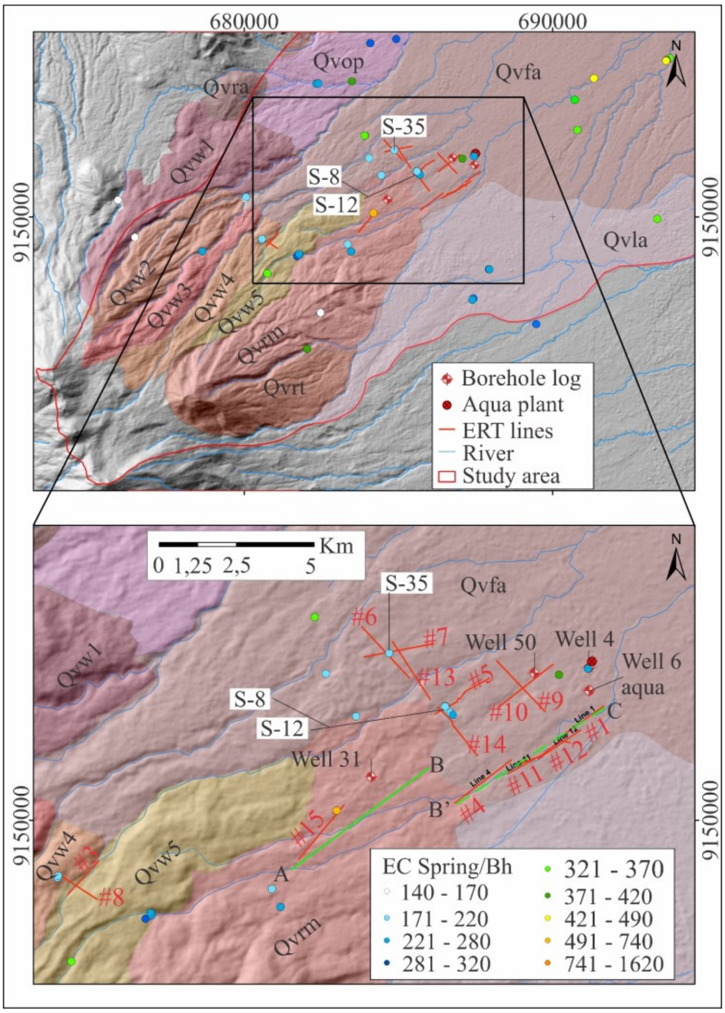

Fig.3 ERT lines plotted on the interpreted surface geological units and borehole logs to tie the resistivity value and interpret its geological units/aquifer, all geological units explained on Geology & Hydrogeological sub-section

main steps: (i) geology of the research area, (ii) comparison of the geophysical data with borehole logs, outcrops, and springs, (iii) identification of the relationships between geological facies and aquifers/aquicludes, (iv) resistivity ranges, discussion about geological facies as regards the relationships between resistivity and lithology, (v) correlation between the various ERT profiles and the hydrogeological conceptual model.

2. RESEARCH SIGNIFICANCE

This research aims to propose a methodology to interpret ERT with a hydrogeological purpose in an andesitic volcanic context and propose a conceptual model of geological and aquifer structures for the research area. Major contributions of this work from geological-hydrogeological investigation to have preliminary interpretation continued by the interpretation of ERT data will support the practice of hydrogeologists or engineers working especially in andesitic volcanic aquifers for water supply and management.

3. MATERIAL AND METHOD

Arjuno Welirang volcano is part of Pasuruan regency, East Java Province (Fig.2). Geographically, Arjuno Welirang mountain is located at 7°40'-7°53' and 112°31'7" – 112°42'52" [11] As regards surface water watersheds, the research area belongs to the western part of the Pasuruan watershed and part of the Kedunglarangan sub-watershed. Arjuno Welirang area is a volcanic complex area with a maximum 3350 m elevation above sea level.

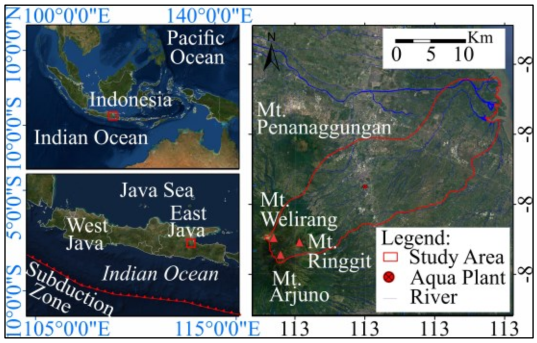

Fig.2 Research area on google earth images

The general methodology is divided into two steps, first is geological mapping to understand the lateral sequences and geological units for each volcanic facies also hydrogeological mapping to locate springs with their physical properties, such as emerging context, discharge, and physicochemical parameters. Second, ERT surveys were performed on known geological/hydrogeological settings such as outcrops, boreholes, and springs to tie resistivity value and interpret the subsurface geological and hydrogeological units (aquifers/aquicludes). The correlation between geology, hydrogeology, and various ERT lines lead us to complete previous hydrogeological conceptual models.

3.1 Geology & Hydrogeology

Previous geological studies were reviewed to prepare a preliminary interpretation of the geological units and the volcanic facies. Volcanic geological mapping by [12] showed various volcanic products on the volcanic slopes (upstream): Ringgit lavas, Penanggungan Lavas, and Welirang Lavas interbedded with pyroclastic layers. The midstream–downstream area was well described regionally [13]. It is mainly composed of the Arjuno Welirang pyroclastics, followed by the older Kabuh volcano-sedimentary formation downstream. The midstream–downstream area is divided into two main different units after geological mapping based on remote sensing [14]: on the northeastern part, the volcanic products of Arjuno, and on the northern part, the volcanic products emitted from the Welirang and Penanggungan volcanoes.

We performed a field geological mapping and observed 110 geological outcrops. It enabled us to identify different types of rocks: lava, tuff breccia, sand, and gravel deposit, chalky limestone, tuff, lahar breccia, and lapilli tuff.

On volcanic rock formations dominated by rocks such as lava, pyroclastic, and lahar which are mostly found as massive blocks, the geological structure is very difficult to identify. Therefore, the approach taken to identify the existing geological structures was by using the digital elevation model (DEM) analysis by PCI Geomatica software.

122 dug wells, 59 springs, 17 boreholes, and 10 artesian boreholes were identified during the hydrogeological campaign, with their discharge and their physicochemical properties (electrical conductivity). Afterward, the distributions of all hydrogeological features were overlaid on the geological map.

3.2 Electrical Resistivity Tomography (ERT) Data Acquisition

A geophysical survey was carried out using two-dimensional electrical resistivity tomography (ERT) to image the aquifers' structures. The acquisition used an IRIS Instruments Syscal Pro resistivity meter with 64 electrodes. Lines are presented in (Fig.3). ERT has a resolution defined by the spacing of the electrodes, 10 m in our research. Thus, it will not be possible to image fine structures as the 10 m spacing will reflect 2 m of thickness as the geometry factor effect. The resistivity images are sensitive to the great variability of the subsoil properties: saturation, groundwater mineralization, lithology, and clay content [15]. 15 ERT profiles were performed, concentrating on major springs (25 – 100 L./s) and artesian boreholes in the midstream part (proximal-medial facies) of the watershed. First, profiles need to be sited with known geological/hydrogeological settings to interpret inverted resistivity profiles. This calibration step is mandatory to obtain reliable and accurate results and reduce absolute error, absolute error is the difference between the measured and calculated apparent resistivity values. After that, the geophysical acquisition can be extended in the direction of the area of interest to substantiate volcanic facies and hydrogeological hypotheses.

Table 1 Summary of ERT acquisitions from line 1 to line 15.

Lines	Length (m)	Line Orientation	Absolute error
Line 1	630	SW-NE	1.0
Line 2	790	SW-NE	2.3
Line 3	630	SW-NE	4.1
Line 4	950	SW-NE	17.7
Line 5	950	SW-NE	2.9
Line 6	950	NW-SE	1.5
Line 7	940	SW-NE	2.3
Line 8	630	SW-NE	2.7
Line 9	950	NW-SE	3.9
Line 10	950	SW-NE	3.4
Line 11	540	SW-NE	1.0
Line 12	710	SW-NE	3.5
Line 13	950	NW-SE	2.5
Line 14	950	NW-SE	2.5
Line 15	950	SW-NE	6.0

We prioritized depth of investigation over lateral resolution. The acquisition sequence is therefore defined with an electrode spacing of 10 m using the Wenner-Schlumberger sequences setup listed in Table 1. Wenner-Schlumberger is a hybrid array combining both advantages of Wenner alpha and Schlumberger classical arrays and provides good imaging of horizontal and vertical structures. Volcanic and volcano-sedimentary formations are organized by the following slope, thus, we set up profiles along (parallel) or perpendicular to the main slope.

Then, all apparent resistivity values were filtered using Prosys III software to eliminate bad data, for example removing data with too large deviation and negative apparent resistivity. Using the Res2dinv software, apparent resistivity data were inverted. We considered that the inverted resistivity model is unreliable if the error is greater than 10%.

2D inverted resistivity profiles were tied to geological outcrops using borehole logs surrounding all ERT lines. Borehole logs were acquired from the department of energy and mineral resources in east Java Indonesia [16].

ERT interpretation was performed in a few stages: first, standardization of borehole logs. Second, resistivity range classification related to geological units and aquifers/aquicludes. Third, is a comparison of ERT, geological outcrops, and borehole logs with the implication of hydrogeological interpretation to explain the spring's appearance or aquifer system. Fourth, is the extrapolation of various ERT profiles to propose an updated hydrogeological conceptual model.

4. RESULTS

4.1. Geology & Hydrogeology

4.1.1 Geological structure

The fractures and or faults were rarely seen on outcrops. Only a few of them were observed on lava as geological fractures/cooling fractures on the slope of Arjuno Welirang. These few fractures were observed on four stations: station 6 part of Qvw1 with strike/dip N342^{0}E/55^0, station 9 (Qvw3) with strike/dip N145^{0}E/48^0, station 28 and 29 (Qvrm) with strike/dip N259^{0}E/78^0 and N241^{0}E/64^0 respectively. The lineament pattern is dominated by the northeast-southwest orientation, but it could be biased ith as the result of the valley and ridge in volcanic terrain (Fig.4a), distributed mainly on the slope. This is coherent with the relative direction of the known Meratus pattern that develops in the north of east Java [17]. This high lineament density may favor the groundwater recharge of the watershed according to [18].

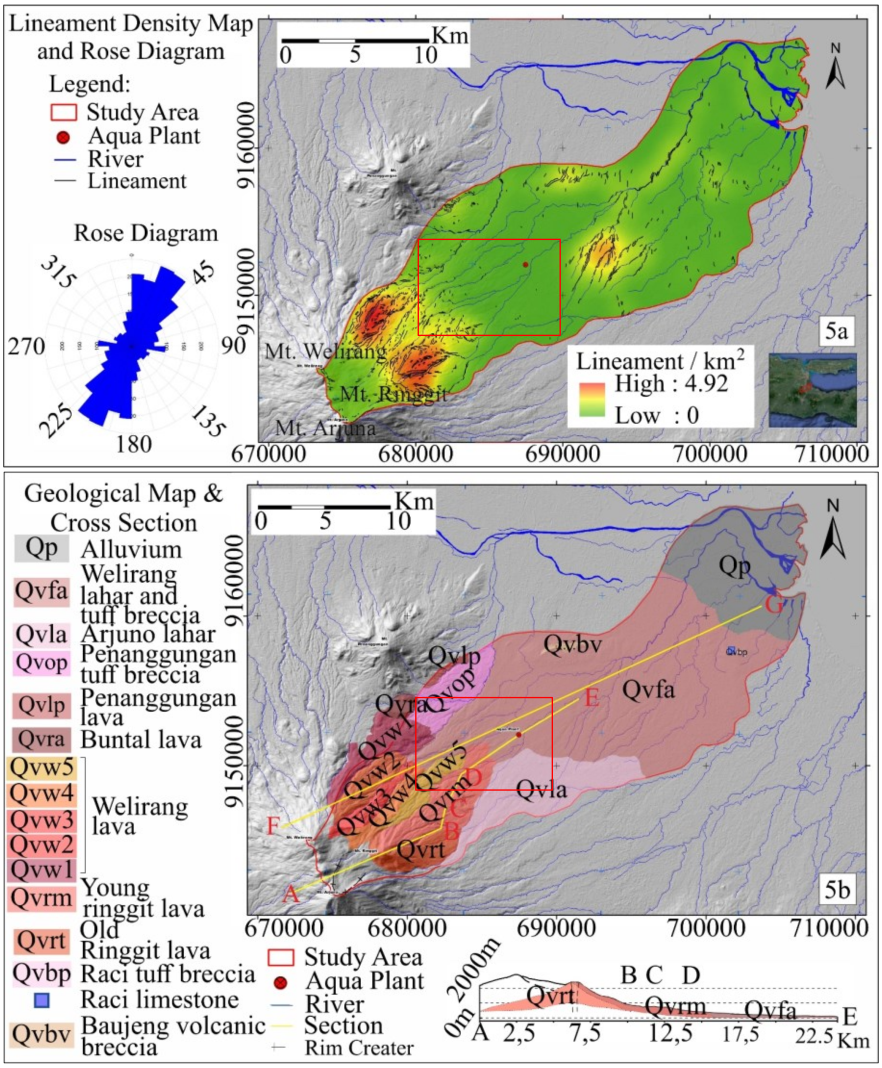

Fig.4a Lineament and lineament density map. Fig.4b Geological map and geological section A – E and F – G (ERT focus on the red square)

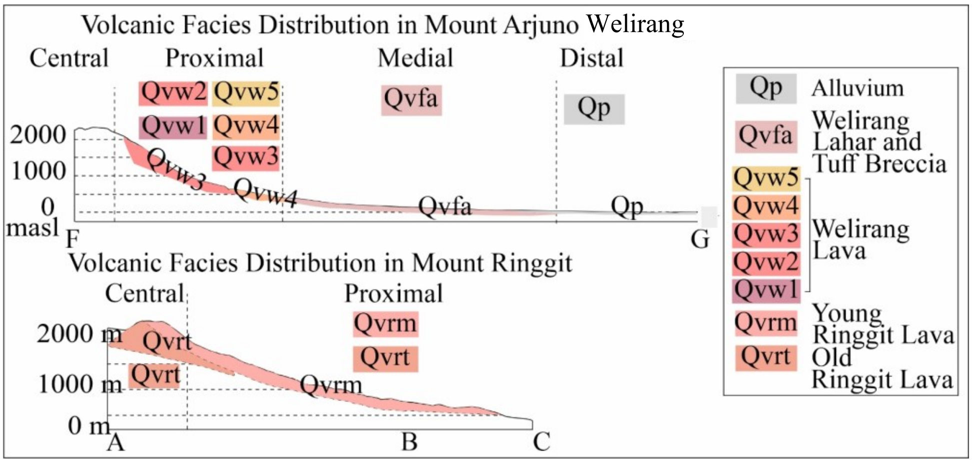

Fig.5 Arjuno Welirang & Ringgit volcanic facies on F – G and A – B – C cross-section

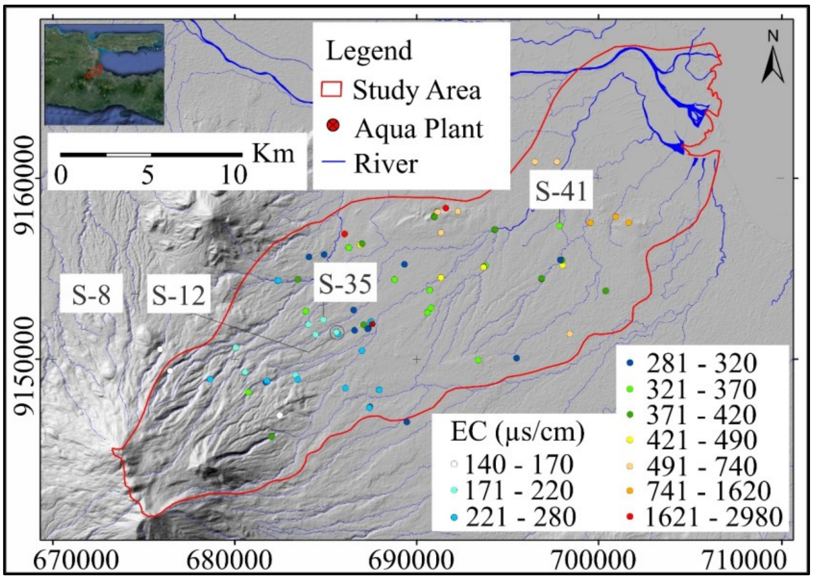

Fig.6 Electrical conductivity map of springs, boreholes, and artesian boreholes

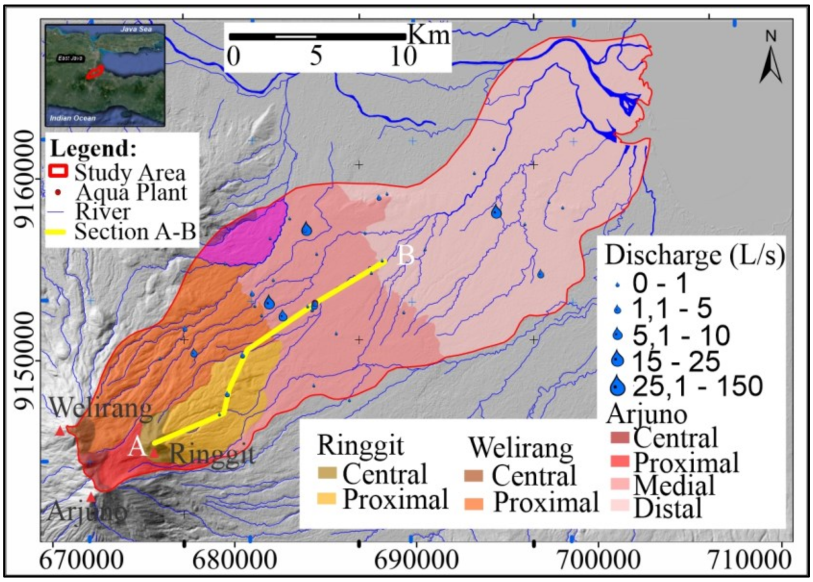

Fig.7 Discharge of springs and boreholes on volcanic facies map, discharge magnitude indicated by size, section A – B (Ringgit volcanic facies to Arjuno volcanic facies) will be used to build the hydrogeological conceptual model diagram

4.1.2 Stratigraphy

Based on geological mapping, we identified 15 different geological units (Fig.4b), divided into two main groups: various lavas at the slope of the volcano, and volcanic sedimentary units on the plain. The stratigraphy was following previous regional studies. To understand the lateral change of geological units we created two geological facies cross-sections (F – G) and (A – B – C) referred to the previous geological map on two volcanic edifices (Arjuno Welirang & Ringgit) in Fig.5.

Arjuno Welirang volcanic facies on proximal facies are composed of Welirang lava intercalated with pyroclastic deposits (Qvw1 – Qvw5). Numbers represent old to young deposits. Medial facies are composed of Arjuno lahars and pyroclastic deposits (Qvfa) and are composed dominantly by a volcanic sedimentary deposit of Arjuno Welirang (Qvfa). The distal part of Arjuno Welirang is only composed of river alluvium (Qp) with fine sediments such as clay, sand, and other unconsolidated materials. Meanwhile, Ringgit volcanic facies in the central part are composed of old Ringgit lava (Qvrt) and the proximal facies are composed of young Ringgit lava (Qvrm).

4.1.3 Hydrogeology

The low EC of springs spread along the upper slopes of Arjuno Welirang (Fig.6) could represent the local groundwater flow released in the short groundwater flowline. Meanwhile, the medium EC values found on the midstream for the artesian boreholes, boreholes, and springs could represent the start of the regional aquifer system, as conductivity value has a direct correlation with total dissolved solid and this value is broadly controlled by the contact time between water and rocks.

Spring discharge is also important to explain the aquifer structure (Fig.7). This practical hydrogeological investigation could help hydrogeologists as it may indicate the aquifer's distribution. We highlighted some interesting points: low discharge springs around <10 L/s spread along the upper slopes of Arjuno Welirang. This supports the previous interpretation of low EC values and local groundwater flow. Higher discharges are observed in the midstream, with the Plintahan Spring (S-35), 100 – 125 L/s, the Telogosewu (S-8 – S-12) Spring complex, 25 – 30 L/s, and also on the north midstream area the Toyoarang Spring (S-3), around 35 L/s. This last spring could emerge from the Penanggungan volcano aquifer system. The last observed high discharge spring is located downstream on the medial-distal facies of Arjuno Welirang: Sumbersono Spring (S-41), 40 – 50 L/s, the other low discharge springs, these significant springs are considered as important hydrogeological features in this watershed.

4.2 Electrical Resistivity Tomography (ERT) & Integration of Outcrops and Borehole Logs

4.2.1. Standardization of borehole logs

To define the geological structure of each resistivity profile, the borehole logs surrounding the ERT profiles are gathered to (i) construct lithological transects, and (ii) interpret 2D resistivity profiles. However, the available data are heterogeneous as for the same lithology, two logs could have a different symbology (figures of different colors and patterns).

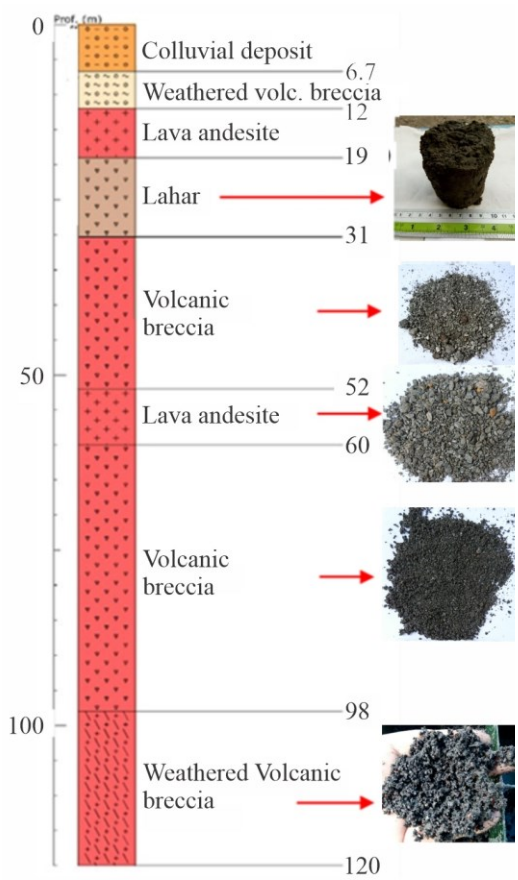

Fig.8 Well 6 Aqua borehole log (depth in m)

To standardize, we used 1 borehole log (well 6 Aqua) as the baseline (Fig.8) as this log is equipped with cuttings/coring to be tied with resistivity value on line 10. Each lithology was associated with a colored figure and then applied to all wells with their correlated resistivity value and gathered similar and comparable lithologies. It has however to be noted that line 10 is only covering the low – medium resistivity values. The other borehole log reaching a higher resistivity value will be interpreted only based on the surface geological map, and outcrops correlation where available. At this point, we could also interpret the geological stratification from well 6 Aqua and its hydro stratigraphy units: 0 to 20 m is composed of colluvial deposits, weathered volcanic breccia, boulders interpreted as lahars (superficial low permeability aquifer, tapped by dug wells), 20 – 30 m: clayey layer/lahars (aquiclude), 31 – 52 m: volcanic breccia (aquifer), 52 – 60 m: lava andesite (aquifer/aquifuge?), 60 – 98 m: volcanic breccia (aquifer), 98 – 120 m: weathered volcanic breccia (aquifer).

ERT line 10 with well 50 (Fig.9a) and ERT line 15 with well 31 (Fig.9b) are examples of log standardization results based on well 6 Aqua and their correlated resistivity profiles. The previous

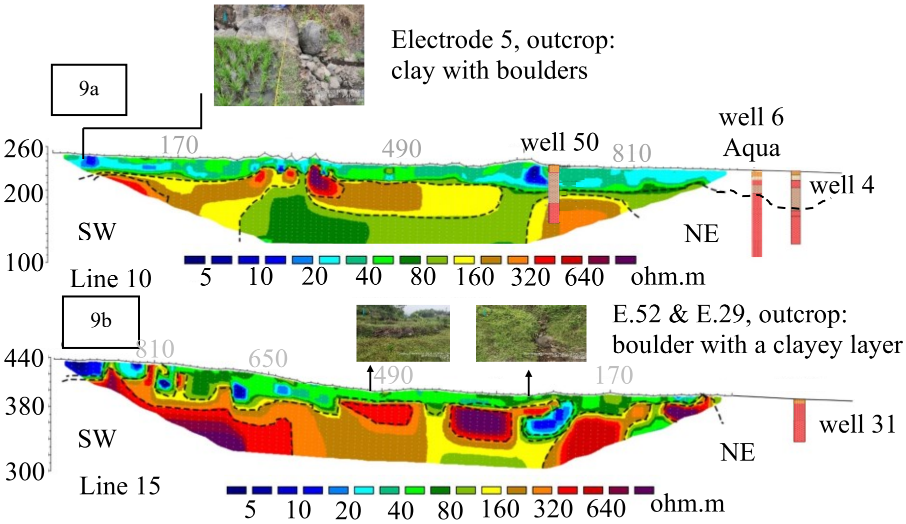

Fig.9a Geological analysis steps using borehole logs on ERT line 10. Fig.9b line 15

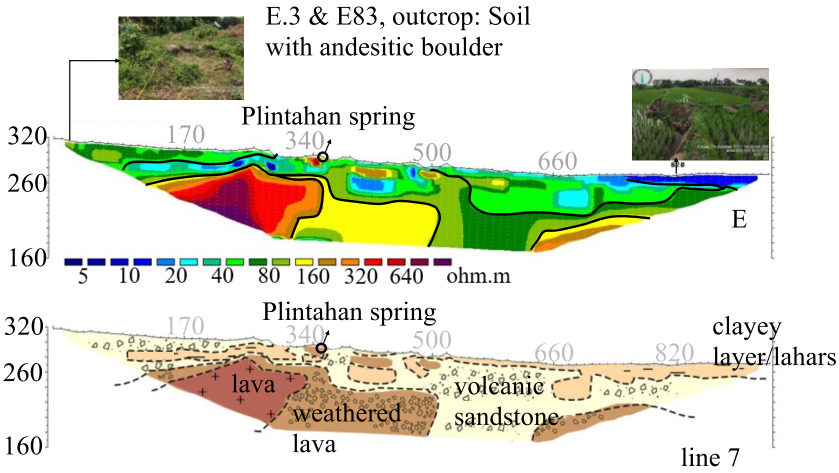

Fig.10 ERT line 7 and geological unit interpretation to explain the spring appearance

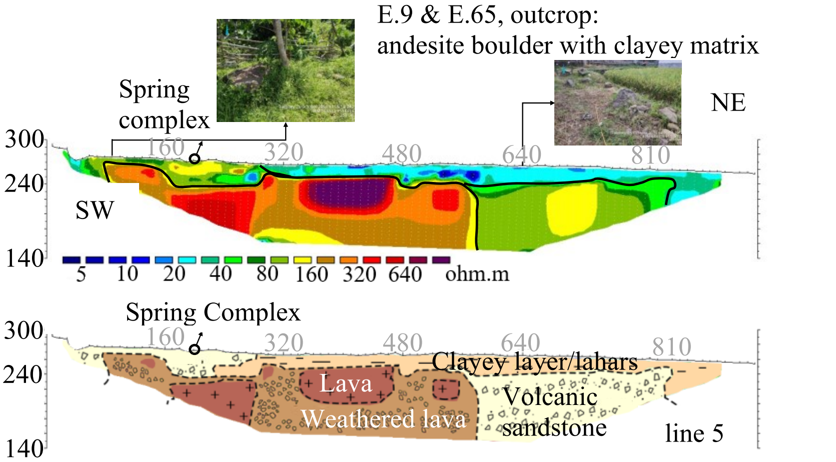

Fig.11 ERT line 5 and geological interpretation to explain the spring appearance of Telogosewu spring complex

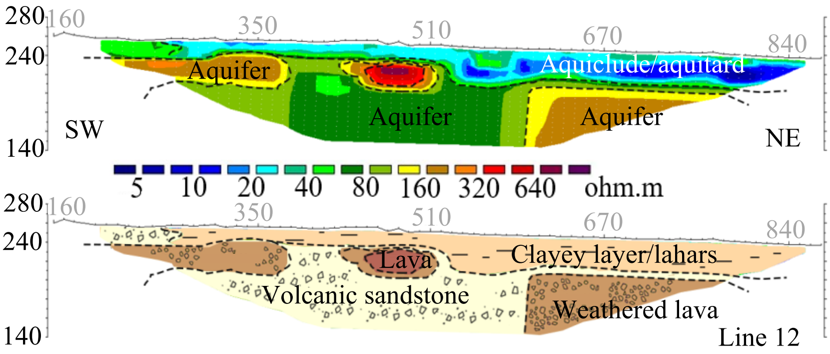

Fig.12 Line 12 hydrogeological interpretation

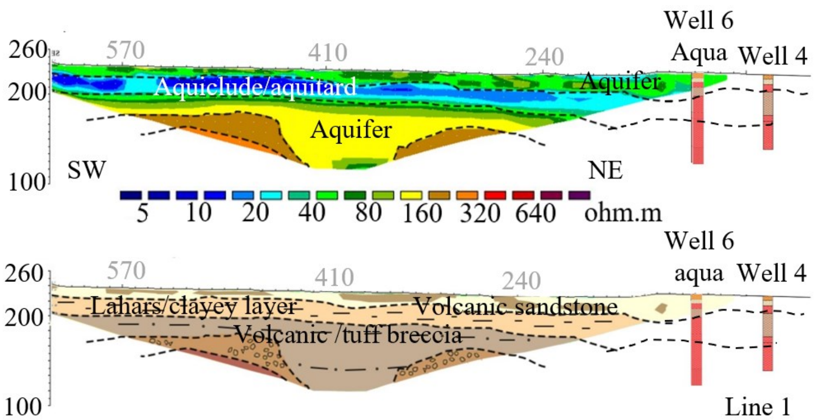

Fig.13 Line 1 hydrogeological interpretation

interpretation of unstandardized log seems to be very ambiguous, for example, sand and sandy tuff are correlated with high resistivity on the ERT profile if we extend the nearest profiles. It could happen as this geological log was made by a traditional driller, not a geologist; for example, a lava/volcanic breccia cutting could be interpreted as sand.

4.2.2 Comparison of ERT, geological outcrops, borehole logs implication of hydrogeological interpretation

Lava and location of major springs

Regarding the correlation between geological and hydrogeological interpretation, we highlight two ERT lines that cross the major springs. First is ERT line 7 (Fig.10) which crosses the Plintahan spring parallel to the main slope. This spring's discharge is around 100 – 125 L/s and it is used for municipal water supply. We transform the ERT profile into the interpreted geological profile to visualize and explain the spring appearance. Plintahan spring appears on a medium resistivity unit (interpreted as volcanic sandstone) that lies above a high resistivity body detected from 40 m down to 120 m below ground level at the west of the profiles interpreted as lava. This lava was first detected at ERT lines 3 and 8, but on the geological map, this lava is extending up to the central part of the Arjuno Welirang volcano and covers almost all the geological units in this area (Qvw4 & Qvw5). Its high lineament density supports the hypothesis of its secondary porosity by its fracture/faults. So we inferred these lavas as the aquifer. As this lava (aquifer) ended, the clayey layer/lahars unit (confining layer) was surely broken due to pressure as the water needs to flow out at this lava tip.

The second ERT profile that confirms this lava implication to major spring appearance is line 5 (Fig.11). It crosses the Telogosewu Spring complex, which has 4 spring outlets reaching 25 – 30 l/s groundwater discharge each and is used as a water park by the local community. The spring complex discharges the groundwater through the medium resistivity layer (volcanic sandstone) above the high resistivity units interpreted as lava, but not exactly on the lava tip. The hypothesis for this spring is similar to the Plintahan spring but distributed on several discharge outlets.

Another finding based on these two profiles is the development of a low resistivity layer interpreted as clayey layer/lahars. The ending of the lava unit and the development of this clayey layer/lahars unit could reflect the transition between proximal–medial volcanic facies. This low resistivity layer is detected from 0 – 30 m below the ground and thickened to the northeast as identified on the cutting well 6 Aqua downstream (Fig.8) at 19 – 31 m depth.

From these two lines, we conclude that these lavas (Young Ringgit lava and Welirang lava) play a vital role as the aquifer at the proximal area supporting the water supply for these two major springs. Also, the transition zone where the lahar/clayey layer developed plays an important role as the confining unit of the first confined aquifer.

Clayey layer/lahars and its implication to hydrogeological interpretation

As previously discussed, the area downstream of the major spring (Plintahan & Telogosewu Spring complex) is defined as the transition zone between the proximal and medial facies. In fact, as the volcanic sedimentary facies of Arjuno-Welirang develop, a geological unit like lava or primary pyroclastic products should become less visible or rare downstream of ERT line 5 and 7. To validate this hypothesis, we will discuss it using a few lines downstream. First, line 12 (Fig.12), parallel to the main slope, is located at a lower elevation, on the southeast of the above described major springs. As expected, the lower conductivity layer seems to cover the upper part of the profiles. Here we wanted to define the geological units and the implication of hydrogeological interpretation. No borehole log was calibrated on this profile. The low resistivity value is the indication of the confining unit, and the medium to high resistivity value is interpreted as aquifers. Here we start to notice that below the major springs, the confining unit starts to be developed along the medial facies capping the new porous aquifers.

Second, line 1 (Fig.13) is the continuation of line 12 downstream. It has the same orientation as the main slope and is tied with 2 borehole logs. This ERT profile not only captured the clayey layer as an aquiclude but also another aquifer that lies above the clayey layer and lies on a medium resistivity layer interpreted as volcanic sandstone. The 2 borehole logs: well 6 Aqua (120 m deep) and well 4 (100 m deep) confirm this multilayer aquifer (confined–unconfined aquifer) divided by a clayey layer/lahars lithology at 20 – 50 m depth. This result is coherent with the line 12 interpretation. For the newly identified aquifer above it, if we refer to the hydrogeological section, it is representative of the aquifer for the dug wells used for the domestic needs that developed on the medial facies reflecting the starting development of confined–unconfined aquifer.

The contrasting geological unit change in the midstream area could explain how these aquifers developed where the upstream lava flow intercalated with pyroclastic deposits (Qvrt and/Qvw1 – 5) shift into downstream lahars and pyroclastic deposits (Qvfa). For instance, lahars are composed of a clayey matrix that supports them as an aquiclude/aquitard. If this formation is widespread, confining the tuff breccia/volcanic breccia aquifer units that also developed on the medial facies, it could lead to the development of the regional confined aquifers system.

4.2.3 Resistivity range classification of geological and hydrogeological unit

Upon the ERT interpretations above, we could summarize all information acquired from all ERT profiles, borehole logs, and outcrops to determine the geophysical signatures from the various layers for all volcanic facies (Table 2):

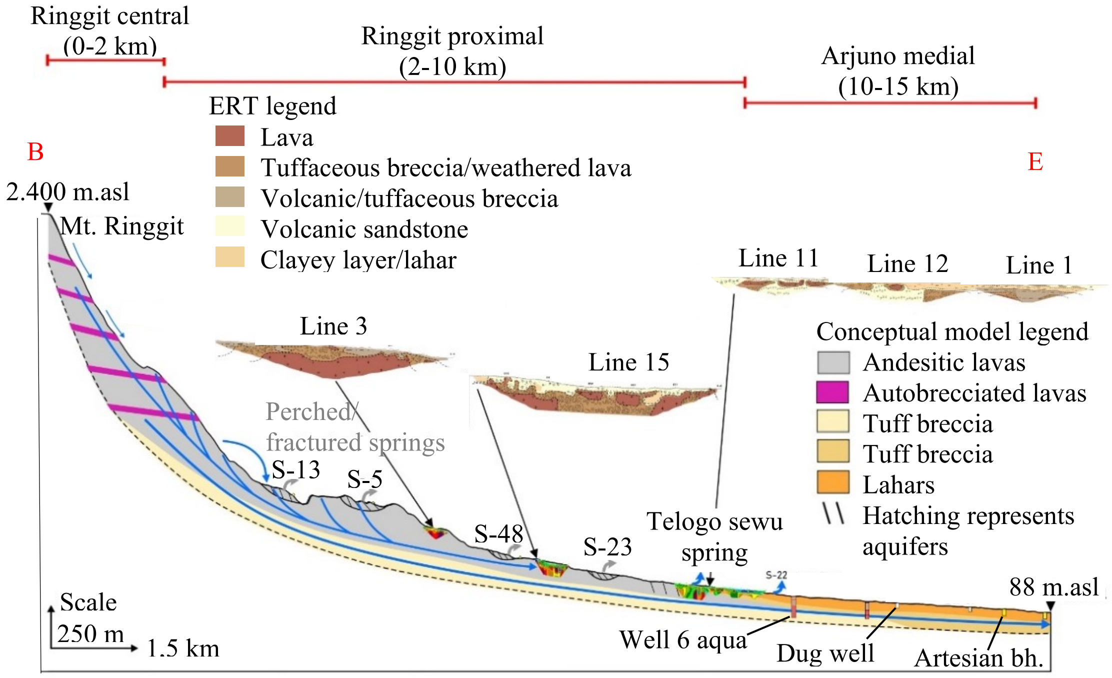

Fig.14 Extrapolation of various ERT profiles on Section A – B (Ringgit to Arjuno volcanic facies) and hydrogeological conceptual model diagram of the northeast slope of Arjuno Welirang volcano

- Lava units found from the proximal to proximal–medial facies exhibit high resistivity values between 300 – 1000 Ω m with an overall thickness of 100 m on the proximal zone and 50 m on the proximal–medial zone.
- Weathered lava units were found thicker in the proximal–medial zone compared to the proximal one. The resistivity values of these units have the same range as the one interpreted as tuffaceous breccia ranging from 150 – 300 Ω m, with an overall thickness of 60 m. This unit ends at the proximal–medial facies, as it is associated with lava units, weathered lava also ends in this transition zone.
- Volcanic sandstone (tuff, coarse tuff, lapilli tuff) unit was first detected on the proximal area, as a thin layer above the lava. Between 30 – 120 Ω m, this layer is thicker on the transition zone with an overall thickness of around 80 m below the clayey layer/lahars. Into medial facies, this unit developpes near the surface reaching 25 m of thickness, and below the clayey layer reaching 100 m of thickness.
- Tuffaceous breccia unit has the same distribution as well as volcanic sandstone, around 150 – 300 Ω m. Widely found in the medial zone, this unit is not largely extending horizontally. Vertically its thickness varies from 20 to 100 m.

4.2.4 Extrapolation of various ERT profiles (Hydrogeological conceptual model)

To explain the volcanic facies and aquifer structures to complete the previous hydrogeological conceptual model, the extrapolation of selected lines from central to medial facies was made on the interpreted hydrogeological conceptual model diagram. Line 3 and line 15 are representative of the proximal facies of Ringgit volcano.

The lava flow facies are dominant as visualized in the hydrogeological section. As andesitic lavas are sometimes intercalated with pyroclastic deposits, small discharge springs (perched springs) in this area reflect the development of local aquifers. As from lineament analysis, this area has a high lineament density, this lava can produce secondary porosity and support the groundwater recharge process. Line 14 has the same elevation as lines 7 and 12. It is the transition zone of proximal-medial facies, where lavas end and laterally change into volcanic sandstone and tuffaceous breccia. The upper clayey layer/lahars are capping this unit. This sudden change in lithology explains the location of the springs. Telogosewu spring complex is projected onto line 4 on the hydrogeological model diagram as one of the major springs. Lines 4, 11, 12, and line 1 which are in the medial zone are mainly composed of volcanic sedimentary deposits: lahars (mix between volcanic sandstone, clayey layer/lahars) at the top, and tuff breccia below. All these lines image the development of confined and unconfined aquifers.

5. CONCLUSIONS

Electrical resistivity tomography in combination with geological and hydrogeological data enabled defining the hydrogeological framework of Arjuno Welirang volcanic facies from the Central to Medial zone. An updated hydrogeological conceptual model is proposed (Fig.14):

- The central zone: mainly composed of andesitic & autobrecciated lavas.
- Proximal zone: andesitic lavas. There the aquifers begin to develop and are a groundwater recharge zone.
- Proximal-medial (transition zone): clayey layer/lahars develop as the lava flow end.
- Medial zone: volcanic sandstone, clayey layers at the top (0 – 30 m), and tuff breccia at the bottom (>30 m). They represent the development of unconfined-confined aquifers.

In an andesitic volcanic context, the ERT survey needs to be started in known geological/hydrogeological settings with lines oriented mostly parallel to the main slope to capture the lateral changes. An optionally perpendicular profile is needed to compare the profiles one with the others. A careful reiteration process of the resistivity data acquisition is mandatory to increase reliability and decrease the absolute error. The calibration to surface outcrops, borehole logs, and hydrogeological information is mandatory to support the interpretation.

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