Preliminary conceptual model of the Arjuno Welirang hydrogeological system, and comparison with the Bromo Tengger: An illustration of the hydrogeological systems diversity in volcanic areas

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Abstract. While basaltic volcanic aquifers are well described in the literature, andesitic groundwater systems are less studied. Nevertheless, these aquifers supply a large population in all the subduction areas, where this volcanism mainly occurs. In Indonesia, the growing needs of the population induce an increase of the pressure on such aquifers. We present in this paper the case study of the Arjuno-Welirang, and compare it with a well-known hydrogeological system, the Bromo-Tengger. Based on geological, geomorphological, and water chemistry data, this study highlights the diversity of andesitic history inherent to this kind of volcanism, and its strong implications on the groundwater availability downstream. The aim of this paper is also to show that simple investigations can help building a preliminary conceptual model (PCM) of complex volcanic settings. Such PCM is needed to define further detailed hydrogeological investigations required to set-up aquifer exploitation, management and preservation rules.

1. Introduction

In all countries, the socio-economic development and well-being of the population are closely linked to the access to water resources. In Indonesia, a large part of the growing needs is fulfilled by access to groundwater. This country is located on the subduction area of the Indo-Australian plate under the Eurasian plate. Therefore, volcanic aquifers are numerous in this country. This is particularly the case in the Eastern part of the Java Island where this research is focused. Most of these aquifers provide a large quantity of high-quality groundwater, more or less accessible depending on their geological setting.

The regional hydrogeological map of that area (Figure 1), even though old, is quite accurate and provides valuable information about the springs, the aquifers productivity and the deep borewells uses at the time of its publication. But this map may lead to think that all the volcanic edifices (a volcanic morphological unit that can be the result of a complex geological history and, as such, is different from a simple “volcano”) all have a similar hydrogeological pattern, which contrasts with the geological complexity of the volcanic aquifers’ structure and the springs location in the plains around these...
volcanoes. Our preliminary results on the Arjuno-Welirang complex, and their comparison with the detailed study performed in [1] on the neighbour complex of the Bromo-Tengger illustrate the diversity of the aquifer types, whereas the hydrogeological map suggest an elevation-dependent structure with, from the bottom to the top of the volcanic edifice (Figure 1):

- **Blue colour**: Porous aquifers (coastal plains, intermontane basins and foot of strato-volcanoes), the darker blue the higher productivity.
- **Green colour**: Fractured aquifers (slope of strato-volcanoes), the darker green the higher productivity.
- **Orange Colour**: Porous or fractured aquifers of poor productivity, low transmissivity, limited shallow groundwater resources.
- **Red Colour**: Regions without exploitable groundwater.

These apparent similarities between different volcanic edifices on the hydrogeological map can lead the local authorities to miscalculate while planning water management policies at local scale, as the water availability may be very different from that inferred by the map, and from one volcanic edifice to the others. Thus, our research aims at strongly encourage to build up local conceptual models (CM) of the hydrogeological systems. Indeed, CM are a first step to summarize all the available knowledge on the water cycle at a local scale, necessary to implement numerical modelling and water management scenario testing, and reducing the numerical modelling uncertainties [2–4]. This will help to identify the key missing data to be acquired, in order to address the local water issues like the cities/activities/land use development, and ensure matching human activities and water resources sustainability. To illustrate this, the Arjuno Welirang volcanic complex, located on the Eastern part of the Java Island (Figure 2) is studied. We focus on its eastern flank, where the Pandaan city is located, at 40km from Surabaya in the Pasuruan district. The area was studied for its geothermal potential [5–8] on the northern/western part of the volcanic edifice. But on its eastern flank, the city of Pandaan is relying more and more on the less studied groundwater system of the Arjuno-Welirang to sustain its development (industrial, domestic, agricultural).

![Figure 1. Hydrogeological map of Indonesia][9]– See the explanation of the colour legend in the text.
2. Method and results

As described in [2], there are two types of CM:
- The consensus model, with an iterative integration of all the data into a single CM.
- The multi-model approaches, with several CM tested at the same time.

In such a preliminary stage of study as ours, the PCM approach is more likely to be a consensus model, until there are enough data to raise several hypotheses on the geological settings or water fluxes. The goal of a PCM is to gather all the existing data available to date and define the additional data that can be acquired efficiently during the phases of the project to come. This method is developed on the study case of the Arjuno-Welirang, East Java. A preliminary conceptual model has been built based on a comparative study with the well-studied Bromo-Tengger system [1] on three linked thematic: the geological settings of the volcanic edifice, the measure of the aquifer(s) outflows, and insights on the aquifers’ functioning, on the basis of hydrochemical data.

2.1. Structure

To build a preliminary hydrogeological conceptual model, the first step is, as far as possible, to unveil the geological settings of the hydrogeological system.

By settings, we mean the geological units, their geometry, their lithology and, from this last information, at least a qualitative characterization of their permeability (aquifer, aquitard, aquiclude) and of the type of permeability (interstitial, fractures, etc.). For such an identification, the local or regional geological maps provide valuable data. To complete the identification of the geological settings, geomorphological approaches can be easily performed with the use of Google Earth images and the
Digital Elevation Model, that helped delineate broad structural units, and to localize outcrops easy to reach later, once on the field.

The available maps for the study area are the ones of [10], [11], and [12] for the Northern volcano, the Penanggungan (Figure 3). These maps present numerous differences, as their scales and their original purposes are different. Therefore, their accuracy for hydrogeological purpose is highly variable, even though all of them provide valuable information. In order to build a stronger preliminary conceptual model, and with field access restriction due to the COVID 19 outbreak during the study (national lockdown, and international travel restrictions), a “geological mapping” through Google maps georeferenced images was performed. On natural touristic sites, plenty of pictures/selfies are taken by visitors and georeferenced on the Google maps. While remote sensing/satellite-based approach allow regional geomorphological studies of the geological bodies, this Google Maps “database” allows to visualize local outcrops, that we broadly described at different levels:

- 1st level: inferred lithology (lava flow, pyroclastic flow/ lahars, etc.);
- 2nd level: secondary features such as apparent thickness, cooling fractures, erosion processes, etc.;
- 3rd level: comments about the reliability of these data (number of pictures available, etc.), and also complementary data such as the identification of some springs.

Figure 3. Regional geological sketch elaborated from the maps of the Arjuno Welirang, the Penanggungan and the Tengger Complex, after [1,10,11], and Google photographs. The detailed units description are provided by [1,10,11]. Coordinates WGS84 - UTM 49S.
To ensure that the pictures were correctly referenced, the studied location had to comprise at least 10 pictures with similar outcrops view, consistent altogether from different sources/photographers. A geomorphological work can also be performed from Google Earth. Of course, the use of a precise Digital Elevation Model (DEM) may enhance the quality of the work. This geomorphological work provides additional quality information on the geological maps. Indeed, in volcanic edifices, the dynamics of construction, erosion, collapses, etc. by various types of eruption and volcanic activity creates complex structures, highly different from one edifice to another. Such processes are well described on Java island, especially on the Bromo-Tengger edifice [1], and on the Merapi [13].

These sites were then compared with the geological maps and their units’ descriptions. It turned out that, on the Arjuno Welirang volcanic edifice, the map of [11] seems to be the most accurate to our study purpose, with precise lithological description and location. Thanks to these lithological descriptions, potential aquifers/impervious bodies can be identified, and the kind of aquifers (fractured/porous) as well. But its spatial extension is limited to the volcano; downstream geological information is not available and were then summarized from [10] and confirmed by [1].

2.2. Aquifer outlet identification and outflow measurements

Most of the time, a hydrogeological study is performed in order to evaluate the water budget of an aquifer, for instance to implement water management strategies. The estimation of the water budget might be time consuming, especially to collect input data such as the rainfall, the effective rainfall or the evapotranspiration. But a first step of the water budget easy to carry out on field, or thanks to remote data, is the identification of the aquifer’s outflows, natural or anthropogenic, on the study area. The type of outflows and their location already provide valuable information about the groundwater availability, and therefore the number and type of aquifers (unconfined/confined), and sometimes their extent and type.

For instance, in the case of the Arjuno Welirang, a survey of the outflows and a comparison with a similar work on the Bromo-Tengger/Pasuruan plain helped to identify 7 types of outlets on both study areas (Figure 4):

- Low discharge springs (< 20 L/s)
- Medium discharge springs (≈ 100 L/s)
- High discharge springs (>>250 L/s)
- Dug wells (shallow unconfined aquifer)
- Pumped wells (deep aquifer)
- Artesian wells (self-flowing wells from artesian confined aquifer)
- Locally, geothermal springs and fumaroles (geothermal systems)

These different types of outflows indicate the presence of several different aquifers, that may be multi layered, which may communicate between each other or not. The relations between these aquifers are to be explored in the future steps of the project.
Figure 4. Main types of groundwater outlets on the Arjuno-Welirang, Bromo Tengger and Pasuruan plain, from available data on Dec. 15th, 2020 [1,14]. See a more detailed description in the text. Coordinates WGS84 - UTM 49S.

The main outputs of this comparative study between Arjuno Welirang and Bromo-Tengger were the following:

- High discharge low elevation springs (>>250 L/s) are only found, with numerous self-flowing wells, at the feet of the Bromo-Tengger volcanic edifice where there are identified as natural/anthropogenic outlets from an important and unique artesian volcano-sedimentary aquifer fed by recharge on the volcanic edifice [15]. No such important aquifer seems to exist at the feet of the Arjuno Welirang;

- Additionally, the upstream part of the Bromo-Tengger shows only a few very low discharge springs related to very small perched aquifers, the quite totality of the effective rainfall recharging the above cited main volcanic aquifer [15]. On the opposite, the Arjuno Welirang shows several medium discharge springs (≈ 100 L/s), emerging at medium elevation (Figure 4 and Figure 5), which are interpreted as the outlets of small to medium size aquifers bounded by impervious boundaries, that explain the groundwater outflows. The northern flank of the Arjuno Welirang is thus interpreted as the juxtaposition and/or superposition of several aquifers, pyroclastic and/or lavic, their lithology being identified from the geological maps, “field observations” (see section 3.1.), and boreholes geological logs. The coexistence of artesian wells and dug wells on this same area suggest the existence of superimposed confined and unconfined aquifers;

- The Arjuno Welirang downstream plain mostly shows no self-flowing wells. This is consistent with smaller aquifers than at the feet of the Bromo-Tengger, less recharged than on this latter area (as most groundwater seems to outflow at medium elevation springs) although the recharge elevation still needs to be defined (with 18O data notably).

From these data a sketch of the piezometry may be drawn for the Arjuno Welirang.
2.3. Aquifer Functioning

Along with the outflows field survey described above, an easy quick data gathering is the measurement of basic water chemistry parameters, such as pH, water temperature, and electrical conductivity, as field multiparameter probes are quite affordable, easy to carry on the field, and measurements are quick to perform. More detailed water sampling campaign can be organized after collecting this elementary data, on field or through bibliographic works. This will provide complementary data to the “Outflows measurement”, notably the identification of the different aquifer bodies (depth and lateral extent).

Once again on our study area, a first look at the EC data (Figure 5) shows that the waters sampled above 350 masl have a low electrical conductivity, as on the Bromo-Tengger volcanic edifice [1], suggesting low water-rock interactions, and probably small extension perched aquifers.

But, between 350 and 100 masl, the electrical conductivity on the Arjuno-Welirang is much higher than on the Tengger at the same elevation (with only a few perched aquifers on this latter), at all the water points (samples, dug wells, borewells), and is closer to the one of the springs and self-flowing wells located at the foothill of the Tengger. This can be explained by different types of water-rock interactions, and/or different residence times, and confirms the conclusions raised from the outflow’s location and measurements (section 2.2), and thus the type of identified aquifers: several medium size aquifers. Additionally, the relative homogeneity of the EC data between the springs and dug wells suggest that the confined aquifer may supply the subsurface unconfined ones.

The potential incidence of geothermal processes, as well as potential anthropogenic contaminations will however have to be investigated, notably from further hydrochemical and isotopic data.

![Figure 5. Electrical conductivity (µS/cm) of the springs and unconfined aquifer on Arjuno-Welirang and Bromo-Tengger complex. The 100 – 350 masl area is highlighted by the two dotted contours. Coordinates WGS84 - UTM 49S.](image)

3. Conceptual Model

The building-up of a preliminary hydrogeological conceptual model of the area enables gathering all the collected data (geological settings, first estimates of the water budget, aquifer functioning: *i.e.* notably
Flow directions in the aquifer from recharge area to discharge areas). Such a conceptual model will be enhanced all along a hydrogeological project, as more and more data will be available to feed it. It will also help to identify the key missing gaps in the overall knowledge. Thus, appropriate research projects can then be launched and their cost evaluated.

[15] provided the complete conceptual model over his study area (Figure 6). This provided valuable data to elaborate a numerical modelling tool, which is a pedagogic and precise tool to provide and test water management scenarios [1].

On the Arjuno Welirang complex, our preliminary conceptual model is provided on Figure 7, as partly described in the previous section of this paper. First of all, on the upstream part of the study area, the water users in the Pandaan district are relying on several medium size, medium elevation aquifers, exploited with shallow (dug wells) and deeper wells: self-flowing borewells, some of them being—no more—self-flowing due to neighbour abstractions, or due to their specific location within the given aquifer. The picture is very different from that of the Bromo Tengger Complex at the same elevation characterized by a unique and deep aquifer with a too deep piezometric level to enable the drilling of acceptable cost wells, and also dug wells. Second, there are no major springs identified at the feet of the Arjuno Welirang volcano, an opposite configuration compared to the Merapi [13], or to the Bromo-Tengger [1]. This leads us to hypothesise that most of the water infiltrated along the flanks of the volcanic edifice outflowed at the above described higher elevation springs, due to local low permeability boundaries/layers/geological bodies. The relatively high electrical conductivity, not observed at such elevations on the Bromo-Tengger, confirms this scheme, with quite long water residence time.

![Figure 6. Hydrogeological conceptual model of the Bromo-Tengger [15].](image)

![Figure 7. Arjuno Welirang Conceptual model 01/2021, after [10,11].](image)
4. Discussion and perspectives

Our results allowed to elaborate a first hydrogeological conceptual model of the Arjuno Welirang complex, with numerous layered aquifers on the flank of the volcano, with highly diverse productivity. Of course, at this point our study isn’t enough to provide usable science for sustainable water management policies. And as studied in [2], our PCM is subject to high uncertainties due to the lack of data. Nevertheless, this PCM gives us a clear view for future research project, and illustrates that our research area has a completely different behaviour than the Bromo Tengger North flank unlike what the regional map (Figure 1) may suggest. It highlights the key missing data to build a robust conceptual model that includes all the processes of the water cycle.

In order to have a continuous improvement of the conceptual model, the priority should be given to:
- Acquire geological data, especially in the “midstream” area, where there is the less data, but also the most water extraction (springs, dug wells, borewells pumped & artesian). As stressed earlier in the paper, improving the knowledge about the geological structure of the aquifer will be fundamental, as the geology of these aquifers was poorly characterized in this PCM.
- Acquire piezometric levels for all the different water outlets (springs and wells), in order to build a piezometric map, and get a first idea of the water fluxes, underground sub-watersheds, etc.
- Estimate the water outflows (natural & anthropic) amounts (analysis of various data bases compiling water volume for various water uses (domestic, industrial, …), field survey, remote sensing, …).
- As it appears that there are several multi-layered aquifers with a plenty of natural (and anthropic) outflows, it is expected that the aquifers have limited lateral extend. Therefore, the north east flank of the Arjuno-Welirang would be composed of several small to medium extension aquifers. To differentiate them, and then estimate precise water budget, an extensive water sampling campaign is necessary. This concerns the water major and minor ions, but also the water isotopes ($^{18}O$ and $^{2}$H).
- The rivers/groundwaters interaction is still unknow, and shall be checked all over the study area (upstream, midstream, downstream), as it may affect the water budget estimation, and/or potential pollutant transfer. For this, gauging and electrical conductivity measurements will be performed during the dry season in the river beds. This will also complete the geological and hydrogeological characterization of the aquifers and the aquitards/aquicludes.
- In order to precise local geological & hydrogeological parameters, notably in areas without significant outcrops, geophysical campaigns will be performed, and will be calibrated on existing wells and outcrops, as well as on the observations performed along the rivers.
- A rigorous meteorological dataset acquisition will be performed, with collection of existing and new hydrometeorological data (raingauges, temperature, humidity, river discharge, etc.), with in situ station and remote sensing/climate models, in order to compute water budget estimates (rainfall, evapotranspiration, share between recharge and runoff…).

5. Conclusion

Our study shows that despite apparent similarities between volcanic edifices at the regional scale, the hydrogeological patterns of neighbour volcanoes can be very contrasted. Simple investigations enable building-up a preliminary conceptual model (PCM) of complex volcanic settings. Such PCM is needed to define further detailed hydrogeological investigations required to set-up aquifer exploitation, management and protection rules. This is well shown by the comparison of the PCM of the Arjuno Welirang volcanic complex and the CM of the Bromo-Tengger north flank. The Bromo Tengger North flank conceptual model comprises small extension aquifers above 100masl, with an important recharge that feeds an important and productive volcano-sedimentary aquifer at the foot of the volcano. Whereas the Arjuno Welirang PCM suggest small extension aquifers only at high elevation, and an important multi-layered aquifers system a medium-low elevation. The contribution of these aquifers or a deeper infiltration to the volcano-sedimentary/sedimentary plain remains completely unknown for the moment.
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