STUDY OF GROUNDWATER AGE DATING IN DIENG HYDROTHERMAL SYSTEM, INDONESIA

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ABSTRACT

Tritium is a radioactive isotope of hydrogen which occurs in precipitation. In groundwater studies tritium measurements give information on the time of recharge to a system; the tritium content of precipitation being used to estimate the input of tritium to the groundwater system. In Dieng, the tritium contents in precipitation and groundwater samples from production wells and manifestations were measured in the wet season. The precipitation has 2.7 ± 0.8 TU. In the hot springs the tritium content ranges from 1.0 to 4.0 ± 0.8 TU, while in production wells from 4.0 ± 0.8 TU. These values indicate that the groundwater systems around Dieng contain a mixture of old recharge and recent recharge (water younger than 50 years).

1. INTRODUCTION

The most commonly used environmental isotopes are oxygen-18, deuterium, tritium, carbon-13, and carbon-14 (Pearson, 1991). This paper deals with the tritium (^3H) content in natural waters in The Dieng Plateau. The tritium content in manifestations and in well fluids can be used as a guide to determine mixing between old water and recent waters containing at least a contribution of recent precipitation.

Tritium is a radioactive isotope of hydrogen which occurs in precipitation and originates from two sources, one natural, and the other man-made. It is naturally produced in the upper layers of the atmosphere from the action of cosmic rays on nitrogen according to the reactions:

$^{14}N + n \rightarrow \text{tritium} + {}^{12}C$

$^{14}N + n \rightarrow 3{}^4He + {}^3H$

The other source of tritium is man-made as, since 1952, it has been generated by thermonuclear explosions in the atmosphere (Fontes, 1983). This atmospheric testing injected periodic pulses of tritium into the atmosphere so that its concentration in precipitation increased in the northern hemisphere during 1963 - 1964 by three orders of magnitude above that arising from cosmic rays (Cook and Herezeg, 2000).

The tritium is rapidly oxidized and enters into the hydrologic cycle as "tritiated" water. The production rate of tritium in the whole atmosphere has been estimated at 0.25 atoms/cm^2/s (Fontes, 1983). The concentrations in precipitation vary between about 5 to 20 TU (Tritium Units) depending on the geographic location in the northern hemisphere. It generally increases with increasing latitude (IAEA, 1983).

However, since the middle 1960s its concentration has decreased to the so called pre-bomb level, most especially in southern countries, like Indonesia, where there are no nuclear facilities which might locally affect the present hydrologic cycle.

Knowledge of the tritium content of precipitation is a prerequisite for estimating the input in a given area for interpreting tritium concentrations in groundwater in the target area. The advantage of the environmental tracers (natural or anthropogenic) like tritium is that they provide in-situ information at the moment of sampling.

The tritium content of groundwater can be used as a guide to distinguish between old (pre-bomb water, older than 40 years) and water containing at least a contribution of recent precipitations, in a semi quantitative manner. The tritium content of current precipitation/recharge measured at Dieng is not much above the pre-bomb level.

Water with zero tritium (in practice < 0.2 TU) is dated, as prior to 1953; water with little but measurable tritium (0.2 - 2 TU) seems to be a mixture of pre-1953 (palaeo-groundwater) and post-1953 water; water with a concentration greater than some 2 TU is of a post-1953 age; and water with a significantly higher concentration (> ~ 30 TU) indicates recharge during the 1960s.

2. MATERIALS AND METHODS

2.1 Area of Study

The Dieng geothermal field is located in The Dieng Plateau, 26 miles north of the city of Wonosobo, Central Java and it is a two-phase, liquid-dominated reservoir. The field has an installed capacity of 60 MW electricity supplied by its 8 production wells from the Sileri reservoir (Figure 1).

2.2 Geology and Hydrogeology

The Dieng mountain complex is composed of Quaternary volcanic rocks aligned similarly to the regional structural features. The E-W trend extends from Gunung Butak on the west to Gunung Prau on the east. The peaks of these mountain complexes rise to elevations of between 2200 and 2555 masl. The surface rocks in this area are covered by Quaternary andesite lava flows and pyroclastic units (van Bergen, *et al.*, 2000).

The Dieng Volcanic Complex (DVC), which is within the Central part of Java Island, is characterized by a collapse structure containing 17 post intra-caldera eruptive centers. This volcanic complex shows long-term volcanic activity of about 3 M.a. and is a possibly record of the long-term magma evolution at a single volcanic complex (Setijadji, 2010).

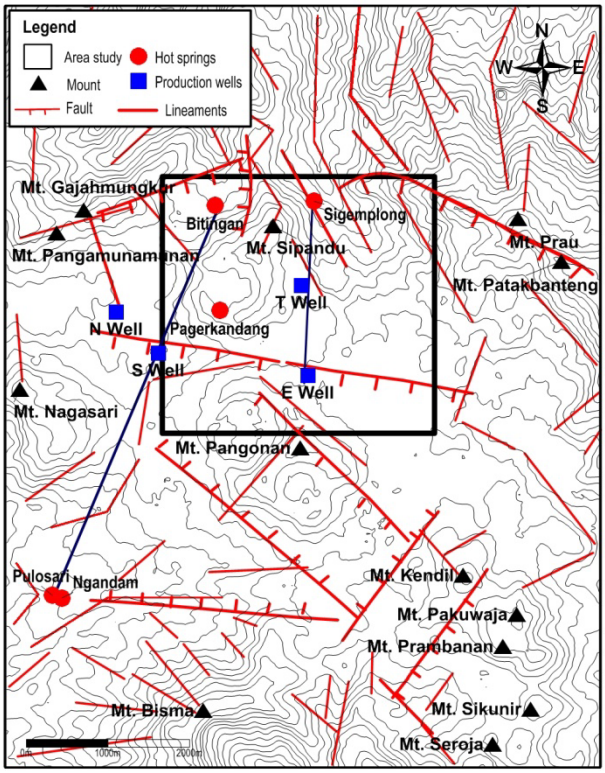

Figure 1: Geology map of study area.

Since the eruption of lava domes and flows in the eastern Dieng Mountains, no deposits of magmatic eruptions, explosive or otherwise, have been identified in the Dieng region. Numerous historic and prehistoric phreatic or hydrothermal explosive eruptions have occurred. Some of the eruptions have produced single, steep-walled, circular craters while others have produced a series of connected or elongated craters or fissures (Sukhyar, 1986).

The climate is characterized by two distinct seasons; the wet and dry seasons of nearly the same duration. During the wet season, monsoonal rains fall between October/November and March/April. Measurable annual rainfall ranges from 1,000 mm/year to more than 4,000 mm/year with on average rainfall occurring on as many as 114 days/year. At the peak of the rainy season, January, rainfall can reach more than 500 mm/month. The dry season lasts from April/May to September/October (BMKG, 2012).

Maximum air temperature in the Dieng Volcanic Complex is 24.4°C, the average is 14.2°C and the lowest temperature in July and August, can reach as low as 5°C, with humidity ranging from 84-86% (BMKG, 2012).

Based on the hydrogeological map at 1:1.000.000 Scale (Sheet XII of Bakosurtanal (2004)), the Dieng Geothermal Field is dominated by a local productive aquifer. The transmissivity of the aquifer is diverse with a deep water tables and springs that discharge at low rates.

This aquifer is composed of Younger Volcanic Rocks, sedimentary rocks and volcanic Old Prau. Younger Volcanic Rocks consist of fresh tuff, agglomerate, volcanic breccia, lava and lahar sediments (Sukhyar, 1986).

The drainage system is dominated by the Wonosobo and Karangkobar Groundwater Basins. Wonosobo Groundwater Basin at 900-1,200 meters above sea level has an unconfined groundwater recharge of about 210 million m^3/year, and confined groundwater flow of about 8 million m^3/year. The Karangkobar Groundwater Basin is located at 1,000 meters above sea level, and has a number of unconfined groundwater recharges, totalling 153 million m^3/year, and a confined groundwater flow of 4 million m^3/year (Effendi, 1985).

There are several main seasonal streamlets, like Kali Belo and Kali Tulis in the north, Kali Dolok in the middle of the DVC, Kali Sedangdang and Kali Condong on the southwestern, and Kali Merdeka on southern parts that flow into Lake Merdada (Figure 2).

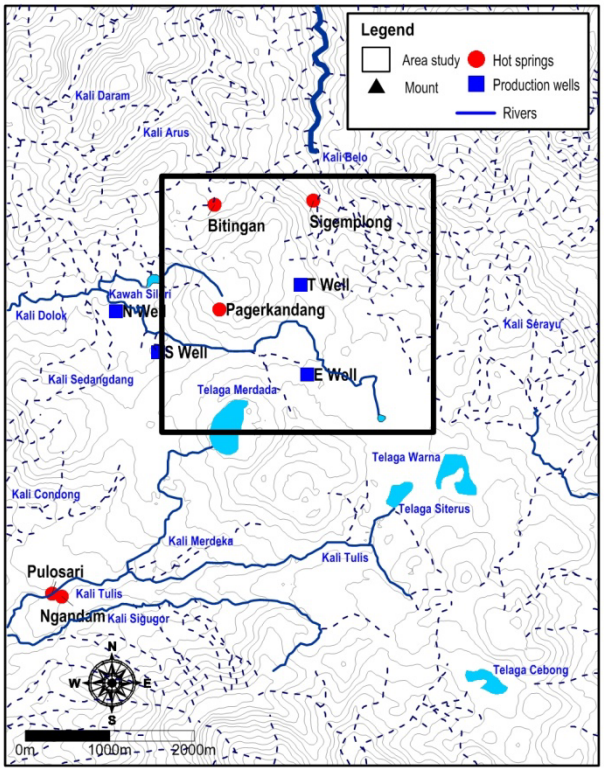

Figure 2: Hydrology map of the study area.

3. RESULTS

3.1 Water Sampling and Analyses

Five hot spring waters samples on November were collected in 500 ml polyethylene bottles. On January, 4 production well fluids (S Well, E Well, N Well, and T Well) were collected in 500 ml polyethylene bottles. These samples were transported to the laboratory of The National Agency for Atomic Energy (BATAN) Jakarta for chemical, stable isotope, and tritium analyses.

All the tritium analyses (following standard procedure) were completed by liquid scintillation PACKARD counter. The results of the analyses are presented in Table 1.

3.2 Chemical Composition

For comparing the thermal waters with mineral and peripheral waters, a $Cl\text{-}SO_4\text{-}HCO_3$ ternary plot was used. This diagram covers the entire spectrum of naturally occurring waters from virtually pure chloride, over mixed chloride-sulfate, to bicarbonate (Giggenbach, 1988; Nicholson, 1993). For the $Cl\text{-}SO_4\text{-}HCO_3$ hydrogeochemical data, some cluster into the steam-heated/condensates and dilute $Cl\text{-}HCO_3$ sectors (Fig. 3).

The Cl-SO_4-HCO_3 ternary diagram is used to classify natural waters (Giggenbach, 1988). It helps to identify immature unstable waters and gives an initial indication of mixing relationships. The diagram distinguishes several types of thermal waters, including peripheral waters, volcanic waters, and steam-heated waters. It gives a preliminary statistical evaluation of groupings and trends.

Figure 3 shows that all production well fluids have a high Cl content relative to HCO_3 and SO_4 as does typical mature water. The Pulosari and Ngandam hot springs plot close to the mature water sector because of their high concentrations of Cl. Pagerkandang plots on volcanic and steam heated water sector. The other hot spring samples (Sigemplong and Bitingan) plot in the peripheral water sector.

The Na-K-Mg diagram is used to classify waters into fully equilibrated, partially equilibrated, and immature waters. It can be used to predict the equilibrium temperature and also the suitability of thermal waters for the application of ionic solute geothermometers. It is based on the temperature dependence of the full equilibrium assemblage of potassium and sodium minerals that are expected to form in the Dieng area (Giggenbach, 1988).

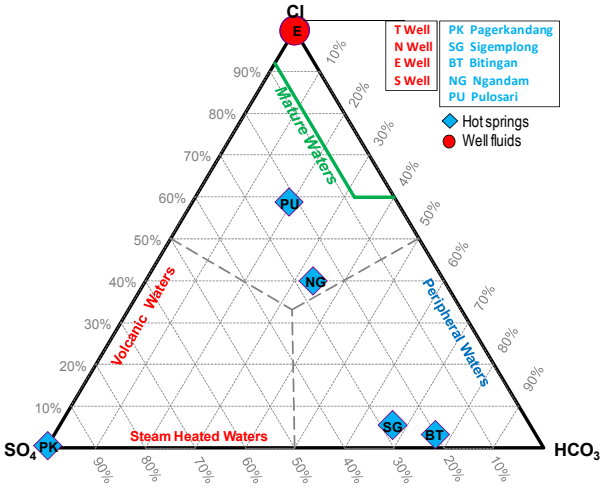

Figure 3: Relative Cl-SO_4- HCO_3 contents of thermal waters on weight basis in Dieng.

According to Figure 4, the well production fluids are only partly equilibrated. This partial equilibration may be due to reactions with wall rock during upflow from the reservoir or could result from mixing of waters of different compositions. All hot springs plot in the immature waters field, indicating reservoir fluids have mixed with groundwater.

3.3 Tritium in Precipitation

The natural tritium content in precipitation which once was between 7 and 10 TU has decayed down to about 1 to 4 TU in the 1980s (Fontes, 1983). Thus the practical rule to identify old groundwater (age > 50 years) would be ≤ 7.4 TU or even ≤ 10 TU at Dieng; and tritium content of 10 – 50 TU would correspond to recharge between 1962 and 1971; the tritium content of 50 – 300 TU would be the recharge during 1957 – 1962 (obviously of recent origin).

This rule assumes no mixing, with the groundwater remaining quite separately segregated according to age during transit. Accordingly, no water younger than 40 years is present in the well production fluids sampled at Dieng. This means that more than 40 years is required for water to reach the sampling points from the recharge area. These aquifers would therefore contain pre-bomb recharge. This is important for water resources management.

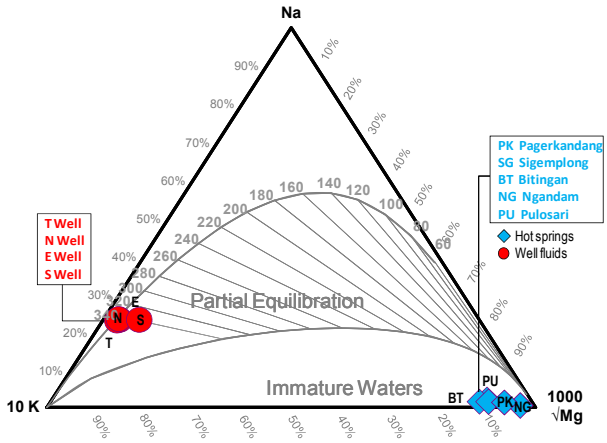

Figure 4: Na-K-Mg diagram shows partial equilibrated and immature waters in all samples.

In practice, however, mixing between different water bodies may take place because of the dispersive effect of the granular aquifer material, and so tritium peaks and valleys could be smoothed out. Where mixing takes place, Fontes & Edmunds (1989) observed that no simple process can explain the minimum tritium value required to provide evidence of a significant contribution of recent water in an aquifer. In those circumstances the low, or the lack of, tritium does not necessarily preclude present day recharge because the transit time in the unsaturated zone may be considerably longer than 30 – 40 years. The TU peak is dependent on infiltration percolation characteristics and on the thickness of the unsaturated zone above the water table. An assumption may thus be made of uniform TU values in the saturated zone resulting from mixing of waters of different recharge periods due to the dispersive effect of granular aquifer material.

The tritium content of current recharge (Fig. 4) is not much above the natural level. This introduces ambiguity in the interpretation of tritium data. The question of recharge of both deep and shallow aquifers systems is one of the most critical issues for groundwater management. It is important to know if recharge is currently taking place and at what rate. Another problem groundwater hydrologists face in Dieng is the poor knowledge of the recharge zone and of the flow system because of a lack of observation points or because natural flow patterns are extensively modified by withdrawal.

In several parts of the world the IAEA monitored the variations of tritium in monthly precipitation. One of the IAEA stations with a long record data on tritium in precipitation close to Dieng is Jakarta Station. IAEA maintained a station at Jakarta from July 1957 to December 1991. The values presented on the curve represent the variations of weighted monthly tritium content of precipitation at Jakarta.

The peak concentrations occurred in 1962-1964 and have fallen steadily to a little above the pre-bomb level of 2 to 6 TU (Figure 5). The records have been corrected for radioactive decay. These values may represent the present recharge at Dieng.

3.4 Tritium in Thermal Fluids

The measurement of tritium concentration in hot spring waters would provide information on the origin and subsurface behavior of thermal fluids. As the half-life of tritium is 12.43 years, it is practicable in beneficial occurrences to approximate the residence time of hot spring waters through tritium measurements.

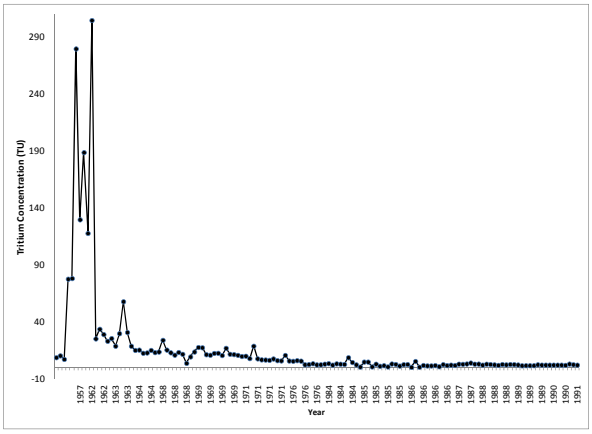

Figure 5: Variation of tritium in precipitation at Jakarta Station (IAEA, 1981).

The tritium content in hot spring waters at Dieng varied between 1.0 to 4.0 ± 0.8 TU in November, while in production wells it was 4.0 ± 0.8 TU. These values are rather low in concentration. Water with a significant tritium concentration (±30 TU) is either of sub-recent age (younger than 50 years) or more likely a mixture of older and recent waters (Fontes & Edmunds, 1989).

In Figure 5 the tritium content of groundwater samples is plotted against borehole depth. An examination of the results indicates a decrease in concentration with increasing depth. This would be expected if good mixing (of young and old waters) is responsible for the variation in tritium contents in the groundwater samples. The mixing is probably taking place in the borehole or by hydraulic connection (leakage) between the different aquifer strata. A small portion of recent water combined with a major portion of tritium free water may mean old water or a small amount of thermonuclear tritium, is present.

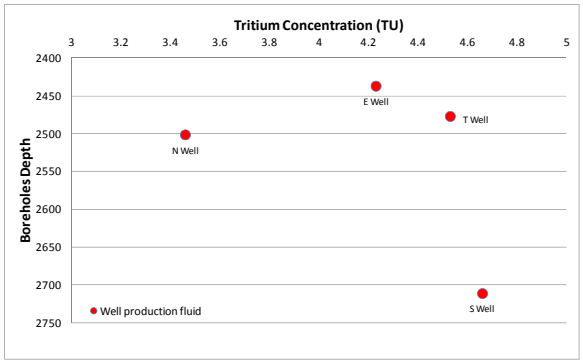

Figure 6: Variation of tritium content in groundwater with depth for deep boreholes at Dieng.

3.5 Residence Time

The residence time of the thermal fluids is defined as the time since they were last secluded from the atmosphere. Geothermal parent fluids are tritium free. The presence of tritium in the thermal water is an indicator of dilution by the shallow groundwater.

Groundwater dating with tritium decay is based on the assumption that the input of tritium into the groundwater is 6 TU (IAEA, 2010). So the residual tritium that measured in the groundwater is the result of decay following the equation:

$$a_t{}^3H = a_0{}^3H\, e^{-\lambda t}$$

Where: $a_0{}^3H$ is initial number of nuclei present at time t = 0

λ is the decay constant, proportional to $(\ln 2)/t_{1/2}$

$t_{1/2}$ is the half life of tritium = 12.33 years.

So that, $t = -17.93 \ln (a_t{}^3H/a_0{}^3H)$

The initial number of nuclei tritium activity ($a_0{}^3H$) in precipitation in the Southern Hemisphere (including Indonesia) is stable at 4 to 6 TU (Satrio, personal communication). Assuming that initial number of nuclei tritium activity in Dieng precipitation is 6 TU, the residence time of groundwater (t) is as shown in Table 1.

3.6 Rate Recharge

Groundwater recharge is the addition of water to a saturated zone and the downward movement of the water into aquifer systems. Nearly all of the water recharging the KVD comes from rainfall.

Rainfall percolating downward from land surface to the Karangkobar aquifer system usually passes through the unsaturated soil zone, the surficial aquifer system, and the intermediate aquifer system. In this vertical movement, water moves from an area of higher water level to an area of lower water level. The rate of recharge is governed, therefore, by both the leakage characteristics of intervening units, especially clays, and the hydraulic head between aquifers.

The elevation of the bottom of the casing was assumed to be equal to the elevation of the top of the Karangkobar aquifer. Recharge water is treated as being added at the top of the aquifer. The very top of the aquifer could not be sampled because of the manner in which the well had been constructed. However, a portion of the top of the aquifer was sampled. If the depth to the bottom of the well was used instead of the depth at the bottom of the well casing, the estimated recharge rate using isotopes would be greater.

Isotopic recharge rate is estimated using the following equation from Toth (1995):

$$RR \geq \frac{12\,\Phi\,|CD-(EL-WT)|}{A}$$

Where: RR = recharge rate in inches per year

CD= depth at the bottom of the well casing measured in feet

EL = elevation of land surface in feet above mean sea level

WT = elevation of the water table in feet above mean sea level, generally the water level in the surficial aquifer system

12 = constant to convert feet to inches

(|> = porosity of stratigraphic column (unitless)

A = age of ground water in years, based on tritium

Table 1. Calculation of residence time (t) and recharge rate (RR) of groundwater in KVD.

Location	Elevation (m)	Production Casing Depth (m)	^{3}H Content (TU)	Residence Time (year)	Rate Recharge (inch/year)
S Well	2063	2711.24	4.66	4.49	≥ 90.54
E Well	1825	2436.90	4.23	6.21	≥ 66.55
N Well	2070	2501.29	3.46	9.78	≥ 40.22
T Well	1900	2476.91	4.53	4.99	≥ 79.72
Bitingan hot spring	2137	-	3.97	7.34	-
Ngandam hot spring	1740	-	4.17	6.47	-
Pagerkandang hot spring	2120	-	1.93	20.16	-
Pulosari hot spring	1688	-	3.65	8.83	-
Sigemplong hot spring	1800	-	4.09	6.81	-

As we can see from Table 1, Pagerkandang hot springs contains water with little, but measurable, tritium (0.2 - 2 TU), that seems to be a mixture of pre-1953 (palaeo-groundwater) and post-1953 water. The rest of the hot springs are categorized as post-1953 age/modern water (water with a concentration greater than 2 TU).

If KVD has rainfall of about 390 – 1.500 inches/year with an average recharge rate of 69.26 inches/year, about 5 to 22% of the precipitation is assumed to percolate into the aquifer system.

4. DISCUSSION

A number of chemical investigations have been made on Dieng thermal waters including well production and hot spring waters. The extensive tritium values and other chemical data of the hot springs allow detailed discussion of their origin and the flow processes in the subsurface.

The analysis results for deuterium, tritium and chloride are given in Table 1. The tritium values are plotted against deuterium values on Figure 7. In Figure 8, tritium values are plotted against chloride concentration. In Figure 9, the relationship between the deuterium values and chloride concentration is shown.

Table 1, Figure 7 and 8, show that:

1. High temperature, chloride-rich well production waters have high deuterium values of -45‰ ~ -60‰ and low tritium concentrations of 3.5 – 4.7 TU.

2. Hot spring waters of medium chloride concentration have low tritium concentration (3.7 - 4.2 TU), and deuterium -60‰ ~ -55‰.

3. Cold carbonate spring waters have lower tritium concentrations of 1.9-4.2 TU and low deuterium values of about -55‰~-70‰

A straight line (A-line) can be drawn through the points for all well fluids. Another line (B-line) can be drawn through the points for hot springs with medium chloride and carbonate springs, which crosses line A at about 4.3 TU and deuterium -54.5‰.

Figure 7 suggests that Cl-rich hot spring waters result from the mixing of two types of water, viz., one having a deuterium level of -45‰ and low tritium, and the other having a deuterium level of -50‰~-70‰ and tritium of about 1.9 – 4.2 TU.

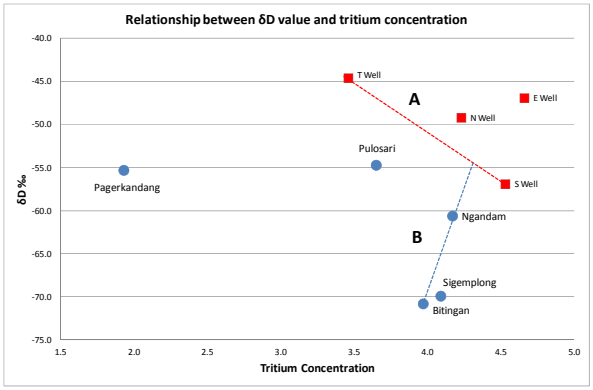

Figure 7: Relationship between deuterium and tritium concentration.

Pagerkandang water does not fall on the mixing line (Figure 7). It may have aged after mixing. It is also possible that the Pagerkandang hot spring water is formed by mixing of two sorts of water, i.e. chloride-rich which condensed near surface water and old meteoric water with a deuterium level of less than -50‰ and tritium 2-3 TU.

The Pulosari hot spring water, N Well fluid, and E Well fluid are contaminated by meteoric water with a high tritium concentration. Pulosari discharges on the west side of the Kali Tulis River, whereas N Well and E Well discharge near the Kali Dolok River (Figure 2). So that the meteoric water may have been derived from another hydrological unit. This conclusion is also supported by the mixing with meteoric water (Figure 4).

Figure 8 also suggests that Cl-rich hot spring waters are mixture of two sorts of water, viz., one having a Cl concentration of 324.9 mg/kg with less tritium, and the other Dieng groundwater which has less chloride with a tritium concentration of about 2-4 TU.

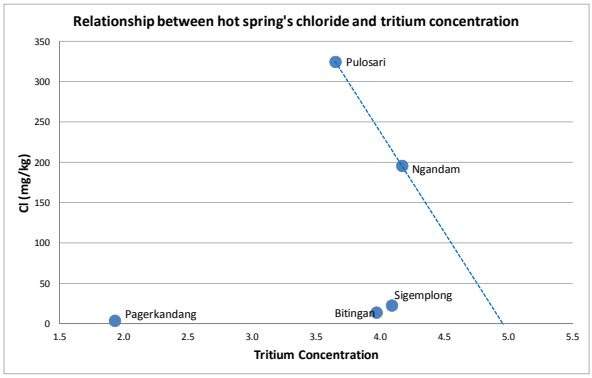

Figure 8: Relationship between chloride and tritium concentrations in hot springs.

It is very likely that water of deep origin has no tritium, and hence we can conclude that one of its end members is derived from the deep water characterized by no tritium, Cl of 23.000 mg/kg and a deuterium level of -44.6‰.

The other water is the Dieng groundwater which has a deuterium level of -70‰ and tritium concentration of about 5-6 TU and less chloride.

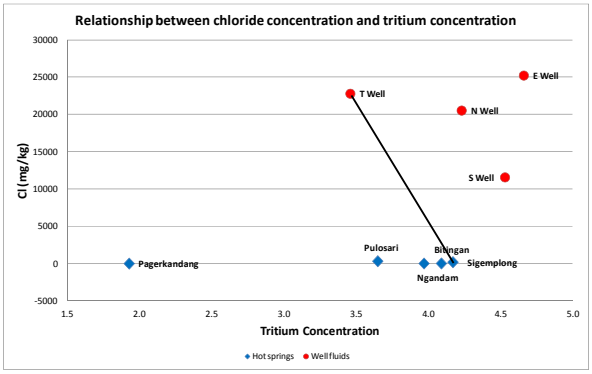

Figure 9: Relationship between chloride and tritium concentrations in hot springs and well fluids.

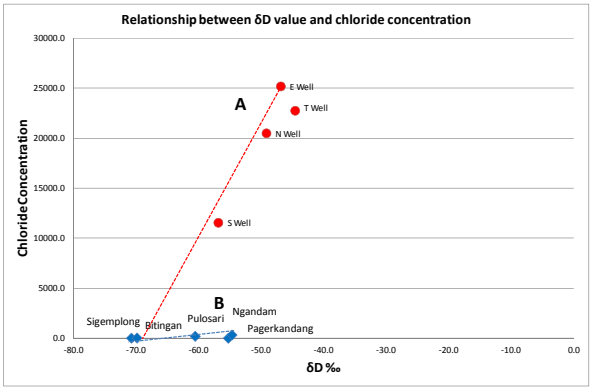

Figure 10: Relationship between chloride concentration and deuterium values.

However, it is difficult to determine the real age of these waters, because water from each hot spring has mixed to some extent before discharge. Kusakabe *et al*. (1970) suggest that mountainous stream waters are derived mostly from a well-mixed subsurface reservoir.

5. CONCLUSIONS

We can deduce from the analyses that there are probably two groundwater sources, one from a shallow aquifer with recent recharge (tritium concentration near precipitation concentration, 5-6 TU) and the other from a deeper aquifer with low tritium concentration but higher chloride concentration. In this connection, note that the contribution of older water causes an increase in tritium concentration in the discharging water.

Recent recharge is made up of from 5 to 22% of the precipitation per year in the KVD, that is assumed to percolate to the local productive aquifer system through permeable zones that is composed of Younger Volcanic Rocks, sedimentary rocks and volcanic Old Prau.

Although some ambiguity remains, we can make some conclusions with respect to the origin of waters in the Dieng hot springs and well fluids, as shown schematically in Fig. 7. Deep chloride water is mixed with groundwater that originated from the latest rain water that is only a few years old.

6. RECOMMENDATION

The relationship between the δD versus Cl contents is used to determine firstly whether or not the water is a mixture of two or more different waters. If no mixing is indicated, then we should note the difference in tritium concentration in water from each spring, caused by the age effect. So, the tritium concentrations in rain water and in the hot spring waters during the rainy and dry seasons should be compared.

Although this seems not to be a good dating method because the age of thermal water is far beyond the limit (about 100 year) of the tritium method, determination of the groundwater residence time by tritium may be collectively assisted by carbon-14 dating.

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Table 2. Analytical results on deuterium, tritium and chloride in Dieng.

No	Location	Fluid type	Elevation (mdpl)	T (°C)	pH	Na^+	K^+	Li^+	NH_4^+	Ca^{2+}	Mg^{2+}	Fe^{2+}	As^{3+}	B	SiO_2	SO_4^{2-}	HCO_3^-	Cl^-	F^-	δD	$\delta^{18}O$	δ^3H
						mg/L														‰		TU
1	E Well	Well fluid	2063	58.6	6.3	7688.0	2348.0	50.0	0.0	611.8	1.7	0.5	60.0	297.8	1480.3	10.7	0.0	15916.4	1.0	-46.9	0.3	4.7
2	N Well	Well fluid	1825	70.3	7.1	12098.0	3845.0	66.4	0.0	1376.2	3.2	1.2	700.0	568.9	1167.8	67.5	21.0	25222.8	0.3	-49.2	0.1	4.2
3	T Well	Well fluid	2070	72.1	6.2	10232.0	3313.0	61.3	0.0	743.1	1.7	0.9	90.0	429.5	1449.8	1.0	19.3	20526.1	0.5	-44.6	1.9	3.5
4	S Well	Well fluid	1900	70.5	6.7	11420.0	3619.0	65.7	0.0	1095.2	2.3	3.1	500.0	490.7	1081.6	18.1	15.6	22787.5	1.0	-56.9	-3.0	4.5
5	Bitingan	Hot spring	1860	52.3	5.9	8.6	6.3	0.0	2.4	42.9	12.7	0.2	0.0	1.8	164.7	85.4	324.9	13.9	1.4	-70.8	-10.6	4.0
6	Ngandam	Hot spring	1740	55.6	6.6	107.2	15.5	0.0	3.1	83.3	24.1	0.2	0.0	3.6	191.4	128.7	164.7	195.9	2.4	-60.6	-8.6	4.2
7	Pagerkandang	Hot spring	2120	93.7	3.8	8.8	0.0	0.0	4.9	78.2	24.3	7.5	0.0	0.0	127.8	544.3	0.0	3.7	0.9	-55.3	-4.3	1.9
8	Pulosari	Hot spring	1688	56.0	5.6	87.9	35.1	0.1	3.3	107.5	34.7	0.1	0.0	5.7	194.2	120.3	107.1	324.9	2.3	-54.7	-7.2	3.7
9	Sigemplong	Hot spring	1800	61.2	5.4	4.3	0.8	0.0	5.0	42.8	23.7	1.6	0.0	4.9	177.9	114.3	278.5	22.7	2.5	-69.9	-10.2	4.1