Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Estimating the Isotopic Composition of Meteoric Water Index in Geothermal Fields in the Philippines

Noel D. Salonga

Energy Development Corporation, One Corporate Center Bldg., Julia Vargas corner Meralco Avenue, Ortigas Center, Pasig City 1605

salonga@energy.com.ph

Keywords: meteoric water index, stable isotopes, Philippines.

ABSTRACT

This paper updates the Philippine Meteoric Water Line (PMWL) and presents methods in estimating the Meteoric Water Index (MWI) in Philippine geothermal fields. The updated PMWL has an equation of: δ2H = 8 δ18O + 12.5 + 0.5. This equation which was based on 680 samples has good correlation factor of 0.96.

MWI is a set of numbers that may represent the composition of all the meteoric waters that became part of the groundwater resource. The MWI, together with the meteoric water line is often established by collecting monthly rain samples for two to five years. In areas with no intensive sampling of rainwaters, several approaches of estimating the composition of MWI are proposed. The approaches use isotopic compositions of the rivers, ground waters, sulphate springs, chloride springs and deep geothermal waters to estimate MWI. The regression lines generated by the four type of waters often intersect the meteoric water line at points close to MWI. The concept is tested in the geothermal fields of Tongonan, Palinpinon, Bacman and Mt. Apo in the Philippines. The projected MWI from the modeling of the four areas plotted close to the MWI that was calculated from the rainwater data.

1. INTRODUCTION

Stable isotopes technology has been proven useful as geochemical tools for exploration and management of geothermal resources. The breadth of application of stable isotope ranges from tracing the origin of groundwater or geothermal resources to quantifying the proportions of mixing of two or several water components, to modeling the subsurface flow of the geothermal reservoir (e.g. Salonga, 1996; Technical Services Sector, 2012).

Among the applications of stable isotopes technology, construction of mixing models is one of the most useful as mixing models provide straight-forward interpretation of geothermal resources. The requirement of mixing model is simply well-defined end members of participating fluids in mixing process, which may be seawater, groundwater, geothermal water or industrial waters. In cases of seawater and industrial waters, determining their isotope composition may just involve direct sampling. In the cases of the other two types of water, however, determining representative composition may be more complex and may involve numerous sampling campaigns. For the geothermal waters for example, periodic sampling of production wells is recommended in order to keep track of the changes of the isotopic composition with time.

This paper focuses on the groundwater end-member in geothermal systems in the Philippines. The paper will explore various ways of estimating the isotopic compositions that may represent the groundwater end-member in mixing diagrams. This paper will also update the Meteoric Water Line of the Philippines using the new and numerous samples collected in the past 10 years.

2. THE PHILIPPINE METEORIC WATER LINE

The Philippine Meteoric Water Line (PMWL) was first determined in 1970's based on a single rainfall station in Manila. Monthly rain samples were collected and analyzed for Deuterium (δ^2H) and Oxygen 18 ($\delta^{18}O$) composition from January 1961 to December 1976, which comprised only of 46 data points. The generated PMWL has the equation similar to the Global Meteoric Water Line (Equation 1a), and has a correlation factor (r^2) was about 0.83.

$$\delta^2H = 8\ \delta^{18}O + 10 \qquad \text{Equation 1a}$$

It took more than 30 years to update the PMWL. The updated PMWL was determined using the monthly rainfall data collected from the following areas (Locations of the areas where rainfall sampling stations were installed are shown in Figure 1.):

- Manila rainfall station from January 1961 to December 1976
- Quezon City station from January 2000 to December 2007
- Tongonan geothermal field from January 1991 to May 2012
- Palinpinon geothermal fields from January 1991 to December 1998
- BacMan geothermal field from January 1990 to December 1998
- Mt. Apo geothermal field from December 1994 to June 2012

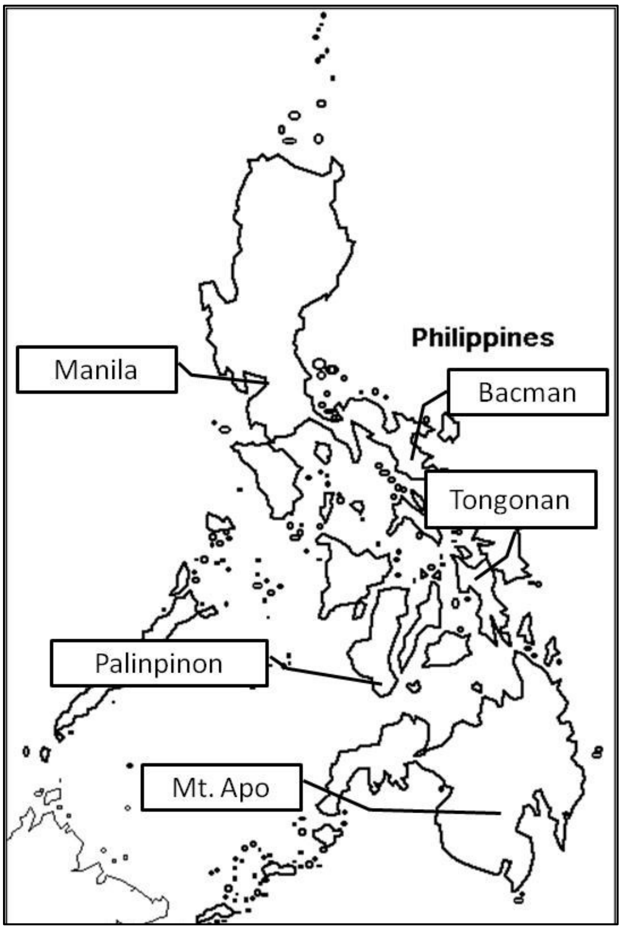

Figure 1. Map of the Philippines showing the location of the areas mentioned in this report.

There are about 680 data points from all of the above stations and the data are presented in various reports and papers (Salonga, 1996; Dacillo and Salonga, 2004; Salonga and Siega, 1996; Gerardo et al., 1991; Technical Services Sector, 2012). The plot of all data points are shown in Figure 2. Using regression analysis, the equation of the updated PMWL is shown in Equation 1b. It has with a correlation factor (r^2) of 0.96, which is higher than the earlier equation.

$$\delta^2H = 8\ \delta^{18}O + 12.5 \pm 0.5 \qquad \text{(Equation 1b)}$$

The slope of PMWL adopted the slope of the Global Meteoric Water Line (GMWL) of 8.0. It was also observed that the value of the excess deuterium, or the y-intercept, has slight variation in the study areas, from 12.5 in Palinpinon to 13.2 in Mt. Apo.

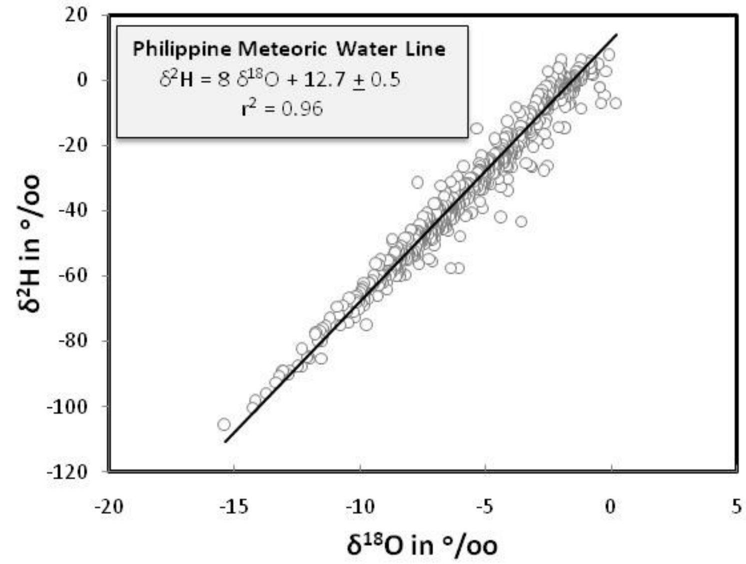

Figure 2. The plot of δ2H vs. δ18O of all rain samples in the Philippines. The updated Philippine Meteoric Water Line based on about 680 data points is also shown in the plot.

3. THE METEORIC WATER INDEX

In a typical hydrological cycle, precipitation or rainfall is the main inputs to the groundwater budget. Once the rainfall touched the ground, it may either become part of surface waters in rivers or lakes, or infiltrate the ground to become part of the groundwater resource. The fate of surface waters is to be susceptible to evaporation. Depending on the degree of evaporation, the isotopic composition of the surface waters may be modified. Using the principles of Rayleigh distillation, the isotopic composition of the evaporated waters may be mathematically modeled.

What happens to the rainwater that infiltrated the ground is equally interesting. The reservoir rocks shielded the waters from evaporation, thus preserving the isotopic composition of the source rainwater. The groundwater may be part of shallow groundwater system and may find a near exit through locally-fed groundwater. It may also become part of a deeply-circulating groundwater system which usually has exit points through regionally-fed cold springs. The postulated recharge of geothermal systems is the latter type of groundwater.

Based on the above hydrological cycle, the deeply-circulating groundwater is product of accumulation of the rainwaters that were able to infiltrate the deep level of the reservoir. The isotopic composition of this type of groundwater is typically calculated using the data of rainwaters. The derived isotopic values, in terms of Deuterium (δ^2H) and Oxygen 18 (δ^{18}O) is collectively called as the Meteoric Water Index (MWI).

3.1 Calculation of MWI from rainfall data

The main assumption of calculating the MWI is that there is a good mixing of input in the reservoir, such that the isotopic composition of the groundwater is uniform through time. It must be recalled that the isotopic composition of rainwater is affected by many factors including the atmospheric temperature, humidity and the season. In the Philippines, for example, the isotopic composition of rainwater is more enriched during the dry season, but becomes depleted during the rainy season. To account for these variations, Equations 2a and 2b are used to calculate the weighted mean of δ^{18}O and δ^2H, respectively.

$$Weighted\ mean\ of\ \delta\ \ ^{18}O = \frac{\sum \delta\ \ ^{18}O\ x\ rainfall}{\sum rainfall} \qquad \text{Equation 2a}$$

$$Weighted\ mean\ of\ \delta\ \ ^{2}H = \frac{\sum \delta\ \ ^{2}H\ x\ rainfall}{\sum rainfall} \qquad \text{Equation 2b}$$

The resulting values from the four geothermal fields are presented in Figure 3. The values have inverse relationship with the average elevation the study areas. BacMan field has the most enriched MWI because of its proximity to the sea and lower elevation. Mt. Apo has the most depleted MWI because of its high elevation.

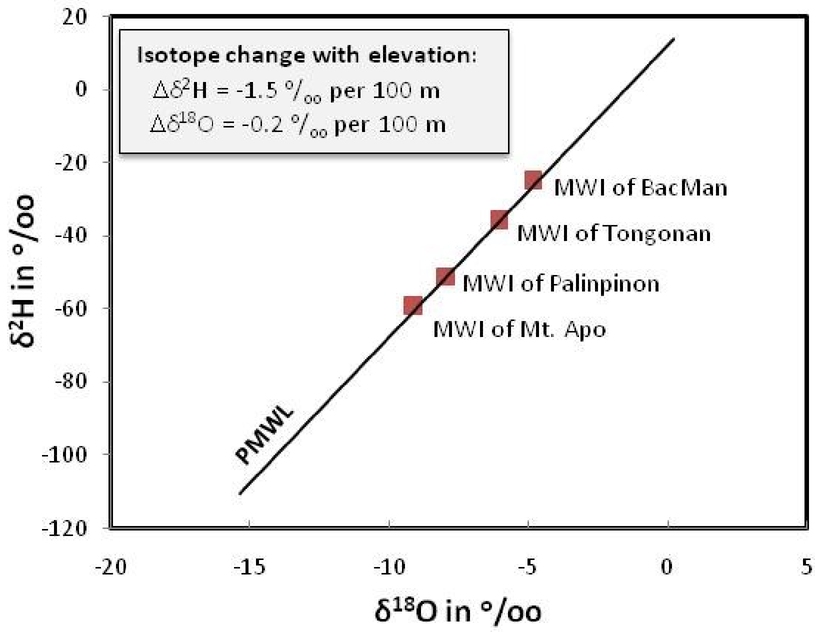

Figure 3. Plot of δ2H vs δ18O shows the PMWL and the calculated meteoric water index (MWI) based on rainfall data. Calculated change in isotope composition of rain with elevation is also shown.

After determining the MWI for each geothermal fields, the composition of actual samples of groundwaters were compared with the calculated MWI. The values are in good agreement as shown by the case of Palinpinon in Figure 4, where the calculated MWI and the groundwater have similar values. This result implies that the isotopic composition of samples of deeply-circulating groundwater may be used as alternative to several years of rainfall collection to represent the MWI.

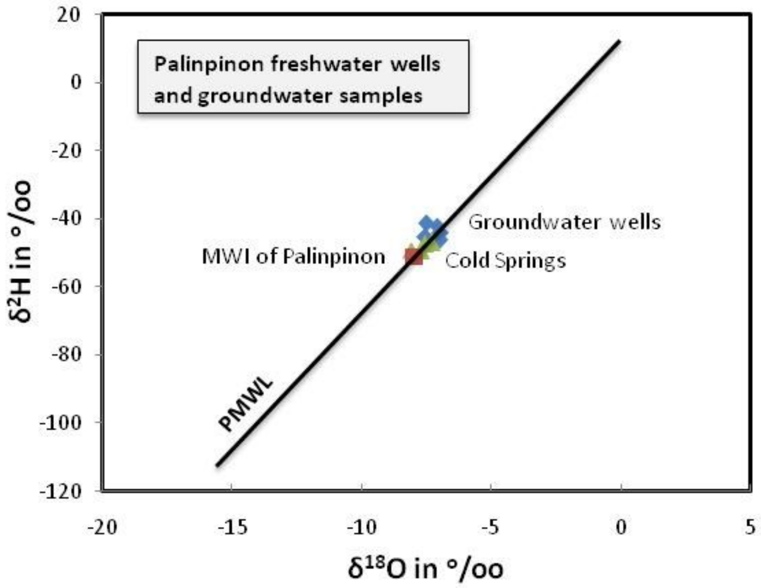

Figure 4. Plot of δ2H vs. δ18O show the PMWL, the MWI of Palinpinon together with the composition of groundwater wells and cold springs.

3.2 Estimate of MWI from surface data

This study also looked at the isotopic trends of other types of waters and the possible relationship with the calculated MWI. One set of data are the samples from rivers and lakes, or the surface waters. The main assumptions for this approach are: (1) the surface waters are product of accumulation of rainwater, and (2) evaporation will modify the isotopic composition of the rain. The process of evaporation may be represented by a line with a steep slope intersecting the meteoric water line at a point close to MWI.

To test the above hypothesis, several samples of surface waters were plotted in the cross plot of δ2H vs. δ18O. Regression line was constructed and the results are presented in Figure 5. The lakes and river waters shown in Figure 4 are the following:

- Bao River in Tongonan
- Lake Belendepaldo in Palinpinon
- Rangas Lake in BacMan
- Lake Jordan in Mt. Apo

It can be seen from the plot that data points of surface waters are moderately deviated from the PMWL, possibly because of high humidity in a tropical country like the Philippines. The generated regression lines have slopes of 5 to 6, or an average of 5.6. The intersection of the PMWL and the evaporation lines all lie close to the calculated MWI in the previous section. It seems that the modeling of evaporation in surface waters can also be used to estimate the MWI values in Philippine geothermal fields.

3.3 Estimate of MWI from sulphate springs

With the good results from the previous section, this study continued with the analysis of acid sulphate type of springs typically found in geothermal areas. Sulphate springs are formed when groundwater are heated by the ascending vapors from the deep geothermal reservoir. This means that the isotopic composition may be modified when the groundwater was heated, and subsequently boiled. Boiling trends mat be represented as lines from sulphate springs intersecting the meteoric water line.

The above concept is presented in a cross plot of δ2H vs. δ18O in Figure 6. The data points of sulphate springs shown in Figure 5 are the following:

- Kapakuhan Springs in Tongonan
- Lipayo Springs in Palinpinon
- Inang Maharang Mudpool in BacMan
- Agco Lake in Mt. Apo

The plot shows that the sulphate springs are deviated from the PMWL, which could be the result of near-surface boiling of meteoric waters. The evapo-dilution line has a lower slope of (between 3.0 to 5.0 and average of 4.0) compared to the surface waters. The intersections of the lines with the PMWL are also close to the calculated MWI of each field. This trend suggests that the sulphate springs can also be used to estimate the values of MWI.

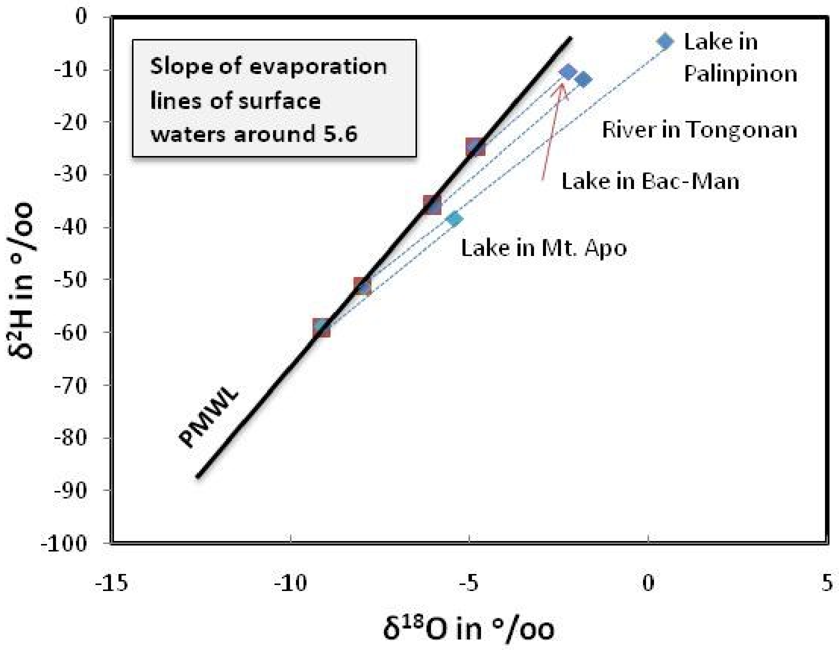

Figure 5. The plot of δ2H vs. δ18O showing the PMWL with the calculated meteoric water index (MWI) based on both rainfall data and the surface waters. The representative surface waters from each area and their respective evaporation lines are also shown.

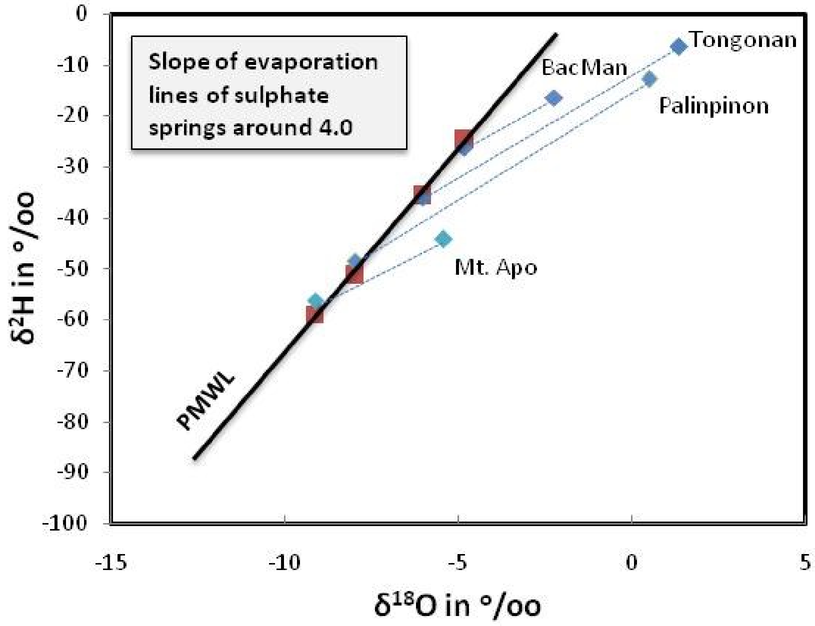

Figure 6. The plot of δ2H vs. δ18O showing the PMWL with the calculated meteoric water index (MWI) based on both rainfall data and the acidic sulphate springs. The representative sulphate springs from each area and their evapo-dilution lines are also shown.

3.3 Estimate of MWI from chloride springs

The neutral chloride springs have different origin from the sulphate springs. Chloride springs receive direct input from the deep geothermal waters. From the deep source the thermal waters continuously mix with the deeply-circulating groundwater, and thus the process can be represented as dilution lines, with thermal waters in one end and the MWI in the other end.

The process of dilution of deep thermal fluids is presented in a cross plot of δ2H vs. δ18O in Figure 7. The data points of chloride springs shown are the following:

- Banat-i Springs in Tongonan
- Palinpinon Springs in Palinpinon
- Naghaso Springs in BacMan
- Marbel Springs in Mt. Apo

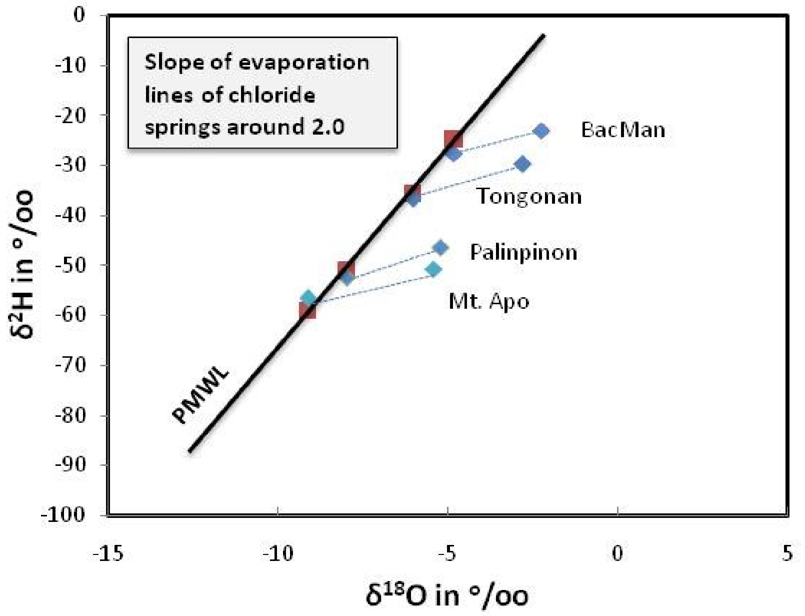

Figure 6. The plot of δ2H vs. δ18O showing the PMWL with the calculated meteoric water index (MWI) based on both rainfall data and the neutral chloride springs. The representative chloride springs from each area and their evapo-dilution lines are also shown.

In the plot, the dilution lines have lower slope from 1.5 to 2.5 (average of 2.0) compared to the sulphate springs. It is explained by the higher temperature conditions of the reservoir feeding these springs, which based on quartz geothermometers, may be between 180°C to 210°C. Interestingly, the intersections of the dilution lines with the PMWL are all close to the calculated MWI. The chloride springs, therefore , can also be used to estimate the composition of MWI in the geothermal areas in the Philippines.

3.5 Estimates of MWI from deep geothermal waters

The story of chloride waters continues with the water samples from the deep wells drilled in the four geothermal fields. The difference is the higher temperature of these waters and the lower rate of groundwater dilution. Following the concept of dilution, all well samples were plotted in cross plot of δ2H vs. δ18O. From the plots, regression lines were determined for each field. The results of this approach are presented in Figure 8.

The most isotopically-enriched data points for the deep wells were considered as representative of the deep fluids. This is called here as the "parent fluids" of each geothermal reservoir. The data points of parent waters shown in Figure 8 are the following:

- Well 410 in Tongonan
- Well PN14 in Palinpinon
- Well OP4D in BacMan
- Well KN3 in Mt. Apo

The generated regression lines have varying slopes of -0.5 in BacMan, and 2.0 in Palinpinon. These values are lower than the slopes generated by the dilution lines of chloride springs. This trend is explained by: (1) higher temperature in the deep reservoir, or (2) direct contribution of andesitic type of waters where the four lines seem to converge at the right part of the plot. Again, the intersections of the line with the PMWL are close to the calculated MWI.

SUMMARY AND CONCLUSIONS

Table 1 presents the calculated isotopic compositions of the Meteoric Water Indices of the areas discussed in this paper. The second and third rows are based on the calculations of weighted average of isotopic composition rainfall, and the next columns are based on the projections to the meteoric water lines of the evapo-dilution lines of surface waters, sulphate springs, chloride springs and geothermal waters.

The calculated MWI are close to the projected MWI of the four types of waters from the four geothermal areas. These results suggest that the evaporation and mixing models of the four types of waters may be used to estimate the composition of meteoric water index in the Philippine geothermal fields.

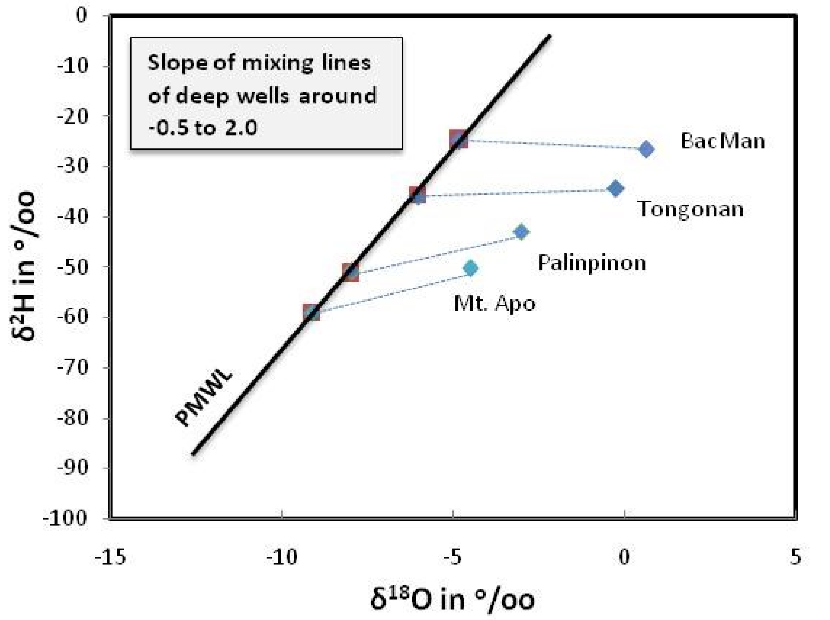

Figure 8. The plot of δ2H vs. δ18O showing the PMWL with the calculated meteoric water index (MWI) based on both rainfall data and the deep geothermal waters. The representative parent waters from each area and their respective dilution lines are also shown.

Table 1. Summary of the calculated Meteoric Water Index (MWI) based on the approaches discussed in this paper.

AREA	RAINWATER		SURFACE WATER		SULPHATE SPRINGS		CHLORIDE SPRINGS		GEOTHERMAL WATERS	
	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$
Tongonan	**-6.0**	**-35.70**	**-6.1**	**-35.81**	**-6.0**	**-36.08**	**-5.9**	**-36.64**	**-6.02**	**-36.00**
Palinpinon	**-7.9**	**-51.16**	**-7.7**	**-51.13**	**-7.9**	**-48.47**	**-7.4**	**-52.53**	**-7.97**	**-50.92**
BacMan	**-4.8**	**-24.70**	**-4.9**	**-24.83**	**-4.5**	**-26.27**	**-4.5**	**-27.65**	**-4.81**	**-24.97**
Mt. Apo	**-9.1**	**-59.07**	**-9.0**	**-58.66**	**-9.2**	**-56.18**	**-9.0**	**-56.59**	**-9.12**	**-59.07**

REFERENCES

Alvis-Isidro, R.R., et al.: The Pre-Exploitation Hydrogeochemical Model of the Greater Tongonan Geothermal Field, Philippines, as Established by Geochemical and Isotopic Techniques, (1992).PNOC-EDC, Makati City, Philippines

Dacillo, D. B. and Salonga, N. D.: Stable Isotopes and Flow Patterns of Deep Thermal Fluids in Mahanagdong Geothermal Field, (2004).PNOC-EDC, Taguig, Philippines

Gerardo, J.Y., Nuti S, D'Amore F., Seastres J.S. and Gonfinatini, R. (1993) Isotopic evidence for magmatic and meteoric water recharge and processes affecting reservoir fluids in the Palinpinon geothermal system. Geothermics 22. Pp 521-533

Salonga, N. D. and Siega, F L.: The Stable Isotope Changes in Tongonan-1 Production Field as a Response to Exploitation from 1983 to 1995, (1996) *Internal Report,* PNOC-EDC, Makati City, Philippines

Salonga, N.D., et al.: Baseline Chemistry of Tongonan Geothermal Field Prior to Leyte-Cebu and Leyte-Luzon Interconnections, (1996).*Internal Report* PNOC-EDC, Makati City, Philippines

Salonga, N. D., Aragon G.M., Nogara, J.B.,and Sambrano B.G.: (1996). Applications of stable isotopes in Hydrological studies of Mt. Apo geothermal field, PNOC-EDC Geothermal Conference, Makati City, Philippines

Technical Services Sector (2012). BacMan Resource Assessment Update 2012. *Internal Report.* Energy Development Corporation