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Determination of Recharge from Stable Isotope Data to the Hydrological Systems in the Southern Negros Geothermal Field and its Environs, Philippines

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ABSTRACT

The Philippine Meteoric Water Line equation of $\delta\,^{2}H = 8\delta\,^{18}O + 12$ is defined from the isotopic composition of rainfall in various geothermal areas of the Philippines. This equation suggests that recharge to the shallow and deeper groundwater systems in the Southern Negros Geothermal Field originates from precipitation at elevations that are about 250 meters lower than the recharge to the deep geothermal system. Rainwater in the rainy months of July to October effectively contribute to recharge, while rainwater in the dry months, although of significant amount, do not recharge the groundwater systems but run off to the surface water bodies.

The identification of such areas promotes better management and protection of the recharge areas and guides reforestation programmes for watersheds.

1. INTRODUCTION

The co-existence of two unique hydrological systems, i.e., the shallow and intermediate cold groundwater, oftentimes tapped by wells up to depths of 200 meters for potable water supply or other uses by man; and the deep hot geothermal system, a confined area of defined volume, heated by a heat source and where hot water usually circulates in a surrounding rock matrix, are primary concerns in the development of the geothermal areas. Understandably, development of geothermal systems always prioritise the search for the high temperature resource and exploitation of the hot fluids for electricity generation. The concern for groundwater systems in the Philippines took a back seat until the late 1990s when environmental awareness increased and the technology for geothermal resource exploitation was advanced.

Geothermal energy in the Philippines is generated from six major areas. One of them -- the Southern Negros Geothermal Field -- has been exploited since 1983 in two geothermal sectors, the Puhagan and the Nasuji-Sogongon where two hydrological systems are prominently defined. One, the deep geothermal system that supplies electricity, and the groundwater system (shallow and intermediate aquifers) that supplies the water requirements of the surrounding communities. Groundwater is manifested either as cold springs in the vicinity of the geothermal field or as both unconfined and confined aquifers tapped by domestic wells and wells of the local water utility company.

The Southern Negros Geothermal Field and its surroundings, is situated in the central part of the Philippines in the south-eastern tip of the island of Negros. It is bounded in the north by Okoy Watershed which has a maximum elevation of 1700 m asl, and in the south by Banica Watershed which has a maximum elevation of over 1400 m asl. The highest elevation in the entire island is 1980 m asl at Mt. Mandalagan, in the northern part and up to 1900 m asl south of the island, closer to the Southern Negros Geothermal Field.

The climate in the island of Negros is influenced by south-west monsoons, from June to October, that provide the main source of groundwater recharge. The area has an average annual rainfall of 2200 mm that is maximum from June to August.

An adequate understanding of the deep geothermal reservoir has been gained from monitoring the chemical and reservoir parameters through the twenty years of production. This author elucidated, with isotope measurements of ^{18}O and ^{2}H the origin of the geothermal fluid and the processes affecting the various types of fluids, such as mixing and steam separation (Gerardo et al., 1993). According to the same work, the stable isotopes provide the evidences that the Southern Negros geothermal reservoir consists of 80% meteoric fluid and 20% magmatic components. The meteoric water recharge has been postulated to originate from at least 1000 meters above sea level (m asl) north-west of the geothermal field. (Gerardo et al., 1993 and Seastres, et al., 1995). From a subsequent investigation that included gas data, D'Amore et al. (1993) indicated that the system contains 25% magmatic fluids, 44% meteoric water and 31% gas of crustal origin. The presence of tritium in limited samples from some deep geothermal wells (unpublished in Gerardo, 1992) also indicates that present day meteoric water recharges the geothermal reservoir.

The understanding of the groundwater system became more extensive in 1994 when the Philippine National Oil Company-Energy Development Corporation commissioned an investigation to determine the hydrological connection between the geothermal fluids and the groundwater. According to investigations conducted by Geotecnica in 1994, the Okoy and Banica watersheds are characterised by contrasting hydrological morphology. The latter has less groundwater storage than Okoy. The aquifer in the Upper Okoy is confined whereas unconfined conditions are encountered in the lower areas dominated by alluvial deposits. The resistivity measurements in the Banica volcanic rocks indicate a relatively dry area. In general, Okoy has much lower resistivity that suggests among others, a more permeable area as well as the presence of a conducting layer dominated by geothermal brine. Geotecnica (1994) postulated that the main recharge zones are in the foothills of the volcanic terrain through the alluvial deposits that overlie the volcanics. The groundwater recharge occurs predominantly through the Campisa Fault (Geotecnica, 1994). The area is relatively massive that precipitation runs-off to the rivers, except at the permeable zone in the vicinity of this fault.

However, the results were not sufficiently conclusive. This author believes that better results would have been obtained had there been an input of isotope data.

2. THE ISOTOPIC COMPOSITION OF RAINFALL IN THE PHILIPPINES

Some isotopic measurements were made from rainwater samples in Manila in the 1980s by the International Atomic Energy Agency (IAEA). The results are part of an IAEA global database on isotopes in precipitation.

An intensive application of stable isotopes in the Philippine hydrological investigation, was reactivated for groundwater studies in urban areas in 1986. This was revived in 1989 by the Philippine National Oil Company in the exploration and management of geothermal areas.

Investigation of the hydrological systems where isotopes have important roles to play, inherently starts with the precipitation, it being the source of recharge.

Two major factors generally control the isotopic composition of precipitation (Kondoh and Shimada, 1997):

◊ Isotopic composition of the condensing parent vapour which results from the meteoric history of the original air mass, most important being upwind losses by precipitation and addition of evapo-transpirational recycling. This is dependent on the variability of rain and monsoons; and

◊ Temperature of condensation and the physical state of the condensate (liquid vs solid) determines the isotopic partitioning during condensation. This is influenced by the uniformity or variability of average temperature and humidity over the country

Considering the above factors and in order to fully understand the isotopic variability in the Philippine rainfall and in the Southern Negros geothermal field, the various climatological characteristics of the country, as these are relevant to the isotopic composition of fluids were examined.

2.1 The Philippine Climate

The Philippines has a tropical climate characterised by humidity or moisture content between about 70% to 85% that is highest in September. The humidity is high due to the temperatures of the surrounding seas in the archipelago. The country is affected by three different air streams that in turn affect the amount of rainfall and dictates the seasonal variability. The rainfall pattern is highly influenced by the source of the moisture bearing winds and the presence of mountain systems. The mean annual rainfall could be as high as 4000 mm in the eastern part of the country while it could be as low as 950 mm in the southern part of the country.

As it is situated in the northern hemisphere very close to the equator, it has a high and relatively uniform temperature throughout the year, ranging from 25°C to 29°C although it is cooler at higher elevations. There is no distinct variation in the temperature from north to south.

The Philippine weather is characterised by only two seasons, the wet season which occur in June to October, and the dry season which is cool from December to February and hot from March to May. The climatological condition of the country is highly influenced by typhoons. It is mainly exposed to the different air streams of the Northwest monsoon, Southwest monsoon, North Pacific Trades and the Inter tropical convergence zone that control the rainfall pattern over the different regions of the country.

Estoque et al. (2003) examined the monthly variations of rainfall and wind in the Philippines from a network of 80 stations over an area of 5000 sq. km. from 1982 to 1993. This period coincides with the main coverage of the isotopic measurements from which the Philippine Meteoric Water Line (discussed in later sections).

The western parts of Luzon, Mindoro, Palawan, Panay and Negros, where the study area is located, are characterised by pronounced wet and dry seasons where topography is a controlling factor to wind and rainfall patterns. The Philippine Atmospheric, Geophysical and Astronomical Services Administration characterised Negros Island as an area with relatively dry conditions from January and May and wet in most other periods of the year. This characteristic is an important influence in the variability of the isotopic composition that can be seen from rainfall data. As these areas have generally a rugged topography and are situated in the western part of the archipelago, these are fully or partly shielded from the Northeast monsoon and trade winds. They are mainly influenced by the south-west monsoon and the cyclonic storms, that are sometimes frequent.

The eastern part of Negros has no pronounced maximum rain period and has a short dry season of 1-3 months only. Being influenced mainly by the south-western monsoon that is relatively moist, the island experience a considerable amount of rainfall which is predominant from June to September (Estoque et al., 2003). Rainfall develops to a maximum in August.

According to a 45 year record of the mean monthly rainfall in the southern part of the Negros, the highest amount of rain occurs in October, at 164 mm while the lowest is in April with 40 mm. Values as high as over 800 mm during rainy months have been measured during the sampling period in 1991. The amount of rain increases with elevation in January because of orographic effects and because the lower elevations are on the leeward side. The average annual rainfall is 2200 mm.

Although the annual rainfall is dominantly influenced by the seasonal variations, measurements over 10 years and observations in the rain gauges indicate that the sources of moisture varies from month to month (Estoque, 2003). The Island of Negros is influenced mainly by the south-west monsoon, from June to September and the dry months of February are influenced by the north-east monsoon that has an intermediate moisture content.

The patterns of wind during the dry months of December to February and wet months of July to September (Estoque et al., 2003) all over the Philippine archipelago and its surrounding countries are reflected in Figure 1. The wind speed is relatively slower during the wet season and is predominantly south-westerly, which brings a significant amount of rain. It is notable that the wind directions change course during these two seasons. During dry months, the amount of rainfall per month is maximum at 10 to 12 mm in the south-eastern part of the country. During wet months, the amount of rain is more than double and is spread practically all over the country.

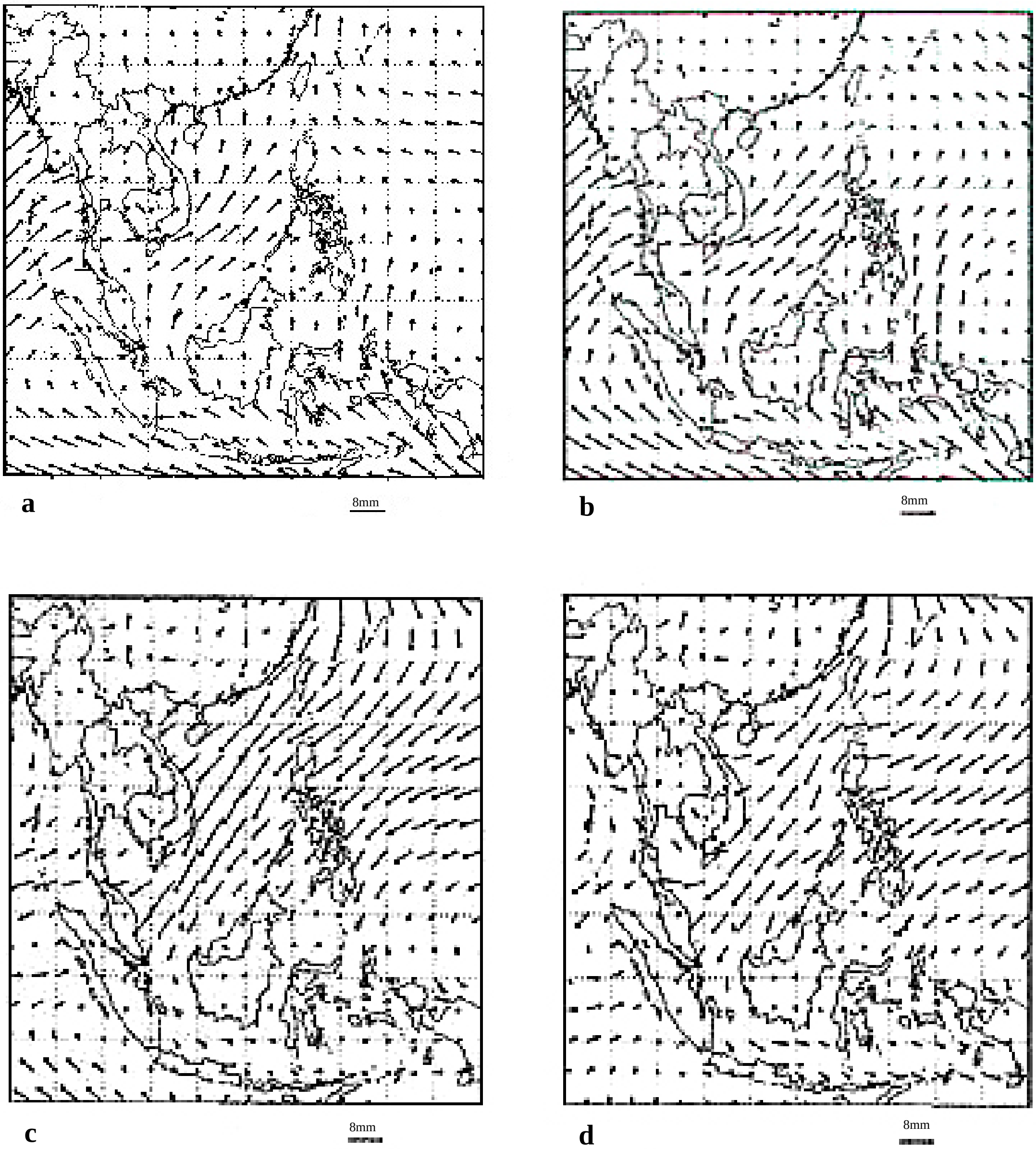

Figure 1: Wind patterns in the Philippines and its surrounding areas for the wet months of July (a) and August (b), and the dry months of December (c) and February (d). The size of the arrows denote the relative strength of the winds. Modified after Estoque et al., 2003.

3. SOURCES OF ISOTOPE SAMPLES AND DATA

In understanding the recharge in the Southern Negros Geothermal Project and its environs, the following data were examined:

a) Rainfall that were collected intermittently from 1961 to 2000. Except for isotopic data in Metro Manila, the rainfall samples were collected systematically in the five geothermal areas of Southern Negros, Bacon-Manito, Leyte, and Mt. Apo. These rainwater samples were collected using raingauge sample collectors set-up by the Philippine National Oil Company at different elevations in the respective geothermal areas where cumulative samples were collected for each station for each month.

   There are no known rainwater collectors for cumulative monthly rainwater sample in Metro Manila. The sample collection for isotope representing rainwater from Metro Manila and Quezon City is assumed to have been done at single rain events.

b) Groundwater from wells tapping the shallow and intermediate aquifers that were collected in the Southern Negros Geothermal Field. The groundwater samples were collected and reported by Caranto, et al. (2001).

c) Warm and hot spring samples, as well as samples from geothermal wells from the Southern Negros Geothermal Field. These data sets were either collected by this author or by other workers.

All the isotopic results were measured in the Isotope Hydrology Laboratory of the International Atomic Energy Agency, Vienna. The oxygen-18 was measured with an uncertainty range of ±0.1‰ and deuterium with ±1.0 ‰.

4. THE PHILIPPINE METEORIC WATER LINE

A meteoric water line provides the benchmark for determining the origin of fluids and the processes that have taken place to reflect the dynamics of flow or mixing. As such, it is considered as a fundamental pre-requisite for interpreting isotopic results. A meteoric water line of a global scale has been constructed from thousands of isotopic measurements in rainfall from 1965 to 1975 (Craig, 1963). From this, a meteoric water line with a priori slope of 8 has been defined, with a deuterium excess, d_{ex}, (Dansgaard, 1964) or the intercept of the line, equal to 10. In many circumstances, and particularly in the absence of long measurements for isotopes in rainfall, the global meteoric water serves the purpose of interpreting results. However, various local effects could not be easily detected without a local meteoric water line. This is particularly important in investigations, more specifically in geothermal systems, where the magnitude of the shift from the meteoric water line is critical to recognise processes other than evaporation. This has been essential in determining the effect of temperature on the enrichment of the isotopic concentration in geothermal fluids.

The Philippine Meteoric water Line (PMWL) is constructed based on available precipitation data from 1961 to 2000 that are included in the Global Network for Isotopes in Precipitation (IAEA, 2001). Figure 2 reflects the isotopic composition of all data points.

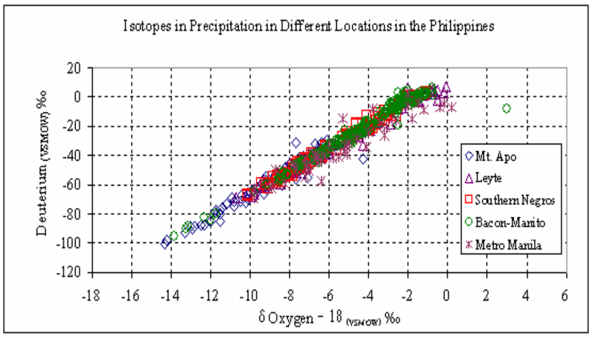

Figure 2: The isotopic composition in rainwater samples all over the Philippines.

The regression analysis of the data (Figure 2) for each area result to the following equations:

Mt. Apo:	$\delta^2H = 8\,\delta^{18}O + 11\pm1$	n= 99, r^2 = 0.98	(1)
Leyte:	$\delta^2H = 8\,\delta^{18}O + 10\pm0.7$	n= 73, r^2 = 0.99	(2)
Southern Negros:	$\delta^2H = 8\,\delta^{18}O + 13\pm0.6$	n= 94, r^2 = 0.99	(3)
Bacon Manito:	$\delta^2H = 8\,\delta^{18}O + 12\pm0.1$	n= 231, r^2 = 0.98	(4)
Metro Manila:	$\delta^2H = 7\,\delta^{18}O + 2\pm1.8$	n= 58, r^2= 0.95	(5)

All samples, except those from Metro Manila, are defined by a regression line with slope of 8. The intercept of the line equates to the deuterium excess where the slope is equal to 8. The results from Metro Manila, however, are defined by a regression line with a slope of 7 and an intercept of 2±1.8.

Figure 2 exhibits the deviation of the isotopic values in precipitation in Metro Manila from the general trend given by all other samples. This value indicates an evaporation trend that may have been a consequence of improper sampling. As there is no certainty how the Metro Manila samples were collected, and as these were analysed by another lab, these are excluded from the calculation of the Philippine Meteoric Water Line.

By a regression analysis of the remaining 497 data points from all over the Philippines, except the isotopic data on Metro Manila, a slope of 7.8 ± 0.1 and an intercept of 11.8 ± 0.4 was obtained at 0.99 correlation coefficient, r^2 (Figure 3). Transforming this into an equation, the following is obtained:

$$\delta^2H = (7.8 \pm 0.1)\,\delta^{18}O + (11.8 \pm 0.4)$$

Noting, however, that the slope coincides with the a priori slope of 8, and the figures can be rounded-off, the equation of the Philippine Meteoric Water Line is defined, as:

$$\delta^2H = 8\,\delta^{18}O + 12 \qquad (6)$$

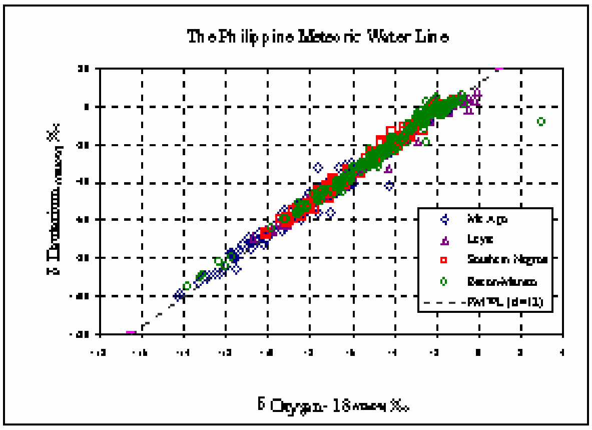

Figure 3: The Philippine Meteoric Water Line

The earlier works by this author and contemporaries have considered local meteoric water lines with deuterium excess of 12 to 14 (Gerardo et al., 1993 and Alvis-Isidro et al.,1993). At that time, the calculations were made from practically only four months of continuous sampling in 1991. In addition, no comparison was made between the isotopic composition of the rain samples from the different geothermal areas. Having a better understanding of the regional climatological patterns, as explained in the previous section and being a small archipelago, the Philippines cannot be expected to have varying meteoric water lines.

In comparison, a greater number of measurements over a period of about 40 years has been taken into account in this calculation.

While there is a clear agreement of data points on a single line, a geographic distribution of points along the line could be recognised from the measurements throughout the country. The samples collected from the southernmost part and the easternmost of the Philippines and at relatively higher elevation are depleted down to –100‰ in deuterium and –14‰ in oxygen-18. The isotopic composition of rainwater from Southern Negros Geothermal Field is distributed along the line from –9 to –1‰ in oxygen-18 and

–80 to 0‰ in deuterium. On one hand the isotopic composition of rainwater from Metro Manila deviate from the line by about 0.5 to 1‰ and are relatively more enriched than the rest of the samples. Metro Manila is located at about 20 m asl. In comparison most of the samples originate from the geothermal areas that are higher by at least 100 meters. In conclusion, the isotopic variation is not affected by the geographic location but rather, the elevation of sample collection.

5. THE ISOTOPIC COMPOSITION OF THE VARIOUS TYPES OF FLUIDS IN THE SOUTHERN NEGROS GEOTHERMAL FIELD AND ITS ENVIRONS

The Southern Negros Geothermal Field and its environs, being an area with intense volcanic activity and sufficient recharge from rain, is characterised by various types of fluids. Figure 4 reflects the various groups through their oxygen-18 and deuterium contents that are examined in detail in the subsequent sections.

a. Rainfall

Rainfall, which reached up to about 800 mm on a rainy month during the period of sampling covered by paper is major source of recharge in Southern Negros. Rain samples were obtained from rainguage stations in the geothermal field which were installed in Nasuji (1100 m asl), Balas-Balas (980 m asl), Puhagan (760 m asl) and Ticala (350 m asl). A regression analysis of the 94 data points collected intermittently at these stations from 1991 to 1998 defines the local meteoric water line for Southern Negros (Equation 3).

The relationship between deuterium and oxygen-18 of the different meteoric waters in the study area reflect the broad range of isotopic values in rain, from –9.6‰ to –1.8 ‰, in oxygen-18 and from –68 ‰ to –4 ‰ in deuterium (Figure 4). In comparison, the isotopic composition of surface and groundwater cluster at a narrower range of –5.8 ‰ to –8.2 ‰, in oxygen-18 and from –52 ‰ to –42 ‰. in, deuterium, with Lake Belenlepaldo having –5.6 ‰ to –5.8 ‰, in oxygen-18 and from –38 ‰ to –40 ‰. in deuterium

b. Shallow Groundwater Wells

Samples were collected from shallow wells, in most cases, twice during the wet seasons of September and October 1999 and 2000. Few samples were also collected in July and August. In addition, the same wells were sampled during the dry season of February 1993 and 2001.

There is no significant variation due to seasonal changes, and the variation in isotopic composition of the shallow wells are within the analytical error range of $\pm$0.1 ‰ in ^{18}O and $\pm$1.0 ‰ in ^{2}H (Figure 5).

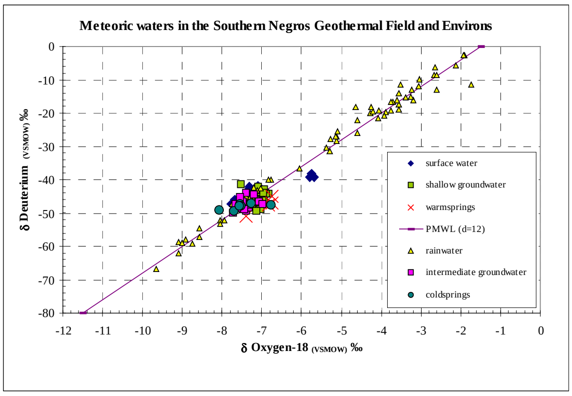

Figure 4: The ^{2}H and ^{18}O relationship of the different types of fluids that were sampled in the Southern Negros Geothermal Field and environs. The data points corresponding to surface waters represent the stable isotopic composition of Lake Belenlepaldo and the rivers. Groundwater includes all samples from groundwater wells drilled through shallow and intermediate aquifer layers as well as coldsprings. The values of the groundwaters from shallow and intermediate aquifer layers are mean values from the different periods of sampling, where the differences are within the analytical error range of $\pm$0.1 ‰ and $\pm$1.0 ‰ in ^{18}O and ^{2}H, respectively. Despite numerous warmsprings in the area, only four sources could be sampled for stable isotopes as reflected in the graph.

Some evaporation trends denoted by data points deviating from the PMWL are observed in shallow wells. These trends (depicted by broken lines in Figure 6) suggest a near-surface occurrence of the water-table tapped by the shallow well that is subjected to diurnal fluctuation of the groundwater surface and is related to evaporation and transpiration. Geotecnica (1994) reports some measurements that indicate evaporation is high in aquifers where the water table is within one foot from the ground surface. This tendency decreases as the water table becomes deeper demonstrating that the amount of moisture that is evaporated is inversely proportional to the depth of the water table. The isotopic evidences reflecting evaporation effects from the deviation of the isotopic results from the PMWL, provide a confirmation to this observation, particularly due to the enriched isotopic composition of water tapped by shallow wells in comparison to the more depleted values in samples obtained from wells that tap the intermediate aquifer layers.

The meteoric water recharge, denoted by the intersection of the trend line (broken line) with the PMWL, to the shallow wells have ^{18}O and ^{2}H contents of -7.4 ‰ and –47 ‰, respectively (Figure 6).

c. Groundwater Wells in Intermediate Aquifer Layers

Similar to shallow wells, there is no variability in the isotopic composition of most wells tapping the intermediate aquifer layers from samples collected at different periods (Figure 5). In general, there is no effect on the isotopic composition of wells due to seasonal changes, although the amount of rain varied between less than 10 to nearly 800 mm per month between seasons at the time of sampling. The groundwater wells in intermediate layers generally fall on the meteoric water line with some exceptions like 52, 53, 54, 56 and 57 (Figure 6), which define a line with a slope of 5 indicating evaporation effects.

The groundwater wells in intermediate layers are generally isotopically depleted than the shallow wells. An overlap between the two groups along the PMWL suggests that there is an interaction between the intermediate and the shallow aquifers. This indicates that the wells tapping the intermediate layers are recharged by meteoric water originating from higher elevations relative to the recharge area of the shallow wells. Being so, recharge from higher elevation will be expected to be deeply infiltrating. The wells drilled to deeper depths may therefore be tapping the intermediate flow whereas the shallow wells are tapping the localised flow from shallow aquifers. An interaction between the intermediate and the shallow aquifer is manifested especially in the overlap in the groupings of isotopic values, suggesting that intermediate flows may be mixing with the shallow flows. The trend lines for the groundwater wells drilled to intermediate layers intersect the PMWL at ^{18}O equivalent to –7.8 ‰ in ^{18}O and –49 ‰ in ^{2}H, suggesting that this is the composition of the meteoric water recharge to the aquifer (Figure 6).

6. ISOTOPIC VARIATIONS WITH ALTITUDE

The isotopic values in rain vary widely due to the altitude from which the samples were collected (Figure 5), thus, the isotopic results are randomly distributed in a broad range of values.

Although there are a few exceptions, Figure 5 suggests that there are generally two groups of isotopic results (reflected by ^{18}O) in relation to altitude. Group I represents the wet season (from July to October) with depleted ^{18}O values from –5.8 ‰ to –9.2 ‰. Group II represents the dry season from –1.8 ‰ to –5.5‰ in the months of December to May, even up to June. There is no clear pattern to explain the random distribution of the isotope composition in the rain with respect to altitude nor season. However, this seemingly random pattern of distribution can only be clarified when the sources of vapour and their shifts in different months are taken into account.

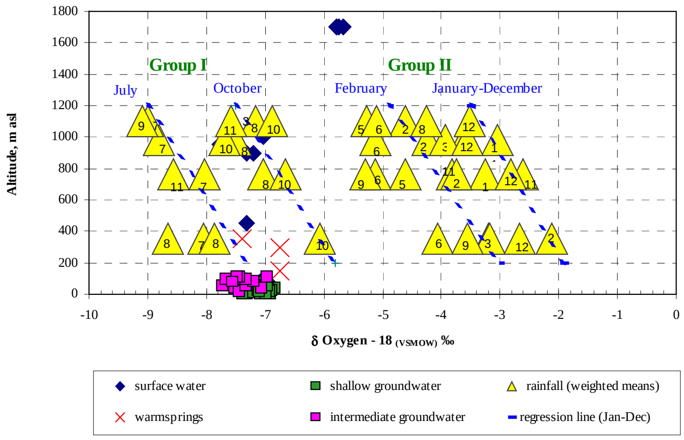

Figure 5: The relationship of monthly weighted mean of ^{18}O with altitude. Numbers represent the months of sample collection. The samples were collected in rainfall stations at different elevations in the geothermal field. The blue broken lines indicates the altitude gradient as calculated from equations 7-11 for the respective months.

The isotopically enriched values (Group II) are associated with the dry months of the year, i.e., December to February, when the sources of moisture associated with dry air form rain that originate from the northeast monsoon. On one hand, isotopic composition in rainfall is at least 1‰ depleted in oxygen-18 (Group I) in the months of July to October that correspond to the rainy months in the island. It is at these months of the year when the southwest monsoon prevails (Figure 1).

A regression analysis relate the weighted mean values of oxygen-18 and altitude, H, for Groups I and II are obtained in Equations 7-11 after mathematical transformation.

December: $$H \pm 175 = \frac{-\delta^{18}O - 1.9}{0.0016} \quad (7a)$$

January: $$H \pm 56 = \frac{-\delta^{18}O - 1.3}{0.0025} \quad (8a)$$

February: $$H \pm 57 = \frac{-\delta^{18}O - 2.5}{0.0019} \quad (9a)$$

July: $$H \pm 154 = \frac{-\delta^{18}O - 7.5}{0.0017} \quad (10a)$$

Aug-Oct: $$H \pm 174 = \frac{-\delta^{18}O - 5.2}{0.0020} \quad (11a)$$

All these equations (7a to 11a), although obtained from the mean values of various monthly samples of both dry and wet seasons, are alike. They could represent the relationship of isotopic composition with altitude that could be used for determining and zoning areas of recharge. Considering these, the ^{18}O gradient in the Southern Negros Geothermal Field can be concluded to be in the range of 0.16 ‰ to 0.25 ‰ for every 100 meter change in elevation

Equations 7a to 11a also indicate that the ^{18}O content of rainwater at sea level (H = 0 m asl) would range from –1.3 ‰ to –7.5 ‰. The data from shallow wells near the coast indicate that groundwater has an ^{18}O value of –7.15 ‰ that approximately corresponds to the values if the July-equation is used. In addition, there are evidences for enriched ^{18}O value of rain to validate the above observations, as indicated by Figure 5 where the January-December regression line intersects H = 0 m amsl at about –1.8 ‰. The equation for the month of July (Equation 10a) provides an initial indication of its greater validity with respect recharge in comparison to the other equations.

The precipitation for the months of January and February apparently mainly contribute to run-off, rather than recharge to groundwater. This is illustrated in Figure 5 where surface water samples could represent the end member of a mixing line defined by the regression line for the month of February. On the other hand, groundwater samples fall within the zone defined by the regression line for July, including August and November. This denotes that these groundwaters have been recharged by rains at least in July. Figure 5 further reflects that rains in dry season do not contribute to groundwater recharge, even to shallow aquifers. This explains why there is no observable variation in the composition of the springs and groundwater wells with season.

These observations prove that rainfall in the wet periods, associated with vapour originating from the southwest monsoon that is dominant from June to September and October, effectively contribute to recharge into the groundwater.

In conclusion, the isotopic composition of the groundwater reflects the effectivity of recharge from precipitation in the wet months, when the monsoon originates from the southwest. This also proves that rains in the dry months do not recharge the aquifers.

For investigations therefore of sources of recharge by isotopes, the equations 10a and 11a that were obtained from the data representing the wet season can be used. These equations are comparable with the following equation proposed by Gerardo et al. in 1993 .

Based on the regression analysis of the weighted means for those rains in the wet season, the altitude gradient for ^{18}O is calculated at 0.17‰ for every 100 meter change in elevation in the Southern Negros Geothermal Field.

7. CONCLUSION

Using the isotopic gradient from Equations 10a and 11a, the ^{18}O content of the recharging meteoric waters to the shallow and intermediate groundwater the altitude of recharge is estimated. If the equation from the month of July with the ^{18}O gradient of 0.17 ‰ per 100 m is used for the calculations, and knowing that the elevation of meteoric recharge to the deep geothermal system is about 1000 m asl, the elevation of recharge to the intermediate groundwater flow would be at about 700 m asl while the recharge contributing to the local flows tapped by shallow groundwater wells is at about 550 m asl, which are both a hydrologically reasonable values for the area.

Based on the calculated altitude gradient for ^{8}O (Gerardo et al., 1993) and the ^{18}O values of the recharging meteoric water, the recharge to the deep geothermal reservoir was estimated to originate from about 1000 m asl. Using the altitude gradient for ^{18}O of 0.2 ‰ per 100 meter from equations 10a and 11a, the recharge area to the intermediate groundwater system is about 300 m lower than the deep geothermal system while the difference in elevation of recharge between shallow and intermediate groundwater aquifer is about 150 m.

This hydrological characterisation implies that the deeper wells that are recharged at higher elevations tap groundwater that has longer flowpaths relative to the shallow groundwater wells. The chemical results that reflect more mineralisation with the presence of sulphate and chloride from the interaction of groundwater with its surrounding matrix supports this observation (Gerardo-Abaya, 2004).

Mixing between the shallow and intermediate aquifer layers is denoted by the intermingling of data points on isotopes and chemical composition of shallow and intermediate groundwater wells. Measurements within the borehole on the directions of flows would have to be made to detect the directions of vertical movements of groundwater.

The hydrological investigation by Geotecnica (1994) proposed that recharge to groundwater takes place though Campisa Fault. This fault occurs from an elevation of about 500 meters which approximately supports the findings above and is consistent with the calculations. The deeper geothermal system on one hand is recharged by meteoric water from an elevation of 1000 m asl, which is consistent with the findings by Gerardo et al., (1993).

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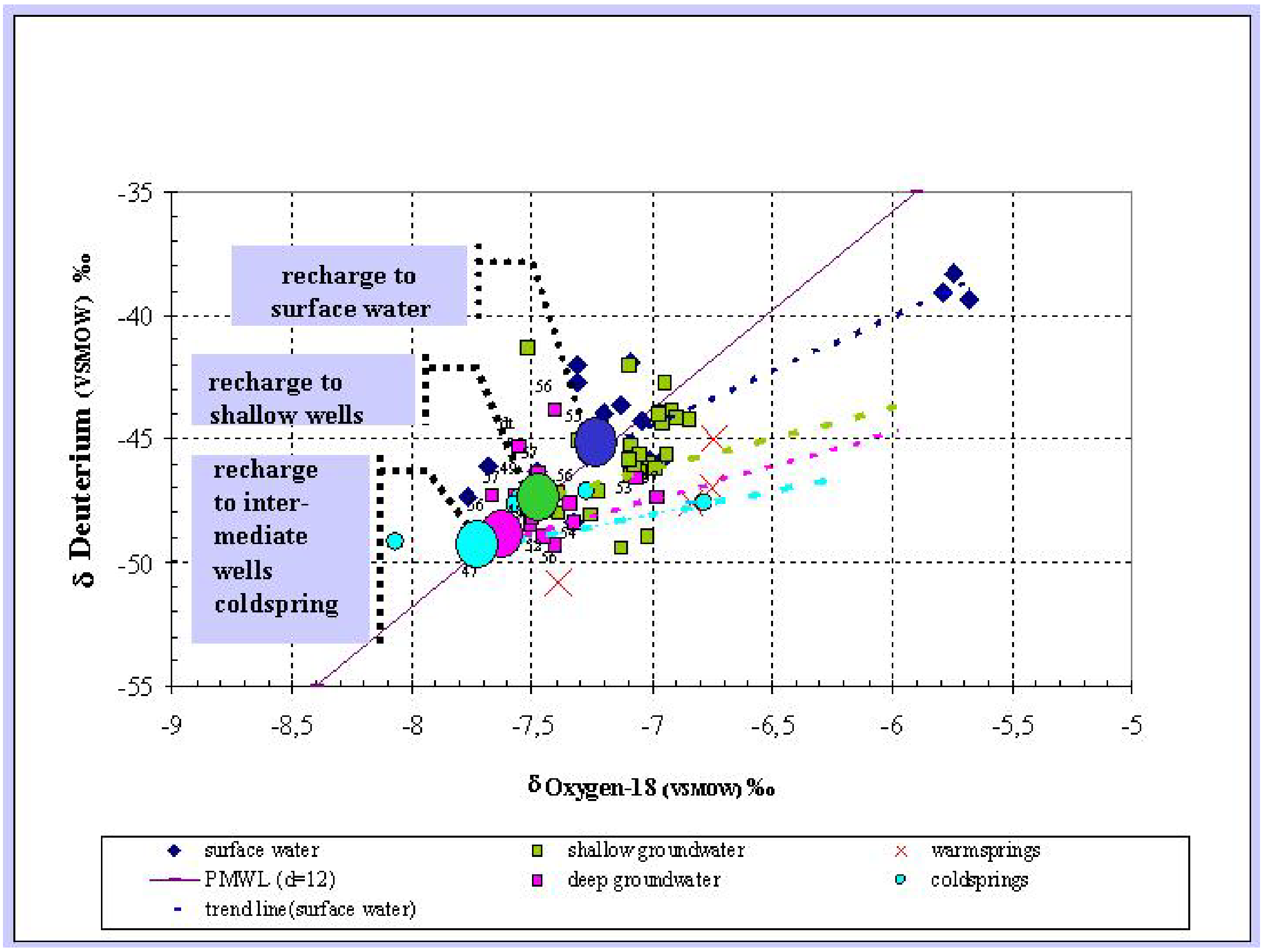

Figure 6: Mean isotopic values of some wells. The intersections of the trend lines (broken colored lines) with the PMWL indicate the isotopic composition of recharging meteoric water. Some of the samples deviate from the PMWL. This deviation is depicted by the different trend lines for the respective water type, due mainly to evaporation at surface conditions. The evaporation trends, particularly for the shallow groundwater is attributed to near surface evaporation where the water table is close to the ground surface. The rainwater that recharges the deep wells are isotopically depleted than those for the shallow wells, denoting that the source of recharge of deep wells are at higher elevations.