CHARACTERIZATION OF STABLE ISOTOPIC FINGERPRINTS OF OXYGEN-18 AND DEUTERIUM IN PRECIPITATION: A CASE STUDY OF MALAYSIAN PENINSULAR NORTHEAST MONSOON

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ABSTRACT

The hydrologic cycle of Malaysian Peninsular is influenced by the monsoon regime driven by Inter-Tropical Convergence Zone (ITCZ). The region, especially the east coast (Kelantan, Terengganu and Pahang) will experience heavy rainfall (Northeast Monsoon) starting from October to late January. Floods are the most common natural disaster at this period of time where 2014 were one of the most devastating events in Malaysia's flood history. This study aims to investigate the moisture supply by using stable isotope technique in "reconstructing" the Northeast Monsoon (NEM) regime in the year 2013, 2014 and 2015. Potentially this work will provide new insight into understanding monsoon regime, the main input of water cycle in the Malaysian Peninsular region. Rainwater samples were collected nationwide from 2013 until 2015. Samples for δ^2H and $\delta^{18}O$ were treated in the Water Equilibration System (WES) prior to analysis through the SERCON Isotope Ratio Mass Spectrometer (IRMS). The $\delta^{18}O$ and δ^2H define Malaysian Meteoric Water Line (LMWL); $\delta^2H = 8\delta^{18}O + 13.255$ ‰ demonstrating a shallower slope with respect to Kelantan LMWL; $\delta^2H = 7.34(\pm0.79).\delta^{18}O + 6.01(\pm4.53)$ ‰, reflecting the origin of vapour mass and seasonal variations of precipitations. The continuous supply of moisture to the monsoon regime during 2014 is one of contributing factors to the flood disaster.

Keywords: Flood disaster, moisture supply, northeast monsoon, precipitation, stable isotope.

INTRODUCTION

Water cycle can be studied by using isotope hydrology. All components of the water cycle involved evaporation, precipitation, plant uptake, plant transpiration can be related to isotope hydrology [1]. In the water cycle, precipitation is the main water input towards the terrestrial. Gat, J. R. [2] stated that the isotope composition of precipitation has some variation depends on the seasonal and interannual scale. These values would form Local Meteoric Water Line (LMWL). This LMWL is useful to identify the isotopic composition of meteoric water. For large numbers of measurements of meteoric water, it would produce a Global Meteoric Water Line (GMWL). Every LMWL of any study area could be different from GMWL [3]

In this research, we want to reconstruct the Northeast Monsoon (NEM) rainfall event which potentially provides new insight in understanding the monsoon regime that drives the water input in Peninsular Malaysia. The study area is located at Kelantan due to the flooding problem that happens annually. Syakir *et al.* [4] showed that on 2013, even though Kelantan having the flooding problem, but the isotope result tells that it is just the normal cycle of precipitation. But on 2014, during NEM, they have flooded disaster and the isotopic result showed that there was a continuous water supply contributing to this huge phenomenon. Therefore, we have decided to further this research in 2015 since El Nino had happened and to see the pattern of precipitation supply.

Climate affecting water cycle

Malaysia is located in the tropical zone, somewhere in equator line with a temperature range between 21°C to 32°C. The driest months of Peninsular Malaysia are between February and June. Therefore, an average rainfall for a few stations in Malaysia recorded less than 10 mm monthly [5]. Based on Trenberth K. E. *et al.* [6], climate change in Malaysia is influenced by the large two oceans behind it which are Pacific Ocean (East) and Indian Ocean (West). Changes in climate can control the monsoon. Greatest warming in the tropics produced a belt of low pressure due to warm condition, rising air and intertropical convergence zone (ITCZ) is formed. It is also called as a band of cloud. During the northern hemisphere winter, the combination of high pressure on China and low pressure over Australia pushes the ITCZ further south, bringing the northeast monsoon (November to February) over Malaysia. The northeast monsoon brings the heaviest rainfall of the year. The converse is true during the northern hemisphere summer with low pressure over Asia and high pressure over Australia and the ITCZ migrating north. At this time Malaysia is influenced by the southwest monsoon (June to September). The Southwest Monsoon normally signifies relatively drier weather. Based on Kassem A. *et al.* [7], almost all types of water are sensitive to climate due to water availability assessment. Hydrologic model of each basin can be determined by the water supplies.

El Nino

Malaysia had experienced El Nino event during the year 1997/1998. An El Nino phenomenon which is also called as El Nino Southern Oscillation (ENSO) can disturb the rainfall pattern over the different part of the world. ENSO events can cause some region experienced dry condition and may lead to drought. This is due to the changes in temperature that can give impacts on climate factor such as evapotranspiration, streamflow and humidity [8].

According to Meteorological Department Malaysia [9], El Nino is a phenomenon that occurred for every two to seven years. It is the circulation of climate in the Pacific Ocean, which will give the impact towards global in term of weather pattern. During El Nino, warm water from the western tropical Pacific Ocean will shift towards east along the equator. The moisture of humid air will condense to form a large area of thunderstorms and heavy rain in the area. In the western Pacific, including Malaysia, atmospheric pressure will increase and result in the drier weather. On 2015, Malaysia had been announced to experience El Nino.

Flood Phenomena

A flood is an overflow of water that submerges land which is usually dry. On December 2014, Kelantan experienced the worst of flood history in Malaysia than in 1967. The water level of Sungai Kelantan passed the danger level of 25 meters, reached up until 34.17 meters compared to 29.70 meters in 2004 and 33.61 meters in 1967 reported by The National Security Council (NSC) [10]. Many have claimed that this flood disaster caused by unsustainable land management, the dwindling number of trees, and exploitation of land resources. Nevertheless, changing of climate patterns and the adverse weather effects might be one of the reasons.

For centuries, Kelantan is separated from the rest of the states by Titiwangsa Mountains, a mountain range running from north to south through the Peninsular Malaysia. This orogeny has become the shed for other states from being affected by the huge rainfall during Northeast Monsoon. Geographically, Kelantan is dominantly covered by lowland area [11] which is also called as the flood plain area. Flood plain is the area that periodically inundated by the lateral overflow of rivers or lakes, and /or by direct precipitation or groundwater. These low-lying areas represent depositional terrain and overlying unconsolidated alluvial, coastal and marine sediments of variable thickness. Due to this condition, Kelantan has high prominent to experienced flood disaster every year.

Isotope Hydrology

Isotope study can provide solutions to address the problem through Rayleigh Distillation concept. The Rayleigh Distillation model gives the understanding of the first event of rainfall that will contribute to the enrichment of isotope composition. Residual vapour and secondary evaporation causes the depletion of isotopic composition compared to the first event. The Rayleigh Distillation model represents the process of condensation to form clouds and precipitation. Water vapor moved up and cooled down, forming a water droplet and fall as precipitation. The isotopic value of precipitation during rainout is largely controlled by the temperature. Reflecting on the 2014 flood phenomena, continuous moisture supply at Kelantan is identified causing the high intensity of monsoon at that time. Figure 1 below shows the illustration of the rainout effect [12,13].

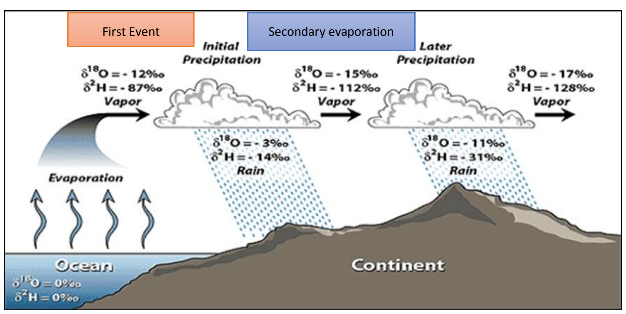

Figure 1. Rainout effect on δ^2H and δ^{18}O values [12,13].

Global Meteoric Water Line (GMWL) as defined by Craig [14] is $\delta^2H = 8\delta^{18}O + 10$. It seems similar to the Local Meteoric Water Line (LMWL) for Malaysia that had been established by Ayub [15] as $\delta^2H = 8\delta^{18}O + 13.255$. Each LMWL is controlled by the local climate, origin of water vapour, secondary evaporation during precipitation and seasonality rainfall [16]. When the slope of LMWL is high, it indicates a high volume of precipitation, due to low temperature. While if the LMWL slope is low, it is due to the secondary evaporation caused by the high temperature. Therefore, it can be concluded that temperature is the dominant controlling factor in isotopic composition [16, 17].

STUDY AREA

Kelantan is positioned on the northeast of Peninsular Malaysia. Peninsular Malaysia is located in the tropics of the equator between 1° and 7° north and from 100° to 103° eastern longitude [8]. Kelantan is bordered by Narathiwat Province of Thailand to the north, Terengganu to the southeast, Perak to the west, which is facing the ridge of Titiwangsa, and Pahang to the south. To the northeast of Kelantan is the South China Sea, which is the major source of moisture supply. The climate of Peninsular Malaysia has consistent in temperature, high humidity and has abundant of rainfall [8]. Kelantan has temperatures from 21 to 32 °C and intermittent rain throughout the year. The wet season, which is Northeast Monsoon (NEM) occurred from November to February and the dry season, which is Southwest Monsoon (SWM) occurred from June until September. The transition period in between the monsoons is known as the inter-monsoon period.

This research was conducted at Kota Bharu, one of the districts that located in Kelantan. Kelantan is selected as the study area due to the previous study done by Syakir *et al.* [4]. The pattern of the isotopic composition of rainfall in 2013 and 2014 was investigated by them. Therefore, this study was conducted to continue and delineate the pattern of isotopic composition for rainfall in 2015. By compiling all these data, the story of monsoon regime that is driving the water input in Malaysia can be reconstructed. Figure 2 below, shows the map with sampling location labeling.

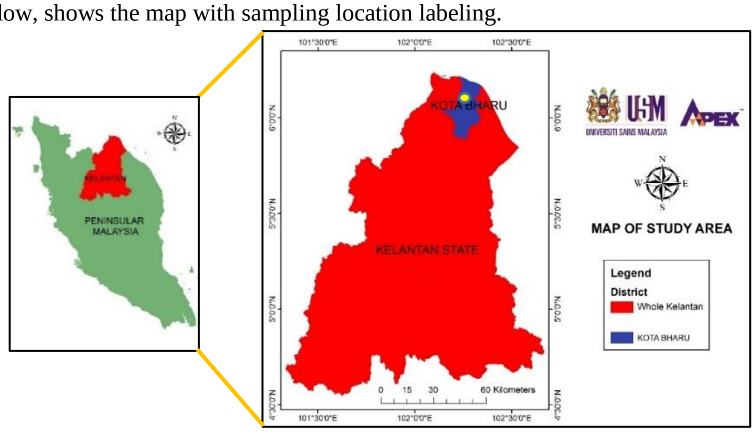

Figure 2. Map of Study Area

MATERIAL AND METHODS

34 samples of rain water were collected on event basis during the NEM 2015. The volume of rainfall on each event was also determined. Monthly rainwater samples also have been used as the secondary data provided by the Malaysian Nuclear Agency to support this study. Rain water samples collected were stored in 60 ml polypropylene bottle and the δ^2H and $\delta^{18}O$ were measured using the SERCON Isotope Ratio Mass Spectrometer (IRMS) after being treated in the Water Equilibration System (WES) at Malaysian Nuclear Agency [18].

Stable isotope compositions are generally reported as δ (pronounced delta) values. The δ values are calculated using the equation below (for example, δ^2H or Deuterium):

$$\delta^2\mathrm{H} = \frac{RSample - RStandard}{R\ Standard} X\ 1000 \tag{1}$$

where R represents the ratio of heavy to light isotope ($^2H/^1H$), and R_{Sample} and $R_{Standard}$ are the isotope ratios in the sample and the standard respectively. The sample is called depleted (more negative) if the δ values are lower, and enriched (more positive) if the δ values are higher with respect to a reference. Standard acts as the Reference used for the sample analysis. According to Rao [3], previously, the standard used for water samples is Standard Mean Ocean Water (SMOW) which contains the average value of all ocean water around the world. However, when this standard gets depleted, the International Atomic Energy Agency (IAEA) decided to make one new standard which is almost similar to SMOW and it is known as Vienna Standard Mean Ocean Water (VSMOW). For this analysis, a secondary or laboratory standard which can be traced back to VSMOW was used.

RESULT AND DISCUSSION

Stable isotope in precipitation

The purpose of this study is to compare with the previous study done by Syakir *et al.* [4] and figure 3 (a) and figure 3 (b) explained some evident stated by them. They had been collected rainwater samples at Kelantan from October until December on 2013 and 2014. The δ^{18}O value for NEM 2013 was ranging from -10‰ to -1‰. It showed the dynamic pattern of moisture supply during the NEM. At the beginning, rain with enriched isotopic composition form during October 2013 and moving towards depleting as November 2013 was entered. Then, they were replenishing during December 2013 resulting in high isotopic composition. Meanwhile, NEM 2014 showed some weirdness on the isotopic composition of $\delta^{18}O$ with the value, ranging from -5‰ to -7‰. Its meteoric water line was reflecting on being less evaporation and suggesting that consistent moisture supply occurred on NEM 2014, causing extra amounts of rainfall and flood disaster to be happened during that year.

Based on Figure 3 (c), the rainfall on NEM 2015 gives the result of $\delta^{2}H$ values range from -6.32‰ to -79.25‰ and $\delta^{18}O$ values in the range from -0.67‰ to -11.28‰. This figure clearly shows that in November 2015, the rainfall is well distributed while in December it is being clustered together at certain area. Plus, in early of November 2015 the isotopic composition shows more positive reading, which is enriched and moving towards late of November, the isotopic composition shows more negative which is depleted. It shows the continuous moisture supply and follows the Rayleigh Distillation concept with the dynamic pattern of moisture cycle. As mention by Tian et al [19], during the wet season when a value of $\delta^{18}O$ is low due to low in temperature, rainfall formation is affected by the monsoon. This implies to this NEM 2015 event of rainfall.

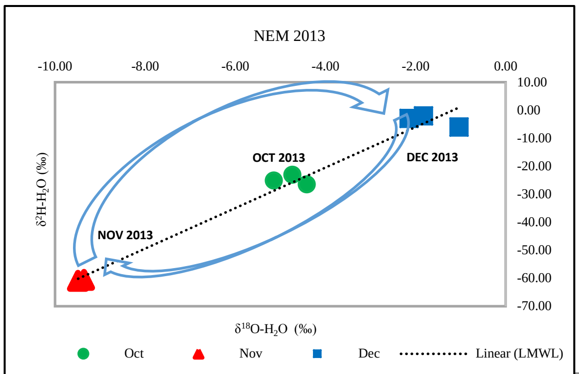

Figure 3(a). Isotope composition of $\delta^{2}H$ vs $\delta^{18}O$ for NEM 2013

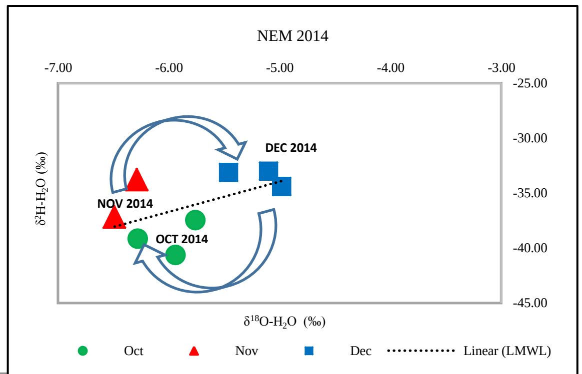

Figure 3(b). Isotope composition of δ2H vs δ18O for NEM 2014

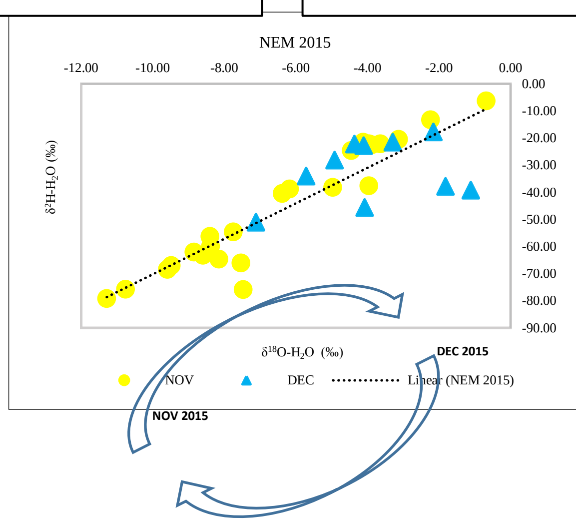

Figure 3 (c). Isotope composition of δ2H vs δ18O for NEM 2015

Local Meteoric Water Line (LMWL)

In water cycle system, the values of $\delta^{2}H$ and $\delta^{18}O$ in water vapor and precipitation would define as $\delta^{2}H = 8\delta^{18}O + 10$; also called as the meteoric water line (MWL) [14]. Precipitation in the form of rain produced by the cooling of vapour mass. When the temperature drops, rainout will proceed. Thus, the rain will have isotopic composition controlled by equilibrium fractionation with vapor. The slope of meteoric water line will be closer to eight and it relates to the ratio of the equilibrium fractionation factor for ^{2}H and ^{18}O. The slope result will approach eight when the surface is at high temperature. Additionally, slope also can be affected by evaporation that occurs after condensation [16].

These LMWL equations were derived from the regression line based on the weighted mean value. These results are based on the secondary data on monthly rainwater samples provided by the Malaysian Nuclear Agency from 2013 until 2015. Therefore, two regression lines were formed, Peninsular Malaysia LMWL and Kelantan LMWL. The regression line for

Peninsular Malaysia is $\delta^2H = 6.73(\pm0.30).\delta^{18}O + 3.24(\pm1.88)$ ‰ with $r^2=0.8736$ and confidence interval of 95%. While for the regression line of Kelantan LMWL is $\delta^2H = 7.34(\pm0.79).\delta^{18}O + 6.01(\pm4.53)$ ‰ with $r^2=0.9356$ and confident interval at 95%. The regression line produced by Peninsular LMWL demonstrating a shallower slope with respect to Kelantan LMWL. Kelantan LMWL reflects the origin of vapour mass and seasonality of precipitations. Therefore, ones can conclude that each LMWL is controlled by the climate of that area, the origin of the vapor mass, secondary evaporation during rainfall and by the seasonality precipitation. These few variables give impacts toward the slope of the regression line and the deuterium excess [16].

Amount of Rainfall

The rainfall amount is measured in millimeter for each rainfall event. The study done by Syakir *et al.* [4] recorded the Kelantan NEM and SWM rainfall in 2013 and 2014 as shown in figure 4(a) below. They had done this study by collecting rainfall amount monthly. The highest rainfall amount was recorded on November 2014 with the reading of 941.40 mm compared to the rainfall amount on November 2013 which is 500.2 mm. It is clearly seen that there were huge differences in rainfall amount during NEM 2014 compared to 2013. This clarified the massive flood disaster experiencing by Kelantan during 2014. Statically, this figure had clearly differentiated the rainfall amount during NEM and SWM. It is proved that during NEM, Malaysia which is located at the tropical region experiencing wet season while during SWM, having such dry season.

For 2015 NEM, 27 events of rainfall were collected as can be referred to the figure 4(b) below. S1 until S24 represent the rainfall event during November while S25 until S27 for the rainfall event on December. It is clearly seen that the highest rainfall amount is recorded on November which is at S12 with the reading of 32.74mm. During this year, no serious flood is recorded due to the less amount of rainfall. As mention before, this is reflected by El Nino phenomena that hits Malaysia during that time.

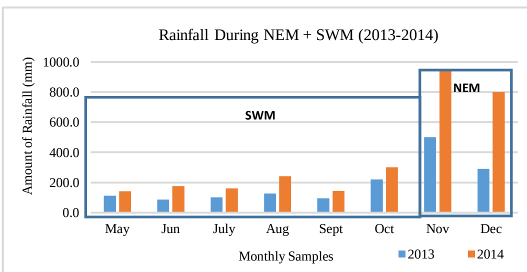

Figure 4 (a): Kelantan rainfall amount during NEM and SWM (2013-2014)

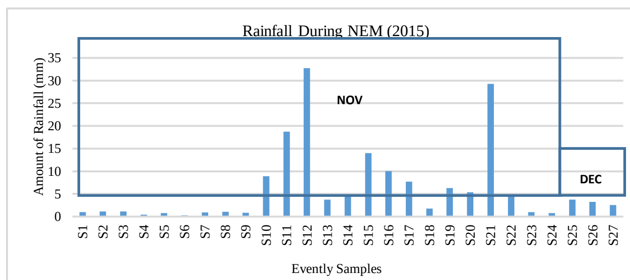

Figure 4 (b): Kelantan rainfall amount during NEM 2015

Reconstruction of NEM Rainfall event

Based on plotted shown in figures 3 (a), (b) and (c), it is shown that the samples are well distributed at enriching and depleting position. Why enriched and why depleted? This is due to isotopically enriched rain forming and fall from a replenished vapor mass while depleting rain is formed by the residual vapor. In other words, the first event of rainfall will contribute to the enrichment of isotope composition. In terms of fractionation, equilibrium fractionation is describing as the condensation process of water vapour to form liquid precipitation and responsible for separating the isotopic composition between a cold region and warm region [16].

The illustration shown in figure 5 below is therefore constructed based on the result that had been discussed before. On 2013, the pattern of rainfall and flood event was considered to be normal to be happening for every NEM. Moving forward to 2014, the system in Kelantan has totally collapsed caused by the huge rainfall happens due to the continuous moisture supply, causing the worst flood disaster in Malaysia to be recorded. On the next following year (2015), El Nino phenomena had hit the tropical region, causing the weather to be very hot until the river becomes shallow and dry. During NEM of that year, rainfall still produces as usual and follow the pattern as in 2013 but in the small amount and did not cause a serious flood event at Kelantan. Overall, it is proved that the study by Syakir *et al.* [4] which the monsoon regime that drives the water input in Malaysia during 2015 follows the pattern on 2013 but having some changes caused by El Nino. Therefore, this rainfall systematically implies the Rayleigh Distillation perspective [16].

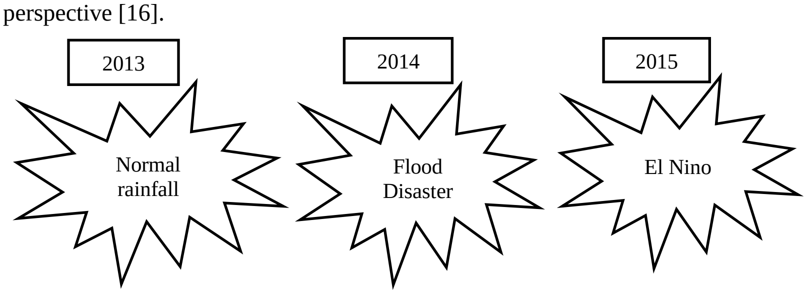

Figure 5. Chronology of rainfall pattern from 2013 until 2015

CONCLUSION

Kelantan experienced flood every year caused by the geographic condition of this state and its neighbor state. Changes in climate can give impact towards moisture supply for precipitation. When there is too much rainfall form and hit the land continuously, the soil could not hold the water anymore and cause flooding to happen. However, Zafirah *et al*. [20] said that when the barriers in managing the watershed are identified, it will lessen the vulnerability of the catchment at a certain area. In terms of reconstruction of the rainfall event, normal rainfall is observed on 2015 as it follows the rainfall pattern during 2013. However, Malaysia has reported to have El Nino on 2015, causing the rivers in Kelantan to be shallow and drained due to the small amount of rainfall produced. Besides that, the most stable isotope of hydrogen and deuterium can provide useful information geochemically as they separated by geological or cosmological process compared to the other stable isotope. Therefore, they can act as a useful tool in reconstructing the conditions in understanding the monsoon regime [21].

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