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Using stable hydrogen and oxygen isotopes to reveal monsoonal and related hydrological effects on meteoric water in the Western Pacific monsoon region: A case study of the Ilan region, northeastern Taiwan

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ABSTRACT

This study analyzes the isotopic compositions (δ^2H and δ^{18}O) of meteoric waters, including precipitation and stream water, to reveal what major hydrological processes affect the hydrological regime of the Ilan region, northeastern Taiwan. The isotopic results indicate monsoonal flows as the fundamental factors affecting studied precipitation and stream water. Summer precipitation sourced from southerly air mass exhibits lower δ and deuterium-excess (d^E) values than winter precipitation sourced from northerly air masses. The δ^{18}O and d^E values are respectively −7.7‰ and 8‰ for summer precipitation and −3.3‰ and 24‰ for winter precipitation. Furthermore, semi-quantitative estimations using d^E evidence indicate that summertime southerly air masses generally contribute more to stream water than wintertime northerly air-mass flows (approximately 54% vs. 46%). However, the contribution fractions are controlled by the orientation of catchments to the windward side of respective monsoonal flows. Northern catchments, located on the windward side of southerly air masses, receive about 60% of their water from precipitation condensed from the southerly air masses, and 40% from the northerly air masses. By comparison, southern catchments, located on the windward side of northerly air masses, receive about 59% of their water from northerly air masses and 41% from southerly air masses. Additionally, catchment effect, induced from δ value, is notable in stream basins with high elevations but this is not related to catchment sizes. Besides this, altitude effect, which is determined in terms of δ^{18}O values, was derived using data from four precipitation stations of northern Taiwan. It ranges from −2.5 to −3.0‰ per 100 m depending on the season; moreover, based on the d^E evidence, secondary evaporation effects are apparent with moisture recycling influencing inland summer precipitation and raindrop evaporation influencing inland winter precipitation.

1. Introduction

Meteoric water is an important water resource for daily life worldwide (Gleick, 1993). In Taiwan, yearly water consumption is about 176 × 10^8 m^3; of which, about 66% comes from surface water, including stream water (81 × 10^8 m^3) and reservoir water (36 × 10^8 m^3) (Water Resources Agency, 2014). Consequently, understanding the hydrological processes governing meteoric water supply is essential for water resource management (Peng et al., 2015).

Stable isotope compositions (δ^2H, δ^{18}O) in water have proven to be very successful in meteorological, hydrological, and hydrogeological studies. For example, these water isotopes are frequently used to study regional-precipitation air-mass sources (Gat and Carmi, 1970; Araguás-Araguás et al., 1998; Lee et al., 2003; Liu et al., 2010; Peng et al., 2010; Langebroek et al., 2011; Vodila et al., 2011; Stumpp et al., 2014), the extent of moisture recycling and rain drop evaporation on precipitation (Tsujimura and Tanaka, 1998; Wang and Yakir, 2000; Rothfuss et al., 2010, 2012; Peng et al., 2011), and seasonal contributions of precipitation to surface water and groundwater (Moravec et al., 2010; Kebede and Travi, 2012; Jeelani et al., 2013). Additionally, they are often employed to study stream water generation (Jeelani et al., 2010; Meriano et al., 2011; Klaus and McDonnell, 2013; Dahlke et al., 2014), essential processes connecting surface water and precipitation

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(Peng et al., 2015), and hydrological relations between surface water and groundwater (Peng et al., 2008; Praamsma et al., 2009; Duque et al., 2011; Wassenaar et al., 2011; Mohammed et al., 2014). In this paper, stable hydrogen and oxygen isotopes are employed to identify the hydrological processes governing meteoric water in northern Taiwan.

This case study is located at Ilan County, northeastern Taiwan (Fig. 1). Taiwan is an island in the Western Pacific monsoon belt. Summer and winter monsoons are the two major climate systems differentiating seasonal rainfall in the region. According to Peng et al. (2010), three prevailing air masses originating from polar continental (Pc), equatorial maritime (Em) and tropical maritime (Tm) regions control the δ^{18}O (or δ^{2}H) and deuterium-excess (defined as $d^{E} = \delta^{2}H - 8\delta^{18}O$ (Dansgaard, 1964)) of Taiwan's precipitation (Fig. 1a). During the winter monsoon period, the prevailing Pc air mass supplies precipitation in Taiwan with relatively high δ^{18}O (or δ^{2}H) and d^{E} values. Further, because of its geographical location, the Ilan region receives early-stage precipitation condensed from Pc air masses as they pass over Taiwan (Fig. 1). In contrast, during the summer monsoon period, the prevailing Tm/Em air mass contributes precipitation to Taiwan with low d^{E} and δ^{18}O (or δ^{2}H) values.

Furthermore, while these various air masses of the Pc, Tm, and Em travel through Taiwan, secondary evaporation effects further modify the isotopic characteristics of inland precipitation. For example, raindrop evaporation reduces d^{E} in winter precipitation, and moisture recycling increases d^{E} in summer precipitation (Peng et al., 2010). Beside those secondary evaporation effects on precipitation, catchment effect and base-flow are two main hydrological processes influencing the isotopic compositions of stream water in mountain regions of central Taiwan (Peng et al., 2015).

With the above isotopic background conditions in mind, any study of the Ilan region must keep in mind two important factors. Firstly, Ilan is located in the northeastern corner of Taiwan (Fig. 1), which tends to receive any initial precipitation from Pc air masses. Therefore, establishing baseline isotopic-data conditions for precipitation in the Ilan region is fundamental to any derivative isotopic hydrological studies in Taiwan. Secondly, understanding the isotopic composition of meteoric waters is imperative to understanding the key processes affecting the hydrological environment. This understanding should lead to better management of regional water resources. Besides hydrological processes such as monsoon effect, secondary effect, or catchment effect, which have been mentioned in previous studies, this study is aimed at gaining a comprehensive understanding of hydrological conditions in the Ilan region, and therefore at discovering if there are any new factors governing hydrological processes in the Ilan area or isotopic features as yet unreported.

Consequently, the purpose of this study is to reveal major hydrological processes in the Ilan region based on stable isotope compositions in precipitation and stream water. To this end, the study first characterizes seasonal hydrogen and oxygen isotope compositions of precipitation and stream water to better understand the meteoric waters from which precipitating vapors are sourced. Next, the study elucidates the isotopic hydrological relations between studied precipitation and stream water to better understand what the major hydrological processes in the region are.

2. Materials and methods

2.1. Study area

The study area is located at Ilan, northeastern Taiwan. In the Ilan region, the Langyang Stream is a major river system (Fig. 1). It has the second largest catchment (979 km^{2}) and second longest waterway (73 km) of all rivers in northern Taiwan. The Langyang Stream has two major sources in its upper reaches. These are the Madang and Mimoden Streams (Fig. 1b), which converge at Mimoden (near UT-3 in Fig. 1b). After this confluence, the Langyang

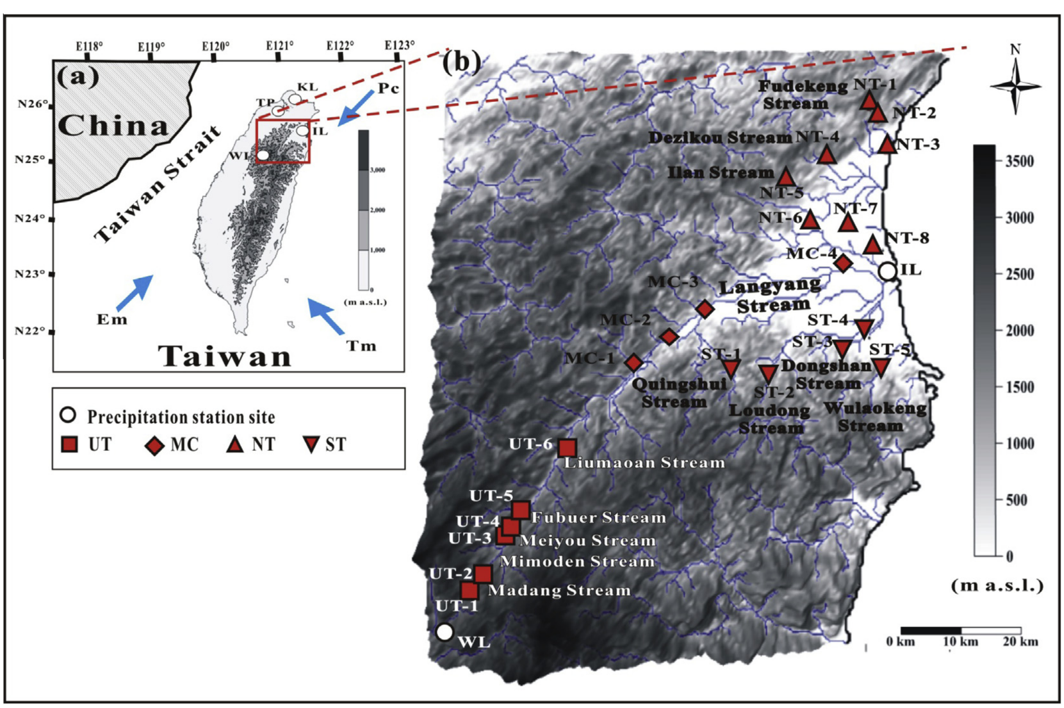

Fig. 1. Study area. (a) Locations of the four precipitation stations. Pc represents polar continental air mass from the Asian continent; Em: equatorial maritime air mass from the South China Sea, and Tm: tropical maritime air mass from Northern Pacific (Peng et al., 2010). (b) Locations of stream water samples. Abbreviation UT represents stream water collected in up-stream tributaries of the Langyang Stream; MC, in the reaches of the Langyang Stream in the Ilan Plain; NT, in the tributaries of the northern catchments of the Ilan Plain; ST, in the tributaries in the southern catchments of the Ilan Plain.