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Tracing water flow from sloping farmland to streams using oxygen-18 isotope to study a small agricultural catchment in southwest China

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ABSTRACT

Knowledge of the age and origins of water and its movement from hillslopes to streams is important in mapping aquifers, conserving water supplies, determining water-use policy, and controlling pollution. In a sloping farmland-dominated agricultural catchment in southwest China, a stable isotope tracer (^{18}O) combined with hydrometric measurements was tested to determine the rainwater movement from a hillslope to a stream during three storm events. The results showed that underflow in finely fractured rocks accounted for the highest proportion of the total flow on the slope, indicating that vertical flow was the predominant water flow pattern on the hillslope. The surface flow had basically the same $\delta^{18}O$ value as the coinstantaneous rainfall, indicating that it was a Hortonian overland flow. The two end-member separation model showed that pre-event water accounted for a large proportion of the hillslope subsurface flows and streamflow especially during the initial stage. The first sample of underflow and interflow water always contained significant rainwater, indicating that macropore flow was prevalent in this Entisol. Event water dominated the peak streamflow and accounted for 70.4%, 95.6% and 80.4% of the peakflow amount during the three storm events. In general, the results suggested that pre-event water dominated the initial stage of stormflow generation and that event water dominated the peakflow. During the recession period, hillslope subsurface flows were the main source of the streamflow, as indicated by the similar volume-weighted $\delta^{18}O$ value in subsurface flows and stream water. In future studies, hydrological processes under various land uses should be monitored synchronously to better understand the mechanisms of stormflow generation and transport regarding non-point source pollution in agricultural catchments.

1. Introduction

Information on the hydrological pathways by which water moves over and through hillslopes to streams is important for a hydrological, ecological and geochemical understanding of the Earth's surface (Genereux and Hooper, 1998). In addition, an understanding of the dominant runoff generation processes at the hillslope and catchment scales is also required for efficient water resource management. A thorough understanding of flow generation and the dominant process that occurs from hillslope to catchment is useful for designing an integrative hydrological model for flow simulation and prediction. Additionally, the water content characteristics, infiltration and movement on hillslopes have important implications for slope stability and erosion. Finally, the prediction and control of non-point source pollutants and dissolved carbon also requires an understanding of the pathways through which water moves to streams because different pathways provide different opportunities for contact with organic soil and rock (Genereux and Hooper, 1998; Stieglitz et al., 2003; Yang et al., 2009).

Nevertheless, the exact mechanism of pre-event water movement from hillslope to stream remains unclear in many regions due to different hydro-climatic and geographic conditions. Answering this question requires knowledge of how these hillslope flow paths are linked to the rainfall regime during the transformation of rainwater to streamflow. It is particularly important to determine subsurface pathways and water sources to better control non-point source pollution in agricultural catchments (Tang et al., 2012a,b; Zhang et al., 2012).

The application of environmental isotopes such as oxygen-18 and deuterium have been used to trace water flow paths at the hillslope and catchment scale, providing new insights into hydrological processes with respect to water sources, dominant flow processes and pathways (Kendall and Caldwell, 1998;

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Munyaneza et al., 2012). However, some specific questions remain. How much pre-event or event water contributes to storm-induced runoff? Which component dominates the stormflow? Many catchment studies have shown that stormflow is supplied largely by pre-event water that moves via subsurface routes to a channel (Gremillion et al., 2000; McDonnell, 2003, Abdalla, 2009). Genereux and Hooper (1998) concluded that the total stormflow runoff from rainstorm events is dominated by pre-event ("old") water in a majority of small hillslope catchments. In addition, Saito (2000) and Mul et al. (2008) assumed that the isotopic concentration of subsurface runoff was identical to the value of pre-event water for use in hydrograph separation. In contrast, a few researchers have found that stormflow is dominated by event water (Bonell et al., 1998; Schellekens et al., 2004). Marc et al. (2001) also claimed that subsurface runoff came from the rain event without involving pre-existent water stored in the soil layer.

No consistent conclusions can be generalized from these studies. This means that studies should be carried out in a wider range of hydrological environments to explore the links between hydrological processes and isotopic responses (Sklash, 1990). In southwest China, water problems such as floods, droughts and water pollution negatively affect society and economic development, indicating a need for an in-depth understanding of hydrological processes in this region, specifically regarding how rainwater becomes runoff.

Purple soils, which are classified as Regosols by FAO Taxonomy or Entisols by USDA Taxonomy (Gong, 1999), are widely distributed throughout the hilly parts of southwest China and have a total area of 260,000 km^2. Purple soil is a valuable agricultural resource with high nutrient contents and productivity. This Regosol is characterized by a thin soil layer and abundant macropores, and fractures in purplish parent mudstone are quickly formed by the weathering process. It has been reported that runoff can be quickly generated in purple soils, especially in the subsurface (Zhu et al., 2009), which was thought to be responsible for many environmental problems such as eroding soil that poured into the Yangtze River (E, 2008). In addition, the non-point source pollution from this agricultural soil is also believed to be the main cause of water quality deterioration in the Yangtze River (Tian et al., 2010). Therefore, the mechanism of rainwater movement from hillslope to stream on the catchment scale in this region is very important and is highly relevant to the agricultural sustainability and water quality of the Yangtze River, especially since the construction of the Three Gorges Dam.

Although some studies concerning runoff processes have been conducted in this region (Zhu et al., 2009; Tang et al., 2012a), runoff sources and dominant flow paths are still poorly understood. Little work has been attempted using isotope tracers to provide insights into the hydrological processes of this region. In this study, the stable isotope ^{18}O was used in combination with hydrometric measurements to explore the physical controls of runoff generation that dominate the hydrological process relating to streamflow in a small agricultural catchment. We present the following hypotheses for testing in this research: (1) subsurface flow dominates hillslope hydrology, (2) event water is the major source of stream stormflow due to the macroporous nature of the study soil, and (3) the contributions of pre-event water to the subsurface flow from hillslope and to stream water are basically equal during hydrological processes.

2. Materials and methods

2.1. Study site

This in situ experiment was conducted at a headwater catchment of 0.35 km^2 (31°16′N, 105°28′E) in the middle of a purple soil-dominated hilly area in southwest China (Fig. 1a). Sloping farmland accounts for 50% of this catchment and the other portions consist of forestland and residential areas. Impermeable surfaces comprise approximately 9% of the area and consist of residential buildings and roads. There is no saturated zone near the stream; instead, a paddy field in the valley comprises 8% of the total catchment area. The dominant landscape unit is sloping farmland (Fig. 1c). This region is characterized by a moderate subtropical monsoon climate with an annual mean temperature of 17.3 °C and a mean annual precipitation of 826 mm from 1981 to 2006. Annual precipitation is distributed at 5.9%, 65.5%, 19.7% and 8.9% during the spring, summer, autumn and winter, respectively. Due to the temporal variation of rainfall, the study stream is ephemeral with no flow during the dry periods of the year. The purple soil in question is loam soil with average textural data of 27.1% sand, 51.6% silt and 22.3% clay (USDA classification system). The soil is characterized by a pH of approximately 8.3, an average bulk density of 1.33 g cm^{-3}, an average organic matter content of 8.75 g kg^{-1}, and a saturated hydraulic conductivity of 10^{-1} to 10^{-2} mm min^{-1} (Wang et al., 2012).

2.2. Field sampling and hydrometric measurements

Rainfall quantities were measured with an automatic tipping bucket with an error of ±0.1 mm (HOBO, USA). Each rainfall event was sampled from the monitored hillslope with a 20 cm-diameter glass funnel connected to a 1-L high density polyethylene bottle. A table tennis ball was placed in the funnel to reduce evaporation. All of the storms were sampled at one hour or half-hour time intervals depending on the rain amount in order to evaluate the isotope inter-variance in rainwater.

The hillslope flows were monitored at two adjacent plots. A schematic diagram of the field plot on the hillslope cropland is shown in Fig. 2. The plots were hydrologically separated from peripheral soil and mudstone with cement wall of about 2 m depth. The length, width and slope gradient of the plot were 8 m, 4 m and 7°, respectively. The thickness of the soil layer was 38 cm for plot 1 and 44 cm for plot 2. The thickness of the finely fractured mudstone layer was 29 cm in plot 1 and 35 cm in plot 2. The plow depth of the two plots was approximately 15 cm. The plots were assumed to be representative of the sloping farmland units within this catchment. The average slope and soil layer thickness of the sloping farmlands was 7° and 40 cm. The physical and chemical properties of the soils in the two plots were also similar to the values provided above in the study site description. However, hydrological spatial heterogeneity can be observed in the two plots. In this study, the hydrological and isotopic information observed in these plots was used to represent the hillslope hydrology characteristics of the entire catchment.

Corn was planted in the plots at a density of four plants per square meter. In the study period, the corn was in the elongation stage. A preliminary study showed that the corn did not significantly change the rain isotopic composition through interception, with a difference of 0.2‰ for Oxygen-18. In addition, the retention effect by corn on the water quantity was not ignored, but this research addressed how rainwater becomes runoff. In fact, the biomass of corn was relatively small and was presumed to have little effect on the water quantity on the hillslope flow during the study period, especially for a storm event. The surface flow, interflow in soil and underflow in fractured mudstone were measured by a self-recording (HOBO event data logger, UA-003-64) tipping bucket gauge with collection grooves. A water sample was taken with a beaker every 30 min. The volume of each tipping bucket was calibrated before and after each storm event. The flow rate was calculated at 30-min intervals. Five ceramic soil water lysimeter samplers (Soil Moisture Equipment Co., USA) with inner