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Runoff generation in small catchments under a native rain forest and a rubber plantation in Xishuangbanna, southwestern China

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Abstract

For the purpose of assessing the potential influence of tropical rain forest conversion to rubber plantation on catchment hydrology, a stable oxygen isotope was used as a tracer to identify the event water and prestorm water components of storm runoff during low- and high-flow conditions in a native tropical rain forest catchment (TRFC) and an artificial rubber plantation catchment (ARPC) in SW China. Isotopic hydrograph separations for the storm of April and September 2004 reveal that the event water made up only a small proportion of discharge (29 and 31%, respectively) at peak flow in the TRFC, while it made up the dominant component at peak flow (62 and 69%, respectively) in the ARPC. The analyses suggest that in the ARPC, the universal presence of compacted terraced tracks associated with land management would encourage infiltration-excess overland flow. This isotopic investigation demonstrates that tropical rain forest conversion to rubber plantation would markedly change the runoff generation processes in this area.

Introduction

Vegetation cover change has a profound influence on the hydrological cycle. During the last several decades, the adverse effects of deforestation and land cover change on soil erosion, water yield, groundwater and salinity have become increasingly important and recognized (Joerin *et al*. 2002). Many studies indicated that forest structures are a principal cause of hydrological differences between watersheds (Kendall *et al*. 1995; Bonell *et al*. 1998; Brodersen *et al*. 2000; Goller *et al*. 2005). Thus, an understanding of relationships between forest structure and runoff processes is essential for the quantitative prediction of the effects of deforestation and changes in vegetation (Bosch & Hewlett 1981; Bent 2001; Lanea & Mackay 2001).

In Xishuangbanna, southwestern China, studies on rainfall partitioning into its components are available for a few primary and artificial forest watersheds (Wang *et al*. 2006; Liu *et al*. 2008). However, comparisons of the influence of vegetation changes on either the isotopic composition in stream flow or runoff processes are sorely lacking. Because rubber plantation, which is mostly at the cost of tropical rain forests, is a critical component of the local economy and is still a large-scale practice in this developing region (Li *et al*. 2008), the hydrologic balance and runoff processes in this forest deserve to be important topics regarding the search for sustainable agricultural uses.

For isotope hydrology studies, the variations in the isotopic composition of precipitation, groundwater and stream water can provide information on a wide variety of hydrologic processes within a watershed, including: evaporation, subsurface residence time of water and the source–water components of stormflow (Maloszewski *et al*. 1983; Lakey & Krothe 1996; Rose 1996; Burns & McDonnell 1998; Gibson *et al*. 2000). In many cases, isotope studies have led to the enhancement or revision of conceptual models of catchment hydrology, even in catchments, which were thought to be well understood (Kennedy *et al*. 1986; McDonnell *et al*. 1990; Hooper *et al*. 1998; Gremillion & Wanielista 2000; Soulsby *et al*. 2000; Elsenbeer 2001). Isotope hydrograph separation techniques have been widely applied to characterize runoff generation mechanisms, for delineating flow pathways, and for estimating the water storage capacity (Harris *et al*. 1995). The hydrograph separation technique using isotopic compositions have been successfully conducted in watershed studies to separate stormflow hydrograph measurements into two time–source components, the 'new' rainwater (event water) and the 'old' prestorm components (Fritz *et al.* 1976; Sklash *et al.* 1986; Buttle 1994; Genereux & Hooper 1998; Schellekens *et al.* 2004).

In this study, two perennial streams, one under a primary tropical rain forest and another under a rubber plantation forest, were investigated for comparison of the source–water components and flowpaths of the two streams during storm discharge events in the dry season and the rainy season through the two-component mixing model. In addition, the mean catchment residence times of the two streams at base flow through a comparison of seasonal fluctuations in $\delta^{18}O$ were also estimated. The objective of this study was to compare the underlying hydrological mechanisms of the two streams during low- and high-flow conditions. This research is a part of our previous study on the hydrological and chemical effects of rainfall in a tropical rain forest and an artificial forest. However, the earlier works just focused on the difference of fog/or rainfall interception between the two forest types (Liu *et al.* 2005, 2008), and not on the runoff generation mechanisms.

Materials and methods

Study site

The experiment was carried out at a tropical seasonal rain forest catchment (TRFC, 51.1 ha) and an artificial rubber plantation catchment (ARPC, 19.3 ha) in Menglun town (21°55′39″N, 101°15′55″E) of Xishuangbanna in southwestern China, which is about 800 km from the Bay of Bengal on the southwest. The distance between the two forest catchments is about 5 km. The site was selected based on its representativeness of local forest types. The TRFC (dominated by *Pometia tomentosa* and *Terminalia myriocarpa*) spans an altitudinal range of 600–760 m a.s.l. and yields a perennial stream. The average slope of the catchment is about 13°. This tropical rain forest differs from tropical Asian lowland rain forests in that some of its tree species are deciduous, with the forest canopy being about 36 m high. Another catchment (ARPC) for this study is covered with an 18-year-old artificial forest of *Hevea brasiliensis Muell*.-Arg., or rubber tree, which is approximately 20 m high. The ARPC spans an altitudinal range of 550–680 m a.s.l. with an average slope of 15°, and yields a perennial stream too. The rubber trees were planted in terrace patterns after a complete clear cut of forest in 1986–1988 and cultivated for economic development purposes. Both of the catchments are underlain by Jurassic sandstones and shales. Soils under the two forests are lateritic soil developed from siliceous rocks, such as granite and gneiss, and are about 1.2 and 1.4 m deep, respectively. These experimental sites are permanent plots dedicated to the long-term ecological research managed by the Tropical Rain Forest Ecosystem Station, Chinese Academy of Sciences. Further details of the site characteristics, soils and forest structures are available elsewhere (cf. Cao *et al.* 2006).

Climate records (1965–2005) at the ARPC site show that the mean annual air temperature is 21.7 °C. Mean annual rainfall is 1487 mm, of which 1294 mm (87%) occurs in the rainy season (May–October) vs. 193 mm (13%) in the dry season (November–April). Class A pan evaporation varies between 1000 and 1200 mm/year. The mean monthly relative humidity is 87% (Liu *et al.* 2007).

Water sampling

The field investigation was conducted in two stages. During the first stage, the weekly isotopic compositions of stream baseflow water samples at the two catchments were determined concurrently from January to December 2004 and analysed by Liu *et al.* (2007). These data were used to estimate the mean catchment residence times for baseflow using the well-mixed model (Maloszewski *et al.* 1983). The water level was recorded continuously using a water level recorder (SW-40, ChongQing Institute of Hydrological Instruments, China) at 90° V-notch gauging weirs at the outlet of each catchment. These water level data were used to calculate the stream flow volume according to Hewlett (1982). Additionally, bulk rainwater samples were collected at each rain event during the study period when rainfall exceeded 5 mm at the weather station adjacent to the ARPC. Previous study showed that no isotopically significant difference was found between the two forest stands in rainfall (Liu *et al.* 2005).

The second stage of sampling concentrated on the short-time variability of isotopic composition in water with changes in the discharge brought about by two storm events: in 18–19 April 2004 (53.1 mm), corresponding to the driest time of the year, and in 8–9 September 2004 (124.9 mm), during the wettest time of the year. More intense water sampling began just before the onset of precipitation and continued throughout the storm and the following day until the stage of the stream returned to or near to prestorm levels. Stream water at the two catchments was collected manually and concurrently, and the sampling frequency was carried out every 2 h during the first 30 h of discharge and every 4 h following the initial discharge recession. In addition, rainwater samples were collected manually every 2 h during the two storm events and hourly rainfall amount data were available from the weather station.

All water samples were collected in white, high-density polyethylene plastic bottles and were tightly sealed to prevent evaporation. Samples were immediately stored at $-20\,^{\circ}C$ in a refrigerator until analysis.

Oxygen-18 analysis

The oxygen isotope analyses were performed at the Geochemistry Department, the Test Center of Lanzhou Branch, Chinese Academy of Sciences. The stable oxygen isotope composition was determined from a gas sample generated from a pure liquid introduced into an isotope ratio mass spectrometer (Finnigan MAT-252, Bremen, Germany). The values are reported as the relative deviation of the isotope ratios (e.g. $^{18}O/^{16}O$) from that of V-SMOW; these are denoted as $\delta^{18}O$ (Coplen 1996). The precision ($\pm$SD) of oxygen isotope result is 0.5‰. The isotopic composition of each sample was analysed at least twice to check for the repeatability of analysis, and the standards were analysed to check for the accuracy of analytical procedures.

Data analysis

Bulk values of tracer concentration during precipitation have usually been used for the ‘new’ water measurement. Thus, intrastorm isotopic variation of rainfall has often been neglected in hydrograph separation. It is, however, recognized that there were large variations in the isotopic concentrations of rainfall during storm periods (McDonnell *et al*. 1990; Kendall *et al*. 1995; DeWalle *et al*. 1997). In this study, rainwater isotopic compositions were determined using the incremental volume-weighted mean approach (McDonnell *et al*. 1990) over the duration of the storms to incorporate temporal variations in the isotopic composition of the rains. By this method, only the isotopic data of rains, which have fallen up to a particular point in time on the hydrograph, are included in the separation calculation and data from later rains are not included (McDonnell *et al*. 1990). Precipitation monitoring for this study did not attempt to assess the enrichment resulting from throughfall effects, such as leaf storage, stem-flow and depression storage (Gremillion & Wanielista 2000). Thus, rain water samples were used for the ‘new’ water measurement.

If it is assumed that discharge at a particular point in the catchment is derived by simple mixing between two components, prestorm water and event water, then two mass balance equations can be written that describe the water flux and the isotope flux at that point (Fritz *et al*. 1976). In this study, the incremental volume-weighted mean isotopic compositions of rainwater (McDonnell *et al*. 1990; Lakey & Krothe 1996) were used to define the rain $\delta^{18}O$, and the monthly $\delta^{18}O$ of the stream base flow water before each of the study storm event was used to define the $\delta^{18}O$ of prestorm water (Burns & McDonnell 1998; Renshaw *et al*. 2003). The event water contribution to discharge at any instant in time can be determined according to Burns & McDonnell (1998). More realistic but more complex open-system models have been developed (Harris *et al*. 1995) but are not warranted in the present application owing to lack of detailed information on the physical and isotopic changes occurring in the source reservoirs. However, the separations using the two-component mixing model can act as reasonable first approximations of the amounts of prestorm and event water that contribute to storm discharge (Lakey & Krothe 1996).

Mean residence time of the two streams at base flow can be computed based on a simple steady-state, well-mixed model, in which precipitation is assumed to mix immediately with all water in the soil reservoir (Maloszewski *et al*. 1983; Stewart & McDonnell 1991). The model assumed that the decrease in the amplitude of outputs relative to inputs provides a basis for determining residence times (Unnikrishna *et al*. 1995; DeWalle *et al*. 1997). For our study, the mean catchment residence time, through a comparison of the amplitude of a best-fit sine curve for rainfall to the amplitude of a similar curve for stream water, is determined according to Maloszewski *et al*. (1983). Given the simple nature of the model and data limitations, the result was taken only as indicating the residence time to a first approximation. However, studies elsewhere suggested that the model should be reasonably useful for such preliminary assessment (Maloszewski & Zuber 1993; Soulsby *et al*. 2000).

In our analysis and calculations, short-time variations of the isotopic data in this study were compared with seasonal isotopic data of rainfall and stream water from our previous results (Liu *et al*. 2005, 2007).

SPSS 13.0 for Windows (SPSS Inc., Chicago, IL, USA) was used for all statistical calculations.

Results

April storm

During 18–19 April, 53.1 mm of rain fell over a 25-h period, in four separate rain showers (Fig. 1a). The amount of rainfall at the two catchments was identical, and the isotopic composition was not significantly different (Liu *et al*. 2005). Before this storm, the base flow discharge at the TRFC was 0.007 m^3/s, while at the ARPC, it was 0.001 m^3/s (Fig. 1b) indicating quite dry antecedent conditions. As a result of the uncontinuous storm event, the discharge at the TRFC gradually increased to a maximum of 0.078 m^3/s within 16 h during the storm, in response to a peak delay of about 2.5 h compared with the peak of the storm (17.5 mm/h). During the next 8 h,

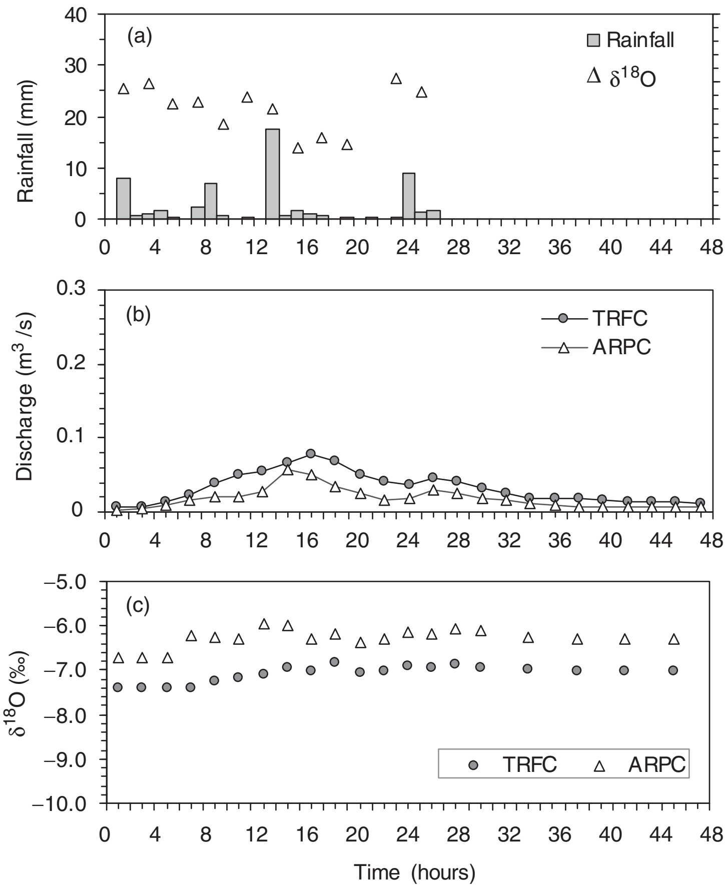

Fig. 1. Rainfall history and temporal variation of $\delta^{18}O$ in the rainfall (a), storm hydrograph (b) and temporal variation of $\delta^{18}O$ in the discharge (c) at the tropical seasonal rain forest catchment (TRFC) and the artificial rubber plantation catchment (ARPC), 18–19 April 2004.

the discharge slowly decreased, and then slightly increased again following a short rain shower (9.0 mm/h), to a second peak of 0.045 m^3/s in the next 4 h. After the second peak, the discharge slowly decreased within the next 8 h and remained very steady for the following time. For the ARPC, the discharge gradually increased during the first 8 h, and then quickly reached to its first peak of 0.057 m^3/s within the next 5 h, in response to a peak delay of about 1.0 h compared with the peak of the storm. After this first peak, the discharge showed the same changing pattern as the discharge in the TRFC.

Rainfall $\delta^{18}O$ during this storm showed considerable variation ranging from − 5.95 to − 4.94‰, and decreased gradually after the onset of the storm (Fig. 1a). This decreasing trend occurred because of the Rayleigh distillation process, which describes an isotopic fractionation process and rainout effects (in rain events, the initial liquid phase of rain is enriched in ^{18}O and ^2H as compared with the later precipitation, and consequently it gets lighter as the rain continues, a phenomenon known as rainout effect or amount effect; Gat & Airey 2006).

$\delta^{18}O$ of the discharge just before the onset of the storm was − 7.42 and − 6.73‰ at the TRFC and the ARPC, respectively (Fig. 1c), showing lighter values than those of the storm water. During the first 14 h, when the discharge increased gradually, $\delta^{18}O$ increased by only 0.53‰ in the TRFC and 0.82‰ in the ARPC. During the next 16 h, when the discharge decreased, the isotopic shift was slower and $\delta^{18}O$ value remained nearly stable for both catchments. $\delta^{18}O$ of the discharge for both catchments became lighter during the remainder of the recession but did not attain values seen in the prestorm discharge.

September storm

The storm event of 8–9 September lasted 24 h and had three maxima with rainfall intensities of 31.0, 13.1 and 9.4 mm/h, respectively, and with 124.9 mm of rainfall fell (Fig. 2a). The discharge responses of the two catchments were significantly different from those observed in April because of the heavy rain spell (Fig. 2b). The discharge at the TRFC increased rapidly from 0.033 to 0.236 m^3/s in 8 h since the beginning of the storm, in response to 74.6 mm of rainfall. Compared with the peak of the storm (31.0 mm/h), the peak discharge in the TRFC was delayed by 2.2 h. During the next 14 h, the discharge slowly

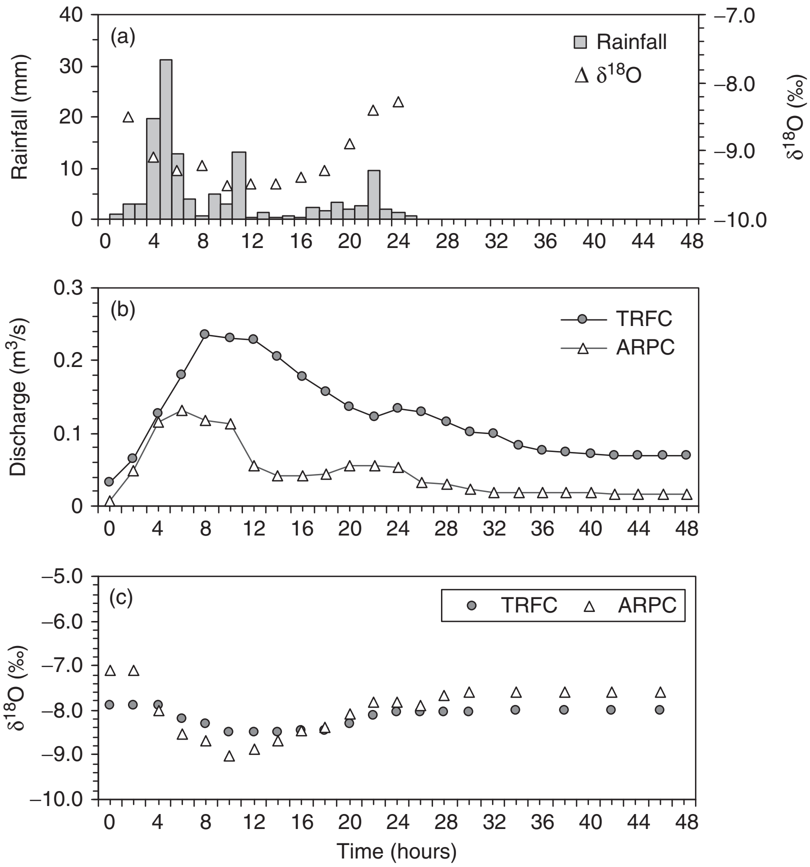

Fig. 2. Rainfall history and temporal variation of δ^{18}O in the rainfall (a), storm hydrograph (b) and temporal variation of δ^{18}O in the discharge (c) at the tropical seasonal rain forest catchment (TRFC) and the artificial rubber plantation catchment (ARPC), 8–9 September 2004.

decreased, and then increased again following the third intensive rainfall, in response to a peak delay of about 1.0 h compared with the peak of the third intensive rainfall (9.4 mm/h). During the following time, the discharge gradually decreased. For the ARPC discharge, it quickly increased to a peak of 0.132 m^3/s within 6 h during the storm, in response to a peak delay of about 1.3 h compared with the peak of the storm. During the next 6 h, the discharge levelled off, and then decreased sharply within the next 6 h. The second peak discharge of 0.056 m^3/s occurred within the next 8 h, in response to the peak of the third intensive rainfall.

The distribution of δ^{18}O values in this storm showed considerable variation ranging from − 9.52 to − 8.21‰ (Fig. 2a). During the first and the second shower, δ^{18}O value of the rainfall gradually decreased, indicating the so-called amount effect (Gat & Airey 2006). During the third shower, δ^{18}O values increased and reached to the heaviest at the end. This rapid increase might be caused by the change of the origin of the vapour mass.

δ^{18}O of the discharge before the onset of the storm was − 7.91 and − 7.10‰ at the TRFC and the ARPC, respectively, showing heavier values than those of the storm water (Fig. 2c). During the first 10 h, when the discharge increased sharply, δ^{18}O of the TRFC decreased by only 0.64‰, while at the ARPC, it decreased by 1.92‰. During the next 8 h, when the discharge of the TRFC decreased, δ^{18}O value remained nearly stable, and then increased slowly to a stable value of − 8.02‰. For the ARPC discharge, δ^{18}O value gradually increased within the next 18 h following an irregular linear fashion, and then reached a stable value of − 7.59‰ during the remainder of the recession.

Hydrograph separation

Hydrograph separations were estimated using the two-component mixing model (Lakey & Krothe 1996), as shown in Figs 3 and 4. In our calculations, the δ^{18}O values of the prestorm water for the two catchments during the April storm were taken as − 7.42 and − 6.73‰, respectively, which are the monthly δ^{18}O values of the stream base flow before the April storm event, while during the September storm, the δ^{18}O values of the prestorm water were taken as − 7.91 and − 7.10‰, respectively, which are the monthly δ^{18}O values of the stream base flow before the September storm event. For the April storm, the event water accounted for approximately 29% of the

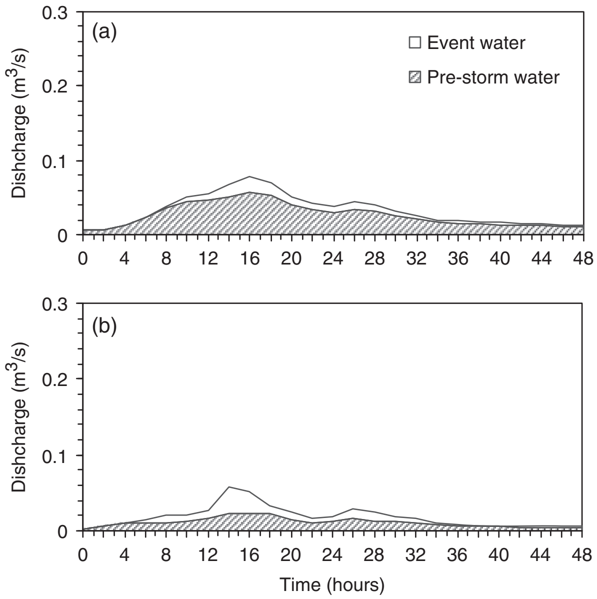

Fig. 3. Hydrograph separation of discharge into event water and pre-storm components from (a) the tropical seasonal rain forest and (b) the artificial rubber plantation catchment, 18–19 April 2004.

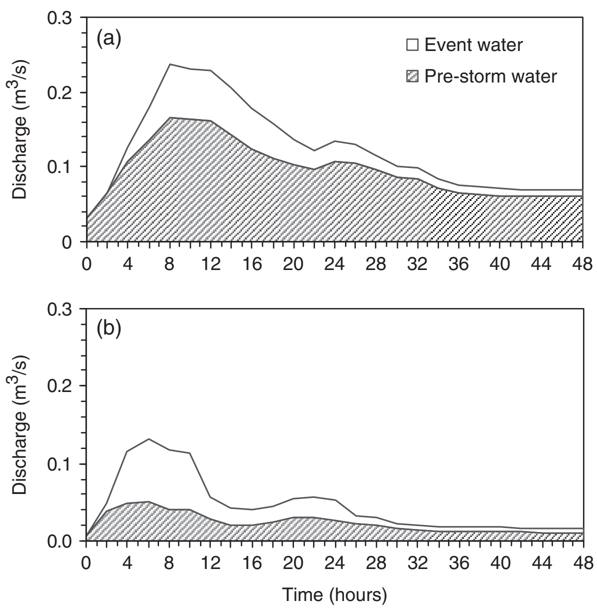

Fig. 4. Hydrograph separation of discharge into event water and pre-storm components from (a) the tropical seasonal rain forest and (b) the artificial rubber plantation catchment, 8–9 September 2004.

instantaneous discharge at the first peak flow in the TRFC, whereas in the ARPC, it accounted for 62% (Fig. 3). At the second peak flow, the event water accounted for approximately 25 and 47% of the instantaneous discharge in the TRFC and in the ARPC, respectively. Notably, the proportion of event water in the ARPC decreased from this second peak point to a very small, undetectable component, 42 h into monitoring. For the entire 2 days of monitoring, the event water made up 25% of the total discharge at the TRFC, while at the ARPC, it made up 49%.

For the September storm, the event water made up approximately 31% of the instantaneous discharge at the first peak flow in the TRFC, whereas it accounted for 69% in the ARPC (Fig. 4). At the second peak flow, the event water accounted for approximately 20 and 46% of the instantaneous discharge in the TRFC and in the ARPC, respectively. As the recession proceeded, the prestorm water evidently began to contribute more substantial fractions of water to stream flow, although absolute discharge of groundwater was also receding. For the 2 days of monitoring, the event water made up 26% of the total discharge at the TRFC, while at the ARPC, it made up 58%.

Mean residence times at base flow

Mean residence times at base flow were computed for the hydrological year of 2004 in the two catchments using the well-mixed model (Maloszewski *et al*. 1983; Stewart & McDonnell 1991), as shown in Table 1. Preliminary analysis of this hydrological year suggests that the catchment base flow at TRFC has a mean residence time of 341 days (0.9 years), whereas ARPC has a residence time of 193 days (0.5 years). This implies that an increased coverage of forest in the TRFC, together with an increasing catchment size, allows effective mixing of input waters and sustains flows with relatively constant isotope signatures for prolonged periods.

Discussion

While discharge increased slowly during the April storm, it increased rapidly during the September storm at both catchments. This can be attributed to the dry and humid antecedent conditions of soils in the dry season and the rainy season, respectively (Liu *et al*. 2008). The slow increase of discharge during the April storm in both catchments may be attributable to the initially high recharge capability of the unsaturated soil, which indicates that there was considerable absorption of rain into the soil profiles. As drought conditions persisted for more than 5 months before the April storm, vadose zone water storage should be at a minimum, which can be seen in the rapid rate of the discharge recession, especially in the ARPC. During the dry season, when the discharge is minimal, a more geochemically evolved groundwater is discharged as base flow for both catchments. These very low flows may be sustained by groundwater discharge from a perennially saturated zone deep within the soil, as

Table 1 Mean $\delta^{18}O$ levels in rainfall and in stream base flow, and modelled amplitude of seasonal regression model and mean residence times at base flow (Maloszewski *et al*. 1983; Stewart & McDonnell 1991) in the tropical seasonal rain forest catchment (TRFC) and the artificial rubber plantation catchment (ARPC) for the hydrological year of 2004 in Xishuangbanna, southwest China

Water type	Mean (‰)	Amplitude (‰)	Mean residence time (days)	Adjusted R^2 for fit of sine function to data	*n*
Rainfall	− 7.9	3.15	–	0.81	43
TRFC stream	− 7.5	0.53	341	0.75	24
ARPC stream	− 6.9	0.91	193	0.77	24

pointed out by Rose (1996). Nonetheless, the volume of water stored in the vadose zone may have been significantly enough to cause a shift in the isotopic composition of discharge during the storm. This is consistent with the variation in the isotopic composition of discharge, which shows a dampening of the more variable $\delta^{18}O$ signal in rain water (Fig. 1c).

During the April storm, the discharge at the TRFC gradually reached a peak flow within 16 h after the beginning of the storm, in response to a peak delay of about 2.5 h compared with the peak of the storm, while the discharge of the ARPC responded quickly to the peak of the storm showing only a short peak delay of about 1.0 h. This result is not surprising, considering the universal presence of compacted terraced tracks in the ARPC, which resulted from the daily rubber latex collection processing. However, the discharge responses of the two catchments during the September storm were significantly different from those observed during the April storm because of the heavy rain spell and the humid antecedent conditions. Compared with the peak of the storm, the peak flow in the TRFC was delayed by about 2.2 h, while it show only a short peak delay of about 0.9 h in the ARPC. Additionally, the discharge at the ARPC decreased sharply within the following 12 h after the peak flow despite continued occasional light rain, whereas the discharge decreased slowly at the TRFC. These indicate that the discharge of the ARPC responded quickly to the high rainfall intensity despite the fact that the antecedent soil moisture content was quite different between the dry season and the rainy season (Liu *et al*. 2008). These findings strongly suggest that stream waters in the ARPC during the peak discharge were dominated by the event water, which has quickly reached the stream channels by using near-surface flow paths. This is also confirmed by the rapid change and greater variation of $\delta^{18}O$ signal in the stream water directly during the storm event in the ARPC (Figs 1c and 2c). Clearly, only surface flow can explain these rapid responses and the greater variation of isotopes in the stream water in the ARPC.

Around the time of peak event runoff at the TRFC on 8 September at 08:00 hours, the isotopic composition of the stream flow reached a minimum, depleted only by 0.7‰ compared with the prestorm stream flow (Fig. 2), evidently as a result of the presence of some the event water. The isotopic recession to base flow continued for at least 10 h, indicating gradually diminishing contributions of event water, and was extended by at least several hours relative to the discharge recession. This lag effect should be attributed to the isotopic modification of groundwater by event water, indicative of a system where surface and subsurface hydrology are strongly linked in the TRFC. The September monitoring occurred at a time of high recharge to the groundwater systems, and soil contained large volumes of water, as can be seen in the slow discharge recession (Fig. 2). This observation essentially suggests that when storm water is vertically recharged into the aquifer, the existing ground water is forced out of storage to discharge into the stream channels. As pointed out by Bonell *et al*. (1998), the soil hydraulic properties of primary/undisturbed forest surface horizons are strongly influenced by the occurrence of soil macropores from the proliferation of roots and related soil fauna activity (which are more prolific under dense forests), and subsurface storm flow should be the more preferred pathway. Our hydrograph separations reveal that the event water made up only a small proportion of the discharge at peak flow in the TRFC for both storms, whereas in the ARPC it made up the dominant component, consistent with the above analysis. Bonell *et al*. (1998) describe an analogous hydrological and isotopic response in high-rainfall response-dominated tropical forested catchments of New Zealand and Australia with sallow soil (<3 m) overlying a bedrock. At low-rainfall intensities, they observed that water generally is routed to stream flow via the soil groundwater system, which can be predominantly characterized as a first-in-first-out system, that is, stream flow is dominated by old water (prestorm water). Our data in the TRFC are consistent with this result. In many other investigations, the preferred pathways are reported to have caused rapid infiltration of water during a rain event (Genereux & Hooper 1998; Iqbal 1998; Elsenbeer 2001; Goller *et al*. 2005). Clearly, the TRFC is capable of absorbing nearly all rainfall to be later released as delayed flow (subsurface flow), and preventing the occurrence of overland flow. Peak event water contributions are also diminished by the delaying effect of storage resistance of the dense canopy (Brodersen *et al*. 2000; Soulsby *et al*. 2000), which may also limit direct precipitation to near-stream areas in the TRFC.

The rapidly increasing and decreasing discharge in the ARPC indicate that there must be substantial recharge through the rapid transmission of water through soil surface via overland flow. In the ARPC, the universal presence of compacted terraced tracks associated with land management can strongly influence the soil hydraulic properties and lead to greatly reduced soil infiltration capacity (Liu *et al*. 2000). Under these conditions, the reduced infiltration capacities may encourage infiltration-excess overland flow, which otherwise would not occur on the undisturbed forest floor (Sandstrom 1995; Bonell *et al*. 1998; Elsenbeer 2001; Goller *et al*. 2005). This is consistent with the empirical observation that during the storm, especially during the September storm, overland flow on the terraced tracks was observed around the time of the peak event runoff. It is apparent that there is a tendency for the relocation of the subsoil soil 'impeding' layer (Bonell *et al*. 1998) towards the surface, which encourages the greater occurrence of overland flow and a corresponding increase in the erosive potential. Thus, we estimate that a great part of the event water has resulted from a near-surface water flow within the ARPC, possibly as infiltration-excess overland flow and without mixing with other waters, and then contributed to the peak runoff. A study of Sandstrom (1995) also found that when concerning the degraded catchment, the corresponding storm hydrographs almost exclusively consisted of event water, irrespective of the storm magnitude. The reduction in opportunities for the discharge of old water from the degraded catchment, correspond with the loss of contributions from the subsurface stormflow pathways, which had manipulated previously the former soil macropore networks (Sandstrom 1995). Bonell *et al*. (1998) suggested that any form of disturbance seems to cause the surface soil fabric to collapse, thus inducing a depression storage of water. Consequently, the translation to the surface of an impeding layer from forest conversion could encourage a dramatic change in the preferred stormflow pathways, and lead to the frequent occurrence of infiltration-excess overland flow. Factors influential to this effect are the intensity of surface compaction, associated with land management, coupled with the effects of raindrop compaction (Bonell *et al*. 1998; Burns & McDonnell 1998; Genereux & Hooper 1998).

Hydrograph separations for the storm of April and September reveal that more event water in the TRFC than in the ARPC had resided. Isotopic data also indicate that there was no large rainwater pulse contributing to the discharge at peak flow in the TRFC. The lower event water proportion in the TRFC suggests that the TRFC is able to retain a large amount of event water during the storm, irrespective of the dry or wet antecedent conditions. This is consistent with the mean residence times at base flow for the TRFC and the ARPC (Table 1), and suggesting that the dense coverage in the TRFC, together with an increasing catchment size, allow effective mixing of input waters and sustain flows with relatively constant isotope signatures for prolonged periods. The larger catchment area at the TRFC can also increase the flow path length for subsurface water to reach the stream outlet, which can increase the opportunity for subsurface mixing and storage. In addition, slopes on the TRFC are less steep and soils are deeper than at the ARPC.

Clearly, any reduction in area of protective vegetation cover encourages greater exposure of the surface soil to raindrop impact and other anthropogenic effects, both of which induce compaction and consequently a greater occurrence of overland flow (Bonell *et al*. 1998). Although reforestation and soil conservation measures can reduce enhanced peak flows and storm flows associated with soil degradation, cumulative soil erosion during the postclearing phase may have reduced the soil water storage opportunities too much for remediation to have a net positive effect. Hence, we conclude that tropical rain forest conversion to rubber plantation in this area would markedly change the runoff generation processes and consequently the regional water balance.

Conclusions

(1) Isotopic hydrograph separations for the storm of April and September 2004 reveal that the event water made up only a small proportion of the discharge (29 and 31%, respectively) at peak flow in the TRFC, while it made up the dominant component at peak flow (62 and 69%, respectively) in the ARPC.
(2) The analyses suggest that in the ARPC, the universal presence of compacted terraced tracks associated with land management would encourage infiltration-excess overland flow.
(3) Mean catchment residence times at base flow for the TRFC and the ARPC are 0.9 and 0.5 years, respectively.
(4) This isotopic investigation demonstrates that tropical rain forest conversion to rubber plantation would markedly change the runoff generation processes in this area.

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References

Bent, G.C. (2001) Effects of Forest-Management Activities on Runoff Components and Ground-Water Recharge to Quabbin Reservoir, Central Massachusetts. *For. Ecol. Manage.*, **143**, 115–129.

Bonell, M., Barnes, C.J., Grant, C.R., Howard, A. and Burns, J. (1998) Oxygen and Hydrogen Isotopes in Rainfall – Runoff Studies. *In* Kendall, C. and McDonnell, J.J. (eds). *Isotope Tracers in Catchment Hydrology*, pp. 347–390. Elsevier, Amsterdam.

Bosch, A.D. and Hewlett, L. (1981) A Review of Catchment Experiments to Determine the Effect of Vegetation on Water Yield and Evapotranspiration. *J. Hydrol.*, **55**, 3–23.

Brodersen, C., Pohl, S., Lindenlaub, M., Leibungut, C. and Wilpert, K.V. (2000) Influence of Vegetation Structure on Isotope Content of Throughfall and Soil Water. *Hydrol. Process.*, **14**, 1439–1448.

Burns, D.A. and McDonnell, J.J. (1998) Effects of a Beaver Pond on Runoff Processes: Comparison of Two Headwater Catchments. *J. Hydrol.*, **205**, 248–264.

Buttle, J.M. (1994) Isotope Hydrograph Separations and Rapid-Delivery of Pre-Event Water from Drainage Basins. *Prog. Phys. Geogr.*, **18**, 16–41.

Cao, M., Zou, X.M., Warren, M. and Zhu, H. (2006) Tropical Forests of Xishuangbanna, China. *Biotropica*, **38**, 306–309.

Coplen, T.B. (1996) New Guidelines for Reporting Stable Hydrogen, Carbon and Oxygen Isotope-Ratio Data. *Geochim. Cosmochim. Acta*, **60**, 3359–3360.

DeWalle, D.R., Edwards, P.J., Swistock, B.R., Aravena, R. and Drimmie, R.J. (1997) Seasonal Isotope Hydrology of Three Appalachian Forest Catchments. *Hydrol. Process.*, **11**, 1895–1906.

Elsenbeer, H. (2001) Hydrologic Flowpaths in Tropical Rainforest Soilscapes – A Review. *Hydrol. Process.*, **15**, 1751–1759.

Fritz, P., Cherry, J.A., Weyer, K.U. and Sklash, M. (1976) Storm Run-Off Analysis Using Environmental Isotopes and Major Ions. *In* International Atomic Energy Agency (ed). *Interpretation of Environmental Isotope and Hydrochemical Data in Groundwater Hydrology*, pp. 111–131. International Atomic Energy Agency, Vienna.

Gat, J.R. and Airey, P.L. (2006) Stable Water Isotopes in the Atmosphere, Biosphere, Lithosphere Interface: Scaling-Up from the Local to Continental Scale, Under Humid and Dry Conditions. *Glob. Planet. Change*, **51**, 25–33.

Genereux, D.P. and Hooper, R.P. (1998) Oxygen and Hydrogen Isotopes in Rainfall–Runoff Studies. *In* Kendall, C. and McDonnell, J.J. (eds). *Isotope Tracers in Catchment Hydrology*, pp. 319–346. Elsevier, Amsterdam.

Gibson, J.J., Price, J.S., Aravena, R., Fitzgerald, D.F. and Maloney, D. (2000) Runoff Generation in a Hypermaritime Bog–Forest Upland. *Hydrol. Process.*, **14**, 2711–2730.

Goller, R., Wilcke, W., Leng, M.J., Tobschall, H.J., Wagner, K., Valarezo, C. and Zech, W. (2005) Tracing Water Paths through Small Catchments Under a Tropical Montane Rain Forest in South Ecuador by an Oxygen Isotope Approach. *J. Hydrol.*, **308**, 67–80.

Gremillion, P. and Wanielista, M. (2000) Effects of Evaporative Enrichment on the Stable Isotope Hydrology of a Central Florida (USA) River. *Hydrol. Process.*, **14**, 1465–1484.

Harris, D.M., McDonnell, J.J. and Rodhe, A. (1995) Hydrograph Separation Using Continuous Open System Isotope Mixing. *Water Resour. Res.*, **31**, 157–171.

Hewlett, J.D. (1982) *Principles of Forest Hydrology*. The University of Georgia Press, Georgia.

Hooper, R.P., Aulenbach, B.T., Burns, D.A., McDonnell, J.J., Freer, J., Kendall, C. and Beven, K. (1998) Riparian Control of Stream-Water Chemistry: Implications for Hydrochemical Basin Models. *Int. Assoc. Hydrol. Sci. Pub.*, **248**, 451–458.

Iqbal, M.Z. (1998) Application of Environmental Isotopes in Storm-Discharge Analysis of Two Contrasting Stream Channels in a Watershed. *Water Res.*, **32**, 2959–2968.

Joerin, C., Beven, K.J., Iorgulescu, I. and Musy, A. (2002) Uncertainty in Hydrograph Separations Based on Geochemical Mixing Models. *J. Hydrol.*, **255**, 90–106.

Kendall, C., Sklash, M.G. and Bullen, T.D. (1995) Isotope Tracers of Water and Solute Sources in Catchments. *In* Trudgill, S.T. (ed). *Solute Modelling in Catchment Systems*, pp. 261–303. Wiley, London.

Kennedy, V.C., Kendall, C., Zelleweger, G.W., Wyerman, T.A. and Avanzino, R.J. (1986) Determination of the Components of Stormflow Using Water Chemistry and Environmental Isotopes, Mattole River Basin, California. *J. Hydrol.*, **84**, 107–140.

Lakey, B. and Krothe, N.C. (1996) Stable Isotopic Variation of Storm Discharge from a Perennial Karst Spring, Indiana. *Water Resour. Res.*, **32**, 721–731.

Lanea, P.N.J. and Mackay, S.M. (2001) Streamflow Response of Mixed-Species Eucalypt Forests to Patch Cutting and Thinning Treatments. *For. Ecol. Manage.*, **143**, 131–142.

Li, H.M., Ma, Y.X., Aide, T.M. and Liu, W.J. (2008) Past, Present and Future Land-Use in Xishuangbanna, China and the Implications for Carbon Dynamics. **255**, 16–24.

Liu, W.J., Zhang, K.Y., Ma, Y.X., Liu, Y.H., Zhang, Y.P. and Li, H.M. (2000) Rainfall-Runoff Generation in a Rubber Plantation in Xishuangbanna, SW China. *For. Sci. Technol.*, **25**, 17–19.

Liu, W.J., Zhang, Y.P., Li, H.M. and Liu, Y.H. (2005) Fog Drip and its Relation to Groundwater in the Tropical Seasonal Rain Forest of Xishuangbanna, Southwest China: A Preliminary Study. *Water Res.*, **39**, 787–794.

Liu, W.J., Liu, W.Y., Li, P.J., Gao, L., Shen, Y.X., Wang, P.Y., Zhang, Y.P. and Li, H.M. (2007) Using Stable Isotopes to Determine Sources of Fog Drip in a Tropical Seasonal Rain Forest of Xishuangbanna, SW China. *Agric. For. Meteorol.*, **143**, 80–91.

Liu, W.J., Liu, W.Y., Li, J.T., Wu, Z.W. and Li, H.M. (2008) Isotope Variations of Throughfall, Stemflow and Soil Water in a Tropical Rain Forest and a Rubber Plantation in Xishuangbanna, SW China. *Hydrol. Res.*, **39**, 437–449.
Maloszewski, P. and Zuber, A. (1993) Principles and Practice of Calibration and Validation of Mathematical Models for the Interpretation of Environmental Tracer Data in Aquifers. *Adv. Water Resour.*, **16**, 173–190.
Maloszewski, P., Rauert, W., Stichler, W. and Herrmann, A. (1983) Application of Flow Models in Alpine Catchment Area Using Tritium and Deuterium Data. *J. Hydrol.*, **66**, 319–330.
McDonnell, J.J., Bonell, M., Stewart, M.K. and Pearce, A.J. (1990) Deuterium Variations in Storm Rainfall: Implications for Stream Hydrograph Separation. *Water Resour. Res.*, **26**, 455–458.
Renshaw, C.E., Feng, X.H., Sinclair, K.J. and Dums, R.H. (2003) The Use of Stream Flow Routing for Direct Channel Precipitation with Isotopically-Based Hydrograph Separations: The Role of New Water in Stormflow Generation. *J. Hydrol.*, **273**, 205–216.
Rose, S. (1996) Temporal Environmental Isotopic Variation within the Falling Creek (Georgia) Watershed: Implications for Contributions to Streamflow. *J. Hydrol.*, **174**, 243–261.
Sandstrom, K. (1995) *Forests and water-friends or foes? Hydrological implications of deforestation and land degradation in semiarid Tanzania*. PhD Thesis, Linkoping Studies in Arts and Science 120, Linkoping University, Linkoping, Sweden.
Schellekens, J., Scatena, F.N., Bruijnzeel, L.A., van Diji, A.I.J.M., Groen, M.M.A. and Van Hogezand, R.J.P. (2004) Stormflow Generation in a Small Rainforest Catchment in the Luquillo Experimental Forest, Puerto Rico. *Hydrol. Process.*, **18**, 505–530.
Sklash, M.G., Stewart, M.K. and Pearce, A.J. (1986) Storm Runoff Generation in Humid Headwater Catchments, 2. A Case Study of Hillslope and Low-Order Stream Response. *Water Resour. Res.*, **22**, 1273–1282.
Soulsby, C., Malcolm, R., Helliwell, R., Ferrier, R.C. and Jenkins, A. (2000) 'Isotope Hydrology of the Allt a' Mharcaidh Catchment, Cairngorms, Scotland: Implications for Hydrological Pathways and Residence Times. *Hydrol. Process.*, **14**, 747–762.
Stewart, M.K. and McDonnell, D.R. (1991) Modeling Base Flow Soil Water Residence Times from Deuterium Concentrations. *Water Resour. Res.*, **27**, 2681–2693.
Unnikrishna, P.V., McDonnell, J.J. and Stewart, M.L. (1995) Soil Water Isotope Residence Times Modelling. *In* Trudgill, S.T. (ed). *Solute Modelling in Catchment System*, pp. 237–260. John Wiley and Sons Ltd., Chichester.
Wang, X., Zhang, Y.P. and Liu, W.J. (2006) Modeling Canopy Rainfall Interception of a Tropical Seasonal Rain Forest of Xishuangbanna, Southwest China. *Acta Ecol. Sin.*, **26**, 722–729.

Amendments

Corrections were introduced to the paper on 30 March 2010 after its first publication online in Wiley InterScience on 10 December 2009.

Please find below the list of changes made:

Page 3, section Oxygen-18 analysis: the manufacturer detail of Finnigan MAT-252 'Thermo Electron Corporation, Waltham, MA, USA' has been changed to 'Bremen Germany'.

Page 3, section April storm: values have been changed from 0.021, 0.007, 0.233 to 0.007, 0.001, 0.078 respectively.

Page 4, Figure 1 has been corrected.

Page 4, section April storm: values have been changed from 0.137, 0.170, −4.95, −3.94, −6.52, −5.83 to 0.045, 0.057, −5.95, −4.94, −7.42, −6.73 respectively.

Page 4, section September storm: values have been changed from 0.051, 0.373 to 0.033, 0.236 respectively.

Page 5, Figure 2 has been corrected.

Page 5, section September storm: values have been changed from 0.311, 0.133, −7.51, −6.74, −7.62, −7.20 to 0.132, 0.056, −7.91, −7.10, −8.02, −7.59 respectively.

Page 5, section Hydrograph separation: values have been changed from −6.52, −5.83, −7.51, −6.74 to −7.42, −6.73, −7.91, −7.10 respectively.

Page 6, Figure 3 and 4 have been corrected.