Supplement of

The hydrological regime of a forested tropical Andean valley

K. E. Clark et al.

Correspondence to: K. E. Clark (kathryn.clark23@gmail.com)

S1. Materials and methods

S1.1. Catchment wide rainfall estimates

The calibration of the TRMM data and calculation of catchment wide rainfall for the Kosñipata Valley used the following series of steps: (1) For individual met stations, monthly rainfall (mm month^{-1}) was compared to the TRMM data (mm month^{-1}) and a linear regression was determined (Table S7). (2) These regression equations were used to estimate a calibrated monthly rainfall (mm month^{-1}) for the 9 meteorological stations for each TRMM month from 1998 to 2012 ($n = 180$). The mean annual estimated rainfall (mm yr^{-1}), from adding these monthly values over each year, ranged from 1600 to 5260 mm yr^{-1} for the various met stations (Table S2). The mean monthly estimated rainfall for the study period calculated by this method coincided well with the measured met station rainfall (Fig. 2a). (3) For each TRMM month ($n = 180$) another linear regression was determined between the elevation of each met station and the estimated rainfall for the respective station (from step 2). (4) The elevation distribution and its proportion within each river catchment at 1 masl intervals were determined in ArcGIS at a $90 \text{ m} \times 90 \text{ m}$ pixel resolution using Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM), using the catchment boundaries in Figure 1a. (5) For each month, the linear regression equation developed in step 3 was applied to the elevation distributions in order to estimate rainfall by month (mm month^{-1}), yielding valley-averaged monthly rainfall estimates over the duration of the TRMM record (Fig. 4). (6) For our study period the monthly data were summed to yield seasonal and annual estimated rainfall. The estimated catchment wide monthly rainfall data from the TRMM study period (1998 to 2012) was summed to yield annual results (mm yr^{-1} ; Table S4).

S1.2. Discharge and runoff measures

S1.2.1. Kosñipata River at the San Pedro gauging station

In the Kosñipata River at the San Pedro gauging station ($13^{\circ}3'37''\text{S}$, $71^{\circ}32'40''\text{W}$; 1360 masl), river velocity was measured using handheld velocity meters and, during portions of the year when it was too dangerous to enter the river, using a float method with 5 replicates (Baud et al., 2005; McMahon, 1957). Metered stream velocity was measured with a Flow Probe (Global Water FP101); this probe records average and maximum stream velocity across the full cross-section of the river. We corrected all float-measured velocities based on the regression of mean velocity and max velocity measurements. As a check on our measurements, we compared our corrected maximum velocity with a theoretical hydrodynamic velocity, adopting the Jarrett (1984) modification of Manning's Equation for mountain rivers. The slope (S) of the Kosñipata channel at San Pedro is 0.04, determined independently by two methods: 1) from Quickbird orthorectified imagery and GPS waypoints of two different points along the river, and 2) from a LiDAR-based digital elevation model from the Carnegie Airborne Observatory (CAO) (Asner, 2014). The hydraulic radius was measured in the field, over the dry season and ranged from $R = 0.40 \text{ m}$ to 0.49 m ($n = 8$). The difference between the empirical velocity measurements and those determined from theory using these S and R values ranged from -9.7% to 13.1%, with a mean difference of 0.65% (n

= 7). Given the range of assumptions in both the theoretical and empirical values, we view this similarity as encouraging validation of our methods.

Discharge was calculated by multiplying corrected velocity times the river cross-sectional area, determined by measuring in-stream river profiles and out-of-stream bank area at low flow several times over the span of the study. Discharge and river stage height were used to construct a power-law stage-discharge rating curve for the Kosñipata River at the San Pedro gauging station ($n = 13$; $r^2 = 0.93$, $P = < 0.0001$):

$$Discharge \left(\frac{m^3}{s} \right) = 34.9952 \pm 2.3189 \times Stage\ ht\ (m)^{1.0448 \pm 0.1146} \quad (S1)$$

The Kosñipata River measured at the San Pedro gauging station had an almost continuous river height record for the study year, from a pressure transducer (Global Water W16 level logger) recording river height every 15 minutes. The instantaneous discharge associated with each height measurement was calculated using Eq (S1). During the gap in logger between mid-July and early-August, three manual river height measures were taken and linear interpolation was conducted on daily mean discharge to fill-in the gap. Monthly instantaneous discharge ($m^3\ s^{-1}$) was determined from the total monthly flow, and seasonal discharges ($m^3\ s^{-1}$) and annual discharge ($m^3\ s^{-1}$) were determined from the monthly instantaneous discharges by summing over the appropriate time periods.

Baseflow was determined for the Kosñipata River at the San Pedro gauging station using the method outlined in Gustard et al. (1992): (1) The 5-day minimum mean daily discharge was determined for non-overlapping 5 day blocks over the study period. (2) The 5-day minima were multiplied by 0.9, and if this value was less than either the preceding or subsequent 5-day minimum, it was assigned to be part of the baseflow. (3) Mean daily discharge values were linearly interpolated in between the selected 5-day minimum discharge values selected in step two. (4) If the linearly interpolated daily baseflow discharge value was less than the actual mean daily discharge value, the actual value was replaced by the interpolated value for that day. Base flow index (BFI) was calculated as the ratio of the total volume of baseflow divided by the total volume of streamflow.

S1.2.2. Kosñipata River at the Wayqecha gauging station

Stream velocities at Wayqecha gauging station ($13^{\circ}9'46''S$, $71^{\circ}35'21''W$; 2250 masl) were measured using an MJP Student Stream Flow Meter as close as possible to the middle of the channel, at 75% of the total vertical depth down from the water surface, or by float method when necessary. The shallow depth and broad width of the Kosñipata at Wayqecha meant that these methods yielded indistinguishable results, and float velocities were not corrected at this site.

At the Wayqecha station, field discharge measurements were taken weekly to monthly over the one year study period ($n = 44$), plus a two week intensive wet season study period from the end of January to mid-February 2010 ($n = 15$; Fig. 3). Four river profiles were used over the course of the study year because of the changing channel morphology, with unique

power-law stage-discharge rating curves (cf. Eq. S1) used for each of the 4 river profiles. Instantaneous discharge ($\text{m}^3 \text{s}^{-1}$) measurements were used to determine mean monthly discharge. The annual discharge was calculated as the mean of the monthly discharge rates (there were no measurements in September, so the monthly value was extrapolated linearly based on August and October). There are significant uncertainties associated with the discharge and runoff of the Kosñipata River measured at the Wayqecha gauging station, since the data comes from only 59 spot measurements throughout the year. Given the large uncertainties, the discharge data from Wayqecha is not used in the analysis in the main text but is provided at the end of this Supplement for reference.

S1.3. Actual evapotranspiration estimates

Evapotranspiration (ET) was calculated as the sum of soil evaporation (LE_s), canopy transpiration (LE_c), and evaporation of canopy intercepted water (LE_i) using the Priestley and Taylor - Jet Propulsion Laboratory (PT- JPL) model (Fisher et al., 2008). The five most important parameters for calculating ET via this method are: net radiation (R_n), normalised difference vegetation index (NDVI), soil adjusted vegetation index (SAVI), maximum air temperature ($T_{\max}$), and water vapour pressure (ea). NDVI was used to predict SAVI and minimum relative humidity ($RH_{\min}$) and $T_{\max}$ were used to predict water vapour pressure. The PT-JPL model (Fisher et al., 2008) was applied to all meteorological stations with $RH_{\min}$, $T_{\max}$, and R_n data. R_n was estimated from solar radiation (R_s) or photosynthetically active radiation (PAR) data (Table S2). PAR was divided by 2.1 to estimate solar radiation (R_s) which is largely a conversion from μmol to PAR ($\text{m}^{-2} \text{s}^{-1}$) to total radiation R_s (W m^{-2}) (Monteith and Unsworth, 2013). R_n was estimated by multiplying R_s by 0.75, a typical fraction for tropical forests (Fisher et al., 2010; Malhi et al., 2002). AET metrological station results (Table S2) were in agreement with estimates of AET for other montane cloud forests (Bruijnzeel et al., 2011). The model was applied at the catchment level, on a monthly basis for the study period. To extrapolate to the catchment scale, a linear regression was run between met station $RH_{\min}$ or $T_{\max}$ and elevation. Values for the wet season and the dry season were determined for each catchment based on mean catchment elevation and the linear regression equations. The valley wide input values for the Kosñipata Valley at San Pedro were: $T_{\max_wet} = 15.8^\circ\text{C}$, $RH_{\min_wet} = 0.790$, and $T_{\max_dry} = 15.9^\circ\text{C}$, $RH_{\min_dry} = 0.679$. Solar radiation (R_s) measurements from meteorological stations were found to be comparable to R_s measurements from the GL model v1.2 which models mean daily solar radiation averaged per month (INPE, 2012). The solar radiation estimated by the GL model was converted to net radiation (R_n). For the mean catchment elevation for Kosñipata Valley at the San Pedro gauging station (2790 masl; Table 1), a valley-wide NDVI of 0.85 was determined using an elevation-based linear regression for NDVI (Asner et al., 2014). Carnegie Airborne Observatory (CAO) AToMS includes a visible-to-shortwave Infrared (VSWIR) imaging spectrometer (Asner et al., 2012) with collection including near infrared (NIR at 800 nm) and visible (VIS at 680 nm) wavelengths that were used to generate a high resolution NDVI along the altitudinal gradient in the Kosñipata Valley (Asner et al., 2014).

119

120 **S1.4. Water isotope measurements**

121 Rainfall samples collected in 2010 and 2011 were collected in a rinsed plastic
 122 container left out in an open area near the San Pedro River gauging station and Wayqecha
 123 River gauging station during river water sample collection. Additional rainfall samples were
 124 taken February 2011 from elevations of 2050, 2130, 2300 and 2400 masl. Samples were
 125 transferred into 15 mL glass exetainers with rubber septa after filtration and stored
 126 refrigerated and unpreserved. Rain water samples from 2009 (Horwath, 2011) consisted of
 127 fresh precipitation as well as rainwater pools on leaves and were collected at elevations of
 128 1500, 2000, 2500, 3000, and 3600 masl over the course of ~1 week in April 2009, in July
 129 2009, and in September 2009 (Table S3a).

130 Cloud water vapour samples are from Horwath (2011) and were collected below the
 131 tree canopy using a ‘double action hand pump’ (Galert) to draw ambient air into a cryogenic
 132 trap (liquid N₂) continuously over the course of 15-20 minutes. Cloud vapour samples were
 133 collected at the same elevations and during the same time periods as the rainwater with the
 134 exception that there were no cloud water vapour samples collected during April 2009.

135 River water samples were collected from the river surface with a clean polypropylene
 136 graduated cylinder, filtered onsite with a 0.2 µm nylon filter, and stored unpreserved in a 60
 137 mL HDPE bottles. To test the suitability of storing the samples in HDPE bottles, a subset of
 138 the samples were also collected into 15 mL glass exetainers with rubber septa after filtration
 139 and stored unpreserved. Upon returning the laboratory, all of the samples were stored at 3°C
 140 until analysis. Comparisons between the two different collection methods (i.e. HDPE bottles
 141 vs. glass exetainers) did not reveal any systematic differences and agreed within the
 142 analytical uncertainties.

143 Isotopic analyses of water samples were performed with a Picarro L1102-i cavity ring
 144 down spectrometer (CRDS) at the University of Southern California or at the University of
 145 Cambridge. Values are reported in delta notation relative to the VSMOW standard where:

$$146 \quad \delta D = \left(\left(\frac{D/H_{sample}}{D/H_{VSMOW}} \right) - 1 \right) * 1000 \quad (S3)$$

147 and

$$148 \quad \delta^{18}O = \left(\left(\frac{{}^{18}O/{}^{16}O_{sample}}{{}^{18}O/{}^{16}O_{VSMOW}} \right) - 1 \right) * 1000 \quad (S4)$$

149 Both the average value and the standard deviation of the replicate injections are reported in
 150 Tables S3, S5 & S8. Isotopic analyses of river water samples collected in glass exetainers
 151 were performed with either a Los-Gatos DLT-100 Liquid Water Isotope Analyzer at the
 152 California Institute of Technology or a Delta V Advantage IRMS equipped with a Gasbench
 153 II system at the University of Oxford. These analyses were used to check the accuracy of the
 154 Picarro CRDS results.

S1.5. Water isotope mixing model

Only the samples collected in the Kosñipata River at the San Pedro gauging samples were used in the mixing calculations, because there is a noticeable isotopic offset between the samples from the San Pedro gauging station and the Wayqecha gauging station (Tables S5 & S6). The isotopic offset is most likely the result of the different sampling elevations, but it is not possible to separate quantitatively the effect of elevation on the isotopic composition of rainfall with the currently available data.

We used an isotope mixing model on Kosñipata River samples from the San Pedro gauging station to distinguish contributions to river runoff from wet season rainfall, dry season rainfall, and cloud water. In order to use the water isotope data to make quantitative estimates of the water sources to river flow, three end-member isotopic mixing was simulated with the mixing equations:

$$\delta D_{river} = f_1 (\delta D_1) + f_2 (\delta D_2) + f_3 (\delta D_3) \quad (S5)$$

$$Dxs_{river} = f_1 (Dxs_1) + f_2 (Dxs_2) + f_3 (Dxs_3) \quad (S6)$$

and

$$1 = f_1 + f_2 + f_3 \quad (S7)$$

where

$$Dxs_{river} = \delta D_{river} - (\delta^{18}O_{river} \times 8) \quad (S8)$$

To calculate the mixing proportions (i.e. f_1 , f_2 , and f_3), the matrix inversion function of MATLAB 2013a was used. Due to the observed variability in the three end-members (Fig. 5 in main text), which is known to significantly influence the results of end-member mixing calculations (Phillips and Gregg, 2001), 10,000 random end-member δD and Dxs values were generated using the observed ranges for each end-member. For each sample, the mixing proportions were determined for all of the 10,000 end member combinations, but only a fraction of the combinations (18-72%) yielded plausible results (i.e. mixing proportions between 0 and 1). The mean, 5th percentile, 50th percentile, and 95th percentile of all possible ($0 \leq \Sigma f \leq 1$) mixing proportions are presented in Table S6. The effect of the analytical uncertainty on the individual rainwater samples on the calculated mixing proportions was considered by generating 1000 pseudo-random synthetic data for each sample and determining the mixing portions for each of the 10,000 end member combinations (i.e. 10^7 simulations per sample). For each sample, the pseudo-random values were generated from a normal distribution with the measured sample mean and standard deviation. To assess whether or not 10^7 simulations per sample yielded re-producible results given the large number of possible end-member and sample composition combinations, replicate model

calculations using different randomly generated datasets for the same input parameters were performed. These replicate calculations yielded between 0.1 and 5% variation in the statistical parameters (i.e. mean, median, and 5th and 95th percentiles) of the distribution of fractional contributions for each end-member.

End-member compositions were defined based on observed precipitation data for selected time intervals. The wet season rainfall end-member was determined based on the average and standard deviation of the December 2010, March 2010, January 2011, February 2011, and March 2011 rainwater data (Fig. 5). For dry season precipitation, the average and standard deviation of the September 2009, July 2009, June 2010, and June 2011 rainwater data was used. The cloud water vapour was defined by the average and standard deviation of the July and September 2009 cloud water data, which was the only available data (Table S3b).

S2. Results

S2.1. Isotopic analyses

Rainwater δD and $\delta^{18}O$ values display considerable seasonal variation whereas variation with elevation during a given season is less pronounced (Table S3a; Fig. S1). Rainwater δD and $\delta^{18}O$ values are enriched during the dry season. Kosñipata rainwaters defined the local meteoric water line (LMWL, the relationship between δD and $\delta^{18}O$ in precipitation; Fig. S1) defined by $\delta D = 8.6561 \times \delta^{18}O + 21.119$, close to the global meteoric water line (GMWL) of $\delta D = 8.20 \times \delta^{18}O + 11.27$ (Rozanski et al., 1993; Craig, 1961). Dxs, which is the deviation from the GMWL, shows minimal seasonal variation in the Kosñipata rainfall samples (Fig. 5).

The Kosñipata cloud water vapour has similar δD and $\delta^{18}O$ to rainwater (Fig. S1) probably because of the orographic mechanism of cloud formation at this site (Scholl et al., 2011). Kosñipata cloud water has slightly depleted $\delta^{18}O$ and slightly enriched δD (i.e. higher Dxs, by $> +20$ ‰) compared to the LMWL. The deviation of cloud water from the LMWL is probably due to local water recycling (Horwath, 2011; Froehlich et al., 2002). The higher and more variable Dxs of the cloud water vapour samples separates this cloud source from the rainfall samples and is the main isotopic characteristic that allows them to be differentiated in the mixing model (Fig. S1; Table S3b). Dxs has been used as a tool to evaluate water recycling in other tropical montane cloud forests (Scholl et al., 2007; Rhodes et al., 2006) and tropical forests such as the Amazon (Martinelli et al., 1996; Salati et al., 1979), and to evaluate the sources of fog (Liu et al., 2007), but as far as we are aware, this is its first use as a fingerprint of cloud inputs to streamflow.

Streamwater samples fall along the LMWL, suggesting that evaporation most likely is not a major determinant of stream water isotopic composition (Fig. S1). This is consistent with similar Cl concentrations in rainwater (2 – 20 μM) and streamflow (2 – 12 μM) (Torres et al., 2014). Stream water isotopes in the Kosñipata River are consistent with other samples measured from the Amazon and Andes (Lambs et al., 2012; Lambs et al., 2007), i.e. they are similar to values previously measured from high Andean sites that are relatively depleted

compared to the lowland Amazon due to Rayleigh distillation during orographic rain-out (Gat, 1996).

S2.2. Results from the Wayqecha gauging station

S2.2.1. Catchment wide rainfall

The Kosñipata sub-basin of Wayqecha had a lower catchment wide rainfall than the larger catchment at San Pedro (Table S4). This was apparent in the distribution of rainfall throughout the valley (Fig. 2d) and reflects variation in annual rainfall as a function of elevation (Table S2). Seasonal differences suggest that the wet season is slightly more dominant in the Wayqecha sub-basin (+4% compared to the same period in the larger basin measured at the San Pedro gauging station) and that the dry season rainfall is slightly more dominant in the larger basin measured at the San Pedro gauging station (+3% compared to the same period in the Wayqecha sub-basin; Tables 2 & S9).

S2.2.2. Discharge and runoff measured in the Kosñipata River at the Wayqecha gauging station

The Wayqecha sub-basin in the Kosñipata Valley, with a mean elevation 3195 masl and a catchment area of 48.5 km², was estimated to have a mean annual discharge of 4.7 m³ s⁻¹ with an annual runoff of 3065 mm yr⁻¹ (8.4 mm d⁻¹; Table S9). The catchment had a seasonal range in monthly mean values of 2.3 to 8.8 m³ s⁻¹ (4.1 to 14.1 mm d⁻¹). There are significant uncertainties in these annual totals for the Wayqecha station as they are based on only 59 spot measurements of discharge. The seasonal variation in flow was greater in amplitude at the Wayqecha gauge (Table S9) than compared to that of the San Pedro river gauge (Table 2). This suggests that the discharge and runoff in the Kosñipata Valley sub-basin of Wayqecha follows a similar pattern to the larger Kosñipata Valley measured at San Pedro, but may be subjected to more short-term variation.

S2.2.3. Water isotopes at Wayqecha station

At the Kosñipata River gauging station at Wayqecha, δD and $\delta^{18}O$ values were more depleted than at the Kosñipata River gauging station at San Pedro as a result of altitude effects on water isotope ratios (cf. Lambs et al. (2012)). At the Wayqecha gauging station, values for δD , $\delta^{18}O$, and D_{xs} ranged from -107.0 to -88.9 ‰, -15.9 to -13.5 ‰, and 18.3 to 20.5 ‰ (Table S8). Relative to samples collected in the Kosñipata River at the San Pedro gauging station, seasonality in the Kosñipata River at the Wayqecha gauging station was less pronounced.

References for supplementary information

- ACCA: Weather data San Pedro station, Asociación para la conservación de la cuenca Amazónica <http://atrium.andesamazon.org/index.php>, (last access: April 2012), 2012.
- Asner, G. P., Knapp, D. E., Boardman, J., Green, R. O., Kennedy-Bowdoin, T., Eastwood, M., Martin, R. E., Anderson, C., and Field, C. B.: Carnegie Airborne Observatory-2: Increasing science data dimensionality via high-fidelity multi-sensor fusion, *Remote Sens. Environ.*, 124, 454-465, <http://dx.doi.org/10.1016/j.rse.2012.06.012>, 2012.
- Asner, G. P.: unpublished data, 2014.
- Asner, G. P., Anderson, C. B., Martin, R. E., Knapp, D. E., Tupayachi, R., Sinca, F., and Malhi, Y.: Landscape-scale changes in forest structure and functional traits along an Andes-to-Amazon elevation gradient, *Biogeosciences*, 11, 843-856, <http://dx.doi.org/10.5194/bg-11-843-2014>, 2014.
- Baud, O., Hager, W. H., and Minor, H. E.: Toward nonintrusive flood discharge measurement, *J. Hydraul. Eng.*, 131, 1031-1035, [http://dx.doi.org/10.1061/\(ASCE\)0733-9429\(2005\)131:12\(1031\)](http://dx.doi.org/10.1061/(ASCE)0733-9429(2005)131:12(1031)), 2005.
- Bruijnzeel, L. A., Mulligan, M., and Scatena, F. N.: Hydrometeorology of tropical montane cloud forests: emerging patterns, *Hydrol. Process.*, 25, 465-498, <http://dx.doi.org/10.1002/hyp.7974>, 2011.
- Craig, H.: Standard for Reporting Concentrations of Deuterium and Oxygen-18 in Natural Waters, *Science*, 133, 1833-1834, <http://dx.doi.org/10.1126/science.133.3467.1833>, 1961.
- Fisher, J. B., Tu, K. P., and Baldocchi, D. D.: Global estimates of the land-atmosphere water flux based on monthly AVHRR and ISLSCP-II data, validated at 16 FLUXNET sites, *Remote Sens. Environ.*, 112, 901-919, <http://dx.doi.org/10.1016/j.rse.2007.06.025>, 2008.
- Fisher, J. B., Whittaker, R. J., and Malhi, Y.: ET come home: potential evapotranspiration in geographical ecology, *Global Ecol. Biogeogr.*, 20, 1-18, <http://dx.doi.org/10.1111/j.1466-8238.2010.00578.x>, 2010.
- Froehlich, K., Gibson, J. J., and Aggarwal, P.: Deuterium excess in precipitation and its climatological significance, *Proceeding of Study of Environmental Change Using Isotope Techniques*, Vienna, Austria, 23-27 April 2001, IAEA-CSP-13/P, 54-66, 2002.
- Gat, J. R.: Oxygen and hydrogen isotopes in the hydrologic cycle, *Annu. Rev. Earth Pl. Sc.*, 24, 225-262, 1996.
- Girardin, C. A. J., Silva-Espejo, J. E., Doughty, C. E., Huaraca Huasco, W., Metcalfe, D. B., Durand-Baca, L., Marthews, T. R., Aragao, L. E. O. C., Farfan Rios, W., García Cabrera, K., Halladay, K., Fisher, J. B., Galiano-Cabrera, D. F., Huaraca-Quispe, L. P., Alzamora-Taype, I., Equiluz-Mora, L., Salinas-Revilla, N., Silman, M., Meir, P., and Malhi, Y.: Productivity and carbon allocation in a tropical montane cloud forest of the Peruvian Andes, *Plant Ecology and Diversity*, 7, 107-123, <http://dx.doi.org/10.1080/17550874.2013.820222>, 2014.
- Gustard, A., Bullock, A., and Dixon, J.: Low flow estimation in the United Kingdom, Low flow estimation in the United Kingdom, Institute of Hydrology, Wallingford, UKpp., 1992.
- Horwath, A.: Epiphytic bryophytes as cloud forest indicators: Stable isotopes, biomass and diversity along an altitudinal gradient in Peru, Doctor of Philosophy, Plant Sciences, University of Cambridge, Cambridge, 260 pp., 2011.
- Huaraca Huasco, W., Girardin, C. A. J., Doughty, C. E., Metcalfe, D. B., Baca, L. D., Silva-Espejo, J. E., Cabrera, D. G., Aragão, L. E. O., Davila, A. R., Marthews, T. R., Huaraca-Quispe, L. P., Alzamora-Taype, I., Equiluz-Mora, L., Farfan-Rios, W., Cabrera, K. G., Halladay, K., Salinas-Revilla, N., Silman, M., Meir, P., and Malhi, Y.: Seasonal production, allocation and cycling of carbon in two mid-elevation tropical montane forest plots in the Peruvian Andes, *Plant Ecology and Diversity*, 7, 125-142, <http://dx.doi.org/10.1080/17550874.2013.819042>, 2014.

INPE: Radiacion solar y terrestre, Division de satellite y sistemas ambientales: Ministerio de ciencia y tecnologia Instituto nacional de investigacion espacial, http://satelite.cptec.inpe.br/radiacao/?i=es#/radiacao_new.jsp, (last access: 11 May 2012), 2012.

Jarrett, R. D.: Hydraulics of high-gradient streams, *J. Hydraul. Eng.*, 110, 1519-1539, 1984.

Lambs, L., Muller, E., and Fromard, F.: The Guianese paradox: How can the freshwater outflow from the Amazon increase the salinity of the Guianan shore?, *J. Hydrol.*, 342, 88-96, <http://dx.doi.org/10.1016/j.jhydrol.2007.05.022>, 2007.

Lambs, L., Horwath, A., Otto, T., Julien, F., and Antoine, P. O.: Isotopic values of the Amazon headwaters in Peru: comparison of the wet upper Río Madre de Dios watershed with the dry Urubamba-Apurimac river system, *Rapid Commun. Mass Sp.*, 26, 775-784, <http://dx.doi.org/10.1002/rcm.6157>, 2012.

Liu, W. J., Liu, W. Y., Li, P. J., Gao, L., Shen, Y. X., Wang, P. Y., Zhang, Y. P., and Li, H. M.: Using stable isotopes to determine sources of fog drip in a tropical seasonal rain forest of Xishuangbanna, SW China, *Agr. Forest Meteorol.*, 143, 80-91, <http://dx.doi.org/10.1016/j.agrformet.2006.11.009>, 2007.

Malhi, Y., Pegoraro, E., Nobre, A. D., Pereira, M. G. P., Grace, J., Culf, A. D., and Clement, R.: Energy and water dynamics of a central Amazonian rain forest, *J. Geophys. Res.*, 107, 8061, <http://dx.doi.org/10.1029/2001JD000623>, 2002.

Martinelli, L. A., Victoria, R. L., Sternberg, L. S. L., Ribeiro, A., and Moreira, M. Z.: Using stable isotopes to determine sources of evaporated water to the atmosphere in the Amazon basin, *J Hydrol.*, 183, 191-204, [http://dx.doi.org/10.1016/0022-1694\(95\)02974-5](http://dx.doi.org/10.1016/0022-1694(95)02974-5), 1996.

McMahon, J. P.: DDT-treatment of rivers for eradication of Simuliidae, B. World Health Organ., National Center for Biotechnology Information, Bethesda MD, USA, 541 pp., 1957.

Monteith, J. L., and Unsworth, M. H.: Principles of environmental physics: Plants, animals, and the atmosphere, Academic Press, Oxford, UK, 357 pp., 2013.

Phillips, D. L., and Gregg, J. W.: Uncertainty in source partitioning using stable isotopes, *Oecologia*, 127, 171-179, <http://dx.doi.org/10.1007/s004420000578>, 2001.

Rapp, J. M., and Silman, M. R.: Diurnal, seasonal, and altitudinal trends in microclimate across a tropical montane cloud forest, *Clim. Res.*, 55, 17-32, <http://dx.doi.org/10.3354/cr01127>, 2012.

Rhodes, A. L., Guswa, A. J., and Newell, S. E.: Seasonal variation in the stable isotopic composition of precipitation in the tropical montane forests of Monteverde, Costa Rica, *Water Resour. Res.*, 42, W11402, <http://dx.doi.org/10.1029/2005WR004535>, 2006.

Rozanski, K., Araguás-Araguás, L., and Gonfiantini, R.: Isotopic Patterns in Modern Global Precipitation, in: Climate Change in Continental Isotopic Records, edited by: Swart, P. K., Lohman, K. C., McKenzie, J., and Savin, S., American Geophysical Union, Washington, DC, 1-36, 1993.

Salati, E., Dall'Olio, A., Matsui, E., and Gat, J. R.: Recycling of water in the Amazon basin: an isotopic study, *Water Resour. Res.*, 15, 1250-1258, <http://dx.doi.org/10.1029/WR015i005p01250>, 1979.

Scholl, M., Eugster, W., and Burkard, R.: Understanding the role of fog in forest hydrology: stable isotopes as tools for determining input and partitioning of cloud water in montane forests, *Hydrol. Process.*, 25, 353-366, <http://dx.doi.org/10.1002/hyp.7762>, 2011.

Scholl, M. A., Giambelluca, T. W., Gingerich, S. B., Nullet, M. A., and Loope, L. L.: Cloud water in windward and leeward mountain forests: The stable isotope signature of orographic cloud water, *Water Resour. Res.*, 43, W12411, <http://dx.doi.org/10.1029/2007WR006011>, 2007.

SENAMHI: Clima: Datos históricos Peru, http://www.senamhi.gob.pe/main_mapa.php?t=dHi, (last access: 5 May 2012), 2012.

Torres, M. A., Clark, K. E., and West, A. J.: Variation in the hydrologic influence on chemical weathering across a mountain-to-floodplain transition in the Peruvian Amazon, in preparation, 2014.

Supplementary tables

TABLE S1: Catchment-wide mean monthly estimated rainfall (mm month⁻¹) 1998 to 2012 showing seasonality.

Kosñipata Valley measured at:	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
San Pedro	389±43	401±64	406±41	213±20	132±14	127±13	132±14	126±12	152±15	203±23	219±23	309±39
Wayqecha	330±40	342±57	346±38	167±18	92±13	89±12	92±13	87±11	111±14	158±22	173±22	256±36
Months	15	15	15	15	15	15	15	15	15	15	15	15
Season*	wet	wet	wet	wet-dry	dry	dry	dry	dry	dry	dry-wet	dry-wet	wet

*Rainfall patterns indicate that the wet season runs from December to March (green), the wet-dry transition season runs throughout April (blue), the dry season runs from May until September (yellow), and the dry-wet transition season runs through October and November (red). Error bars are 2 × standard error.

TABLE S2: Station descriptions for meteorological data from the Kosñipata Valley.

# in Fig. 1a	Met station	Gauge type	Elevation (masl)	Lat/long coordinates (S, W)	Land cover type	Landscape description	Aspect	Slope (°)	<i>n</i>	<i>T</i> _{max} (°C)	<i>RH</i> _{min} (%)	<i>R</i> _n (W m ⁻²)	Met station annual rainfall (mm yr ⁻¹)	TRMM calibrated rainfall [§] (1998 to 2012) (mm yr ⁻¹)	Estimated AET
1	Acjanaco	manual	3460	13°11'45.674", 71°37'14.818"	Puna grassland	rolling mountain top	140	8.6	79	12.1	65.0 [^]	N/A	1908 ^a	1800	N/A
2	TU 3450	Smart Sensors/HOBO	3450	13°6'48.749", 71°36'27.306"	Transition & Scrub-land	rolling mountain top/peak of a mountain ridge	356	26.7	16	11.9	72.3	92*	2148 ^b	2516	744
3	Wayqecha	Campbell Scientific	2900	13°11'18.434", 71°35'9.667"	UMCF	mountain slope just below tree line, far from ridge	122	32.8	45	16.2	70.0	84 [#]	1752 ^c	1600	732
4	TU 2750	Smart Sensors/HOBO	2750	13°6'18.537", 71°35'22.26"	UMCF	mountain ridge	319	28	19	16.0	75.7	87*	2940 ^b	3154	780
5	Rocotal	manual	2090	13°6'47.575", 71°34'14.673"	UMCF/LMCF	mountain slope near road	70.5	32.9	97	20.6	76.4 [^]	N/A	4140 ^a	4152	N/A
6	TU 1800	Smart Sensors/HOBO	1850	13°4'11.331", 71°33'30.215"	LMCF	Mid –mountain slope	321	30.6	18	20.3	72.4	100*	4116 ^b	3998	948
7	San Pedro [‡]	Vantage Pro 2 Plus, Davis Instruments	1450	13°3'21.219", 71°32'48.841"	LMRF	mountain slope near the river	183	13.6	13	23.7	77.0	98 [#]	5436 ^d	4831	984
	San Pedro [‡]	Skye Instruments	1360	13°3'20.191", 71°32'38.305"	LMRF	mountain slope near the river	183	4							
8	SP 1500	Smart Sensors/HOBO	1500	13°2'57.577", 71°32'11.579"	LMRF	mountain slope	170	29.5	13	22.0	74.9	95*	4956 ^b	5191	936
9	Chonta-chaca	manual	887	13°1'26.091", 71°28'4.887"	LTRF	low mountains near road and river	-1	2.1	80	27.3	83.6 [^]	N/A	5316 ^a	5260	N/A

^v Stations 2, 3, 4, 6, 7 and 8 are run by the ABERG consortium.

^a data from (SENAMHI, 2012)

^b data from (Rapp and Silman, 2012)

^c data from (Girardin et al., 2014)

^d data from (Huaraca Huasco et al., 2014; ACCA, 2012)

[‡] Data for the two San Pedro met stations were merged since they were located close to one another and totalled only 13 months of data.

[§] TRMM calibrated rainfall (mm yr^{-1}) from 1998 to 2012 ($n = 180$ months) was determined for each met station as described in the text.

UMCF = Upper montane cloud forest, LMCF = Lower montane cloud forest, LMRF = Lower montane rain forest, LTRF = Lower tropical rainforest.

Aspect and slope were determined by using SRTM DEM at 90 m x 90 m resolution.

n = available months of meteorological station data.

T_{max} = mean max daily temperature averaged monthly

RH_{min} = mean daily minimum relative humidity averaged monthly, $\wedge$ estimated RH_{min} using dry and wet bulb temperatures assuming atmospheric pressure was 1013 hPa, and R_n = mean daily net radiation averaged monthly.

* Photosynthetic active radiation (PAR) ($\mu\text{mol PAR m}^{-2} \text{s}^{-1}$) was converted to estimate R_n by first dividing it by 2.1 to convert it to solar radiation (R_s) (W m^{-2}) (Monteith and Unsworth, 2013) and then converted to R_n .

[#] Solar radiation was converted to estimate net radiation (R_n) by multiplying R_s by 0.75 (Fisher et al., 2010; Malhi et al., 2002) Actual evapotranspiration (AET) estimated using met station data in the PT-JPL model developed by Fisher et al. (2008).

369

370

TABLE S3a: Water isotope data for rainfall collected in the Kosñipata Valley

Season	Date (dd-mmm-yy)	Elevation (m)	$\delta^{18}\text{O}$ (‰)	$\sigma \delta^{18}\text{O}$ (‰)	δD (‰)	$\sigma \delta\text{D}$ (‰)	Dxs (‰)	σDxs (‰)
Dry season	13-Jun-11	1360	-4.63	0.10	-18.89	0.57	18.18	0.98
Wet season	19-Dec-10	1360	-2.46	0.14	-17.70	0.98	1.95	1.46
Wet season	22-Mar-11	1360	-12.44	0.16	-92.29	0.45	7.22	1.36
Wet season	27-Dec-10	1360	-15.22	0.24	-111.36	0.45	10.40	1.98
Wet season	24-Jan-11	1360	-16.49	0.06	-129.76	0.74	2.16	0.87
Wet season	21-Feb-11	1360	-18.58	0.08	-138.96	0.41	9.66	0.75
Dry season	06-Jul-09	1500	-7.19	0.08	-40.73	0.50	16.82	0.81
Dry season	06-Jul-09	1500	-7.18	0.08	-40.69	0.50	16.71	0.81
Dry season	06-Jul-09	1500	-7.16	0.08	-40.73	0.50	16.52	0.81
Dry season	07-Jul-09	1500	-7.39	0.08	-41.90	0.50	17.25	0.81
Dry season	07-Jul-09	1500	-7.41	0.08	-42.00	0.50	17.30	0.81
Dry season	07-Jul-09	1500	-7.57	0.08	-42.96	0.50	17.58	0.81
Dry season	14-Sep-09	1500	-2.55	0.08	1.81	0.50	22.19	0.81
Dry season	14-Sep-09	1500	-2.08	0.08	4.46	0.50	21.08	0.81
Dry season	14-Sep-09	1500	-1.93	0.08	7.70	0.50	23.13	0.81
Dry season	15-Sep-09	1500	-1.56	0.08	3.72	0.50	16.19	0.81
Dry season	16-Sep-09	1500	-2.70	0.08	0.21	0.50	21.84	0.81
Dry season	16-Sep-09	1500	-0.94	0.08	9.36	0.50	16.85	0.81
Dry season	05-Jul-09	2000	-6.62	0.08	-35.67	0.50	17.26	0.81
Dry season	05-Jul-09	2000	-6.57	0.08	-35.59	0.50	16.95	0.81
Dry season	05-Jul-09	2000	-6.58	0.08	-35.49	0.50	17.17	0.81
Dry season	12-Sep-09	2000	-1.61	0.08	6.26	0.50	19.17	0.81
Dry season	12-Sep-09	2000	-3.10	0.08	-2.88	0.50	21.89	0.81
Dry season	12-Sep-09	2000	-1.75	0.08	6.11	0.50	20.08	0.81
Dry season	12-Sep-09	2000	-1.59	0.08	6.70	0.50	19.42	0.81
Wet season	20-Feb-11	2040	-22.81	0.29	-168.28	1.34	14.18	2.65
Wet season	20-Feb-11	2050	-22.50	0.14	-170.76	0.87	9.25	1.39
Wet season	20-Feb-11	2130	-14.71	0.16	-105.35	0.77	12.35	1.51
Dry season	28-Jun-10	2290	-3.88	0.06	-16.21	0.91	14.86	1.03
Dry season	28-Jun-10	2290	-6.73	0.20	-36.95	0.82	16.86	1.80
Wet season	22-Mar-10	2290	-8.32	0.27	-56.74	0.52	9.80	2.19
Wet season	19-Feb-11	2290	-10.40	0.07	-72.11	0.33	11.08	0.64
Wet season	27-Dec-10	2290	-17.72	0.08	-136.09	0.60	5.70	0.89
Wet season	19-Feb-11	2300	-14.52	0.09	-100.38	0.70	15.77	0.99
Wet season	19-Feb-11	2400	-12.46	0.17	-87.71	0.32	11.93	1.37
Dry season	03-Jul-07	2500	-5.69	0.08	-28.75	0.50	16.76	0.81
Dry season	03-Jul-07	2500	-5.50	0.08	-27.76	0.50	16.24	0.81
Dry season	03-Jul-07	2500	-5.82	0.08	-29.33	0.50	17.22	0.81
Dry season	03-Jul-07	2500	-7.97	0.08	-45.49	0.50	18.25	0.81

Dry season	03-Jul-07	2500	-7.96	0.08	-45.77	0.50	17.90	0.81
Dry season	03-Jul-07	2500	-7.95	0.08	-46.08	0.50	17.51	0.81
Dry season	08-Sep-09	2500	-0.85	0.08	14.33	0.50	21.16	0.81
Dry season	08-Sep-09	2500	-0.89	0.08	14.32	0.50	21.48	0.81
Dry season	08-Sep-09	2500	-0.75	0.08	15.40	0.50	21.41	0.81
Dry season	08-Sep-09	2500	-0.85	0.08	14.12	0.50	20.93	0.81
Dry season	08-Sep-09	2500	-0.78	0.08	14.90	0.50	21.17	0.81
Dry season	08-Sep-09	2500	-0.96	0.08	14.23	0.50	21.93	0.81
Dry season	10-Sep-09	2500	-2.19	0.08	3.70	0.50	21.18	0.81
Dry season	10-Sep-09	2500	-4.25	0.08	-12.50	0.50	21.47	0.81
Dry season	10-Sep-09	2500	-3.89	0.08	-10.05	0.50	21.08	0.81
Dry season	10-Sep-09	2500	-2.32	0.08	2.95	0.50	21.47	0.81
Dry season	10-Sep-09	2500	-4.45	0.08	-14.42	0.50	21.19	0.81
Dry season	10-Sep-09	2500	-3.78	0.08	-9.74	0.50	20.54	0.81
Dry season	01-Jul-09	3000	-7.00	0.08	-41.47	0.50	14.51	0.81
Dry season	01-Jul-09	3000	-6.92	0.08	-40.57	0.50	14.83	0.81
Dry season	01-Jul-09	3000	-6.83	0.08	-40.99	0.50	13.66	0.81
Dry season	01-Jul-09	3000	-7.15	0.08	-42.20	0.50	15.03	0.81
Dry season	01-Jul-09	3000	-7.11	0.08	-41.47	0.50	15.42	0.81
Dry season	01-Jul-09	3000	-7.38	0.08	-44.05	0.50	14.97	0.81
Dry season	09-Sep-09	3000	-1.76	0.08	8.20	0.50	22.24	0.81
Dry season	09-Sep-09	3000	-1.68	0.08	9.05	0.50	22.47	0.81
Dry season	09-Sep-09	3000	-2.17	0.08	5.89	0.50	23.21	0.81
Dry season	09-Sep-09	3000	-2.15	0.08	6.22	0.50	23.43	0.81
Dry season	09-Sep-09	3000	-1.29	0.08	9.82	0.50	20.10	0.81

372

TABLE S3b: Water isotope data for cloud water collected in the Kosñipata Valley

	Date	Elevation	$\delta^{18}\text{O}$	$\sigma \delta^{18}\text{O}^*$	δD	$\sigma \delta\text{D}^*$	Dxs	σDxs^*
	(dd-mmm-yy)	(m)	(‰)	(‰)	(‰)	(‰)	(‰)	(‰)
Cloud water	14-Sep-09	1500	-1.40	0.08	15.34	0.50	26.57	0.81
Cloud water	14-Sep-09	1500	-0.47	0.08	19.81	0.50	23.60	0.81
Cloud water	14-Sep-09	1500	-1.48	0.08	14.71	0.50	26.56	0.81
Cloud water	14-Sep-09	1500	-1.86	0.08	14.35	0.50	29.21	0.81
Cloud water	14-Sep-09	1500	-5.09	0.08	-0.04	0.50	40.65	0.81
Cloud water	14-Sep-09	1500	-2.71	0.08	11.87	0.50	33.51	0.81
Cloud water	12-Sep-09	2000	-3.81	0.08	-1.71	0.50	28.76	0.81
Cloud water	12-Sep-09	2000	-2.40	0.08	3.30	0.50	22.48	0.81
Cloud water	12-Sep-09	2000	-7.32	0.08	-18.41	0.50	40.15	0.81
Cloud water	12-Sep-09	2000	-5.77	0.08	-11.47	0.50	34.69	0.81
Cloud water	12-Sep-09	2000	-6.09	0.08	-12.16	0.50	36.53	0.81
Cloud water	03-Jul-07	2500	-8.29	0.08	-41.50	0.50	24.80	0.81
Cloud water	03-Jul-07	2500	-16.04	0.08	-68.33	0.50	60.00	0.81
Cloud water	03-Jul-07	2500	-16.94	0.08	-68.80	0.50	66.75	0.81

Cloud water	03-Jul-07	2500	-12.28	0.08	-42.91	0.50	55.36	0.81
Cloud water	03-Jul-07	2500	-11.65	0.08	-52.50	0.50	40.68	0.81
Cloud water	03-Jul-07	2500	-13.10	0.08	-64.09	0.50	40.74	0.81
Cloud water	10-Sep-09	2500	-4.99	0.08	-9.89	0.50	30.04	0.81
Cloud water	10-Sep-09	2500	-3.31	0.08	-3.67	0.50	22.83	0.81
Cloud water	10-Sep-09	2500	-3.99	0.08	-10.70	0.50	21.21	0.81
Cloud water	10-Sep-09	2500	-7.55	0.08	-23.47	0.50	36.93	0.81
Cloud water	10-Sep-09	2500	-5.36	0.08	-7.96	0.50	34.92	0.81
Cloud water	10-Sep-09	2500	-7.14	0.08	-16.74	0.50	40.40	0.81
Cloud water	01-Jul-09	3000	-12.38	0.08	-66.54	0.50	32.50	0.81
Cloud water	01-Jul-09	3000	-18.29	0.08	-85.17	0.50	61.14	0.81
Cloud water	01-Jul-09	3000	-16.31	0.08	-101.23	0.50	29.27	0.81
Cloud water	01-Jul-09	3000	-18.31	0.08	-86.05	0.50	60.40	0.81
Cloud water	01-Jul-09	3000	-12.46	0.08	-56.25	0.50	43.45	0.81
Cloud water	01-Jul-09	3000	-16.89	0.08	-75.90	0.50	59.19	0.81
Cloud water	09-Sep-09	3000	-6.02	0.08	-10.35	0.50	37.85	0.81
Cloud water	09-Sep-09	3000	-6.00	0.08	-11.65	0.50	36.33	0.81
Cloud water	09-Sep-09	3000	-9.00	0.08	-29.96	0.50	42.03	0.81
Cloud water	09-Sep-09	3000	-8.23	0.08	-32.36	0.50	33.50	0.81
Cloud water	09-Sep-09	3000	-6.13	0.08	-21.52	0.50	27.54	0.81
Cloud water	09-Sep-09	3000	-5.34	0.08	-19.10	0.50	23.64	0.81
Cloud water	30-Jun-09	3600	-9.89	0.08	-48.36	0.50	30.76	0.81
Cloud water	30-Jun-09	3600	-11.76	0.08	-54.14	0.50	39.94	0.81
Cloud water	30-Jun-09	3600	-13.24	0.08	-62.96	0.50	42.99	0.81
Cloud water	30-Jun-09	3600	-13.53	0.08	-62.00	0.50	46.21	0.81
Cloud water	30-Jun-09	3600	-14.47	0.08	-68.30	0.50	47.43	0.81
Cloud water	30-Jun-09	3600	-14.04	0.08	-64.77	0.50	47.57	0.81
Cloud water	07-Sep-09	3600	-3.49	0.08	8.30	0.50	36.23	0.81
Cloud water	07-Sep-09	3600	-4.96	0.08	6.66	0.50	46.34	0.81
Cloud water	07-Sep-09	3600	-8.70	0.08	-12.75	0.50	56.83	0.81
Cloud water	07-Sep-09	3600	-4.16	0.08	13.84	0.50	47.08	0.81
Cloud water	07-Sep-09	3600	-8.99	0.08	-14.35	0.50	57.57	0.81
Cloud water	07-Sep-09	3600	-11.45	0.08	-61.24	0.50	30.34	0.81

* Characteristic analytical uncertainties reported by Horwath (2011).

TABLE S4: Catchment-wide annual rainfall estimates (mm yr⁻¹)

Rank	Year	Kosñipata Valley – San Pedro	Kosñipata Valley – Wayqecha sub-basin
1	2001	3185	2589
2	2010	3161	2567
3	2011	3139	2547
4	2002	3078	2490
5	2003	2908	2332
6	2009	2865	2294
7	2006	2776	2210
8	2012	2764	2199
9	2008	2748	2184
10	1999	2705	2145
11	2007	2684	2126
12	1998	2590	2033
13	2000	2585	2033
14	2004	2580	2029
15	2005	2399	1861
Mean	1998-2012	2811 ± 124	2243 ± 115
Error bars are 2 x standard error on annual values.			

374

375

376

TABLE S5: Water isotope data of stream water collected from the Kosñipata River at the San Pedro gauging station

Date and hour (dd-mmm-yy hr) [#]	$\delta^{18}\text{O}$ (‰)	$\sigma \delta^{18}\text{O}$ (‰)	δD (‰)	$\sigma \delta\text{D}$ (‰)	Dxs	σ Dxs
01-Nov-09	-11.62	0.14	-77.33	0.65	15.64	1.32
07-Nov-09	-10.75	0.15	-67.95	0.42	18.03	1.29
15-Nov-09	-11.47	0.14	-74.89	0.32	16.89	1.20
30-Nov-09	-12.10	0.14	-80.46	0.25	16.34	1.16
30-Jan-10 00	-13.44	0.15	-91.94	0.19	15.61	1.20
04-Feb-10 03	-12.39	0.14	-84.13	0.21	14.96	1.15
04-Feb-10 09	-12.56	0.14	-85.54	0.19	14.97	1.15
04-Feb-10 15	-12.21	0.14	-83.56	0.11	14.10	1.14
04-Feb-10 21	-12.38	0.14	-84.32	0.03	14.72	1.13
05-Feb-10 09	-12.57	0.14	-85.21	0.29	15.35	1.17
05-Feb-10 15	-12.45	0.14	-84.67	0.42	14.90	1.21
05-Feb-10 21	-12.35	0.14	-84.08	0.28	14.75	1.17
06-Feb-10 09	-12.47	0.14	-85.04	0.29	14.72	1.17
06-Feb-10 15	-12.48	0.14	-85.09	0.31	14.75	1.18
07-Feb-10	-12.55	0.14	-86.01	0.16	14.41	1.15
07-Feb-10 03	-12.44	0.14	-84.94	0.48	14.56	1.23
07-Feb-10 09	-12.58	0.14	-84.71	0.51	15.91	1.25
07-Feb-10 15	-12.55	0.14	-84.50	0.33	15.90	1.18
07-Feb-10 21	-12.52	0.14	-85.04	0.28	15.12	1.17
08-Feb-10 03	-12.44	0.14	-85.22	0.29	14.29	1.17
08-Feb-10 09	-12.59	0.14	-84.27	0.07	16.48	1.14
08-Feb-10 15	-12.63	0.14	-84.58	0.09	16.47	1.14
08-Feb-10 21	-12.60	0.14	-84.10	0.39	16.71	1.20
09-Feb-10 03	-12.60	0.14	-85.03	0.22	15.79	1.16
09-Feb-10 09	-12.69	0.14	-85.19	0.25	16.33	1.17
09-Feb-10 15	-12.69	0.14	-85.71	0.13	15.80	1.15
10-Feb-10 03	-12.68	0.14	-85.25	0.43	16.22	1.22
11-Feb-10 09	-12.63	0.14	-85.00	0.46	16.08	1.23
11-Feb-10 21	-11.80	0.14	-78.70	0.11	15.72	1.15
12-Feb-10 05	-11.93	0.14	-81.34	0.39	14.12	1.20
12-Feb-10 09	-12.18	0.14	-82.38	0.22	15.10	1.15
12-Feb-10 14	-12.17	0.14	-81.88	0.54	15.46	1.26
22-Feb-10	-12.53	0.14	-85.18	0.68	15.03	1.32
22-Mar-10	-12.51	0.14	-85.15	0.83	14.90	1.41
29-Mar-10	-12.53	0.14	-85.63	0.07	14.64	1.14
05-Apr-10	-12.09	0.14	-80.72	0.53	16.03	1.25
25-Apr-10	-12.46	0.14	-83.80	0.50	15.85	1.24
16-May-10	-12.38	0.14	-83.30	0.24	15.72	1.16
26-May-10	-12.14	0.14	-81.43	1.18	15.65	1.64
31-May-10	-11.39	0.15	-74.59	0.30	16.56	1.20
14-Jun-10	-12.20	0.14	-81.47	0.13	16.10	1.14
12-Jul-10	-11.27	0.15	-74.51	0.31	15.63	1.21
19-Jul-10	-11.89	0.14	-79.62	0.45	15.53	1.22

Cont. next page...

TABLE S5, cont.: Water isotope data of stream water collected from the Kosñipata River at San Pedro gauging station

Date and hour (dd-mmm-yy hr)	$\delta^{18}\text{O}$ (‰)	$\sigma \delta^{18}\text{O}$ (‰)	δD (‰)	$\sigma \delta\text{D}$ (‰)	Dxs	σDxs
11-Aug-10	-11.68	0.14	-77.67	0.37	15.76	1.20
18-Aug-10	-11.64	0.17	-79.54	0.98	13.55	1.67
23-Aug-10	-11.88	0.14	-80.02	1.31	15.04	1.74
02-Sep-10	-10.37	0.16	-64.99	1.61	18.01	2.04
04-Sep-10	-11.05	0.15	-70.85	1.49	17.55	1.90
13-Sep-10	-11.36	0.23	-76.20	1.06	14.70	2.15
15-Oct-10	-8.94	0.09	-58.85	0.17	12.64	0.71
15-Nov-10	-10.72	0.21	-71.86	0.68	13.90	1.83
19-Nov-10	-10.64	0.24	-68.22	0.57	16.94	1.97
22-Nov-10	-10.63	0.46	-64.93	0.47	20.09	3.74
06-Dec-10	-11.38	0.15	-74.37	0.46	16.68	1.25
13-Dec-10	-12.26	0.18	-76.37	0.31	21.68	1.45
20-Dec-10	-11.49	0.18	-76.90	0.60	15.03	1.57
27-Dec-10	-12.54	0.11	-86.25	0.28	14.05	0.90
03-Jan-11	-11.90	0.14	-80.14	0.36	15.05	1.19
24-Jan-11	-11.63	0.19	-79.70	0.70	13.38	1.69
08-Mar-11	-13.79	0.15	-94.88	0.23	15.43	1.24
05-May-11	-13.04	0.14	-88.81	0.74	15.49	1.37
18-Jul-11	-12.09	0.18	-80.61	0.75	16.08	1.66

Mean isotope values and σ (standard deviation) were from 3 replicate sample injections (see description of methods in Supplementary Text)

hour not reported when only one sample collected on a given date

377

378

TABLE S6: Results of Monte Carlo analysis of mixing fractions for water isotope samples from the Kosñipata River at the San Pedro gauging station

Date and hour (dd-mmm-yy hr) [#]	Wet Rain				Dry Rain				Cloud Water				# of real simulations
	Mean	5%	50%	95%	Mean	5%	50%	95%	Mean	5%	50%	95%	
01-Nov-09	0.56	0.39	0.54	0.77	0.29	0.04	0.30	0.54	0.15	0.020	0.14	0.33	6.27E+06
07-Nov-09	0.49	0.34	0.48	0.66	0.20	0.02	0.19	0.41	0.31	0.151	0.30	0.52	4.70E+06
15-Nov-09	0.67	0.50	0.66	0.86	0.24	0.03	0.24	0.45	0.10	0.008	0.09	0.24	4.05E+06
30-Nov-09	0.60	0.42	0.59	0.83	0.28	0.03	0.28	0.52	0.12	0.011	0.10	0.28	4.98E+06
30-Jan-10 00	0.62	0.45	0.61	0.83	0.27	0.03	0.27	0.50	0.12	0.011	0.10	0.27	5.00E+06
04-Feb-10 03	0.66	0.52	0.65	0.83	0.21	0.02	0.21	0.40	0.13	0.017	0.12	0.29	4.34E+06
04-Feb-10 09	0.65	0.46	0.64	0.87	0.25	0.03	0.25	0.49	0.09	0.007	0.08	0.24	3.48E+06
04-Feb-10 15	0.65	0.48	0.64	0.86	0.25	0.03	0.25	0.47	0.10	0.008	0.09	0.24	4.12E+06
04-Feb-10 21	0.64	0.48	0.63	0.85	0.25	0.03	0.25	0.46	0.11	0.010	0.10	0.26	4.57E+06
05-Feb-10 09	0.64	0.47	0.63	0.84	0.25	0.03	0.25	0.47	0.12	0.011	0.10	0.27	4.74E+06
05-Feb-10 15	0.64	0.48	0.63	0.84	0.24	0.03	0.24	0.45	0.12	0.012	0.10	0.27	4.65E+06
05-Feb-10 21	0.64	0.48	0.63	0.84	0.24	0.03	0.25	0.46	0.12	0.011	0.10	0.27	4.64E+06
06-Feb-10 09	0.64	0.47	0.63	0.84	0.25	0.03	0.25	0.47	0.11	0.011	0.10	0.26	4.60E+06
06-Feb-10 15	0.63	0.48	0.62	0.83	0.24	0.03	0.24	0.46	0.12	0.014	0.11	0.28	4.87E+06
07-Feb-10	0.65	0.48	0.63	0.85	0.24	0.03	0.24	0.46	0.11	0.011	0.10	0.26	4.54E+06
07-Feb-10 03	0.65	0.48	0.63	0.85	0.24	0.03	0.24	0.46	0.11	0.011	0.10	0.26	4.52E+06
07-Feb-10 09	0.62	0.47	0.61	0.81	0.24	0.03	0.25	0.46	0.14	0.017	0.12	0.30	5.13E+06
07-Feb-10 15	0.64	0.48	0.63	0.84	0.24	0.03	0.25	0.46	0.12	0.012	0.11	0.28	4.76E+06
07-Feb-10 21	0.65	0.48	0.64	0.85	0.24	0.03	0.24	0.46	0.11	0.010	0.10	0.26	4.40E+06
08-Feb-10 03	0.62	0.47	0.61	0.82	0.24	0.03	0.24	0.46	0.14	0.017	0.13	0.30	5.09E+06
08-Feb-10 09	0.66	0.49	0.65	0.86	0.24	0.03	0.24	0.45	0.11	0.010	0.09	0.25	4.27E+06
08-Feb-10 15	0.61	0.46	0.60	0.80	0.24	0.03	0.24	0.45	0.15	0.023	0.14	0.32	5.25E+06
08-Feb-10 21	0.60	0.46	0.59	0.79	0.24	0.03	0.24	0.46	0.16	0.025	0.15	0.33	5.29E+06
09-Feb-10 03	0.66	0.49	0.64	0.86	0.24	0.03	0.24	0.46	0.10	0.009	0.09	0.25	4.21E+06
09-Feb-10 09	0.61	0.46	0.60	0.80	0.24	0.03	0.24	0.46	0.15	0.023	0.14	0.32	5.28E+06

09-Feb-10 15	0.62	0.47	0.61	0.82	0.24	0.03	0.24	0.46	0.13	0.017	0.12	0.30	5.06E+06
10-Feb-10 03	0.62	0.47	0.60	0.80	0.24	0.03	0.24	0.45	0.15	0.022	0.14	0.32	5.16E+06
11-Feb-10 09	0.63	0.47	0.61	0.82	0.24	0.03	0.24	0.45	0.13	0.017	0.12	0.30	5.01E+06
11-Feb-10 21	0.62	0.47	0.61	0.81	0.24	0.03	0.24	0.45	0.15	0.020	0.13	0.31	5.12E+06
12-Feb-10 05	0.60	0.43	0.58	0.81	0.27	0.03	0.28	0.51	0.13	0.014	0.11	0.29	5.53E+06
12-Feb-10 09	0.62	0.47	0.61	0.81	0.24	0.03	0.24	0.45	0.14	0.019	0.13	0.31	5.11E+06
12-Feb-10 14	0.62	0.45	0.60	0.82	0.26	0.03	0.26	0.48	0.13	0.013	0.11	0.29	5.12E+06
22-Feb-10	0.64	0.46	0.64	0.86	0.26	0.03	0.26	0.48	0.10	0.008	0.09	0.25	4.19E+06
22-Mar-10	0.63	0.46	0.61	0.83	0.26	0.03	0.26	0.48	0.12	0.012	0.10	0.27	4.92E+06
29-Mar-10	0.64	0.48	0.63	0.84	0.24	0.03	0.24	0.46	0.12	0.012	0.11	0.28	4.64E+06
05-Apr-10	0.67	0.54	0.66	0.85	0.19	0.02	0.19	0.38	0.13	0.016	0.12	0.29	4.01E+06
25-Apr-10	0.64	0.48	0.63	0.84	0.24	0.03	0.24	0.46	0.12	0.012	0.10	0.27	4.55E+06
16-May-10	0.65	0.49	0.64	0.85	0.24	0.03	0.24	0.45	0.11	0.010	0.10	0.26	4.45E+06
26-May-10	0.60	0.44	0.59	0.80	0.26	0.03	0.27	0.49	0.14	0.017	0.12	0.31	5.47E+06
31-May-10	0.62	0.46	0.61	0.81	0.25	0.03	0.25	0.46	0.14	0.016	0.12	0.30	5.15E+06
14-Jun-10	0.65	0.50	0.63	0.83	0.22	0.03	0.22	0.43	0.13	0.015	0.12	0.29	4.54E+06
12-Jul-10	0.62	0.46	0.61	0.82	0.25	0.03	0.25	0.47	0.13	0.015	0.12	0.30	5.18E+06
19-Jul-10	0.61	0.44	0.60	0.82	0.26	0.03	0.26	0.48	0.13	0.014	0.12	0.31	5.08E+06
11-Aug-10	0.56	0.39	0.55	0.78	0.29	0.04	0.30	0.53	0.15	0.019	0.13	0.33	6.23E+06
18-Aug-10	0.60	0.44	0.59	0.80	0.26	0.03	0.26	0.48	0.14	0.018	0.13	0.31	5.47E+06
23-Aug-10	0.58	0.40	0.57	0.81	0.29	0.04	0.30	0.54	0.12	0.013	0.11	0.29	5.71E+06
02-Sep-10	0.61	0.44	0.59	0.82	0.27	0.03	0.27	0.50	0.13	0.013	0.11	0.29	5.33E+06
04-Sep-10	0.60	0.43	0.59	0.80	0.26	0.03	0.26	0.49	0.14	0.017	0.13	0.32	5.30E+06
13-Sep-10	0.59	0.42	0.58	0.81	0.28	0.03	0.28	0.51	0.13	0.014	0.11	0.30	5.60E+06
15-Oct-10	0.62	0.44	0.60	0.83	0.26	0.03	0.27	0.49	0.12	0.012	0.11	0.29	4.78E+06
15-Nov-10	0.65	0.46	0.64	0.86	0.26	0.03	0.26	0.49	0.10	0.007	0.08	0.24	3.63E+06
19-Nov-10	0.49	0.30	0.47	0.72	0.33	0.05	0.34	0.60	0.18	0.026	0.17	0.40	7.14E+06
22-Nov-10	0.53	0.35	0.51	0.75	0.30	0.04	0.30	0.55	0.18	0.025	0.16	0.38	6.52E+06
06-Dec-10	0.60	0.41	0.59	0.83	0.28	0.03	0.28	0.52	0.12	0.010	0.10	0.30	4.55E+06
13-Dec-10	0.64	0.42	0.65	0.83	0.29	0.06	0.28	0.56	0.07	0.004	0.06	0.19	1.88E+06

20-Dec-10	0.59	0.42	0.58	0.81	0.28	0.03	0.28	0.52	0.13	0.013	0.11	0.30	5.50E+06
27-Dec-10	0.50	0.33	0.48	0.72	0.32	0.04	0.33	0.58	0.18	0.033	0.17	0.38	7.23E+06
03-Jan-11	0.56	0.39	0.54	0.77	0.29	0.04	0.29	0.53	0.16	0.023	0.14	0.34	6.31E+06
24-Jan-11	0.59	0.43	0.58	0.79	0.26	0.03	0.27	0.49	0.14	0.020	0.13	0.32	5.63E+06
08-Mar-11	0.52	0.34	0.51	0.76	0.32	0.04	0.33	0.58	0.16	0.019	0.14	0.36	6.49E+06
05-May-11	0.46	0.27	0.44	0.70	0.29	0.03	0.29	0.57	0.25	0.037	0.23	0.52	6.43E+06
18-Jul-11	0.61	0.40	0.60	0.84	0.29	0.04	0.29	0.54	0.10	0.008	0.08	0.26	3.97E+06

[#] hour not reported when only one sample collected on a given date

380

381

382

TABLE S7: TRMM-met station rainfall regressions used to estimate rainfall

Station number (Figure 1a)	Met station name	Rainfall estimate (mm month ⁻¹)	r^2
1	Acjanaco	$0.8395 \times \text{TRMM} + 35.315$	0.73
2	3450 TU	$1.1091 \times \text{TRMM} + 58.255$	0.89
3	Wayqecha	$0.6606 \times \text{TRMM} + 43.022$	0.67
4	2750 TU	$1.239 \times \text{TRMM} + 93.704$	0.84
5	Rocotal	$1.264 \times \text{TRMM} + 173.4$	0.31
6	1800 TU	$1.1793 \times \text{TRMM} + 172.08$	0.79
7	San Pedro	$1.354 \times \text{TRMM} + 217.35$	0.73
8	1500 TU	$1.6807 \times \text{TRMM} + 203.07$	0.83
9	Chontachaca	$1.183 \times \text{TRMM} + 276.69$	0.63

383

384

TABLE S8: Water isotope data of stream water collected from the Kosñipata River at the Wayqecha gauging station

Date and hour (dd-mmm-yy hr) [#]	$\delta^{18}\text{O}$ (‰)	$\sigma \delta^{18}\text{O}$ (‰)	δD (‰)	$\sigma \delta\text{D}$ (‰)	Dxs	σ Dxs
29-Jan-10 09	-13.93	0.16	-98.40	0.74	13.03	1.46
29-Jan-10 15	-14.02	0.16	-98.93	0.22	13.24	1.28
30-Jan-10 03	-14.33	0.16	-101.49	0.29	13.13	1.30
30-Jan-10 09	-14.17	0.16	-100.22	0.54	13.11	1.37
30-Jan-10 15	-14.21	0.16	-99.83	0.27	13.81	1.29
31-Jan-10 03	-14.08	0.16	-99.04	0.72	13.61	1.45
31-Jan-10 15	-13.85	0.16	-98.16	0.66	12.62	1.42
01-Feb-10 15	-13.83	0.16	-97.25	0.86	13.38	1.52
01-Feb-10 21	-13.84	0.16	-96.81	0.47	13.88	1.34
02-Feb-10 03	-13.85	0.16	-97.03	0.84	13.81	1.51
02-Feb-10 15	-13.67	0.16	-96.45	0.77	12.92	1.47
03-Feb-10 03	-13.77	0.16	-97.41	0.53	12.76	1.36
03-Feb-10 09	-13.74	0.16	-96.05	1.16	13.85	1.70
03-Feb-10 15	-13.73	0.16	-96.48	0.38	13.37	1.31
04-Feb-10 03	-13.75	0.16	-96.33	0.29	13.71	1.28
04-Feb-10 09	-13.80	0.16	-96.08	0.93	14.29	1.56
04-Feb-10 15	-13.65	0.16	-95.33	0.27	13.83	1.28
04-Feb-10 21	-13.75	0.16	-96.22	0.33	13.79	1.29
05-Feb-10 09	-13.80	0.16	-96.72	0.84	13.66	1.51
05-Feb-10 15	-13.87	0.16	-97.55	0.58	13.43	1.38
05-Feb-10 21	-13.76	0.16	-96.59	0.32	13.51	1.29
06-Feb-10 03	-13.81	0.16	-96.85	1.15	13.61	1.70
06-Feb-10 09	-13.63	0.16	-96.75	0.16	12.33	1.26
06-Feb-10 15	-13.68	0.16	-96.55	0.21	12.92	1.27
06-Feb-10 21	-13.80	0.16	-96.14	0.23	14.27	1.27
07-Feb-10 03	-13.70	0.16	-96.27	0.76	13.37	1.46
07-Feb-10 09	-13.73	0.16	-96.22	0.24	13.59	1.27
07-Feb-10 15	-13.70	0.16	-96.26	0.05	13.36	1.25
07-Feb-10 21	-13.74	0.16	-96.25	0.73	13.63	1.45
08-Feb-10 03	-13.65	0.16	-95.85	0.42	13.37	1.32
08-Feb-10 09	-13.73	0.16	-96.81	0.74	12.99	1.45
08-Feb-10 21	-13.68	0.16	-96.28	0.18	13.19	1.26
09-Feb-10 03	-13.65	0.16	-95.84	0.16	13.33	1.26
09-Feb-10 09	-13.87	0.16	-97.70	0.39	13.26	1.31
09-Feb-10 15	-13.71	0.16	-96.45	0.46	13.20	1.33
09-Feb-10 21	-13.75	0.16	-96.34	0.19	13.62	1.26
10-Feb-10 03	-13.77	0.16	-96.28	1.26	13.86	1.78
10-Feb-10 09	-13.68	0.16	-96.19	0.16	13.24	1.26
10-Feb-10 15	-13.70	0.16	-96.43	0.55	13.15	1.36
10-Feb-10 21	-13.47	0.16	-94.13	0.26	13.66	1.27
11-Feb-10 15	-13.66	0.16	-95.57	0.39	13.69	1.31
11-Feb-10 21	-13.50	0.16	-94.56	0.53	13.45	1.35
22-Feb-10	-13.81	0.16	-98.09	0.05	12.38	1.25

Cont. next page...

TABLE S8, cont.: Water isotope data of stream water collected from the Kosñipata River at the Wayqecha gauging station

Date and hour (dd-mmm-yy hr)	$\delta^{18}\text{O}$ (‰)	σ $\delta^{18}\text{O}$ (‰)	δD (‰)	σ δD (‰)	Dxs	σ Dxs
01-Mar-10	-13.83	0.16	-97.81	0.57	12.86	1.37
05-Apr-10	-13.58	0.16	-95.45	0.27	13.22	1.27
12-Apr-10	-13.57	0.16	-95.24	0.24	13.31	1.27
19-Apr-10	-13.23	0.15	-93.21	0.37	12.62	1.29
10-May-10	-13.45	0.16	-94.45	0.13	13.16	1.25
16-May-10	-13.33	0.15	-93.77	0.25	12.85	1.27
07-Jun-10	-13.31	0.15	-93.80	0.33	12.71	1.28
28-Jun-10	-12.83	0.15	-88.97	0.37	13.66	1.29
11-Jul-10	-13.05	0.15	-90.93	0.17	13.44	1.25
26-Jul-10	-13.07	0.15	-91.66	0.50	12.89	1.33
22-Aug-10	-13.05	0.15	-91.25	0.30	13.14	1.27
29-Aug-10	-13.10	0.15	-90.49	0.31	14.29	1.27
25-Oct-10	-12.89	0.15	-89.90	0.34	13.21	1.28
20-Dec-10	-13.20	0.15	-91.93	0.25	13.64	1.26
03-Jul-11	-13.37	0.16	-94.66	0.67	12.29	1.41
18-Feb-11	-13.81	0.16	-96.92	0.28	13.58	1.28
21-Mar-11	-14.01	0.16	-99.00	0.51	13.09	1.36

Mean isotope values and σ (standard deviation) were from 3 replicate sample injections (see description of methods in Supplementary Text)

hour not reported when only one sample collected on a given date

385

386

387

TABLE S9: Streamflow results for the Kosñipata Valley at the Wayqecha (WQ) gauging station.

	Q (m ³ s ⁻¹)	Runoff, mm d ⁻¹ (%)	Rainfall [^] mm d ⁻¹ (%)
Wet	8.0±1.1	14.1±2.4 (56.5)	12.6 (62)
Wet-dry	7.8	14.4 (13.5)	5.3 (6.5)
Dry	2.3±0.3	4.1±0.6 (21)	3.0 (18)
Dry-wet	2.6±2.6	4.6±3.4 (9)	5.4 (13.5)
Annual	4.7	8.4 (100)	6.7 (100)

Seasonal contribution as percentage of total annual in parenthesis.

Error values are 2 x standard error based on monthly data.

[^] Catchment-wide rainfall is reported for February 2010 to January 2011, with the contribution from each season as a percentage in parenthesis.

388

389

Supplementary figures

Figure S1: Hydrogen isotope ratio (δD , ‰) plotted versus oxygen isotope ratio ($\delta^{18}O$, ‰) of rainwater, dry season cloud water vapour (blue circles), and river water (red diamonds) from the Kosñipata Valley. Rainwater samples are from the dry season (May to August, green triangles) and the wet season (December to March, purple squares). The global meteoric water line (GMWL, $\delta D = 8.20 \times \delta^{18}O + 11.27$) is shown as the solid line (Rozanski et al., 1993; Craig, 1961). The local meteoric water line (LMWL, $\delta D = 8.6561 \times \delta^{18}O + 21.119$) is shown as the dashed line.