Multi-criteria assessment of water dynamics reveals sub-catchment variability in a seemingly homogeneous tropical cloud forest catchment

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Abstract

To improve the current knowledge of the rainfall-runoff phenomena of tropical montane catchments, the usefulness of several hydrological indicators was explored on a nested cloud forest catchment (76.9 km^2). The used metrics belong to five categories, respectively: base flow mean transit time, physicochemical properties of stream water, land cover, topographic and hydrometric parameters. We applied diverse statistical techniques for data analysis and to contrast findings. Multiple regression analysis showed that mean transit times of base flow could be efficiently predicted by sodium concentrations (higher during baseflows) and temperatures of stream water, indicating a major influence of geomorphology rather than

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topographic or land cover characteristics. Principal Component Analysis revealed that no specific subset of catchment indicators could be identified as prevailing descriptors for all catchments. Hierarchical cluster analysis provided concomitant results, implying larger levels of dissimilarity between smaller sub-catchments (~40%) than between larger ones (~2%). Overall, results point out an intricate interdependence of diverse processes at surface and subsurface level indicating a high level of heterogeneity. Disregarding heterogeneity of nested or paired catchments could lead to incomplete or misleading conclusions, especially in tropical mountain regions where pronounced spatial and temporal gradients are present.

1. Introduction

Over the past decades, a multitude of methods were developed to investigate the hydrological functioning, the dominant water flow paths and the runoff generation processes of catchments. Originating from various research perspectives and questions, those methods give primarily insights to individual components and processes of the hydrological system. No matter what method we use, a single hydrological indicator (e.g., mean transit time) is only suitable to capture one given aspect of the hydrological system and therefore fails to represent the complete range of interacting processes. The latter justifies the search for an integrated analysis of the possible measurable and predictable catchment descriptors (e.g., Tetzlaff *et al.*, 2009).

Primarily due to time restrictions, lack of funding, incomplete knowledge and most often missing data, the simultaneous application of multiple methods within a given catchment is exceptional. Furthermore, the variation in spatial and temporal scales of the processes, requiring for their analysis a diversity of input data, hinders mostly the synchronous application of different methods in a given basin. In any case, multidisciplinary approaches are preferred for validation of findings as they better describe the entire system's behavior compared to single indicators (Soulsby *et al.*, 2008; Moldan and Černý, 1994). The latter is particular true for regions with limited knowledge of their hydrologic functioning (Tetzlaff *et al.*, 2007). Research on the hydrological behavior of small or mesoscale catchments (e.g., McGrane *et al.*, 2014; Sanda *et al.*, 2014; Roa-Garcia *et al.*, 2011; Crespo *et al.*, 2011; Tetzlaff *et al.*, 2008) further provides an important source for upscaling hydrological knowledge to regional scales (Ochoa-Tocachi *et al.*, 2016; Rodgers *et al.*, 2005), which is essential for the sustainable exploitation of a region's water resources. Rainfall-runoff research generally focused on headwater catchments since they constitute the primary sources of runoff (McDonnell and Beven, 2014). They are often well conserved from anthropogenic impacts, simplifying their hydrological characterization. As stated by Dunn *et al.* (2008) and Birkel *et al*. (2011), among other authors, the analysis of nested or paired catchments is ideal to acquire insights about the variability of results and to assess the importance of tributary sources. In terms of improving knowledge, this study highlights the benefits of using various catchment descriptors in parallel for the analysis of the hydrological functioning of a tropical mountain cloud forest catchment, situated in south Ecuador.

In South America, tropical cloud forests are situated in a relative narrow altitudinal range (2,500 and 3,500 m a.s.l.) amidst the western headwaters of the Amazon basin and the eastern escarpments of the Andean mountains. The forested study catchment drains to the Rio San Francisco, and the first results on the rainfall-runoff processes were published by Goller *et al.* (2005) and Crespo *et al.* (2012). Since then, high resolution elevation data (LiDAR, 1m) became available (Silva *et al.*, 2015), allowing more precise estimations of topographic indices, like for instance catchment slopes. Besides, new information, like the re-assessment of the MTT by Timbe *et al.* (2015), using a more robust approach and a denser dataset, yielded results which differ from previous published data (e.g., Crespo *et al.*, 2012). To further improve results, we used in this study in parallel a set of statistical methods such as:

bivariate, multiple regression, principal component, and cluster analysis, enabling the reconstruction of a more complete and precise picture of the hydrological processes at hand.

Building on the currently available dataset of this unique environment, results from individual analysis methods were cross-checked and compared with those already published by Crespo *et al.* (2012) and Goller *et al.* (2005), as basis to complement the current knowledge of the runoff processes in tropical cloud forest catchments. The catchment indicators selected for our analysis, i.e., bivariate and multivariate statistical techniques, belong to the following categories: topographic indices, land cover, hydrometric descriptors, physicochemical parameters and MTT data.

This study is based on the general hypothesis that the degree of knowledge on the hydrological functioning of a catchment is positively correlated with the amount of catchment indicators and the diversity of used analysis techniques; the approach that guarantees identification of the key hydrological variables. Furthermore, it is assumed that: a) the subjacent geology is approximately similar along the catchment, and b) the length of the datasets is sufficient to get a clear picture of the ordinary hydrological conditions and the functioning of the study catchment and its tributaries. Our study seeks to answer the following research questions: 1) is there a dominance of a common catchment indicator that could serve as a descriptor of the runoff processes among all analyzed sub-catchments? and 2) is catchment heterogeneity similar across the nested catchments? Answers to both these questions are essential to define the scale of future catchment inter-comparison studies (e.g., paired catchment approaches). The results of this study will positively impact the current knowledge of this understudied environment, which, regardless of its low distribution area, has a significant effect on the water cycle at larger scales (Wohl *et al.*, 2012; Viviroli *et al.*, 2011; Roa-Garcia *et al.*, 2011; Laraque *et al.*, 2007; Buytaert *et al.*, 2006). Additionally, results presented herein point out priority areas for future research in tropical montane areas in view of their management, restauration and conservation.

2. Study site

The San Francisco catchment is located in the tropical foothills of the southeastern Andean region of Ecuador (3º 58' 30" S and 79º 4' 25" W) i.e., the northwestern headwaters of the Amazon basin. The study catchment (76.9 km^2) and seven tributary sub-catchments (0.7 to 34.9 km^2) were analyzed (Figure 1, Tables 1 and 2). The average catchment elevation is 2,555 m above mean sea level, the topography is steep, and the average slope of the tributary sub-catchments varies between 67 and 94%. Four meteorological stations collect climate data since 1998. Annual average temperatures vary between 15ºC in the lowest part of the catchment down to 10ºC at the ridges, with an altitudinal gradient of -0.57 ºC per 100 m. The reader is referred to Bendix *et al.* (2008) for a detailed description of the climate of the study area. The moist air masses originating in the eastern Amazon basin release large amounts of precipitation at the ridges of the south-eastern side of the catchment, while the eastern and northern sides receive less precipitation (Fries *et al.*, 2014). Rains are generally gentle and constant with a peak from June to August, while they are lowest during the period November-January. Among the climate stations, daily rainfall amounts were correlated; for the period 1998-2012, the minimum coefficient of determination R^2 between stations was 0.61. Snowfall is zero. The contribution of fog to the hydrologic cycle is estimated at 35% at the catchment ridges, decreasing to 5% in the valley bottom (Rollenbeck *et al.*, 2011). Lower temperatures and higher discharges are common during the wettest period, while the inverse behavior is typical for the 'driest' period. Preliminary data suggests that stream water of the catchment and its tributaries are dominated by baseflow, accounting up to 85% of the total runoff (Timbe *et al.*, 2014). The geological formation, homogeneous across the catchment area, belongs to the Chiguinda unit consisting of sedimentary and metamorphic Paleozoic rocks (Beck *et al.*, 2008). Southern catchments are more covered by natural pristine forest than those located in the northern part, which contain large stretches of pasture (*Setaria aphacelata* and *Melinis minutiflora*) and weeds, mainly tropical bracken fern (*Pteridium arachnoideum* and *Pteridium caudatum*) (Goettlicher *et al.*, 2009; Curatola-Fernández *et al.*, 2013). Soils are classified as *Humic Alfisols*, *Humic Acrisols* and *Dystric Leptosols* in the lower part of the catchment (1,000-2,000 m asl), followed by *Terric Histosols* (1,500-2,800 m asl) and *Umbric Regosols*; *Dystric Cambisols* at the ridges (1,800-2,800 m asl) (Beck *et al.*, 2008b; Liess *et al.*, 2009).

3. Data and Methods

Thirty indicators, derived from diverse input datasets (Tables 1 and 2) and grouped in five general categories, were derived; respectively baseflow mean transit time (MTT), stream water physicochemical characteristics, vegetation land cover, topographic indices, and hydrometric parameters. Those metrics were analyzed applying bivariate and multivariate statistical methods. The multivariate analyses comprised multiple linear regression, Principal Component Analysis (PCA, Hotelling, 1933) and agglomerative hierarchical clustering (AHC). PCA and AHC were used as alternative approaches to identify the controlling factors of the water flow paths. Unlike multiple linear regression analysis, they offer visual means to inspect the multidimensional relations of individual indicators and similarities between sub-catchments. The referred analyses permitted to identify the influence of each individual indicator and how they interact within the catchment runoff processes.

3.1. Hydrological indicators and landscape characteristics

Mean transit time estimations

Weekly samples of rainfall and stream flows were collected during a two-year period, between August 2010 and August 2012 (Figure 2, Tables 2), analyzed for their isotopic content (δ^2H and $\delta^{18}O$) using a Cavity Ring-Down Spectroscopy (CDRS) (L1102-i, Picarro, USA), with a precision of 0.1 ‰ for δ^{18}O and 0.5 ‰ for δ^2H, and used to estimate baseflow MTTs for each tributary and the main catchment. Predictions were performed using seven lumped-parameter models based on the convolution method (Timbe *et al.*, 2014): gamma (GM), exponential (EM), exponential-piston (EPM), linear (LM), linear-piston (LPM), two parallel linear reservoirs (TPLR) and dispersion (DM) models. For model estimations, uncertainty assessments were performed. The GM and EPM models provided the best predictions. The effect of the sampling resolution on those predictions was analyzed by Timbe *et al.* (2015). The MTT estimates of both models were similar and among sub-catchments they varied between 2.0 and 4.2 years, indicating a predominance of shallow aquifers (Timbe *et al.*, 2014). The MTT values shown in Table 1 represent the average value of both models. Crespo *et al*. (2012) estimated for the stream water of the study catchment MTT values applying a sinusoidal model, using a considerably smaller isotopic dataset in which rainfall, important as the primal source of stream water, was not sampled but inferred through an online isotope precipitation calculator (www.waterisotopes.org).

Chemical element concentrations of stream water

For the main river and its tributaries, grab samples were collected fortnightly from April 2007 until November 2009, covering several flow conditions. Concentrations of chemical elements were determined via inductively coupled plasma-mass spectrometry (Agilent 7500ce ICP-MS, Agilent Technologies, USA). Data for the period April 2007 - November 2008 were already published by Bücker *et al.* (2010) and Crespo *et al.* (2012). Due to financial constraints, metals like Aluminum (Al) were no longer sampled and analyzed after November 2008. For the catchment, the major cations detected were Sodium (*Na*), Calcium (*Ca*), Magnesium (*Mg*) and Potassium (*K*). Average concentrations of Aluminum (*Al*) or Iron (*Fe*) were comparable, but at much lower concentrations than the major cations. Table 1 shows the median value of the ion composition. Temperature (*T*), *pH* and electrical conductivity (*EC*) of stream waters were measured during the isotope sampling campaign and cross-checked with values from the period 2007-2008. Median parameter concentrations at every outlet are listed in Table 1 while number of samples used for the analyses are indicated in Table 2. As stated by Crespo *et al*. (2012) can *Na* and *Al* in stream water be considered as conservative tracers. Furthermore, Figure 3 clearly depicts that the *Na* concentration in stream water is higher during low flows when baseflow is the dominant stream flow component, while *Al* concentrations are higher during high flows, when baseflow is complemented by shallow subsurface flow.

Topographic indices and land cover

Application of GIS techniques to a digital terrain model of the study area, with a 1 m spatial resolution, derived from a LiDAR survey (Silva *et al.*, 2015), yielded the following five terrain metrics: median catchment area (*A*); perimeter (*P*); catchment altitudinal range (E_{rng}), median (*E*) and maximum elevations (E_{max}); and median catchment slope (*S*). Besides, four common terrain indices were calculated: catchment area-perimeter ratio (*A/P*); drainage density (D_D); topographic wetness index (*TWI*) (Beven and Kirkby, 1979), and the downslope index *DSI* (Hjerdt *et al.*, 2004), for which we used 5 m as the required elevation unit parameter. Two variants of *TWI* were estimated: TWI_{D8} (O'Callaghan and Mark, 1984) and $TWI_{D\text{-}INF}$ (Tarboton, 1997). As they provided similar results (r = 0.98), just the first one was kept for further analyses.

Land cover data was derived from the classification map proposed by Curatola-Fernández *et al.* (2013), which on its turn is based on a Quickbird scene of October 2010 (four multi-spectral bands, 2.5 m spatial resolution). In line with the objectives of the current research were the land cover types regrouped in three general classes: natural forest (LC_{forest}, 62.3% of total surface area), subparamo vegetation ($LC_{subparamo}$, 31.2%) and pasture plus bracken-fern ($LC_{pasture}$, 3.7%). Median values of each class per sub-catchment are listed in Table 1.

Analysis of the current high resolution DEM data of the research area revealed that the average surface slopes between the sub-catchments vary between 66 and 93%, whereas in previous studies based on the information available at that time, it was found that that the average terrain slope of the sub-catchments varied between 48 and 61% (e.g., Crespo *et al*., 2012). Similarly, also apparent differences exist between the recent high-resolution land cover classification map provided by Curatola-Fernández *et al*. (2013) and the previous version of Goettlicher *et al.* (2009).

Hourly discharge data for the period August 2010 - August 2012 were derived from five-minute resolution water level records registered by pressure transducers (accuracy ± 0.25 cmH_2O) (MiniDiver and BaroDiver, Schlumberger Water Services, Netherlands) installed at each tributary and main outlet. Discharge curves were constructed using bi-weekly observed discharge data applying the dilution method, using salt as tracer. For PL, FH, QN and QM, the shape of the curves was cross-checked using the velocity-area method. For QC, the smallest sub-catchment, a sharp triangular 90º weir located at the outlet served as gauging station. River beds at the QP, QR, and QZ gauging stations were unstable and several disruptions of water-level records occurred during the observation period. For those stations, percentages of missing data were between 51 and 69%. An aggregated hydrological rainfall-runoff model, NAM (Nielsen and Hansen, 1973), was used to fill discharge data gaps. NAM was already used in the catchment as a part of an ensemble of models for runoff prediction (Exbrayat *et al.*, 2014). For each catchment, the same modeling approach was used to extend the runoff data series for the period March 1998 - August 2012, for which hourly meteorological information was available. For each model, average hourly rainfall amounts were estimated by Thiessen polygons (Thiessen, 1911), and the reference evapotranspiration was calculated as monthly averages using the Penman-Monteith equation (Monteith, 1981). Among sub-catchments, NSE of predictions varied between 0.65 (QM) and 0.81 (QC), while it was equal to 0.71 for the main outlet (PL). For every discharge outlet, flow duration curves are shown in Figure 4a, while the monthly variation of discharge flows at the main catchment outlet is shown in Figure 4b.

Whereas catchment stream flows normally are characterized using hydrometric statistics (Sawicz *et al.*, 2011; Wagener *et al.*, 2007; Olden and Poff, 2003), in our study we used modeled hourly rainfall-runoff data to calculate four basic mean annual hydrometric features for each catchment (Table 1): specific discharge (S_D), specific rainfall (S_R), hourly peak (M_{APF}) and low (M_{ALF}) flows. Similarly to terrain metrics, composite hydrometric indices were estimated such as the ratio of the standard deviation and the mean of the discharges, known as the coefficient of variation (*CoV*); the slope of the flow duration curve between the 33th and 66th percent of exceedance probability (FDC_{33-66}), considered as an indicator of discharge variability for intermediate flow ranges; the Richard-Baker flashiness index (FI_{R-B}) (Baker *et al.*, 2004); the rainfall-runoff coefficient (R_{QP}) as the ratio between total discharge and total rainfall; and the baseflow index (*BFI*) as the ratio of total baseflow to total discharge.

3.2. Statistical methods

Bivariate and multivariate statistical methods, common techniques in geohydrology and related sciences and very suitable when the analysis involves many variables (Brown, 1998), were used for the analysis and interpretation of the diverse sources of information. More specifically, the use of a given technique depends on the type of observed data and analysis required. When using bivariate analysis, MTT estimations were considered as dependent of at least one data category.

Bivariate correlations and multiple regression analyses

Multiple regression analysis was applied to identify the redundant variables, which by discarding them simplified further analyses. For this task, *p*-values and the Pearson product-moment correlation coefficient (r) were used, which depicts the degree of linear association between two variables. To reduce the number of variables, we looked for highly correlated ones within the same parameter category. Statistically significant linear correlations ($r \geq |0.7|$ and *p*-values < 0.05) were evaluated further by means of bivariate plots. For instance, among the terrain metric variables, catchment area (*A*) and the ratio area-perimeter (*A/P*) were highly correlated, therefore only one of these variables was kept. Selection of one variable over another was based on the degree of association of a scrutinized variable with other variables from a different parameter category. For these cases, the variables depicting strongest correlations were maintained for further analysis.

A stepwise Multiple Regression Analysis, using a General Linear Model, was performed to reduce the number of measured variables, to remove collinearity that may exist between them and to verify for relationships between MTTs and other catchment indicators. In this method, a subset of predictors is sequentially selected from a larger group of predictors through statistical testing of the hypotheses. The main parameter of this analysis is the *t*-test and its corresponding probability. The adjusted coefficient of multiple determination (R^2), was used as a measure of how well the independent variables explain changes in the dependent variable. Since potential predictive models could differ in the number of independent variables involved (i.e., number of model parameters) we used the Akaike Information Criterion (Akaike, 1981) to choose the best option. Standardized residuals of observed and predicted data were checked for homoscedasticity.

Principal component and cluster analyses

Principal Component Analysis (PCA) (Hotelling, 1933) allows examination of the interrelations and variability among measured variables, determines which variables are strongest correlated, and the selection of the smallest number of components that explain most of the total variance. For this method, the main parameters are the factor loadings and the sum of the explained variation. The degree of association between analyzed catchments was cross-checked by a hierarchical cluster analysis. For the PCA, as for cluster analysis, the same preselected variables as for the MRA were used. Before the analysis, variables were standardized (i.e., mean = 0 and standard deviation = 1). The PCA was performed using the sample covariance matrix. For cluster analysis, we applied the Agglomerative Hierarchical Clustering (AHC). For this analysis, Euclidean distances were computed to measure the dissimilarity between pairs of observations, while the Ward's method (Ward, 1963) was applied as the linkage criterion.

4. Results

4.1. Correlation and multiple regression analyses

Redundant variables within the same category were discarded. Among topographic indices, for instance, the catchment area *A* was strongly correlated with the perimeter *P* ($r = 0.96$) and the *A/P* ratio ($r = 0.98$). Conversely, drainage density D_D or topographic wetness index TWI_{D8} did not show significant correlations with any other terrain metric variables. Among terrain metrics, not only the median catchment slope *S* was considered but also the following slope ranges: 0-25, 25-50, 50-75, 75-100 and >100%; all of them showed high correlations to *S* (between 0.74 and 0.99). Based on the redundancy analysis, five topographic metrics were retained: *A/P*, TWI_{D8}, E_{max}, *S* and D_D. Similarly, among the hydrometric variables, three catchment descriptors were selected: baseflow index *BFI*, rainfall-runoff ratio R_{QP} and the slope of the flow duration curve $FDC_{33\text{-}66}$. From the variables describing the physicochemical properties of stream water, four variables were selected: *pH*, temperature *T*, and the median concentration of *Na* and *Al*. Among land cover variables, $LC_{pastures}$ and LC_{forest} were kept for further analyses while $LC_{subparamo}$ was discarded since it was strongly correlated with elevation (Homeier *et al.*, 2008; Curatola-Fernández *et al.*, 2013).

Correlations were analyzed between the fifteen selected variables (Table 3), namely: MTTs, 5 terrain indices, 3 hydrometric descriptors, 4 physicochemical properties and 2 land cover characteristics. The *MTTs* were not correlated to any of the topographic or hydrometric variables, instead, they were associated to the physicochemical characteristics: *Na* (r = 0.89) and *T* (r = 0.82) (Figure 5). Hydrometric and terrain indicators were correlated with *A/P* and $FDC_{33\text{-}66}$ (r = -0.94) variables, and R_{QP} and TWI_{D8} (r = -0.74). Physicochemical parameters were also correlated to hydrometric, land cover and terrain metrics: *Na* with TWI_{D8} (r = 0.92), *MALF* (r = -0.72), R_{QP} (r = -0.73).

The stepwise multiple correlation analysis, considering MTT as potentially dependent of the other variables, described a dependency of MTT on the *Na*, *T* and *A/P* variables. Based on the Akaike Information Criterion (Akaike, 1981) was the best performing function among three preselected predictive models (of 1, 2 and 3 parameters) equal to: $MTT = -3.86087037 - 0.418018*A/P + 0.376705*T + 7.96E\text{-}04*Na$. For this function the adjusted R^2 was 0.97. Among the selected independent variables, *Na* has the greatest effect on MTT; standardized coefficients were 0.614 for *Na*, 0.390 for *T* and -0.205 for *A/P*.

4.2. Principal component and cluster analyses

Three principal components accounted for 88% of the total variance (Figures 6a and 6b). The first principal component PC1 (46%) was significantly associated to at least one parameter from every data category, i.e., factor loadings were largest for TWI_{D8} (0.98), *Na* (0.93), $LC_{pastures}$ (0.92), MTT (0.85) and R_{QP} (-0.79). The second component PC2 (25 %) was mainly affected by hydrometric parameters: *BFI* (0.44) and $FDC_{33\text{-}66}$ (-0.44). The third component

PC3 (17%) was mainly influenced by *Al* (0.58) and D_D (-0.53). The nested catchments could be clustered in three groups based on their degree of affinity to the principal components and their associated variables: a) mainly associated to PC1: QP and QC; b) related to PC3: QM and QR; and c) no distinctive relationship to any of the first three principal components: PL, FH, QN and QZ. The AHC analysis yielded similar results. Degrees of dissimilarity were noticeably higher for small than for larger catchments (Figure 6c).

5. Discussion

Identification of the rainfall-runoff processes is a common challenge in catchment hydrology. Research in this area has been boosted since the wide spread use of tracers to infer catchment water flow paths and their associated MTTs (Soulsby *et al.*, 2009; McGuire and McDonnell, 2006). However until today the use of tracers for the unraveling of the hydrological functioning is limited in tropical montane cloud forest areas (Wohl *et al.*, 2012).

In our study, bivariate correlations point to significant statistical relationships between MTT and physicochemical metrics of stream water: *Na* concentrations and temperature *T*. Since observed data for the main outlet and tributaries depict higher *Na* concentrations during base flows (Figure 3), the correlation between MTT and *Na* means that waters passing through deeper flow paths would have greater *Na* concentrations and therefore higher MTTs. This behavior is also supported by the correlation between MTT and *T*, having in mind that the temperature of stream water is a proxy for the depth of origin of that water (Guzmán *et al.*, 2016). Highest *T* averages, of around 16°C, were registered for two of the smallest sub-catchments (QP and QC), which also have the highest MTTs and *Na* concentrations (Table 1). On the other hand, stream water temperatures are around 14.5°C for the large catchments such as PL or FH. The lack of correlations between MTTs and the other metrics points out that the subsurface characteristics are the main source of divergence between intra-catchment runoff processes. Even when then underlying geology is the same across the San Francisco area (Beck *et al.*, 2008), the bedrock topography would not necessarily match the one of the catchment surface. Soil thickness variability or differences in the soil-bedrock permeability of the interface, as in the case of Mueller *et al.* (2013), are more likely explanations for our results.

The strong control exerted by geology in water flow paths might be responsible for masking other, less dominant catchment indicators. This could be the case for land cover, for which we found no significant correlation with MTTs, although it is contrasting for some of the investigated sub-catchments. Sub-catchment QC (50.8% covered by pastures) and QM (99% covered by pristine forest), not only have considerably different land cover but also MTTs (4.1 versus 2.1 y, respectively). Nevertheless, this actually points out that catchment flows in our study area are governed by a stronger driver than land cover. This is somehow surprising as research on the land use and land cover patterns effect on runoff is well documented at catchment (Ochoa-Tocachi *et al.*, 2016; Molina *et al.*, 2015 ; Roa-Garcia *et al.*, 2011; Neill *et al.*, 2011; Chaves *et al.*, 2008; Coe *et al.*, 2011) and regional scale (Davidson *et al.*, 2012; Coe *et al.*, 2009; Soares-Filho *et al.*, 2006). Several of these studies showed that deforestation reduces evapotranspiration and soil hydraulic conductivity, enhancing during rainfall events via overland flow and shallow sub-surface flow stream flow.

The step-wise multiple linear regression analysis provided similar results than those from the bivariate analysis. For this, even though 15 parameters were included as possible sources of variation of MTT, the best predictive equation reached an almost perfect performance (R^2 = 0.97) with only three indicators: *Na*, *T* and *A/P*. Among them, the dependence of MTT on *Na* and *T* was stronger than the dependence on *A/P*. While the feasible reasons for the dependence of MTT on *Na* and *T* were already discussed, the inverse correlation between MTT and *A/P* ratios (Table 1) indicates that small catchments have relatively longer MTTs than larger ones. As pointed earlier, this behavior could be related to differences among catchment aquifer volumes because of high degrees of heterogeneity in soil thickness or permeability of the soil-bedrock interface (e.g., Hale and McDonnell, 2016; Mueller *et al.*, 2013). The findings of Hale and McDonnell (2016), comparing the runoff-characteristics and MTTs of two nested catchments with similar hydro-meteorological conditions, are pointing in the same direction; they found high degrees of heterogeneity in runoff characteristics mainly due to differences in the underlying geology. However, such marked heterogeneity between study units belonging to the same nested catchment has not been commonly reported. The reason could lie in that, when dealing with nested or paired catchments, we are tempted to assume that geological characteristics are uniform (e.g., Ogden *et al.*, 2013; Roa-Garcia *et al.*, 2011), even when no detailed information is available. As such, assumptions of homogeneous conditions between nested catchments could lead to gross errors (Kirchner, 2016).

It is not unlikely that the observed heterogeneity points out to additional issues. For example, there is no specific metric that keeps the same level of influence among all analyzed catchment runoff processes. More in particular, it is expected that geological features exert greater influence on catchments with large MTTs than on those with shorter ones. In this context, a multidimensional approach consisting of Principal Component Analysis was useful to screen the expected high heterogeneity between catchments and associated governing factors. As for instance, PC1 (46%) depended on at least one metric from each hydrological indicator category. Along PC1, the smallest catchments showed the most marked differences between them (Figure 6, QC vs. QM), while the larger catchments (PL, FH, QN, QZ) responded more similar. Another range of heterogeneity among catchments was depicted by PC2; the southeastern tributaries, QM and QR accounted lower BFI ratios compared to similar sized sub-catchments, QP and QC, located in the northern part of the catchment. Marked differences between two small forest catchments (QR and QM) were also shown along PC3. Higher dissimilarities between smaller catchments than for larger ones were further depicted by HCA results. Catchment heterogeneity depicted by PCA is in line with results described by Tetzlaff *et al.* (2009). Those authors, to contrast the hydrology of three mesoscale catchments and their associated sub-catchments in the Cairngorm mountains of Scotland, used a similar PCA analysis with MTT estimations and topographic indices.

Our findings, based on the simultaneous application of several methods in which higher spatial resolution data are used (e.g., hi-res land cover information and terrain indices derived from a LiDAR 1m DEM), corroborate the results provided by Crespo *et al.* (2012) in their preliminary evaluation of the hydrological functioning of the same nested catchment. Although lateral subsurface shallow flows (like those through the organic soil layer) could eventually occur during storm events, reaching contributions up to 81% of the total flow (Goller *et al.*, 2005), during normal to dry catchment wetness conditions, stream flows are predominantly fed by subsurface flows coming from deeper soil horizons. The latter also means that the control exerted by surficial catchment characteristics are subdued in favor of deeper catchment characteristics, like geology. Our results are also supported by recent findings on a hillslope scale experiment in the same catchment, in which Windhorst *et al.* (2014) combined hydrological modelling with weekly stable isotopes information to account for the fraction of water that vertically percolates (50%) and the fraction that flows lateral near-surface (16%).

The diversity of rainfall-runoff mechanisms present in apparently homogeneous nested catchments, expose the ubiquitous heterogeneity of environmental systems at all scales (McDonnell *et al.*, 2007; Kirchner, 2016). Given previous, it is essential to combine diverse sources of information in studies dealing with the characterization of hydrological processes. Besides, considering the scarce research dealing with rainfall-runoff processes in tropical areas, more field-based studies in catchments with diverse or contrasting behaviors are necessary to identify the most relevant and representative runoff processes (Beck *et al.*, 2016; Wohl *et al.*, 2012). For this, the use of analysis techniques that combine diverse and comprehensive data sets is a must (Bonan, 2008).

Independent of our findings should land cover among the multitude of metrics be considered as a basic parameter, since in many South American ecosystems (Ochoa-Tocachi *et al.*, 2016; Coe *et al.*, 2013; Molina *et al.*, 2015; Tapia-Armijos *et al.*, 2015; Iñiguez-Armijos *et al.*, 2014) man-made changes in natural land cover and land use have been identified as an emerging ecological problem. As for example, for a South American tropical montane cloud forest catchment, Roa-Garcia and Weiler (2010) identified a strong influence of land cover on catchment MTT estimations (0.1 to 1.8 y). Since these changes affect not only hydro-meteorological, or land-surface aspects, but also geomorphological and biogeochemical factors, integral and accurate understanding of the ecosystem requires the simultaneous analysis of as many as possible related variables. Comprehensive analysis of these data, using the widely-known bivariate and multivariate statistical techniques, should be the benchmark for the inter-comparison of catchments' hydrology.

6. Conclusions

The heterogeneity in the nested study catchment points out that special care should be taken with assumptions dealing with the homogeneity of study units when conducting experiments in nested or paired catchments. The implications of overlooking natural heterogeneity at these spatial scales are not trivial. Most studies are conducted in small headwater catchments based on the premise of easier monitoring and the likelihood of the non-interference of a large number of variables present at larger basin scales. In contrast, our results showed larger differences for smaller than for larger sub-catchments. In this context, extrapolation of results for even an apparently similar adjoining catchment, could be risky. Besides, we should consider that among related studies, just a small fraction takes care of tropical montane forest areas, for which the lack of detailed information often result in gross simplifications, e.g., stable conditions are assumed based only on the spatial proximity between study units. Our approach, using diverse and widely-known statistical tools, allowed to crosscheck findings from different perspectives, provides an extra level of reliability, and furnishes guidelines for future monitoring and successful analysis.

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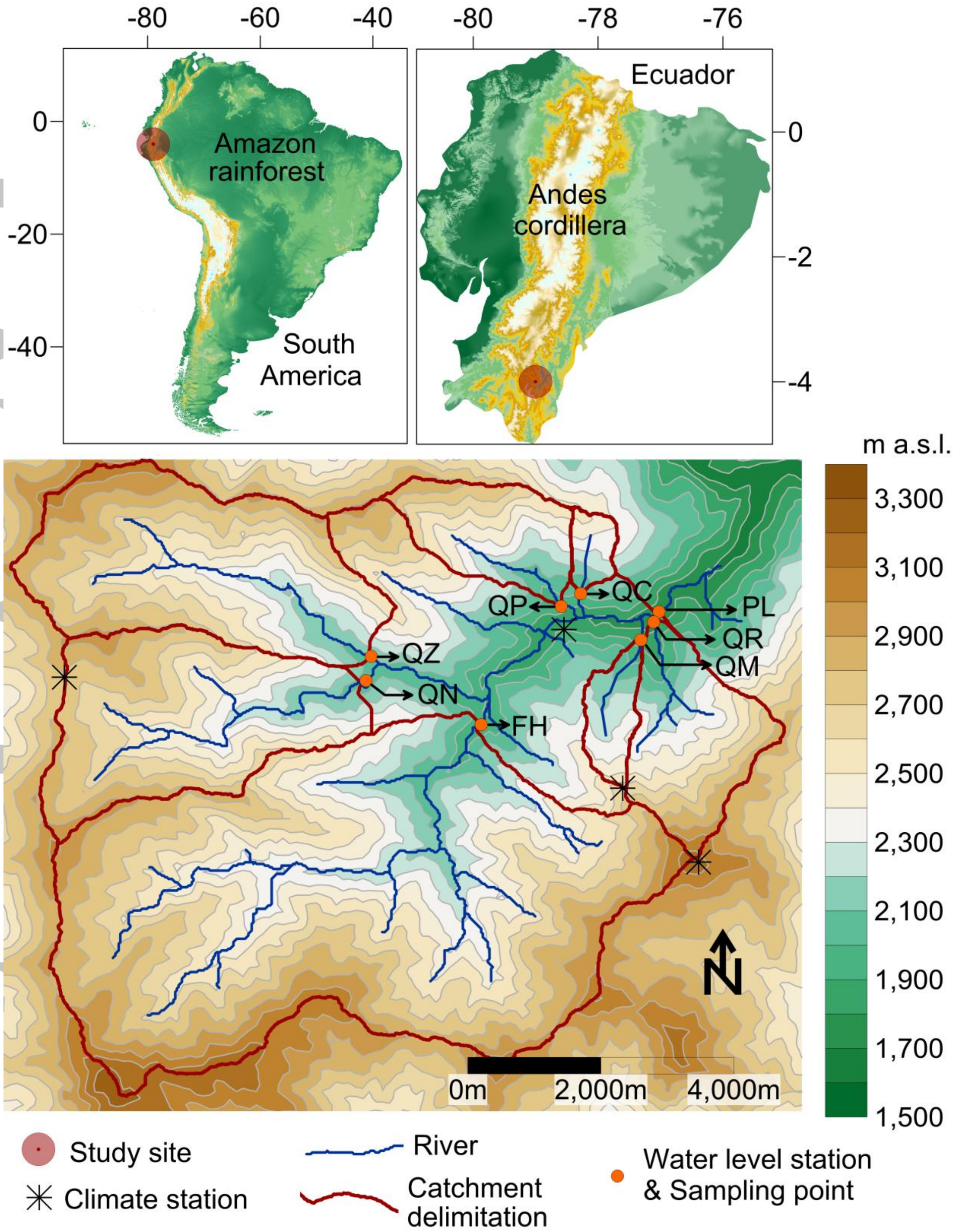

Figure 1. Location and topography of the San Francisco catchment and its tributary sub-catchments: Francisco Head (FH), Zurita (QZ), Navidades (QN), Ramon (QR), Milagro (QM), Pastos (QP) and Cruces (QC). The name of main catchment outlet is Planta (PL).

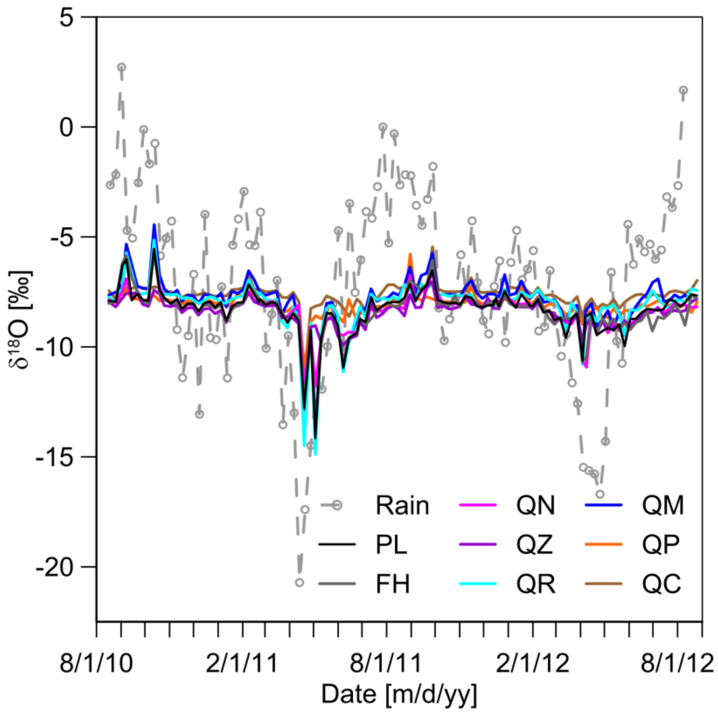

Figure 2. Seasonal variations of water isotope signals of stream water, collected at the main outlet PL and its tributaries: FH, QN, QZ, QR, QM, QP and QC, and for rainfall collected at 1900 m a.s.l. Acronyms are defined in Figure 1.

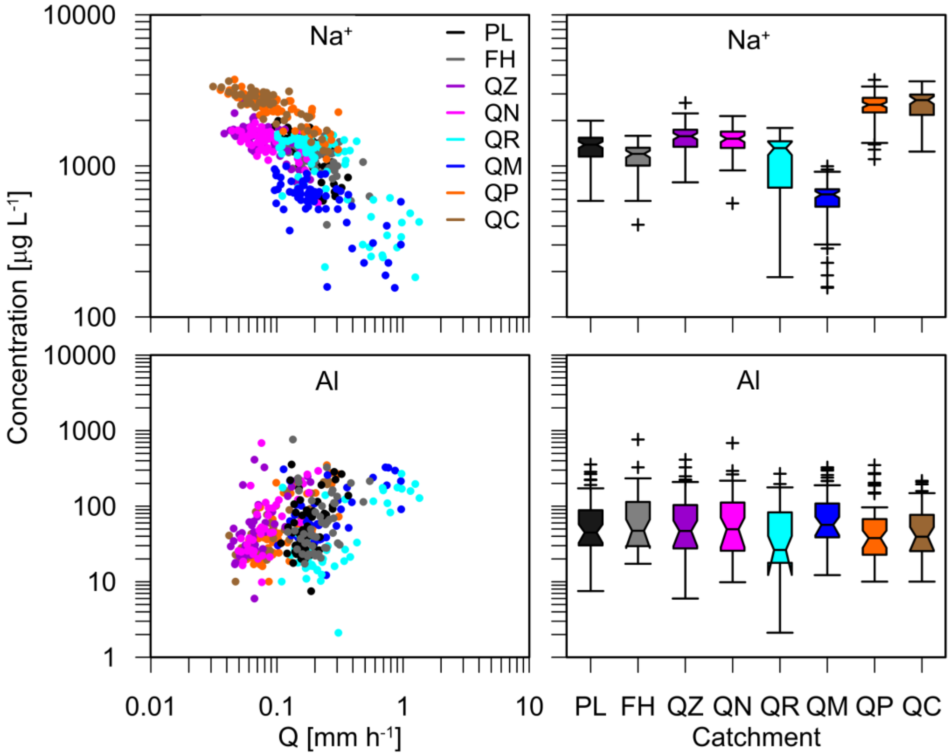

Figure 3. Left column, colored filled dots show observed concentrations of Sodium (*Na*) and Aluminum (*Al*) for the San Francisco stream water and its tributaries corresponding the respective streamflow conditions at sampling. Right column, observed concentrations of *Na* and *Al* of the studied catchments as represented by boxplots (the notches indicate the 95% confidence interval for the medians); values located further away below the first or above the third quartile are considered extreme ones (+). Catchment acronyms are defined in Figure 1.

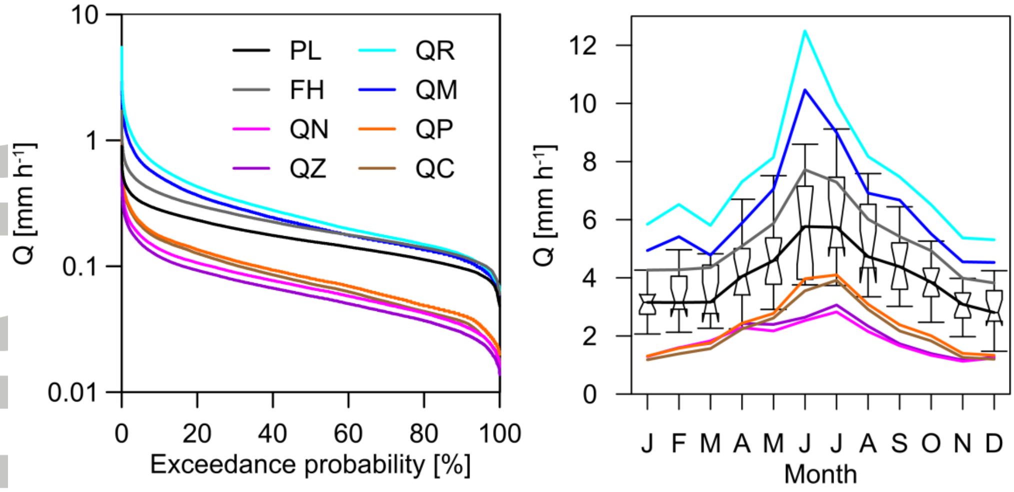

Figure 4. Left, flow duration curves (FDC) for the main catchment outlet PL and its tributaries: FH, QN, QZ, QR, QM, QP and QC. Right, monthly variation of discharge for the referred study units (median values obtained from hydrological modelling for period 1998-2012); boxplots show the monthly variation of discharge at the main catchment outlet PL, notches indicate the 95% confidence interval from the median value. Acronyms are defined in Figure 1.

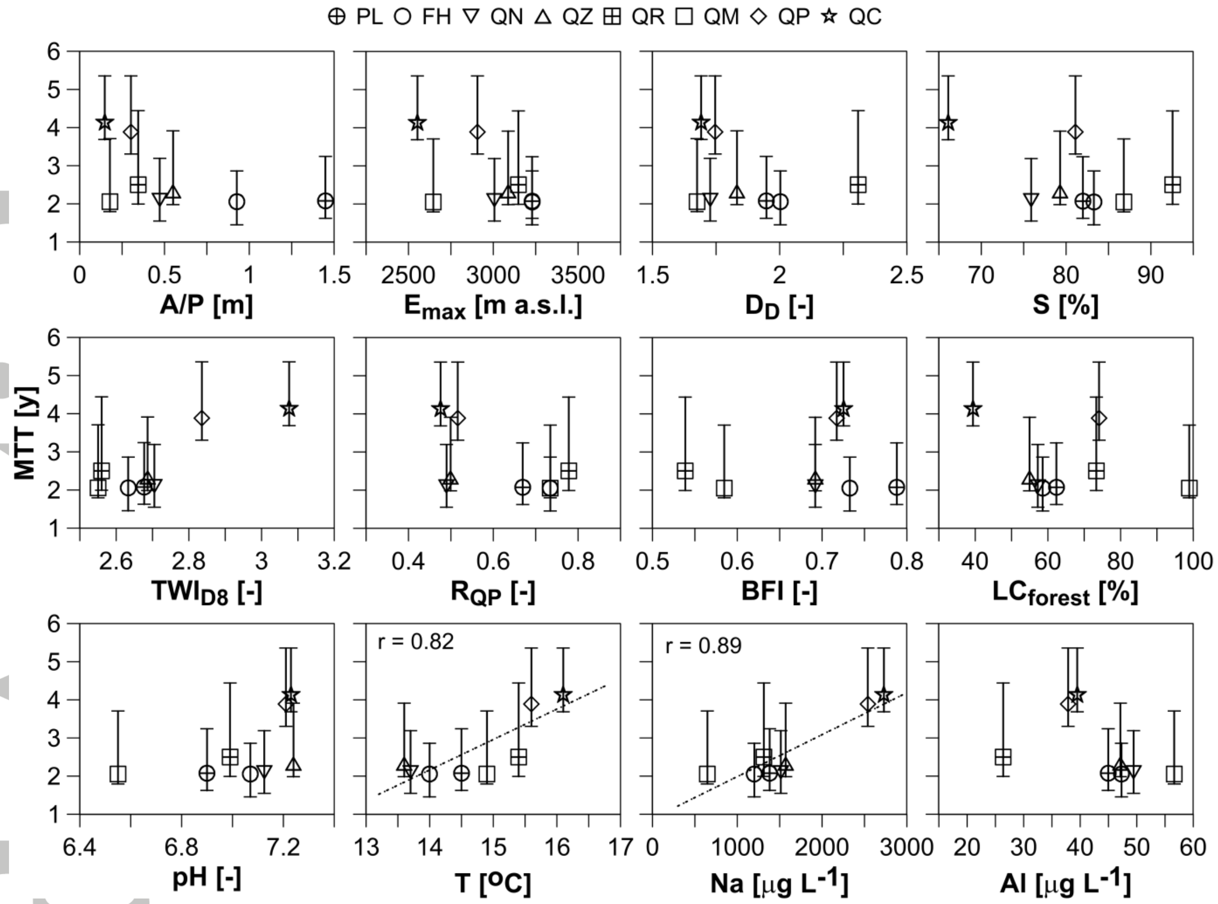

Figure 5. Relationships between baseflow mean transit times MTTs (symbol represents the average value of best predictions provided by GM and EPM models while error bars indicate the averaged 95% confidence limits of those models) and catchment area-perimeter ratio (A/P); catchment's maximum elevation (E_{max}); drainage density (D_D); median catchment slope (S); median topographic wetness index (TWI_{D8}); rainfall-runoff ratio (R_{QP}); baseflow index (BFI); area covered by forest (LC_{FOREST}); median stream water potential of hydrogen (pH) and temperature (T); median stream water concentrations of Sodium (*Na*) and Aluminum (*Al*). Only significant correlations ($| r | \geq 0.7$) are shown.

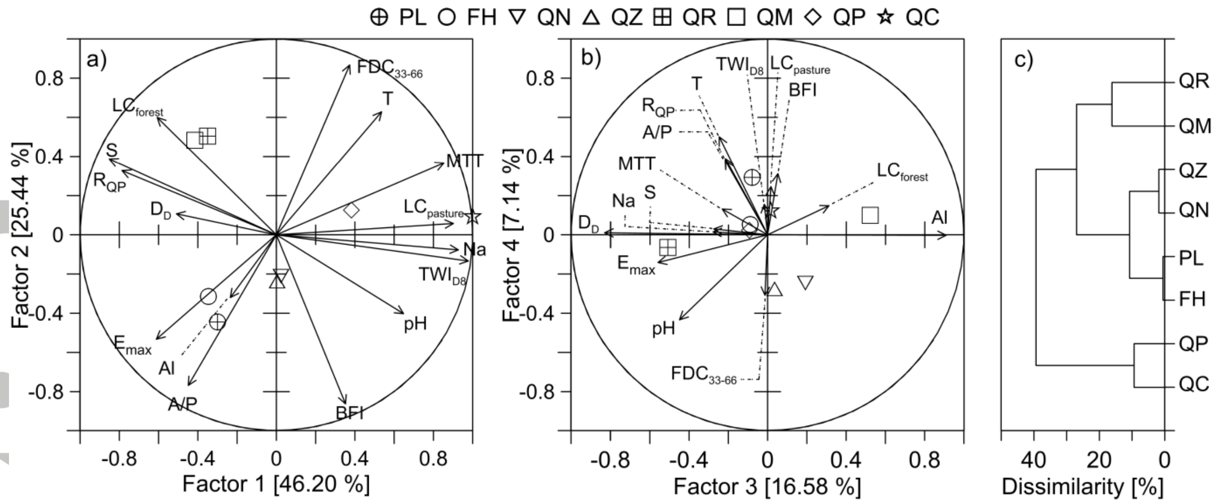

Figure 6. Principal component analysis (PCA) (subplots a and b) and cluster analysis (c) for the San Francisco catchment and its seven tributary sub-catchments. Each catchment was characterized using 15 catchment characteristics (MTT, mean transit time; A/P, catchment area-perimeter ratio; E_{max}, maximum catchment elevation; D_D, drainage density; S, median catchment slope; TWI_{D8}, topographic wetness index; R_{QP}, rainfall-runoff ratio; BFI, baseflow index; LC_{FOREST} and $LC_{PASTURE}$, areas covered by forest and pastures + bracken fern, respectively; pH, median stream water potential of hydrogen; median stream water temperature (T); *Na*, median stream waters concentrations of Sodium; *Al*, median stream water concentration of Aluminum). Arrows indicate the magnitude of component loading. Catchment acronyms are defined in Figure 1.

Table 1. Main characteristics of the San Francisco catchment and its tributaries. Acronyms are defined in Figure 1.

Indicators	Units	Main outlet	Tributary outlet						
		PL	FH	QZ	QN	QR	QM	QP	QC
Transit time									
Mean transit time baseflow	years	2.08	1.97	2.46	2.10	2.83	2.23	4.03	4.23
Land cover indicators									
Forest	%	62.3	58.5	54.9	57.2	73.3	98.9	74.1	39.4
Sub-páramo	%	31.2	38.6	40.3	35.2	25.8	0.0	15.6	0.0
Pasture & bracken	%	3.7	0.7	3.6	3.7	0.2	0.3	8.3	50.8
Land surface indicators									
Area [A]	ha	7674.0	3465.0	1132.8	1008.6	464.4	132.2	339.4	68.8
Max. elevation [E_{max}]	m	3229	3229	3088	3007	3147	2646	2907	2553
Elevation range [E_{rng}]	m	1533	1357	1088	995	1444	794	1017	606
Drainage density [D_D]	km km^{-2}	1.95	2.00	1.83	1.73	2.31	1.68	175	1.69
Area/Perimeter [A/P]	km^2 km^{-1}	1.45	0.93	0.55	0.47	0.35	0.18	0.30	0.15
Median elevation [E]	m	2524	2593	2611	2584	2440	2237	2433	2288
Median catchment slope [S]	%	82.0	83.3	79.3	75.9	92.6	86.8	81.1	66.1
Topographic wetness index [TWI_{D8}]	-	2.68	2.63	2.69	2.70	2.56	2.55	2.84	3.08
Downslope index [DSI]	%	72	73	72	70	84	74	72	60
Hydraulic indicators									
Mean annual specific discharge [S_D]	mm	1546	2028	719	703	2842	2417	849	783
Mean annual specific rainfall [S_R]	mm	2289	2735	1424	1417	3612	3254	1631	1631
Coefficient of Variation [CoV]	-	0.39	0.47	0.59	0.60	0.85	0.77	0.66	0.69
Flow duration curve slope [FDC_{33-66}]	-	1.09	1.21	1.42	1.45	1.69	1.59	1.52	1.64
Flashiness Index [FI_{RB}]	-	0.14	0.19	0.21	0.21	0.37	0.34	0.22	0.22
Mean Annual Peak Flow [MAPF]	mm h^{-1}	0.64	1.20	0.54	0.56	3.58	2.74	0.73	0.71
Mean Annual Low Flow [MALF]	mm h^{-1}	0.08	0.10	0.03	0.03	0.10	0.09	0.03	0.03
Rainfall-Runoff Coefficient [R_{QP}]	-	0.67	0.73	0.50	0.49	0.78	0.73	0.52	0.48
Base Flow Index [BFI]	-	0.79	0.73	0.69	0.69	0.54	0.58	0.72	0.73
Hydro Physicochemical indicators of stream waters									
pH	-	6.90	7.07	7.24	7.13	6.99	6.55	7.21	7.23
Electrical conductivity [EC]	μS cm^{-1}	15.3	13.0	23.9	23.5	14.0	6.2	29.2	29.8
Temperature	°C	14.5	14.0	13.6	13.7	15.4	14.9	15.6	16.1
Sodium [Na]	μg L^{-1}	1382.5	1200.5	1570.5	1514.3	1313.5	647.3	2539.0	2728.5
Calcium [Ca]	μg L^{-1}	1170.0	833.4	1891.5	2130.8	664.7	224.3	1699.0	1783.0
Magnesium [Mg]	μg L^{-1}	393.2	307.8	530.9	443.6	363.2	161.7	798.1	820.1
Potassium [K]	μg L^{-1}	333.8	281.5	359.4	355.8	348.8	265.7	451.2	585.3
Aluminum [Al]	μg L^{-1}	45.0	47.3	47.1	49.5	26.4	56.6	37.9	39.5

[a] The percentage of impervious areas (e.g., road) or water bodies (rivers) is not shown since they have relatively lower values.

Table 2. Number of stream water samples analyzed for their isotopic, physicochemical properties and main element concentrations.

Site	$\delta^{18}O$, $\delta^{2}H$ [a]	pH [a,b]	EC [a]	T [a]	Na [c]	Ca [c]	Mg [c]	K [c]	Al [d]
PL	104	62 (82)	104 (74)	94 (79)	81	79	80	80	56
FH	98	62 (50)	101 (42)	92 (45)	61	61	61	61	47
QZ	103	62 (52)	102 (45)	94 (48)	67	66	67	67	47
QN	104	62 (50)	104 (41)	96 (46)	56	56	56	56	43
QR	104	60 (72)	103 (64)	93 (70)	77	77	77	77	53
QM	104	62 (74)	103 (65)	93 (71)	65	66	67	65	51
QP	103	61 (70)	103 (63)	93 (62)	77	75	77	77	52
QC	102	60 (54)	102 (46)	92 (45)	57	57	57	57	40

[a] According to a weekly sampling scheme, samples for isotopic analysis and in-situ measurements of physicochemical properties (pH, electrical conductivity EC and Temperature T) were performed from August 2010 until August 2012. Values in parentheses correspond to measurements during the sampling campaign for major chemical elements. [b] The harsh moisture conditions of the area caused malfunction of the pH-meter, causing disruptions of the data series. [c] Samples for major elements (Na, Ca, Mg and K) were taken fortnightly since April 2007 until November 2009. Sampling of minor elements like Al started in April 2007 but were discontinued in November 2008.

Table 3. Results of the multiple regression analysis using fifteen selected parameters (indicators) of the catchment.

Parameter	MTT	LC_{forest}	$LC_{pasture}$	E_{max}	D_D	A/P	S	TWI_{D8}	FDC	RQP	BFI	pH	T	Na
LC_{forest}	-0.258													
	0.538													
$LC_{pasture}$	**0.739**	-0.608												
	0.036	*0.110*												
E_{max}	-0.583	-0.102	-0.664											
	0.129	*0.811*	*0.073*											
D_D	-0.249	0.035	-0.392	0.693										
	0.553	*0.934*	*0.337*	*0.057*										
A/P	-0.567	-0.194	-0.361	**0.750**	0.327									
	0.142	*0.645*	*0.379*	***0.032***	*0.430*									
S	-0.461	**0.745**	**-0.817**	0.488	0.663	0.149								
	0.250	***0.034***	***0.013***	*0.220*	*0.073*	*0.725*								
TWI_{D8}	**0.804**	-0.666	**0.920**	-0.542	-0.492	-0.277	**-0.883**							
	0.016	*0.072*	***0.001***	*0.165*	*0.216*	*0.506*	***0.004***							
FDC	0.571	0.204	0.347	-0.649	-0.069	**-0.941**	-0.007	0.204						
	0.139	*0.629*	*0.400*	*0.082*	*0.871*	***0.000***	*0.988*	*0.628*						
RQP	-0.489	0.586	-0.532	0.351	0.659	0.268	**0.826**	**-0.741**	-0.118					
	0.219	*0.127*	*0.175*	*0.394*	*0.076*	*0.522*	***0.011***	***0.035***	*0.781*					
BFI	0.057	-0.600	0.284	0.189	-0.347	0.605	-0.606	0.504	**-0.733**	-0.473				
	0.893	*0.116*	*0.495*	*0.654*	*0.400*	*0.112*	*0.112*	*0.203*	***0.038***	*0.236*				
pH	0.486	**-0.801**	0.414	0.140	-0.023	-0.066	-0.561	0.627	0.015	**-0.707**	0.440			
	0.222	***0.017***	*0.308*	*0.742*	*0.956*	*0.877*	*0.148*	*0.096*	*0.972*	***0.050***	*0.275*			
T	**0.825**	0.078	0.612	-0.588	-0.012	-0.478	-0.124	0.521	0.588	0.015	-0.198	-0.008		
	0.012	*0.855*	*0.107*	*0.126*	*0.977*	*0.231*	*0.770*	*0.186*	*0.125*	*0.973*	*0.639*	*0.985*		
Na	**0.887**	-0.597	**0.751**	-0.352	-0.302	-0.287	-0.693	**0.921**	0.250	**-0.729**	0.430	**0.766**	0.549	
	0.003	*0.119*	***0.032***	*0.393*	*0.468*	*0.491*	*0.057*	***0.001***	*0.551*	***0.040***	*0.288*	***0.027***	*0.159*	
Al	-0.529	0.217	-0.200	-0.198	-0.660	0.140	-0.180	-0.200	-0.379	-0.089	0.239	-0.418	-0.558	-0.452
	0.178	*0.605*	*0.635*	*0.638*	*0.075*	*0.740*	*0.671*	*0.635*	*0.354*	*0.834*	*0.569*	*0.302*	*0.151*	*0.261*

Two values are shown for each catchment indicator (percentages of land covered by forest LC_{forest} or pastures plus bracken fern $LC_{pasture}$, maximum catchment elevations E_{max}, Drainage Density D_D, area-perimeter ratio *A/P*, median catchment slope *S*, Topographic Wetness Index TWI_{D8}, flow duration curve between the 33 and 66% of exceedance probability FDC_{33-66}, rainfall-runoff coefficient R_{QP}, Baseflow Index *BFI*, pH, Temperature *T*, Sodium *Na* and Aluminum *Al* concentrations), values in the top correspond to the Pearson product-moment correlation coefficient (r) and values in the bottom show p-values. Values in bold stand for cases where $r \geq |0.7|$ and p-values < 0.05.