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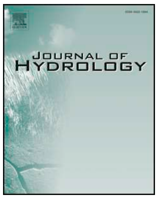

Research papers

Geology controls streamflow dynamics

Claire Carlier*, Stefanie B. Wirth, Fabien Cochand, Daniel Hunkeler, Philip Brunner

Centre for Hydrogeology and Geothermics, University of Neuchâtel, Rue Emile-Argand 11, 2000 Neuchâtel, Switzerland

A R T I C L E I N F O

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A B S T R A C T

Relating stream dynamics to catchment properties is essential to anticipate the influence of changing environmental conditions and to predict flows of ungauged rivers. Although the importance of subsurface processes in catchment hydrology is widely acknowledged, geological characteristics are rarely explicitly included in studies assessing physiographic controls on catchment dynamics. In this investigation of 22 catchments of the Swiss Plateau and Prealpes, we use a simple linear regression approach to analyze the relationship between streamflow indicators and various geological and hydrogeological properties of the bedrock and quaternary deposits, along with meteorological, soil, land use and topographical characteristics. We use long-term discharge percentiles, as well as dimensionless flow duration curves (FDC, standardized by long-term mean discharge) that allow to evaluate the catchment response to climate forcing. While climate conditions dominate the high to medium discharge percentiles (Q5–Q50), the capacity of the catchments to buffer the meteorological forcing can only be attributed to geological characteristics. The sandstone proportion in the catchments explains 54% of the variance of both extremities of the dimensionless FDC (Q5/Qmean and Q95/Qmean) and productive quaternary deposits are responsible of 55% resp. 58% of the variance of the two ratios. Examining the hydrogeological characteristics of both bedrock and quaternary lithologies considerably improves the understanding of catchment dynamics.

1. Introduction

Stream discharge, integrating hydrological processes across various spatial and temporal scales, is a valuable indicator for the assessment of water resources. Understanding stream dynamics implies a thorough characterization of the influence of physical catchment properties on streamflow generating mechanisms. This knowledge is essential for apprehending the behavior of ungauged rivers and predicting the dynamics of gauged ones in response to climate change. Consequently, assessing how catchment properties influence streamflow dynamics is a central topic in hydrological research.

Stream dynamics reflects infiltration, evapotranspiration and interception, overland flow and subsurface flows and is consequently influenced by various catchment characteristics related to vegetation, soil, topography and geology. Numerous studies have been dedicated to assessing the impact of these properties on the catchment response to the meteorological signal, for instance in the framework of hydrological prediction in ungauged basins (*PUB*, see reviews of Hrachowitz et al., 2013 or Blöschl et al., 2013). Another series of studies focuses on expressing the flow duration curve (FDC) based on meteorological and geomorphological attributes (e.g. Müller et al., 2014; Pugliese et al., 2014; Castellarin et al., 2004b; Castellarin et al., 2007; Botter et al., 2007; Doulatyari et al., 2015; Cheng et al., 2012; Coopersmith et al., 2012; Ye et al., 2012). Recession flow in unconfined hillslope aquifers is also a topic studied by many authors using the Boussinesq equation, either solved analytically or numerically (e.g. Brutsaert, 1994; Szilagyi et al., 1998; Verhoest and Troch, 2000, Huyck et al., 2005, Paniconi et al., 2003, Troch et al., 2003, Pauwels et al., 2003; Rocha et al. 2007, Bartlett and Porporato 2018). The relationships between catchment properties and dynamics are also widely used in regionalization methods, which use these established correlations to extrapolate the hydrological understanding of gauged catchments to ungauged ones (e.g. review by Razavi and Coulibaly, 2013).

Among these numerous studies, geological features are rarely considered, while surface properties such as topography, land use and soil are often taken into account. The lack of geological consideration has been pointed out by several authors, e.g. Barthel (2014a), Barthel and Banzhaf, (2016), Haaf and Barthel, (2018). Bloomfield et al. (2009) pointed out the often simplistic representation of geology in studies dedicated to catchment controls on baseflow and advocated for a more systematic quantification of the effect of geology on the baseflow index. Dassargues et al. (1999) also pointed out the necessity to use three-dimensional groundwater models for describing the impact of drought conditions on streamflow regimes. In continuous streamflow

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* Corresponding author.
E-mail address: clacarlier@gmail.com (C. Carlier).

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regionalization studies, Razavi and Coulibaly (2013) highlighted catchment area, elevation, and slope to be the most widely used properties considered by researchers. He et al. (2011) showed that among the 39 characteristics used in several reviewed studies, drainage area is the most frequently used one, followed by land use, slope, soil classification and elevation. They suggest that emphasis should be placed on subsurface descriptors whose influence on catchment dynamics is less understood. Groundwater storage and release mechanisms, defined by geological features, impact catchment dynamics and are of particular relevance during dry periods when the contribution of aquifers to streamflow can be significant (Smakhtnin, 2001). As stated by Oudin et al. (2008) in a comparison of regionalization methods, the difficult characterization of the subsurface remains a major obstacle for the identification of the relevant catchment controls on streamflow based on regression analysis.

Nonetheless, a few studies have integrated geological characteristics and identified the influence of specific lithologies on streamflow. Ward and Robinson (1990) for instance highlighted the role of geology in influencing the FDC shape of catchments in the UK. Based on multiple regression models, Bloomfield et al. (2009) quantified the relative influence of various lithologies on the baseflow index. Both Mayer and Naman (2011) and Jefferson et al. (2008) have shown with their study based in California and Oregon that the geology of the studied catchments significantly determines their response to climate change. Besides, Tague and Grant (2004) pointed out the dominant control of a highly permeable volcanic unit on flow regime of this studied Oregon region. In other studies, the importance of sandstone for streamflow dynamics has been identified. Its influence on mean transit time and its buffering effect on streamflow have been illustrated in two studies in Montana (Jencso and McGlynn, 2011; Nippgen et al., 2011). In Switzerland, the importance of sandstone in sustaining streamflow during dry periods has also been highlighted by Naef et al. (2015). These findings suggest that the bedrock plays an active storage role, as proposed by the hydrologically active bedrock hypothesis (Uchida et al., 2008) and that it can considerably contribute to baseflow (Andermann et al., 2012; Birkel et al., 2014; Welch and Allen, 2012). Especially the hydraulic conductivity of the bedrock seems to be of high relevance for storage processes (Hale et al., 2016; Pfister et al., 2017).

While alluvial aquifers are of major interest in hydrogeology, their effect on streamflow has received little attention in hydrology. It has, however, been shown that these hydrogeological units, although limited in size, can notably impact the catchment outflow under dry conditions (Käser and Hunkeler, 2016). The presence of permeable quaternary deposits can also affect streamflow if infiltration from the stream to the groundwater is important. Naef et al. (2015) showed for instance that catchments for which discharge is measured after an infiltration section are often characterized by lower low flows.

These studies suggest that the understanding of catchment dynamics can benefit from considering the various geological units present in the catchment and their hydrogeological properties. Freeze and Cherry (1979) already articulated the importance of considering a catchment as a combination of the surface drainage area and of subsurface soils and geological formations. They even argued that subsurface hydrological processes might play a predominant role in the hydrological cycle, as subsurface materials govern infiltration rates and thus determine surface runoff. River networks are influenced by the configuration of the water table, which is in turn defined by groundwater processes and the inherent geology. Subsurface flow is constrained by the three-dimensional setting of geological deposits (Freeze and Cherry, 1979) and thus related to topography. Moreover, the hydrogeological properties of the geological formations and especially their hydraulic conductivity determine groundwater flow rates, as expressed by Darcy's law. Moreover, subsurface flow and the associated water table are dependent on recharge and thus on meteorological forcing. Studies by Gleeson and Manning (2008), Haitjema and Mitchell-Bruker (2005), Welch and Allen (2012) have identified the influence of topography, recharge and hydraulic conductivity on subsurface processes, which suggests that these features might also be relevant for catchment dynamics.

Our aim is consequently to improve the understanding of streamflow dynamics by integrating detailed geological descriptors in a study of catchment controls on discharge. The identification of the geological characteristics relevant to streamflow dynamics, along with other possibly important catchment properties, is primarily carried out using simple regression analysis. The influence of the identified descriptors on streamflow indicators is then investigated individually. Although various statistical methods exist to assess this link (Kroll and Song, 2013), this simple approach is preferred to model-based or more complex statistical methods, as it prevents bias from the predefined model structure and parameterization. Moreover, the multicollinearity effects inherent to multiple regression models (Kroll and Song, 2013) are avoided. Our scope is to provide observable predictors for the assessment of catchment dynamics for ungauged catchments or for changing environmental conditions. By quantifying the influence of the various catchment properties on the whole streamflow range, we aim at identifying the relevant physical features for water resources management. Data on geology, soil, land use, topography and meteorological conditions are gathered for 22 Swiss catchments located in the Molasse basin and compared to their long-term streamflow indicators. The discharge indicators are composed of both absolute and normalized (divided by the long-term mean discharge) discharge percentiles. The dimensionless indices allow focusing on the dynamics of catchment response to precipitation (Sauquet and Catalogne, 2011), the meteorological impact being filtered out by the normalization. The use of these various descriptors of stream dynamics might thus enable us to distinguish between the meteorological and the catchment impacts on streamflow indicators.

This study is built on two hypotheses:

- Hypothesis 1: If geology influences low flows (as shown by various studies) by defining the slow-drainage units contributing to the river during dry periods, it should also impact the higher streamflow range, i.e. through storage processes during precipitation events.
- Hypothesis 2: Geology, as it strongly determines storage and release processes, presumably influences the ability of the catchment to buffer the meteorological signal. Its impact on streamflow indicators should be identifiable if geological descriptors actually describe the capacity of geological formations to store and release water.

The paper is structured as follows: A general outline of the methodology and the statistical analysis, the criteria for catchment selection and the associated description of factors such as topography, climatic forcing and geology is provided in the methods section. The results first explore potential cross-correlations between catchment properties, followed by the analysis of the relationship between streamflow indicators as well as the meteorological and catchment properties. In the final sections the results and implications for both hydrology and hydrogeology are discussed.

2. Method and catchment characteristics

The relationship between streamflow indicators of a 20 years period (01.01.1993–31.12.2012) and catchment properties encompassing meteorological, topographical, soil and geological characteristics is analyzed for 22 Swiss rivers using simple linear regression. The investigated time period covers exceptionally dry years (e.g. 2003, 2011) as well as major flood events (e.g. 2005). Data describing topography, soil, land use, geology and hydrogeology, precipitation and evapotranspiration as well as discharge are compiled.

The discharge indicators are obtained from both the absolute and the dimensionless flow duration curves (FDC). The flow duration curve is a widely used tool to characterize streamflow dynamics (see e.g.

review by Smakhtnin, 2001). The dimensionless FDC, obtained by averaging the discharge percentiles by a long-term discharge mean and also known as the “index flow approach”, has been used in various studies, notably for catchment intercomparison and regionalization purposes (Castellarin et al., 2004a; Holmes et al., 2002; Sauquet and Catalogne, 2011; Ganora et al., 2009). The standardization allows focusing on the shape of the curve and hence more on the dynamics rather than on the absolute magnitude of discharge. That way, the dependency of streamflow indicators on climate conditions is minimized and the specificities of the catchment response to meteorological forcing are better identifiable.

The influence of meteorological and catchment characteristics on streamflow dynamics is quantified using a linear regression model between each streamflow indicator and the catchment descriptor. The coefficient of determination R^2 is computed as follows for each relationship and corresponds to the proportion of the variance of the streamflow indicator y explained by the linear model based on the catchment characteristic $LM(p)$, n being the number of studied catchments and i each catchment:

$$R^2 = 1 - \frac{\sum_i^n (y_i - LM(p)_i)^2}{\sum_i^n (y_i - \overline{y})^2}$$

The calculation is also applied between catchment and meteorological characteristics. In this way, potential interdependencies between physical properties and/or climate conditions are identified.

2.1. Catchment selection and description

The geographic location of the 22 catchments is shown in Fig. 1 and the most relevant characteristics are summarised in Table 1. Details on how the indicators have been derived are provided in the following sections. We investigate catchments of the Swiss Plateau and Prealpes, located in the Molasse basin (indicated by yellow lines in Fig. 1). We focus on catchments that are part of the same broad geological environment, the Molasse, to explore in detail its hydrogeological variability and the impact of its different lithologies on streamflow indicators. Besides, this selection excludes regions dominated by glaciers and snow (see “hydrological regime” in Table 1). Additional criteria for the choice of the catchments are the absence of lakes and of important anthropogenic influences, which could influence the water balance (e.g. dams for electricity production or inter-basin water transfers). Finally, the quality of the discharge measurements was also considered, in particular the low-flow range. For example, some measurement stations indicate that below a certain threshold the reliability of the measurements cannot be guaranteed.

The surfaces areas of the catchments range from 0.6 to 416 km^2 and they are located at mean altitudes from 467 to 1159 m. The following hydrological regimes are represented, all of them being characterized by moderate seasonal amplitude: Prealpine nivo-pluvial, superior pluvial, inferior pluvial, Jurassic pluvial (Weingartner and Anschwanden, 1992). The land cover consists principally of a mixture of rural fields and forest.

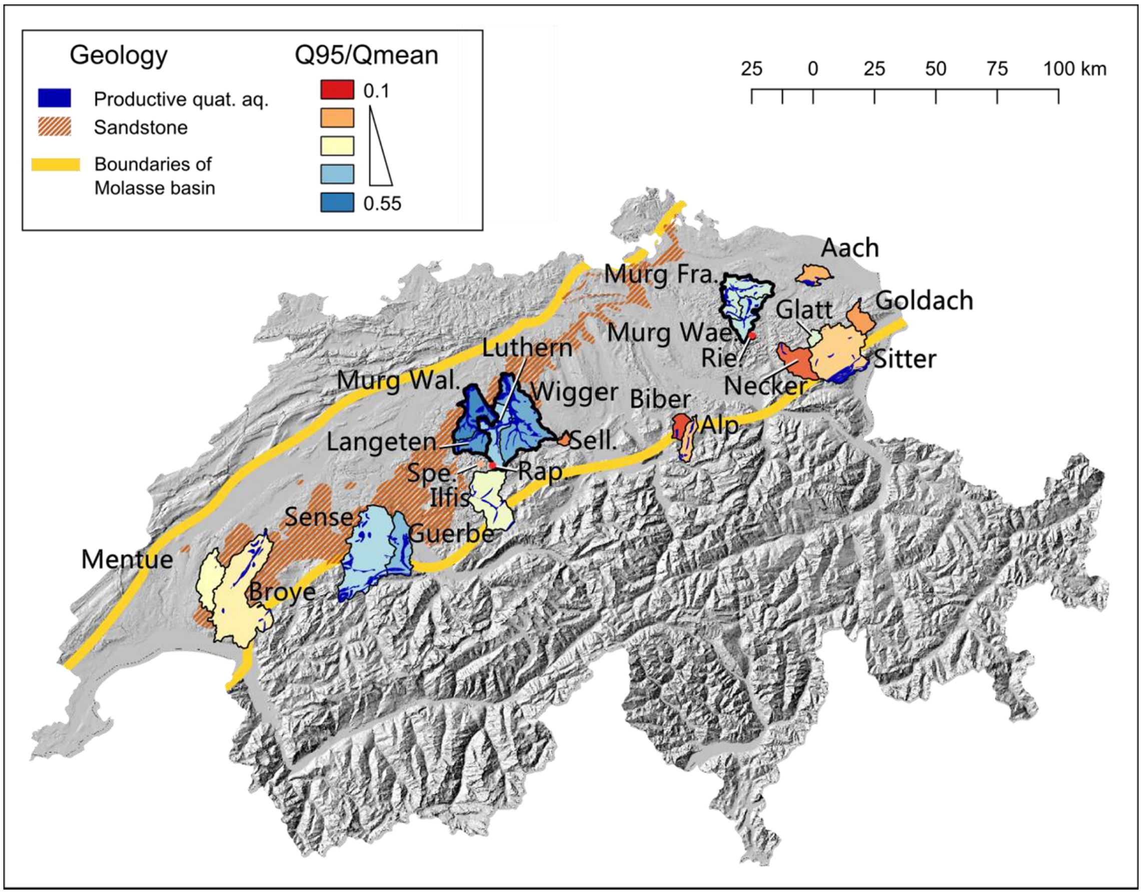


Fig. 1. Location of the 22 investigated catchments in the Swiss Plateau and Prealpes. The results highlighted in this figure are detailed in the discussion. The Molasse basin is approximately delimited by the yellow lines. The presence of sandstone is indicated for whole Switzerland (hatched brown), whereas productive quaternary deposits are only indicated for the selected catchments for visual clarity.

Table 1
Selection of discharge, meteorological, topographical and geological characteristics of the 22 catchments.

Catchments	Hydrological Regime	Qmean [mm/d]	Q5 [mm/d]	Q95 [mm/d]	Q95/ Qmean [-]	Pmean [mm/yr]	ET [mm/yr]	Area [m]	Elevation [m]	% 1st order stream [%]	Mean slope [%]	% 2D prod. aq [%]	Prod. quat. vol. by surface [m]	Bedrock hyd. cond. [m/s]	Sandstone [%]
Aach	Pluvial inferior	1.37	4.32	0.24	0.18	1045	578	47.4	467	45%	3%	13%	0.38	5.05E-08	0%
Alp	Prealpine nivo-pluvial	4.19	13.90	0.79	0.19	2014	369	46.7	1158	55%	15%	16%	0.99	1.00E-06	0%
Biber	Prealpine nivo-pluvial	3.01	10.62	0.44	0.14	1879	478	31.9	1003	55%	11%	6%	0.76	7.25E-07	0%
Broye	Pluvial inferior	1.58	4.88	0.35	0.22	1205	569	415.9	715	49%	7%	6%	1.29	1.14E-05	27%
Glatt	Pluvial superior	3.04	9.33	0.82	0.27	1542	529	16.7	830	52%	10%	0%	0.00	1.00E-07	0%
Goldach	Pluvial superior	2.44	7.73	0.41	0.17	1436	539	50.4	832	52%	11%	1%	0.28	9.78E-06	30%
Guerbe	Pluvial superior	1.97	4.87	0.68	0.35	1284	508	116.2	847	49%	12%	16%	5.02	2.12E-05	66%
Ilfis	Prealpine nivo-pluvial	2.47	6.79	0.66	0.27	1708	546	187.5	1039	57%	17%	7%	0.96	1.90E-07	0%
Langeten	Pluvial inferior	1.78	3.56	0.93	0.52	1322	571	59.9	760	42%	8%	21%	2.95	1.74E-05	55%
Luthern	Pluvial inferior	1.23	3.13	0.41	0.33	1319	582	104.7	750	52%	10%	17%	0.66	2.06E-05	65%
Mentue	Jurassic inferior	1.28	3.64	0.31	0.24	1086	589	105.3	675	46%	5%	1%	0.00	9.49E-06	30%
Murg Waengi	Pluvial inferior	1.98	5.47	0.54	0.27	1351	557	80.2	652	49%	9%	14%	3.80	1.00E-07	0%
Murg Frauenfeld	Pluvial inferior	1.62	4.45	0.44	0.27	1249	566	213.3	597	44%	8%	19%	3.59	1.59E-08	0%
Murg Walliswil	Pluvial inferior	1.57	3.19	0.83	0.53	1235	585	183.4	653	36%	8%	22%	4.07	2.23E-05	70%
Necker	Prealpine nivo-pluvial	3.21	10.48	0.52	0.16	1755	513	88.1	956	57%	14%	2%	0.00	5.50E-07	0%
Rappengraben	Prealpine nivo-pluvial	2.98	10.02	0.40	0.14	1676	610	0.6	1142	78%	18%	0%	0.00	1.00E-07	0%
Rietholzbach	Pluvial superior	2.86	10.13	0.38	0.13	1545	562	3.2	793	72%	11%	0%	0.00	1.00E-07	0%
Sellenbodenbach	Pluvial inferior	1.81	5.64	0.29	0.16	1234	571	10.4	608	48%	5%	0%	0.01	1.00E-09	0%
Sense	Prealpine nivo-pluvial	2.10	5.94	0.59	0.28	1444	491	351.2	1072	55%	14%	7%	0.86	2.55E-05	80%
Sitter	Prealpine nivo-pluvial	3.40	10.65	0.67	0.20	1731	478	261.1	1043	57%	15%	2%	0.01	3.86E-06	10%
Sperbelgraben	Prealpine nivo-pluvial	2.54	7.65	0.52	0.21	1664	610	0.6	1070	66%	19%	0%	0.00	1.00E-07	0%
Wigger	Pluvial inferior	1.33	2.94	0.55	0.42	1220	577	366.2	656	47%	9%	19%	2.02	1.96E-05	62%

2.2. Topography

The geographic information system Quantum GIS (QGIS Development Team, 2014) is used to obtain topographical features and for other operations requiring GIS support. Based on a digital terrain model (DHM25, grid cell resolution of 25 produced by the Swiss Federal of Topography (swisstopo)), the following characteristics are calculated for each catchment (see Table 1): elevation, area, maximum elevation difference, longest distance (straight line) from catchment boundary to outlet ("max. L to outlet"), width to length ratio (aspect ratio), river network density, mean and maximum catchment surface slope, total catchment volume above outlet ("Total vol.") and topographical wetness index ("TWI mean") (see Beven and Kirkby, 1979 for the calculation of the TWI). Combining the digital model and stream order data (Strahler stream order, Swiss Federal Office for the Environment (FOEN)) allows for calculating the following properties: mean slope of 1st order stream ("smallest stream slope"), main river slope, ratio of 1st order stream to total stream network ("% 1st order stream").

2.3. Soil and land use

Land use (Areal statistics 2004/09, Swiss Federal Statistical Office) is classified into 4 categories: rural (vegetated surfaces that are not covered by forest), forested, urban and various (unproductive vegetation or no vegetation). Soil characteristics are derived from the aptitude map of Swiss soils (Swiss Federal Office for Agriculture), that define the following aspects: depth, stone content ("structure"), wetness, hydraulic conductivity and capacity for water storage.

2.4. Geology and hydrogeology

For the characterization of the bedrock geology the GeoCover dataset (1:25000, Geological Vector Datasets, swisstopo) is used. This dataset provides a digitalized compilation of Swiss geological maps that allows evaluating the percentage of selected lithologies at the surface in a certain catchment. With the purpose of a hydrogeological classification of the bedrock occurring in the catchments we first organized the Molasse in four lithologies and then attributed these lithologies with average values for hydraulic conductivity K from existing hydrogeological studies on the Molasse (Balderer, 1997; Gander, 2004; Keller, 1992; Waber et al., 2014). It is noteworthy that few studies aiming at a hydrogeological overview of the Molasse exist. For our study, Keller (1992) is particularly useful because this work discusses the varying Molasse lithologies following a N-S transect through the basin, and it provides average hydraulic conductivities for these lithologies.

The four bedrock lithologies with corresponding hydraulic conductivities for the hydrogeological characterization of the selected catchments are: marine sandstone ("sandstone", $K = 10^{-4}$–10^{-5} m/s), fan conglomerate ("fan", $K = 10^{-6}$–10^{-8} m/s), fine-grained deposit ("fine grained", $K = 10^{-7}$–10^{-11} m/s), and the subalpine Molasse ("sub. Molasse", $K = 10^{-5}$–10^{-7} m/s). The marine sandstone results from deposits in a beach-like environment dominated by tidal processes. These sandstones may represent regional aquifers that are separated from each other by finer-grained deposits (Keller, 1992). The fan conglomerates represent the coarse-grained fluvial deposits deposited proximally to the Alps, while the fine-grained deposits (primarily silt and clay with some sand lenses) represent the distal deposits of the alpine debris. Both are in general considered as aquitards with locally occurring permeable layers (Keller, 1992). The subalpine Molasse is the part of the Molasse that was tectonically overthrusted onto the Molasse basin and that has therefore experienced substantial stress and compaction. Therefore, the subalpine Molasse has a low primary porosity but might be importantly fractured due to uplift and decompression and therefore act as a fractured aquifer.

For every catchment the surface percentage of each lithology is calculated ("% sandstone", "% fan", "% fine grained", "% sub. Molasse") and an average hydraulic conductivity of the bedrock is estimated using the hydraulic conductivities from the literature for the four lithologies (Table 1).

Quaternary hydrogeology is characterized based on available 2D and 3D data. 2D hydrogeological data (Hydrogeological Map of Switzerland: Groundwater Resources 1:500′000, swisstopo) is used to spatially delineate productive quaternary deposits in 2D, obtaining the productive aquifer surface as a percentage of the total catchment area ("% 2D prod. quat"). The GeoMol product, which models the top of the bedrock surface (Diepolder et al., 2013) enables to calculate volumes of quaternary deposits. For each catchment, the raster of the top of the bedrock surface is subtracted from the surface raster. The total volume of quaternary deposits in each catchment and per total catchment area is thus obtained ("Tot. quat. vol. per surface"). The raster of the top of the bedrock is also used to calculate the mean slope of the quaternary base ("Quat. slope"). Combining the GeoMol raster and the 2D hydrogeological map of productive aquifers, it is possible to calculate the productive quaternary volume of each catchment, expressed as volume per total catchment area ("Prod. quat. vol. per surface"). To obtain it, the 2D extent of productive aquifers is used as a clip to extract the volume of productive quaternary deposits from the total quaternary deposits. In doing so, it is assumed that the aquifers marked as productive in the 2D dataset are productive across their entire thickness. The productive quaternary volume is also expressed as percentage of the total rock volume (or "Total vol." defined previously) in the catchment, obtaining "% Prod. quat vol.".

2.5. Precipitation and evapotranspiration

Daily precipitation data for the studied period (01.01.1993-31.12.2012) are calculated from gridded data (Frei, 2014) provided by the national meteorological service of Switzerland (MeteoSwiss) by averaging the spatially distributed values for each catchment area. Mean annual actual evapotranspiration is obtained from the spatially distributed model proposed by HADES (Hydrological Atlas of Switzerland, Table 4.1; see also https://www.bafu.admin.ch/bafu/en/home/topics/water/state/maps/hydrological-atlas-of-switzerland-hades.html). The number of dry days per year is averaged over the 20 years studied. In order to evaluate precipitation dynamics, daily precipitation intensities are sorted separately for each year in the decreasing order. These classified values are then averaged over the 20 years and plotted against the number of days per year when the intensity is reached. The obtained curve is comparable to the flow duration curve (FDC, see section 2.6) for streamflows. For each catchment the obtained "precipitation duration curve" is fitted with the following equation: $PDC(d) = a + b/d^k$, d being the days (1–365), and a, b and k (referred to as PDC_a, PDC_b and PDC_k) the calibrated parameters used to quantify the precipitation dynamics.

2.6. Discharge

All the investigated rivers are part of the Swiss national river-monitoring network and daily discharge measurements for the period 01.01.1993-31.12.2012 are obtained from the FOEN. Three catchments of the selection are nested in other basins: Langete in Murg (Walliselen), Luthern in Wigger and Murg (Wängi) in Murg (Frauenfeld).

To assess the general behavior of the 22 catchments, streamflow indicators are based on the 20 years period (01.01.1993–31.12.2012). Streamflow is described by means of (1) absolute percentiles of discharge (Q5 to Q95 expressed in mm/day), (2) ratios of percentiles Q5/Q50, Q95/Q50 and Q95/Q5 and (3) ratios and characteristics derived from the dimensionless flow duration curve FDC_{norm}. The percentiles are obtained from the flow duration curve FDC that is calculated for each year and averaged over the 20 year period. The absolute values describe the magnitude of discharge from high flows (Q5, the discharge exceeded 5% of the time) to low flows (Q95, the discharge exceeded 95% of the time). The normalized flow indicators (2) and (3) allow filtering out the effect of climate and water balance issues and can thus be interpreted as descriptors of how catchments buffer the meteorological signal. From now on we refer to these indicators as "normalized streamflow" indicators, as opposed to absolute streamflow indicators. We define the buffering potential as the dampening effect the catchment exerts on the precipitation signal: the more stable the streamflow dynamics, the higher this buffering potential. Conversely, a low buffering potential implies erratic stream dynamics with high peaks and low flows close to zero.

The ratios Q5/Q50 resp. Q95/Q50 describe the variability of flows in the higher resp. the lower part of the FDC, whereas, Q95/Q5 is the ratio between low and high flows. The dimensionless flow duration curve FDC_{norm} is obtained by normalizing the flow percentiles with a long-term index flow generally corresponding to the mean annual discharge. The yearly absolute discharge percentiles are divided by the yearly mean, and the resulting yearly FDC_{norm} is averaged over the 20 years. Specific points of the FDC_{norm} are analyzed in this study: the standardized high flow and low flow percentiles Q5/Qmean resp. Q95/Q_{mean}. The shape of the FDC_{norm} is also quantified with a parametric approach: the curve is fitted with the following equation: $\text{FDC}_{\text{norm,calc}}(d) = a + b / d^k$, d being the days (1 to 365), and a, b and k the calibrated parameters. The calibration is done on the logarithmic value of the FDC_{norm} to best reproduce low-flow dynamics. The k parameter of the equation, $k_{\text{FDC,norm}}$ is used as streamflow indicator to describe the shape of the curve.

2.7. Water balances

A first step towards assessing the catchment response to the meteorological forcing is to assess the long-term water balance, which is established by averaging the equation terms (net precipitation and catchment outflow) over numerous years to exclude storage effects from one year to the other. The ratio of annual discharge to annual net precipitation (precipitation-evapotranspiration) is thus averaged for the 20 years period. To account for the uncertainty related to the estimation of evapotranspiration, the ratio is calculated with 10% higher and lower evapotranspiration rates. The resulting ratio with uncertainty margins is plotted in Fig. 2. The majority of the catchments have ratios close to one, which indicates that their water balance is closed.

However, the ratio is consequentially smaller than one even when considering uncertainty margins for the following river catchments: Biber, Ilfis, Luthern, Sense and Wigger. In the case of Luthern, surface flow constitutes only 60% of the net input to the catchment. This indicates that an important amount of water might exit the catchment as groundwater, "unnoticed" by the gauging station. The hydrometric stations should ideally be located on a geological unit that is impervious enough to prevent substantial groundwater flow under the station. This is, however, not the case for all catchments: except for the Biber, the location of the gauging stations of the catchments with Q/(P-ET) ratios lower than 1 is not adequate, as they are situated on top of permeable quaternary deposits. For the Luthern and Wigger catchments, a local study (Arbeitsgemeinschaft Grundwasserforschung Luthern- und Wiggertal, 1978) estimates the groundwater flow in the river section close to the gauging stations to $0.108\,\text{m}^3/\text{s}$ resp. $0.367\,\text{m}^3/\text{s}$. The water balance ratios corrected with the groundwater flow are shown in red in Fig. 2. In both cases the ratio increases, although the improvement is limited. Further reasons for the inability to close the water balance could be higher evapotranspiration and precipitation uncertainties, a discrepancy between the hydrological and the hydrogeological catchment leading to groundwater losses to neighboring catchments, or inter-basin transfers that have not been identified. Although the water balance discrepancies are not corrected, identifying catchments with unclosed water balances can help to identify a biased interpretation of catchment dynamics.

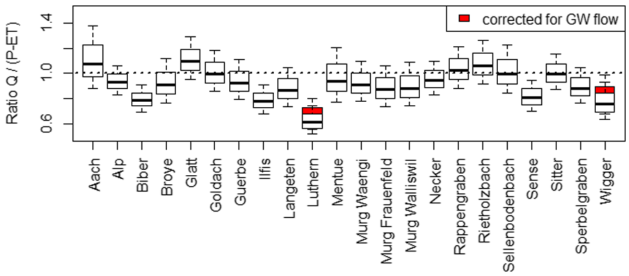


Fig. 2. The ratio of discharge to net precipitation is illustrated for the 22 catchments with a 10% uncertainty margin for ET. In red: ratios for Luthern and Wigger are corrected by taking into account the groundwater discharge flowing under the gauging station. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Analysis of interdependency among catchment properties and meteorological conditions

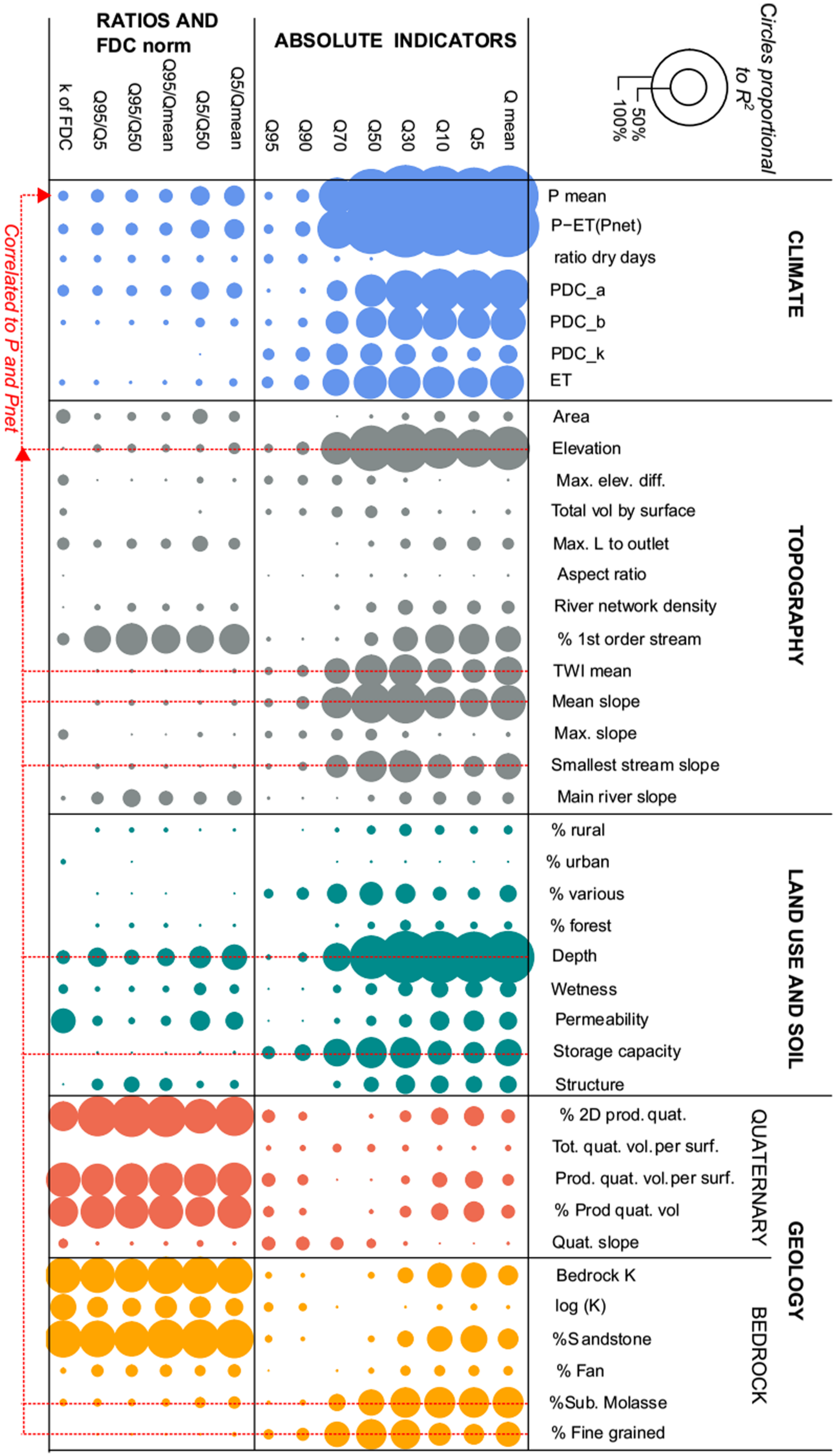
Before analyzing the influence of catchment properties and precipitation on streamflow indicators, the interdependency among meteorological, topographical and geological characteristics is assessed. Identifying potential cross-correlations between the descriptors is crucial to avoid attributing an effect of a specific catchment property on streamflow that is actually due to another characteristic. Mean elevation and mean net precipitation are strongly linearly and positively correlated ($R^2 = 74\%$) due to orographic lifting. Consequently, various catchment properties that vary with altitude also exhibit a notable correlation with meteorological conditions. The following topographical properties are affected: mean catchment slope, smallest stream slope and the topographical wetness index are correlated to elevation (R^2 of 86%, 78% resp. 68%) and to mean net precipitation (R^2 of 59%, 47% resp. 44%). The soil depth and storage capacity decrease with elevation (R^2 of 61% resp. 71%) and are also correlated to mean net precipitation (R^2 of 81% resp. 60%). The high correlation between mean net precipitation and soil depth is due to both the elevation dependency of soil characteristics, and the fact that the evapotranspiration values used in this study are calculated based on the soil depth data. Finally, the percentage of subalpine Molasse and fine-grained material are to a lesser extent correlated to mean net precipitation (R^2 of 51% resp. 39%), which can partially be attributed to the dependency on altitude (R^2 of 28% resp. 46%). For all the mentioned catchment characteristics, potential correlations to streamflow indicators should be considered with care: as precipitation likely strongly governs streamflow, the listed properties might be correlated to discharge indicators even though no physical link exists between them.

Besides, the estimated hydraulic conductivity of the bedrock of each catchment (see methodology section) is highly correlated to the percentage of sandstone present in the catchment ($R^2 = 99.5\%$). Sandstone is characterized by the highest hydraulic conductivity among the identified lithologies and thus exerts a dominating impact on the estimated hydraulic conductivity for catchments with sandstone. For the catchments lacking sandstone, the influences of the other lithologies on the calculated hydraulic conductivity are mixed.

3.2. Relationship between streamflow indicator, catchment and meteorological properties

3.2.1. Overview

Fig. 3 gives an overview of the influence of all climate and catchment characteristics on streamflow indicators and allows identifying



(caption on next page)

Fig. 3. Illustration of the percentage of the explained variance of each streamflow indicator (rows) by each catchment descriptor (columns), based on linear regression. The diameter of the circles is proportional to the R^2 of each relationship. The red dotted lines indicate catchment properties that are correlated to mean net precipitation (see section 3.1).

relevant characteristics for stream dynamics whose importance will be quantified and discussed in next section. In total, 33 catchment properties describing topography, soil, land use and geology and 7 meteorological indices are compared to 14 streamflow indicators. Streamflow indicators are split into two groups: indicators based on absolute numbers (discharge percentiles and mean discharge) and indicators related to the normalized flow duration curve along with ratios of discharge percentiles.

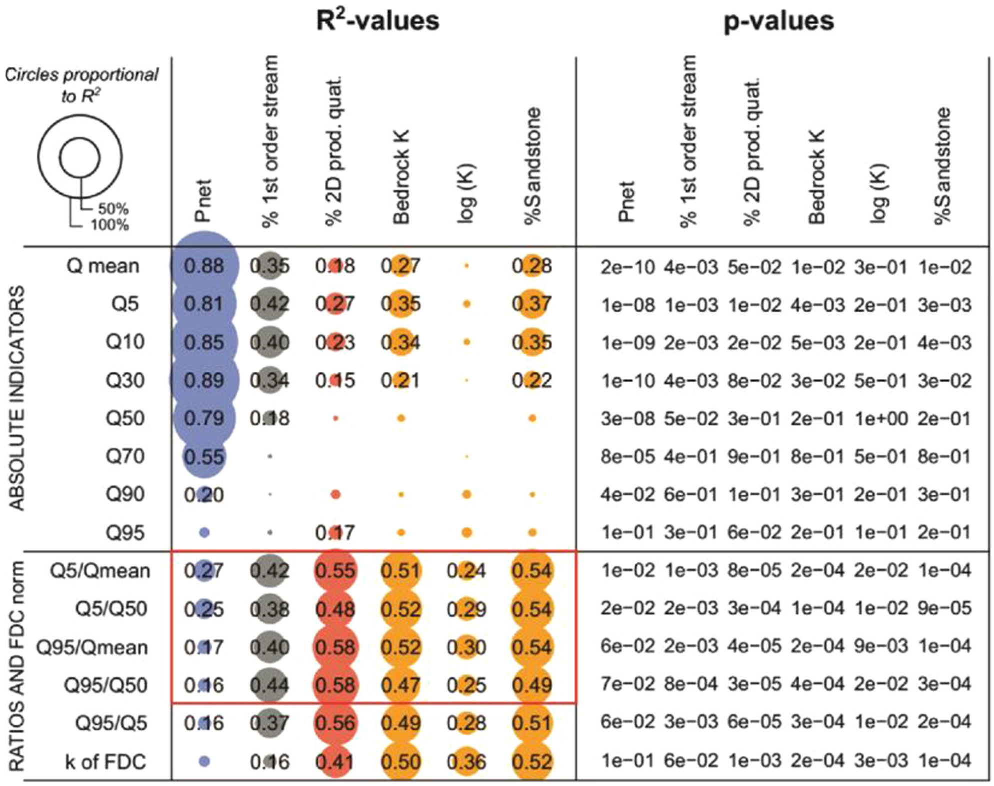
The control of mean precipitation (P mean) and net mean precipitation (P-ET) on the absolute discharge percentiles Q5–Q70, i.e. except the lower ones, is obviously dominant. Most of the catchment properties that seem to influence absolute streamflow indicators correspond to the characteristics that are strongly correlated to precipitation, as indicated by the red vertical dotted lines in Fig. 3. Other features such as the proportion of 1st order stream and bedrock hydraulic conductivity (K bedrock) show a certain relationship to the indicators based on absolute numbers, but their impact is negligible compared to the dominant control of precipitation on these indicators. The discharge indicators Q90 and Q95, describing low flows, are the only streamflow indicators that are not correlated significantly ($R^2 < 20\%$) to any catchment or climate characteristics.

The results are distinctly different from the relative indicators. By expressing streamflow dynamics with ratios or percentiles normalized by mean discharge, the impact of precipitation is excluded as illustrated by the small variance explained by meteorological properties. Consequently, the catchment properties correlated to precipitation and thus to absolute streamflow indicators are not correlated to the relative streamflow indicators. The only characteristics revealing a notable relationship to the indicators describing streamflow dynamics are the geological properties: especially the quaternary feature "% 2D prod. quat." (the surface proportion of catchment occupied by productive quaternary deposits) as well as the bedrock hydraulic conductivity and thus the proportion of sandstone are relevant. Also worth mentioning is the higher influence of the productive quaternary descriptors ("Prod. quat. vol. per surface", "% Prod. quat. vol.") compared to total quaternary descriptors ("Tot. quat. vol. per surface"). The proportion of 1st order stream and to a lesser extent the depth and hydraulic conductivity of the soil characteristics explain a certain part of the variance of the relative indicators, even though their explanatory value is smaller.

3.2.2. *Assessment of the influence of identified relevant characteristics on streamflow dynamics*

Based on the previous section, the characteristics exerting the highest influence on streamflow indicators ($R^2 > 40\%$) are selected for further investigation (see Fig. 4, detailed version of Fig. 3). Catchment properties that are correlated to precipitation and thus to specific absolute streamflow indicators are left out, as we assume that precipitation, the input to the catchment, is the main driver of streamflow magnitude. For climate forcing, only mean net precipitation is kept. For quaternary features, we here focus on the proportion of productive 2D quaternary deposits, as the correlation is slightly higher than for the 3D descriptor and the 2D descriptor is easier to obtain. The importance of the 3D characteristic will, however, be subsequently discussed.

3.2.2.1. Absolute streamflow indicators. Net mean precipitation (P-ET) explains 88% of the variance of mean discharge and between 81% and 89% of the variance of the discharge percentiles characterizing the higher part of the absolute flow duration curve (Q5 to Q30). From Q30 to the low-flow indicator Q95, a clear decreasing trend of the importance of precipitation on discharge percentile is observed. Only 20% of the variance of Q90 is for instance explained by mean net precipitation and the correlation is insignificant for Q95 (p-



		R^2-values						p-values					
		Pnet	% 1st order stream	% 2D prod. quat.	Bedrock K	log (K)	%Sandstone	Pnet	% 1st order stream	% 2D prod. quat.	Bedrock K	log (K)	%Sandstone
ABSOLUTE INDICATORS	Q mean	0.88	0.35	0.18	0.27		0.28	2e−10	4e−03	5e−02	1e−02	3e−01	1e−02
	Q5	0.81	0.42	0.27	0.35		0.37	1e−08	1e−03	1e−02	4e−03	2e−01	3e−03
	Q10	0.85	0.40	0.23	0.34		0.35	1e−09	2e−03	2e−02	5e−03	2e−01	4e−03
	Q30	0.89	0.34	0.15	0.21		0.22	1e−10	4e−03	8e−02	3e−02	5e−01	3e−02
	Q50	0.79	0.18					3e−08	5e−02	3e−01	2e−01	1e+00	2e−01
	Q70	0.55						8e−05	4e−01	9e−01	8e−01	5e−01	8e−01
	Q90	0.20						4e−02	6e−01	1e−01	3e−01	2e−01	3e−01
	Q95			0.17				1e−01	3e−01	6e−02	2e−01	1e−01	2e−01
RATIOS AND FDC norm	Q5/Qmean	0.27	0.42	0.55	0.51	0.24	0.54	1e−02	1e−03	8e−05	2e−04	2e−02	1e−04
	Q5/Q50	0.25	0.38	0.48	0.52	0.29	0.54	2e−02	2e−03	3e−04	1e−04	1e−02	9e−05
	Q95/Qmean	0.17	0.40	0.58	0.52	0.30	0.54	6e−02	2e−03	4e−05	2e−04	9e−03	1e−04
	Q95/Q50	0.16	0.44	0.58	0.47	0.25	0.49	7e−02	8e−04	3e−05	4e−04	2e−02	3e−04
	Q95/Q5	0.16	0.37	0.56	0.49	0.28	0.51	6e−02	3e−03	6e−05	3e−04	1e−02	2e−04
	k of FDC		0.16	0.41	0.50	0.36	0.52	1e−01	6e−02	1e−03	2e−04	3e−03	1e−04

Fig. 4. Selection of Fig. 3 illustrating only the catchment properties that explain a significant part of the variance of some streamflow predictors ($R^2 > 40\%$, except log(K)). Catchment properties that are correlated to precipitation (red lines in previous figure) are left out. The ratios on the left indicate R^2, whereas the corresponding p-values are given on the right. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

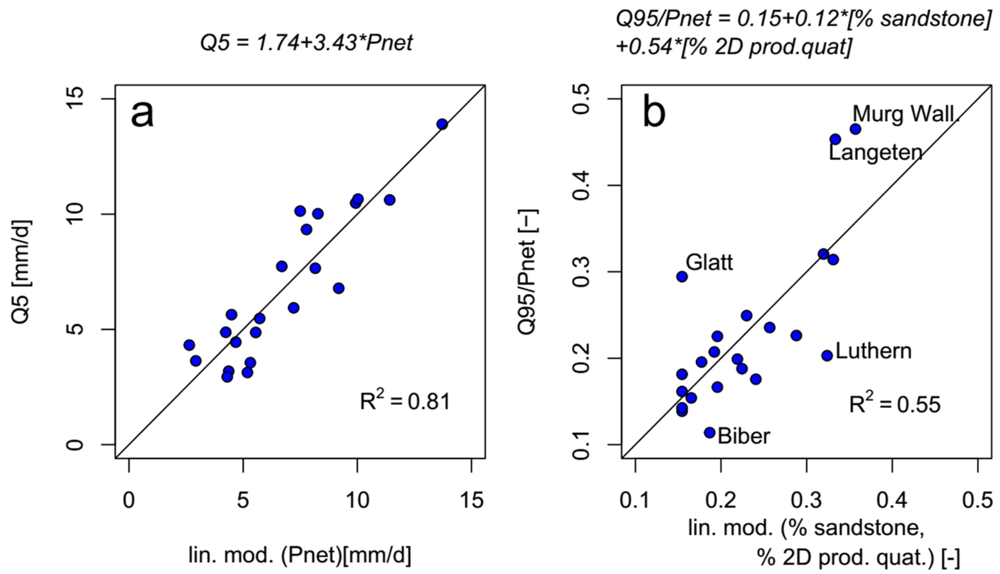


Fig. 5. Simple linear regression between mean net precipitation and Q5 (a, high flow, p-value: $9.74e^{-9}$) and multiple linear regression based on sandstone and productive quaternary aquifer to estimate the ratio between Q95 and mean net precipitation (b, low flow, p-value: $7.19e^{-5}$).

value = 0.1). As mentioned previously, no catchment or climatic characteristic explains a substantial proportion of the variance of Q95.

This is further illustrated in Fig. 5. The coefficient of determination for the Q5 estimation based on mean net precipitation is of 81% (p-value: $9.74e^{-9}$). As Q95 is both dependent on precipitation and catchment properties, we divide the indicator by the net mean precipitation to focus on the influence of the latter (Q95/Pnet, right subplot b). In the x-axis, a linear regression model composed of the percentage of sandstone and the percentage of productive quaternary deposits, whose parameters are fitted against Q95/Pnet (see equation above Fig. 5 b). The correlation between Q95/Pnet, or the part of net precipitation that will be released during dry periods, and the model based on geological parameters is characterized by a R^2 of 55% (p-value: $7.19e^{-5}$). For the Biber and especially the Luthern catchments, the Q95/Pnet ratio is considerably underestimated by geological factors. As indicated by their unclosed water balance (Fig. 2), this discrepancy might be due to groundwater flowing out of the catchment without being measured at the gauging station. In the case of the Glatt, Langeten and Murg Walliswil catchments, actual low flows are higher than the estimation based on sandstone and quaternary deposits. Other storage units in the catchment such as soil or local geological units that are not accounted for might contribute substantially to the stream in the absence of rain.

3.2.2.2. Streamflow ratios and dimensionless FDC descriptors. The normalised flow percentiles describing both the high (Q5/Qmean, Q5/Q50) and the low (Q95/Qmean, Q95/Q50) parts of the dimensionless flow duration curve (highlighted by a red rectangle in Fig. 4) are characterised by similar percentage of explained variance attributed to the catchment properties: 37–44% by the topographical feature "% of 1st order stream", 48–58% by the proportion of productive quaternary aquifer, 47–52% by the hydraulic conductivity of bedrock and 49–54% by the proportion of sandstone, with p-values equal or smaller to 10^{-3} for all these relationships (Fig. 4). The recession parameter of the dimensionless flow duration curve ("k of FDC"), which also describes its shape, is slightly more correlated to bedrock (50–52%) than to quaternary (41%) characteristics, and not significantly explained by the topographical feature (16%).

As expected, due to their high interdependency, bedrock hydraulic conductivity and proportion of sandstone indicate similar R^2 values. The correlation between the logarithm of the hydraulic conductivity of the bedrock and relative streamflow indicators is, however, rather limited (R^2 of 24–36%). This suggests that the hydraulic conductivity of the bedrock might be a less efficient predictor for catchments with low hydraulic conductivity (i.e. the catchments without sandstone). When the hydraulic conductivity of bedrock is limited, other catchment characteristics potentially have a higher explanatory potential. Moreover, the variability of estimated hydraulic conductivities in the absence of sandstone is smaller as the permeabilities of the other geological lithologies are more similar. Among these remaining geological units, none seem to exert a dominant impact on streamflow.

Fig. 6 illustrates the relationship between the relevant catchment characteristics (% sandstone and % productive quaternary deposits) and the normalized high (Q5/Qmean) and low (Q95/Qmean) flow percentiles discussed above. Higher proportions of permeable geological units (sandstone and quaternary deposits) generally imply higher normalized low flow (subplots a and b) and lower normalized high flow percentiles (subplots c and d).

Fig. 7 explores in more detail the relationships between geology and the normalized discharge indicators. In the left scatter plots (a and b), the normalized high and low discharge percentiles are strongly correlated (R^2 = 93%) to each other. The location of the catchment along that line strongly depends on geology, as indicated by the size of circles that are proportional to the sandstone proportion (a) and to the proportion of productive quaternary deposits (b).

On the right side of Fig. 7 (c), catchments are sorted according to decreasing Q95/Qmean, the classification hence approximately following the high-low percentile correlation line from top left to bottom right of subplots a and b. High Q95/Qmean and low Q5/Qmean ratios imply moderate streamflow dynamics and reflect a high buffering potential of the catchment, which substantially dampens the precipitation signal. The 6 catchments with the highest buffering potential correspond to the basins composed of the highest percentage of sandstone (orange bar plots, 60 to 80%). In the 6 cases, the proportion of productive quaternary deposits (coral bar plots) is also significant.

The buffering potential of the catchment is not guaranteed for high proportion of productive quaternary only, as illustrated for instance by the Alp and Aach catchments. To better quantify the importance of quaternary deposits, the volume of productive quaternary averaged by catchment area is included in black in Fig. 7. The productive quaternary deposits, although covering a considerable percentage of the Alp and the Aach catchments, are rather limited in terms of volume, which

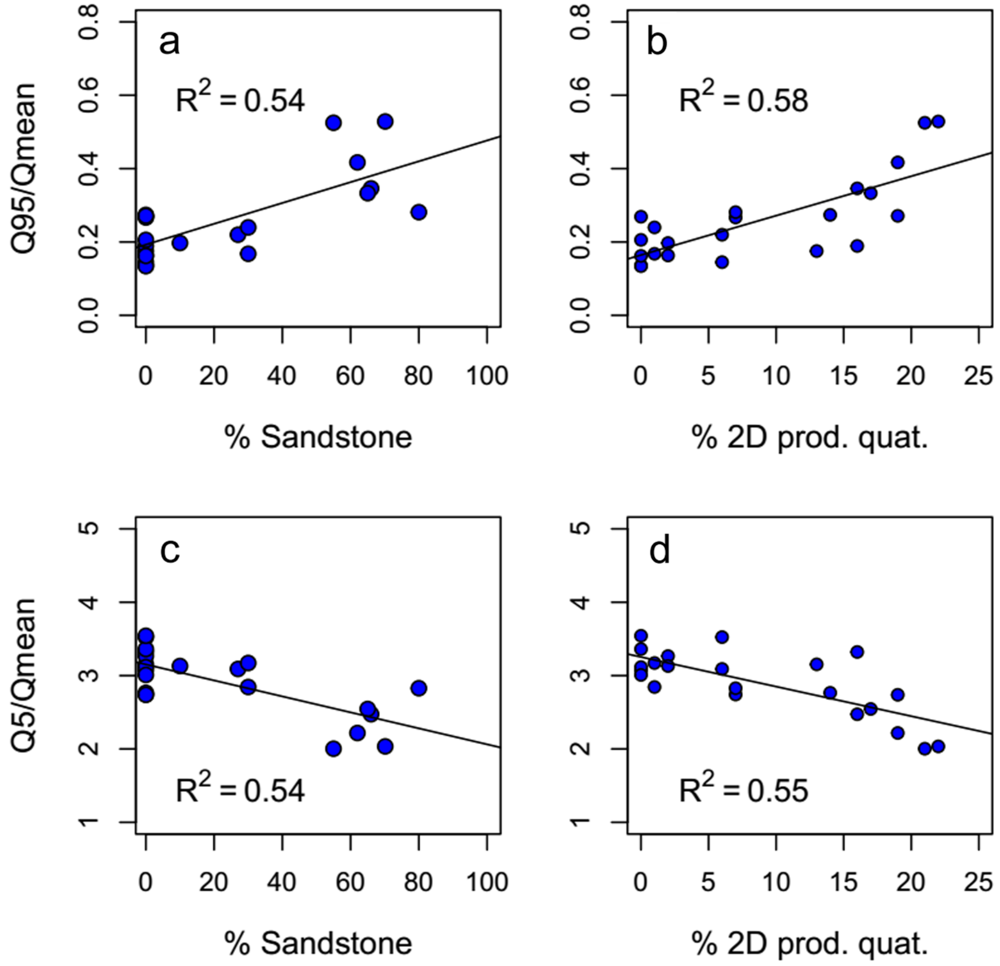


Fig. 6. The normalized low and high discharge percentiles, Q95/Qmean (top) and Q5/Qmean (bottom) are plotted against the surface percentage of sandstone (a and c) and of productive quaternary deposits (b and d). The p-values are all below $1e^{-5}$.

might explain the relatively low buffering potential of the two basins. The Guerbe catchment is characterized by the more important relative volume of productive quaternary. Despite these important deposits and similar sandstone percentage, its buffering potential is lower than in the case of Murg Walliswil, Langeten and Wigger. A more detailed investigation of the valley fillings of the Guerbe valley based on the Hydrogeological Map of Switzerland (Sarine region, 1:100′000, swisstopo) indicated, however, that the deposits are rather heterogeneous with local fine-grained and lacustrine clay units that act as an aquitard. The volume of productive quaternary deposits is therefore overestimated in the case of the Guerbe. Considering this correction, Fig. 7 thus suggests that, for catchments with a high percentage of sandstone, the volume of productive quaternary deposits (averaged by surface) might be the second factor determining the buffering potential of the catchment. We also observe that the Murg Waengi and Murg Frauenfeld catchments, although lacking sandstone, have a relatively high buffering potential that might be owed to the very important volume of productive quaternary deposits.

4. Discussion

4.1. Climate and catchment controls on streamflow dynamics

Numerous catchment properties describing topography, soil, land use and geology, as well as meteorological characteristics are compared to both absolute and normalized streamflow indicators. While climate forcing is dominant on the high to medium absolute flow indicators, this influence decreases for low flows and the buffering influence of the catchment becomes relevant. These results are consistent with the findings of Yaeger et al. (2012) who showed that, whereas the middle part of the flow duration curve is influenced by the precipitation, the low-flow end of the curve reflects catchment characteristics. Moreover, our results show that the use of the dimensionless flow duration curve and discharge indicators indeed allow distinguishing how the catchment buffers the precipitation signal.

Based on the results illustrated in Fig. 3, we propose a conceptualization of climate and catchment control on absolute and normalized long-term flow duration curve (Fig. 8).

Both high- and low-flow normalized percentiles (Q5/Qmean and Q95/Qmean), i.e. the two vertical extremes of the curve, are dominated by the physical catchment properties and are highly correlated to each other. Catchments with high Q95/Qmean and hence relatively high low flows feature an important buffering potential. For these catchments, storage is substantial during precipitation events and their normalized high flows are thus limited. The dimensionless flow duration curve of such catchments will be flatter than for catchments with low buffering potential, their curve following more closely the dynamics of precipitation. This distribution of streamflow between high and low ranges, i.e. the shape of the normalized curve, depends mainly on catchment properties.

Although the mean net precipitation varies considerably among the 22 studied catchments (up to 1000 mm yearly difference), the seasonal distribution of precipitation is rather homogeneous due to their proximity and relatively small differences in altitude. In this study, the

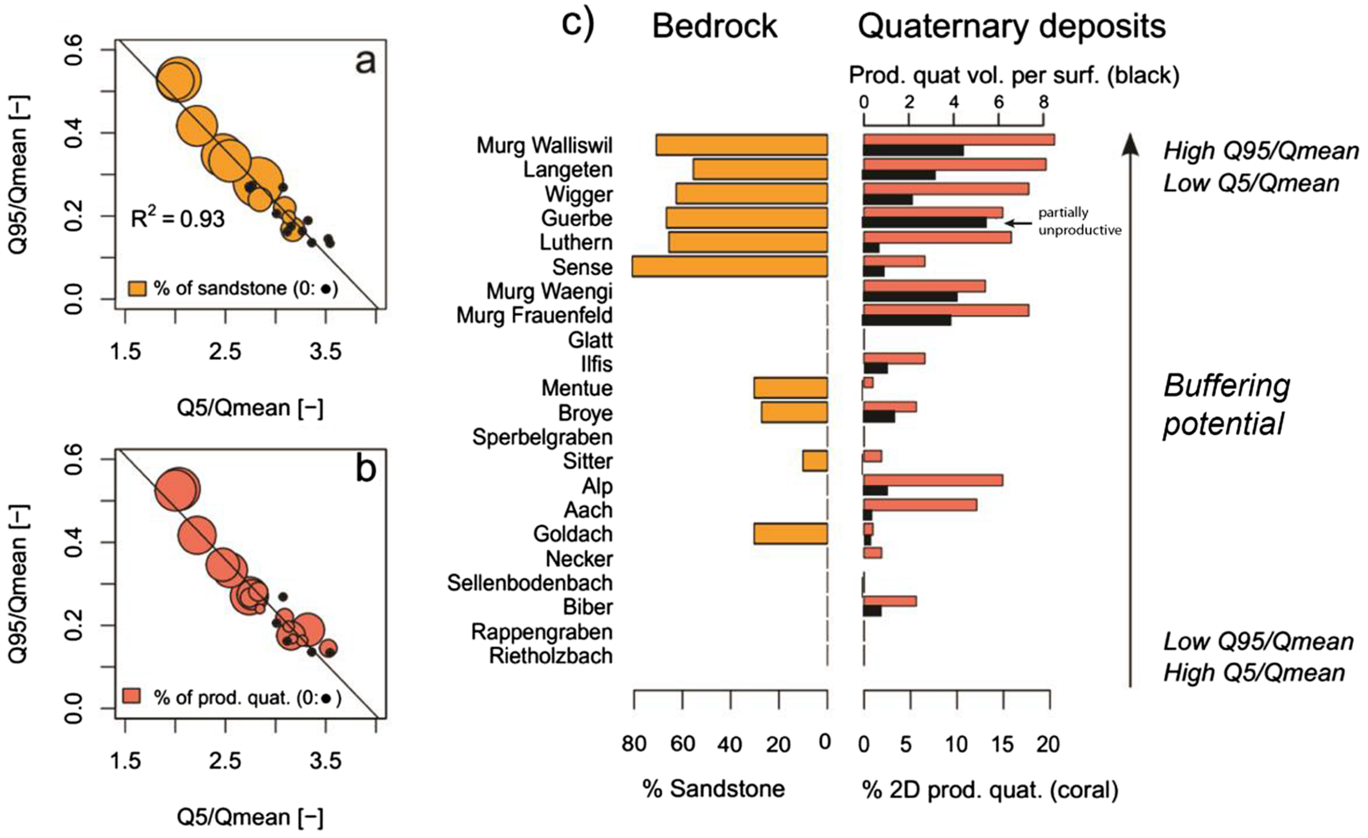


Fig. 7. On the left (a and b), normalized low flows are plotted against normalized high flows for the 22 catchments (p-value: $6e^{-13}$): the presence of sandstone resp. productive quaternary deposits are indicated in the top resp. bottom subplot, the size of the circles being proportional to the ratio of the respective lithologies in each catchment. On the right (c): the 22 catchments are sorted according to decreasing Q95/Qmean, and the % of each relevant geological unit is shown for each catchment. The volume of productive quaternary deposits averaged by catchment area is included in black.

different amplitudes of the dimensionless flow duration curve are thus mainly due to varying catchment properties. For catchments with different precipitation regimes, the shape difference of the curve might, however, also be influenced by the meteorological signal. Nonetheless, the comparison of dimensionless flow duration curves between catchments of similar precipitation regimes is a highly valuable approach to compare catchment buffering potentials. This way, the resilience of catchments to climatic changes and their sensitivity to dry periods can for instance be compared.

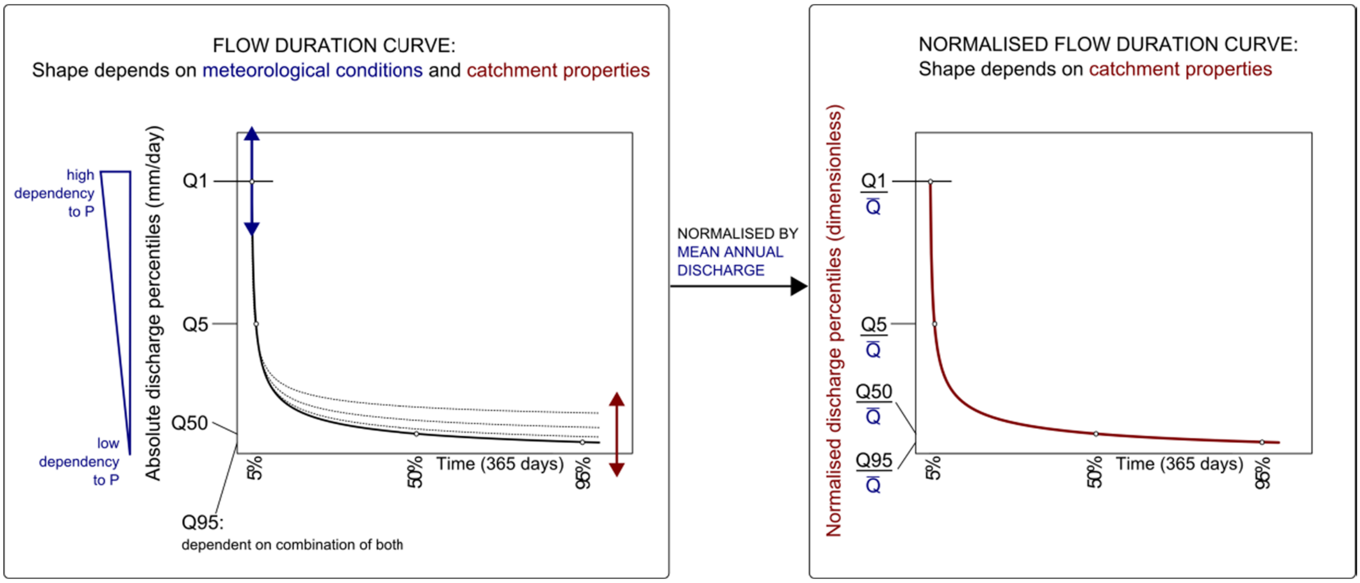


Fig. 8. Conceptualization of the flow duration curve (left) and the dimensionless flow duration curve (right). Blue indicates parameters or sections controlled by meteorological conditions, whereas red shows the control by catchment characteristics. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. The influence of geology on the buffering potential of catchments

Fig. 3 illustrates that, among the 33 catchment properties describing topography, soil, land use and geology, a clear relationship can only be observed between the geological characteristics and the normalized streamflow indicators. The obtained correlations (R^2 around 50%) are slightly lower than the values indicated for instance by Tague and Grant (2004) or Pfister et al. (2017): 76% for the correlation between summer streamflow and the portion of highly permeable volcanic rock, resp. 64% between the impervious part of the catchment and the ratio of summer and winter flow. These studies, however, focus on specific periods of the year, whereas we presently consider the entire streamflow range. The p-values of the correlations between the relevant geological descriptors and relative streamflow indicators, however, are all equal or smaller to 10^{-3}, suggesting that they are statistically significant considering the widely used 95% confidence interval. These findings suggest that the degree of buffering of the precipitation signal exerted by the catchment is mainly governed by geology. As assumed in the introduction (1st hypothesis), geology not only influences low-flow dynamics but equally impacts the entire dimensionless flow duration curve, including Q5/Qmean. The consideration of geological units by taking into account their hydrogeological characteristics thus leads to a better understanding of catchment dynamics. Our results suggest that both the bedrock and quaternary alluvial fillings considerably impact streamflow dynamics.

4.2.1. Bedrock geology

In the studied region of the Swiss Plateau and Prealpes, marine sandstone seems to significantly influence the ability of the catchment to generate a continuous streamflow, this geological unit being relatively permeable (10^{-5} to 10^{-4} m/s). As illustrated in Fig. 7, catchments with the highest buffering potential are all mainly composed of sandstone (60–80% of their surface). This Molasse type, or any geological formation with similar hydrogeological properties, seems to be a prerequisite for high normalized low flows. Its hydraulic conductivity is high enough to store water in the subsurface during precipitation events and low enough to still contribute to streamflow after prolonged dry spells. As an illustration, the estimated hydraulic conductivity of sandstone (10^{-5} m/s for the calculation) corresponds to a daily rate of 864 mm/d and the hydraulic conductivity of fine-grained material can optimistically reach a value of 8.64 mm/d (10^{-7} m/s). Sandstone can store large amounts of water and consequently considerably buffer rainfall events, whereas the second only allows the infiltrating of a limited portion. This buffering potential of sandstone on streamflow corresponds to the findings of various studies (Jencso & McGlynn, 2011; Nippgen et al., 2011; Naef et al. 2015). More generally, these results support the various case studies that highlighted the importance of the hydraulic conductivity of bedrock for low flows (Tague and Grant, 2004; Pfister et al., 2017), giving credit to the hypothesis of the hydrologically active bedrock (Uchida et al., 2008).

4.2.2. Quaternary deposits

Our study also shows the relative importance of productive quaternary deposits for streamflow dynamics. These aquifers, although limited in size, can contribute substantially to outflow, as suggested by the case study by Käser and Hunkeler (2016). The integration of total versus productive quaternary deposits characteristics highlight the importance of using appropriate (hydro)geological descriptors. Whereas the total volume of quaternary deposits in the catchments (“Tot. quat. vol. per surface”) is not correlated to streamflow indicators, the exclusive consideration of the productive portion of these deposits (“Prod. quat. vol. per surface”) allows linking the presence of quaternary aquifers to streamflow dynamics (see Fig. 3). It is thus crucial that the geological characterization of catchments for hydrological purposes focuses on the hydrogeological productivity of the various geological units.

Our results suggest that the use of 2D hydrogeological information describing the productivity of the aquifers already leads to a substantial explanatory power of quaternary deposits on streamflow dynamics (e.g. R^2 of 58% between Q95/Qmean and “% 2D prod. quat.”). Looking at the volumes of these deposits further improves the analysis of the relationship between geology and catchment dynamics in several cases (see Fig. 7). However, the overall correlation between the 3D quaternary indicator (“Prod. quat. vol. per surface”) and streamflow dynamics is not higher than with the 2D descriptor (“% 2D prod. quat.”). This can be attributed to the assumption that quaternary deposits are homogeneous in terms of hydraulic conductivity. It highlights the importance of characterizing the heterogeneity of these structures, as illustrated with the Guerbe catchment (Fig. 7).

Moreover, in a more local context, the presence of permeable quaternary deposits under the gauging station of the catchment can have a determining impact on the measured streamflow and on the water balance. As illustrated in Fig. 2, specific outlet configurations will result in unclosed water balances.

4.3. Buffering potential and dynamic storage: A groundwater perspective

As defined previously, the buffering potential of the catchment on the precipitation signal can be assimilated to the dynamic storage of the catchment, commonly defined as the storage that governs streamflow dynamics (Buttle, 2016). It describes how much water can be stored during precipitation events and subsequently released to the stream. The results of the present study suggest that catchments with relatively permeable geological units have a high buffering potential on precipitation, and hence a notable dynamic storage. In the framework of groundwater studies, bedrock hydraulic conductivity and meteorological input expressed as recharge are commonly related to assess flow processes (Gleeson and Manning, 2008; Haitjema and Mitchell-Bruker, 2005; Welch and Allen, 2012). Gleeson and Manning (2008) and Haitjema and Mitchell-Bruker (2005) notably have highlighted the influence of the ratio between recharge and hydraulic conductivity (*R/K*), along with topographical considerations, on the water table configuration. Groundwater levels in turn impact the partitioning of precipitation into recharge to groundwater and contribution to local stream network. Briefly stated, the mentioned authors show that a high R/K ratio generally implies a water table located close to the surface (*topography controlled*), whereas a low ratio indicates that the water table is *recharge controlled*. In the first case (high R/K ratio), the dynamic storage of the catchment is limited as the water table is constrained by topography. During precipitation events, the overland flow is substantial, and less water is stored and contributions to stream during dry periods are thus limited. When R/K is low, the water table fluctuates according to recharge: the dynamic storage and hence the buffering potential of the catchment is important.

The ratio of 1st order stream is the only topographical characteristic explaining a considerable part of the variance of the normalized discharge percentiles (38–44%), and provides another similarity with the study by Gleeson and Manning (2008). Our results suggest that streamflow dynamics of catchments with a less dense upper stream network will likely be more stable (low peaks and high low flows). Using a groundwater modeling approach in mountainous terrain, the study by Gleeson and Manning (2008) shows that the percentage length of first-order stream with perennial flow (comparable to % of 1st order stream) is a function of the water table which in turn depends on the R/K ratio. They demonstrate that, in case of low percentage of 1st order stream, (less developed upper stream network), the relative recharge contribution to regional groundwater flow is more important. Under the assumption that this groundwater flow contributes to the stabilization of streamflow dynamics (i.e. higher buffering potential of the catchment), our results are consistent with Gleeson and Manning (2008) . In this sense, the ratio of 1st order stream thus reflects the R/K ratio and the geological characteristics of the catchment, as it is directly impacted by infiltration and groundwater processes. These considerations should, however, be further investigated, as the resulting correlations are rather limited.

4.4. Importance of other catchment properties for streamflow dynamics

Topography and soil, as they impact overland flow, infiltration and subsurface processes, are frequently identified amongst the most important controls on streamflow dynamics. In the introduction, some of these "classical" studies are cited. Our results suggest a more differentiated picture and only partially confirm their importance. In fact, except for the percentage of 1st order stream discussed before, our results suggest that no soil and topography characteristics explain an important part of the variance of normalized streamflow indicators. Our results do not exclude the importance of soil characteristics in e.g. humid regions with low relief and do not exclude that other physiographic characteristics might be relevant for regions with climate and relief different to the Swiss plateau. Also, if a catchments' surface is impermeable owing to e.g. widespread soil compaction or urbanization (which is not the case in our catchments) the soil might constitute the limiting factor for infiltration and thus largely control the catchments dynamics. Nevertheless, our results suggest that the relative importance of soil characteristics has so far been overestimated, especially compared to the importance of deeper geological units in steeper regions.

There are several reasons for this. As suggested by various studies (Haitjema and Mitchell-Bruker, 2005; Welch and Allen, 2012;), both topography and hydrogeological properties constrain streamflow dynamics in a combined way and a unique identification of their influence is challenging, especially if the hydrogeological properties are not or only partially considered. Moreover, even if some of the topographical and soil characteristics can be related to absolute streamflow indicators, these relationships can be biased by their correlation to precipitation. Finally, as opposed to the "classical" hydrological studies in catchment hydrology discussed in the introduction, our analysis considers the subsurface in a more explicit way. This additional consideration naturally reduces the relative importance of surface features.

Even though this study goes far beyond the geological information considered in previous studies, more data for the conceptualization of the subsurface would be highly desirable. For example, assessing characteristics of distinct geological units with their specific storage and geometry might improve our understanding of the relationship between catchment properties and dynamics. Such data are, however rarely available to date.

5. Conclusions and implications

In this study, a total of 33 characteristics describing catchment topography, soil, land use and geology are compared to streamflow indicators, along with various meteorological indices. Our approach distinguishes itself from previous studies by including geological characteristics that describe the capacity of different lithologies to store and release water, i.e. their hydrogeological properties, and by considering both the large-scale geological environment (bedrock) and the local scale quaternary deposits. The following conclusions can be drawn:

- For the wide range of catchments we analyzed, geology has by far the largest influence of all catchment characteristics, both for low-flow as well as for high-flow conditions (hypothesis 1). Our results further confirm that the geological characteristics substantially determine the ability of the catchment to buffer the meteorological signal (hypothesis 2). These results underline the crucial need to take into account groundwater dynamics as well as geological factors in hydrological studies.
- We show that both the general geological environment (bedrock) and the more local scale quaternary deposits influence the catchments response to precipitation. This highlights the necessity of considering the hydrogeological productivity of both the bedrock and quaternary deposits. There is an especially large potential for including the bedrock, a so far rarely considered geological unit in hydrological studies. In general, these results demonstrate that the mere classification of aquifers into wide categories (e.g. unconsolidated, porous and fractured) is not adequate for describing the hydro(geo)logical setting of catchments and thus should not be used in catchment classification schemes.
- High-and low flow indicators are highly correlated, an important outcome that can provide insights into a catchments behavior under changing climatic conditions. The flow duration curve is influenced by different geological units, more specifically bedrock and more permeable quaternary deposits. The reproduction of a catchments' response to climatic forcing will thus benefit from an explicit consideration of these different lithologies. The explicit consideration of the bedrock is expected to be especially useful for the simulation of low-flow dynamics.
- The presence of relatively permeable lithologies is an indicator of an important dynamic groundwater storage, and thus sustained low flows. Sandstone-like porous lithologies, which feature a rather high hydraulic conductivity (e.g. 10^{-5} m/s), have a potentially high buffering effect on climate forcing and are thus favorable for the contribution to low flows. The presence of permeable and vertically extended quaternary deposits is also correlated to higher normalized low flows, due to the slow yet sustained release of groundwater.

The importance of high-quality geological data describing both the bedrock and the alluvial aquifers is emphasized in this study. Even though the geological characterization in our study goes far beyond the geological assessment in comparable studies, there is room for improvement. For example, more information concerning the slopes, volumes, specific storage or specific yields of the bedrock would certainly contribute to our current hydrological understanding. We are convinced that the scientific community will strongly benefit from increasing the efforts to characterize the subsurface, rather than continue to focus on easily accessible surface characteristics of catchments. Projects such as *GeoMol* ("Assessing subsurface potentials of the Alpine Foreland Basins for sustainable planning and use of natural resources", Diepolder et al., 2013), that characterize bedrock and quaternary deposits are thus of crucial importance to improve our current understanding of catchment dynamics.

6. Conflict of interest

None.

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