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Simulating future trends in hydrological regimes in Western Switzerland

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ABSTRACT

Study region: This study focuses on a mountainous region experiencing urban sprawl and growing irrigation needs: the canton of Vaud (Switzerland).
Study focus: Switzerland's description as Europe's water tower might evolve by the end of the century, as it should undergo significant hydro-climatic changes. Focusing on Western Switzerland is all the more important because a large part of the Swiss population lives in this area and because this region experienced water shortage episodes during the last decade. Climate change and its impacts on seasonal water resources availability and hydrological regimes were explored for the medium term (2050–2071). Flows were simulated based on a daily semi-distributed hydrological model. A calibration and corroboration procedure was performed over the 1984–2005 period. Future changes were derived from Swiss climate scenarios that rely on ten regional climate models.
New hydrological insights for the region: By the 2060 horizon, the increase in temperature causes a higher ratio of liquid precipitation and a decrease in snow accumulation during winter. These variations give rise to earlier high flow peaks and more severe low flows. Hydrological regimes evolve and rivers become characterized by a pluvial regime. These seasonal hydro-climatic changes are of prior importance in an area where urbanization and irrigation keep increasing: the question arises on the capacity of water resources to meet future water demands.

1. Introduction

Switzerland is often described as Europe's water tower. This status comes from its geographic position in the center of Europe and its mountainous environment with a mean altitude of 1700 m and various summits above 4000 m. From a hydrographic perspective, it holds a privileged position. During the 20th century, mean annual precipitation reached 1431 mm from which one-third evapotranspirated and two-thirds flowed out of Switzerland (Hubacher and Schädler, 2010). It is then an important source of freshwater, notably for large European rivers that begin their course in the country like the Rhine River, the Rhone River and the main tributaries of the Po and Danube rivers (Ticino, Inn). However, Switzerland

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can also be described as a sponge that fills with water during autumn- and winter-time and presses out water during spring and summer. In the Swiss mountains, the seasonality of river flows highly depends on the timing and volume of snow accumulation and depletion (Birsan et al., 2005; Pellicciotti et al., 2010; Hänggi and Weingartner, 2012). In addition to summer rainfall, snow- and ice-melt provide most of the spring and summer runoff. In the lowlands, the hydrological regimes are mainly rainfall-based (Weingartner and Aschwanden, 1992; Birsan et al., 2005). Seasonal variations are expected to change in snow-dominated regions leading to significant changes in the magnitude and timing of flows (see e.g., Adam et al., 2009; Morán-Tejeda et al., 2011; Arnell and Gosling, 2013). This is an issue of prior importance for Switzerland as any changes in its upstream regimes could potentially have major consequences on water supply and on downstream European rivers (see e.g., Middelkoop et al., 2001; Viviroli and Weingartner, 2004; Barnett et al., 2005).

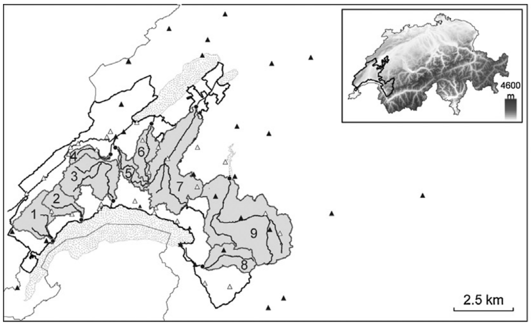
According to the Swiss Advisory Body on Climate Change (OcCC), climate change and some related impacts are already perceptible in Switzerland. During the past 20 years, compared to the 1961–1990 mean, annual temperatures increased by 1–1.5 °C and the 5 warmest years occurred after the year 2000 (OcCC, 2007, 2008; Ceppi et al., 2012). No significant changes were observed in annual precipitation but a significant statistical increase in winter precipitation was identified in Northern and Western Switzerland coupled to a decrease of snowfall days (Schmidli and Frei, 2005; Serquet et al., 2011). These changes are likely to be responsible for the statistically significant positive trend observed in winter streamflow (Birsan et al., 2005). In addition, the snowline moved up by 150 m per degree increase, ice melt and glacier retreat sped up and summer droughts got more intense (OcCC, 2008). These changes in hydrological processes are of particular concern as they may affect water use in some places. As an example, temperatures and precipitation in 2003 were, respectively, higher and lower than the multiannual mean 1961–1990 from April to August (FOEN, 2012a,b). Low flows reached levels never recorded before. Water withdrawals and supplies had to be, respectively, forbidden and restricted several times in the Jura valleys, in the cantons of Vaud, Fribourg and Ticino, and in the Alpine valleys of Engadine and Valais (FOEN, 2012b). Agriculture was also impacted by water restrictions in the Jura Mountains and the canton of Vaud during the dry spring 2011 and dry summer 2015.

National studies were recently carried out to address climate change (CH2011, 2011; CH2014, 2014) and its related impacts on water resources (e.g., FOEN, 2012a; Köplin et al., 2012) for the short- (2025–2046) and long-term (2074–2095). A systemic approach was developed over 189 catchments based on a regionalization scheme (Viviroli et al., 2009a; Köplin et al., 2010). The main findings state that by the short term current climatic trends should remain as they are thus poorly affecting river flows. Climate change mainly emerge at the end of the century with a 3 °C increase in temperature and a 10–30% decrease in precipitation. Western Switzerland and the Alps should be the most affected regions, with less snowfall, changes in seasonal distribution of precipitation, and more intense and longer low flows. A severe glacier retreat should also affect the Southern Alps. In the 2085 horizon, rivers in Western Switzerland and in the Alps could move, respectively, from a pluvio-nival and nival hydrological regime to a pluvial and nivo-pluvial regime. Understanding and anticipating these seasonal variations are essential to ensure water resources availability to ecosystems and human populations and activities (e.g., irrigation; Barnett et al., 2005; Morán-Tejeda et al., 2011; Beniston and Stoffel, 2014). Based on a common method, these studies give a synoptic view of the main evolution trends and identify the most vulnerable areas of the country. They call for broader-perspective studies in these areas.

Several studies were conducted in the Alps and its glaciated areas to report glaciers' evolution and its impacts on runoff (e.g., Huss et al., 2008; Kobierska et al., 2013; Uhlmann et al., 2013), on hydropower production (e.g., Finger et al., 2012; Hänggi and Weingartner, 2012), and to quantify uncertainties in hydrological modeling chains (e.g., Jasper et al., 2004; Addor et al., 2014). Although each study is case specific, both thematically and spatially, all of them identified significant climatic and hydrological changes starting in the mid-21st century. Further research on water resources availability and on their capacity to meet water demands should then be led at this time horizon. Besides, Switzerland defined climate policy objectives to reduce greenhouse gases emissions by the end of the century for which repercussions should already be noted by the mid-21st century (OcCC, 2012).

Furthermore, to the authors' knowledge, no study was recently carried out on the impacts of climate change on water resources in Western Switzerland specifically. Focusing on this area is all the more important given that the majority of the Swiss population does not live in the Alps but in lowland cities (FSO, 2014). Western Switzerland experiences continuous economic and demographic growth and is particularly vulnerable to water stress, especially the canton of Vaud and its Lake Geneva region (SESA, 2012). Between 2000 and 2012, the canton of Vaud experienced the highest demographic growth in Western Switzerland. In each municipality, the population increased by 10–30%, inducing strong urban sprawl, especially along the coast of Lake Geneva (FOSD-ARE, 2013). The canton of Vaud is also the second agricultural canton of the country (FSO, 2006). It covers 17% of the Swiss agricultural lands for which irrigation is more often used in order to save and ensure crop yields (MandaTerre, 2013). Water demands are then on an upward curve. During the latest drought episodes (e.g., 2003 and 2011), competition among water users rose and new water management issues appeared like defining water allocation rates and priorities (FOEN, 2012b; SESA, 2012). Knowledge on the capacity of water resources to meet future water demands under climatic and anthropogenic changes in this area must be improved.

To make up for this gap, a regional study was carried. It explores where and when water tensions are most likely to occur in the 2060 horizon under hydro-climatic and anthropogenic changes (Milano et al., 2015). This paper contributes to this assessment by providing a quantitative evaluation of how hydro-climatic conditions could evolve in Western Switzerland by the mid-21st century. It aims to achieve two objectives: (i) quantify the impacts of climate change on water resources availability, and (ii) define the possible evolution trends of hydrological regimes, for the rivers of the canton of Vaud.



Catchment	Surf. area (km^2)	Mean alt. (m)	Glacial extent (%)
(1) Promenthouse	138	1037	0
(2) Aubonne	108	890	0
(3) Venoge	231	700	0
(4) Nozon	38	440	0
(5) Talent	62	440	0
(6) Mentue	143	679	0
(7) Broye	392	710	0
(8) Grande Eau	134	1560	1.80
(9) Sarine	637	1520	0.61

Fig. 1. Geographical position and characteristics of the nine selected catchments in the canton of Vaud.

2. Study area

All meso-scale catchments of the canton of Vaud with a surface area of at least 30 km^2 and without major influence of lake regulation or hydropower production were considered (Fig. 1). All catchments also had to have at least 5 years of continuous runoff records in daily resolution within the 1983–2005 period for calibration purposes (see Section 3). This period was also used to explore the current water balance (see below). Nine catchments covering 67% of the canton's surface area were thus considered (Fig. 1). They extend from the Jura Mountains (alt. max. 1677 m.a.s.l.) over the Swiss Plateau (400–600 m.a.s.l.) to the high alpine areas (alt. max. 3200 m.a.s.l.). Changes in topography and altitude affect precipitation distribution as well as timing and volume of snowpack development and depletion, giving rise to four different hydrological regimes in the canton according to the regimes' typology of Weingartner and Aschwanden (1992):

- Nivo-pluvial regime. It concerns the mid-altitude rivers of the Lake Geneva region, i.e., the Promenthouse, Aubonne and Venoge rivers, flowing from the Jura Mountains to Lake Geneva (Fig. 1). It is characterized by two mean monthly high flows: one occurs between November and January due to high precipitation (100–200 mm/month; Fig. 2), and a second one, much larger, occurs in March or April, supported by snowmelt from the Jura Mountains. Low flows arise from June to September. Although precipitation can reach up to 130 mm/month during this period, temperatures are high (20 °C on average) resulting in high air evaporative capacity (75–90 mm/month).
- Pluvial regime. It characterizes the rivers of the Swiss Plateau Talent, Nozon, Mentue and Broye (Fig. 1). Mean monthly river flows are high from October to March, with a maximum in February or March, and low from June to September (Fig. 2). Flows are affected by homogeneous precipitation (55–85 mm/month over the Mentue River and 80–120 mm/month over the other catchments) but high changes in air evaporative capacity (10–30 mm/month from October to March against 70–90 mm/month during the rest of the year) due to temperature variability.
- Transition nival regime. It is observed over the Grande Eau River, taking its course 3200 m.a.s.l and flowing into the Rhone River 25 km downstream, 410 m.a.s.l. River flows are characterized by two mean monthly high flows (Fig. 2). The main peak occurs in May or June due to snowmelt from the Alps while the second peak, much smaller, takes place in November due to rainfall.
- Alpine nival regime. It is typical of high altitude catchments where most of the precipitation falls as snow, like over the Sarine catchment (Fig. 1). River flows are influenced by snowmelt, resulting in a single high flow peak in May (Fig. 2).

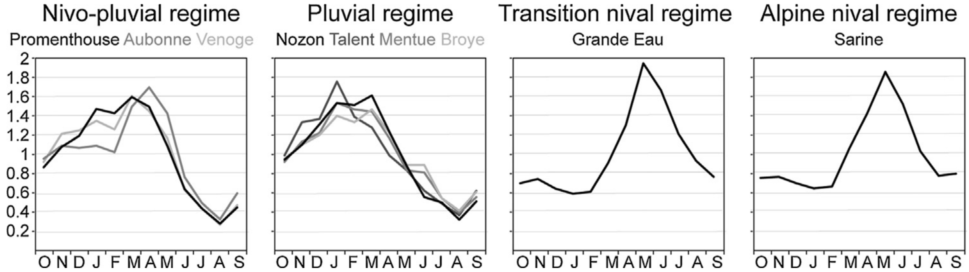


Fig. 2. Hydrological regimes of the nine studied catchments in the canton of Vaud over the 1983–2005 period, based on Pardé's coefficients (1933).

3. Material and method

3.1. Hydrological model

The semi-distributed and process-oriented hydrological model PREVAH (Precipitation-Runoff-EVApotranspiration-Hydrotope-based model; Viviroli et al., 2009b) was used to evaluate seasonal changes in runoff and their impacts on hydrological regimes. It has shown to be a reliable and flexible tool to understand the spatial and temporal variability of hydrological processes in mountainous catchments (Gurtz et al., 1999; Viviroli et al., 2009a,b; Köplin et al., 2010).

An extensive description of the model can be found in Viviroli et al. (2009b). In this section the basic concepts are explained. The PREVAH model is based on the HBV model structure (Bergström, 1976), using hydrological response units (HRU) in order to better consider land surface and soil characteristics, and to enable a dynamic parameterization of every HRU (Gurtz et al., 2003). A series of modules that represent the different components of the hydrological cycle (e.g., snow accumulation, snow- and ice-melt, evapotranspiration, soil moisture, total runoff produced by the combination of quick, delayed and slow runoff) supplement the model structure. The model employs 100 m altitude zones and runs at an hourly time-step, although daily to yearly temporary resolution is allowed for input and output. In this study, the model was run on a daily basis. For each time step and each HRU, water fluxes are computed. The contributions of the HRUs in each catchment are summed to give estimates of total discharge.

3.2. Input data over the reference period

Three types of input data are required to run PREVAH: physiographical information, meteorological data and runoff control files for calibration.

Physiographical properties (elevation, mean slope, soil depth, soil water capacity and land-use) of each catchment were derived from Köplin et al. (2012). This spatial information was gained from a digital elevation model, a soil map and a land-use map provided by the Federal Statistical Office (FSO, 2003).

The required meteorological input variables are air temperature (°C), precipitation (mm/h), relative humidity (%), wind speed (m/s), global radiation (W/m^2) and relative sunshine duration. Data was collected for 30 climatic stations and 28 additional precipitation gauges from the automatic meteorological network of Switzerland (ANETZ, provided by MeteoSwiss, 2008; Fig. 1). This network became fully operational in 1983. In 2006, the database was revised and replaced by new stations (Heimo et al., 2005). Some stations came from the ANETZ network but several were replaced or dismissed. In order to be consistent and have a homogeneous datasets over a whole period and over each catchment, the 1983–2005 period was then considered as the reference period for retrospective modeling. In the end, meteorological station data were interpolated and subsequently averaged for each HRU (Köplin et al., 2010). In this case, interpolation was based on detrended inverse distance weighting, where detrending is based on elevation dependence of climate variables (Viviroli et al., 2007). This technique aims to incorporate both vertical (elevation) and horizontal (distance) components into the climate field's variability (Garen and Marks, 2001). Values are no longer constrained by the range of measured values as in the inverse distance weighting method (USEPA, 2004). In addition, to account for undercatch, observed precipitation was corrected by two parameters, for rain and snow (see Sections 3.3 and 5.2).

Regarding runoff control files, the Federal Office for Environment (FOEN) provided high quality daily discharge series over the 1983–2005 period for 7 catchments (no missing data except for the Promenthouse station, which discharge series start in 1986; FOEN, 2014). The canton of Vaud provided the daily discharge series for the two missing rivers, the Talent and Nozon Rivers. Series started in 1993 (less than 3% missing), the year during which their network became fully operational (Canton of Vaud, 2014).

3.3. Model calibration and corroboration

In this section, basics on the calibration and corroboration procedures are given. More detailed information can be found in Viviroli et al. (2009a).

The PREVAH model comprises an automatic objective procedure to calibrate its 12 tunable parameters pair-wise and sequentially to allow all parameters to adjust to each other. An automatic iterative search algorithm is performed to maximize objective functions defined according to the study's purposes. For each iteration step, the best model run defines the limits of a reduced parameter space to be tested in the subsequent step (Viviroli et al., 2009a; Köplin et al., 2010). The main issue is that several sets of parameters can result in similarly good results (Viviroli et al., 2009b). In this study, the aim of the search algorithm was to catch a robust parameter set which yielded good results in catchments' hydrological behavior. This is particularly important with respect to our objective to provide a quantitative assessment of seasonal water resources availability under climate change and to further address water stress risks (Milano et al., 2015). The model thus aimed to optimize three statistical criteria: the volumetric deviation (VE; Eq. (1)), and the linear and logarithmic Nash-Sutcliffe efficiency coefficient (NSE, Nash and Sutcliffe, 1970) informing on the capacity of the model to correctly represent the seasonal and low flow dynamics, respectively (Krause et al., 2005 Eqs. (2) and (3)). Perfect agreement between the observed and simulated values yields efficiency of 0 for the volume error and of 1 for the Nash-Sutcliffe coefficients. Each statistic criterion is computed for the entire calibration period as well as on a yearly and monthly basis. Corroboration consists in running the model with the parameters optimized during the calibration phase.

$$\mathrm{VE} = \frac{\sum_{t=1}^{N} V_{\mathrm{obs},t} - \sum_{t=1}^{N} V_{\mathrm{sim},t}}{\sum_{t=1}^{N} V_{\mathrm{obs},t}} \quad (1)$$

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{N} (Q_{\mathrm{obs},t} - Q_{\mathrm{sim},t})^2}{\sum_{t=1}^{N} (Q_{\mathrm{obs},t} - \overline{Q_{\mathrm{obs}}})^2} \quad (2)$$

$$\mathrm{NSE}_{\ln} = 1 - \frac{\sum_{t=1}^{N} (\ln Q_{\mathrm{obs},t} - \ln Q_{\mathrm{sim},t})^2}{\sum_{t=1}^{N} (\ln Q_{\mathrm{obs},t} - \ln \overline{Q_{\mathrm{obs}}})^2} \quad (3)$$

where V_{obs} and V_{sim} are the observed and simulated volumes at time t, $Q_{\mathrm{obs},t}$ and $Q_{\mathrm{sim},t}$ are the observed and simulated discharge at time t, $\overline{Q_{\mathrm{obs}}}$ and is the averaged observed discharge over the period.

In order to define the calibration and validation periods, the Khronostat statistical analysis model (Lubès-Niel et al., 1998; IRD, 2002) was applied over the 1983–2005 period. This model aims to identify statistical ruptures, i.e., significant changes in random variable series, in hydro-climatic temporal series based on four common and robust statistical tests: the U-statistic (Buishand, 1984), the non-parametric approach of Pettitt (1979), the Bayesian method of Lee and Heghinian, (1977) and the segmentation procedure of Hubert (Hubert et al., 1989). All methods identified a rupture in 2003 related to the severe drought that affected the canton of Vaud that year. However, a two-year calibration or validation period did not seem reasonable to test the model's efficiency. It is recommended to use periods where the mean annual discharge is representative or close to the long-term mean of the observed period (Poulin et al., 2011). It was thus decided to fit to the five-year calibration period 1993–1997, proved suitable over Switzerland by Viviroli et al. (2009a) and, when possible, to carry out corroboration before and after the calibration period (1983–1992 and 1997–2005 with one year warm-up included).

3.4. Introducing climatic scenarios in the model

Future climate scenarios were based on the outputs of the CH2011 initiative (CH2011, 2011,1). GCM-RCM model chains were used over Switzerland to better capture small-scale atmospheric processes as well as the effects of local topography and land surface. These chains provide data at a daily resolution for 25 km grid cells. This spatial resolution remains too coarse for hydrological impact studies in mesoscale catchments (Köplin, 2012). Climatic data of the CH2011 initiative were then post-processed for future periods by Bosshard et al. (2011) using the delta change method in order to interpolate GCM-RCM model chain datasets to station location. The delta change method consists in scaling observed historical climate series to obtain future climate series by considering changes in spatial and temporal pattern simulated by GCM-RCM model chains. It assumes that changes of the mean atmospheric state are more trustworthy than absolute values (Köplin et al., 2010). This method has been judged acceptable for seasonal climate impact studies (Lenderink et al., 2007; Ruelland et al., 2012). However, it implies that climatic variability is inherited from observed climate, and that the inter-annual runoff relationship over the reference period does not change in the future (Graham et al., 2007; Ruelland et al., 2012). This post-process assessment was applied on the ten GCM-RCM model chains from the ENSEMBLES project (van der Linden and Mitchell, 2009) forced with the A1B emission scenario.

Therefore, expected changes (delta) between the control (1980–2009) and the scenario periods (2046–2075) from the ten GCM-RCM model chains were applied on the daily temperature and precipitation series of each considered station (Fig. 1). Future climate series were then implemented in the hydrological model to simulate future discharge. Glacier retreat was also considered with a mean response time of 50 years. According to the low glacier extent over the studied catchments, an absence of glacier in the medium-term was assumed.

3.5. Hydrological trends and regimes

Trends in water resources availability were quantified based on absolute monthly runoff changes whereas Pardé's coefficients (CP; Pardé, 1933) were used to compare hydrological regimes between catchments and to explore their evolution through time. They are based on the ratio of mean monthly runoff ($\overline{Q_{m,\mathrm{peroid}}}$) to mean annual runoff ($\overline{Q_{m,\mathrm{peroid}}}$) on a multiannual basis (Eq. (4)).

$$\mathrm{CP} = \frac{\overline{Q_{m,\mathrm{period}}}}{\overline{Q_{y,\mathrm{period}}}} \quad (4)$$

4. Results

4.1. Efficiency of the hydrological model

The first results, summarized in Fig. 3, concern the capacity of the hydrological model to represent observed runoff values based on observed climate and therefore on the potential bias of prospective hydrological simulations.

The PREVAH model successfully captures the main features of annual discharge (Fig. 3). It is robust for all catchments with high goodness-of-fit scores. The model accurately simulates flow dynamics with NSE values between 0.80 and 0.96 for the calibration period and between 0.82 and 0.95 for the two validation periods. The main features of annual discharge are well captured, notably low-flows. NSE_{ln} values are always higher than 0.85 for both calibration and validation periods. Goodness-of-fit scores even improve for the validation period over the Aubonne, Nozon, Mentue, Grande Eau and Sarine catchments. Water volumes are also appropriately simulated. The volumetric deviations do not exceed −9% or 5%. This is an encouraging result. It shows that the PREVAH model provides simulations that can also be used to assess water allocation rates or water stress. The dynamic and volumes of the four hydrological regime types found in the canton of Vaud are well represented by the model.

Simulation of runoff dynamics and volumes are only unsatisfactory for the Promenthouse catchment (Fig. 3). NSE values do not exceed 0.55 and 0.61 for the calibration and validation periods, respectively. Low flows are also poorly captured as shown by the low NSE_{ln} values for both calibration and corroboration phases. Analysis of monthly criteria and seasonal hydrographs highlights that the model tend to over-estimate river flows from September to March and to under-estimate them from April to June (Fig. 3). No clear explanation can be provided for such differences in efficiency scores between this catchment and its close neighbors. One reason might be the sparse meteorological network around this catchment while another reason could be the high urban land cover in this catchment. As in other hydrological studies (e.g., Viviroli, 2009b; Addor et al., 2014), it is assumed that systematic model biases do not change with time. Differences between observed and simulated discharge over the reference period are assumed to remain constant in the future. Limits related to this assumption are discussed in Section 5.2.

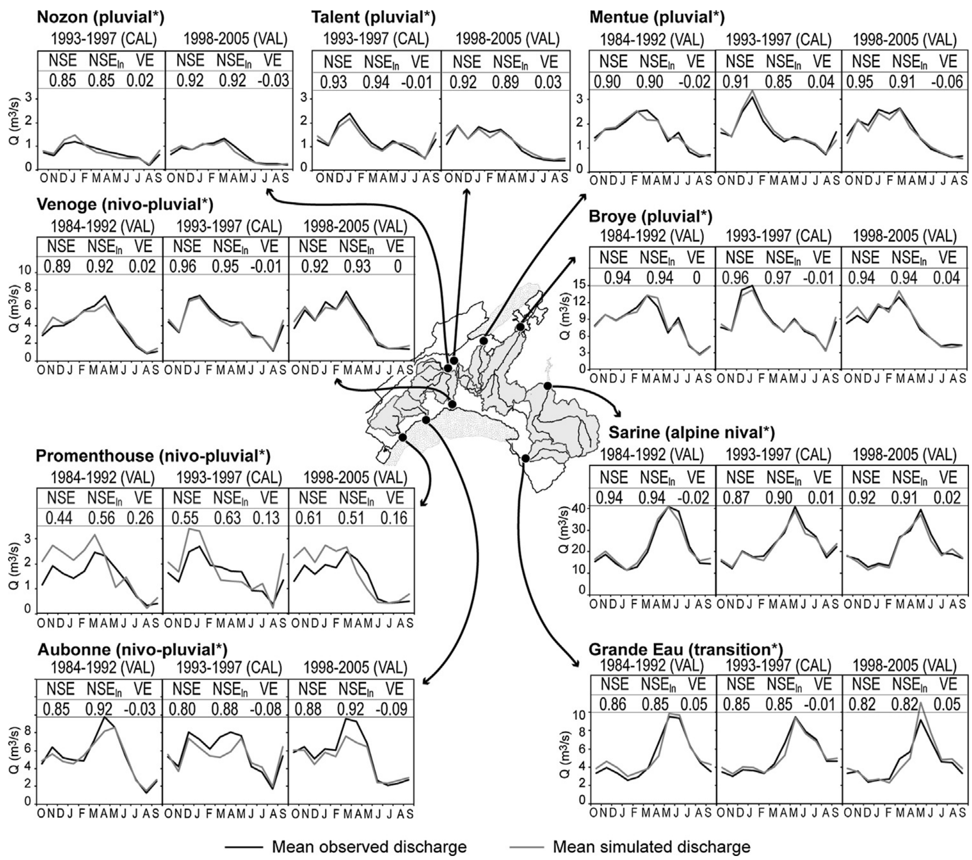


Fig. 3. Mean seasonal hydrographs for observed and simulated discharge at the outlet of each catchment for the calibration and validation periods.
*according to the regimes' typology of Weingartner and Aschwanden (1992).
NSE, linear Nash-Sutcliffe efficiency coefficient; NSE_{ln}, logarithmic Nash-Sutcliffe efficiency coefficient; VE, volumetric deviation.

4.2. Future climatic trends

According to the ten climatic scenarios, temperatures are expected to rise by 3–4 °C during summer and by 2–3 °C throughout the rest of the year over the whole canton by the 2050 horizon (Fig. 4).

Regarding precipitation, different trends were identified over the canton yet they are similar for catchments with the same hydrological regime. Results for one catchment of each cluster are presented in Fig. 4.

In catchments of the Lake Geneva region, precipitation could increase by 10–30% from October to May (Fig. 4a). Precipitation could even reach a 40% increase in December and January over the Venoge catchment. A net decrease in snowmelt should however be observed in these catchments (−60–80%) getting to levels never observed before (Fig. 4a). This results from rising temperatures leading to a higher fraction of liquid to solid precipitation. During the summer months, precipitation should remain near current volumes in June and September and decrease by 10–20% in July and August (Fig. 4a). According to the scenarios based on CNRM-ARPEGE-ALADIN, ETHZ-HadCM3Q0-CLM and HC-HadCM3Q0-HadRM3Q0 model chains, precipitation could even decrease by 40–50% in the Aubonne and Promenthouse catchments in July and August, thus reaching values below the observed variability range (80 mm and 50 mm, respectively, on average over the reference period).

The seasonal distribution and volumes of precipitation should remain as they currently are over the catchments of the Swiss Plateau although an earlier precipitation peak might be observed (May instead of June; Fig. 4b). It is during summer that the biggest changes should be observed. Precipitation could decrease by 20–30% from June to September. A 40–80% decrease is even projected by the most pessimistic climatic scenarios (CNRM-ARPEGE-ALADIN, ETHZ-HadCM3Q0-CLM and HC-HadCM3Q0-HadRM3Q0). Under such circumstances, records could fall below the observed variability range (less than 55 mm/month for Mentue and Nozon catchments and less than 75 mm for Broye and Talent catchments, on average).

Over the Grande Eau and Sarine catchments, similar trends can be identified. In high mountain catchments, seven out of ten climatic scenarios project low to no changes in precipitation from October to February and a 20–30% decrease from June to September (Fig. 4c and d). The three most pessimistic scenarios (CNRM-ARPEGE-ALADIN, ETHZ-HadCM3Q0-CLM and HC-HadCM3Q0-HadRM3Q0) project a 10–25% monthly decrease from October to February and by more than half from June to September, exceeding the current variability. However, in May, precipitation could increase by 20–25%. Snowmelt should also be considerably reduced. It should not exceed three-quarters of current snowmelt volumes, even dropping to none from July to September (Fig. 4c and d).

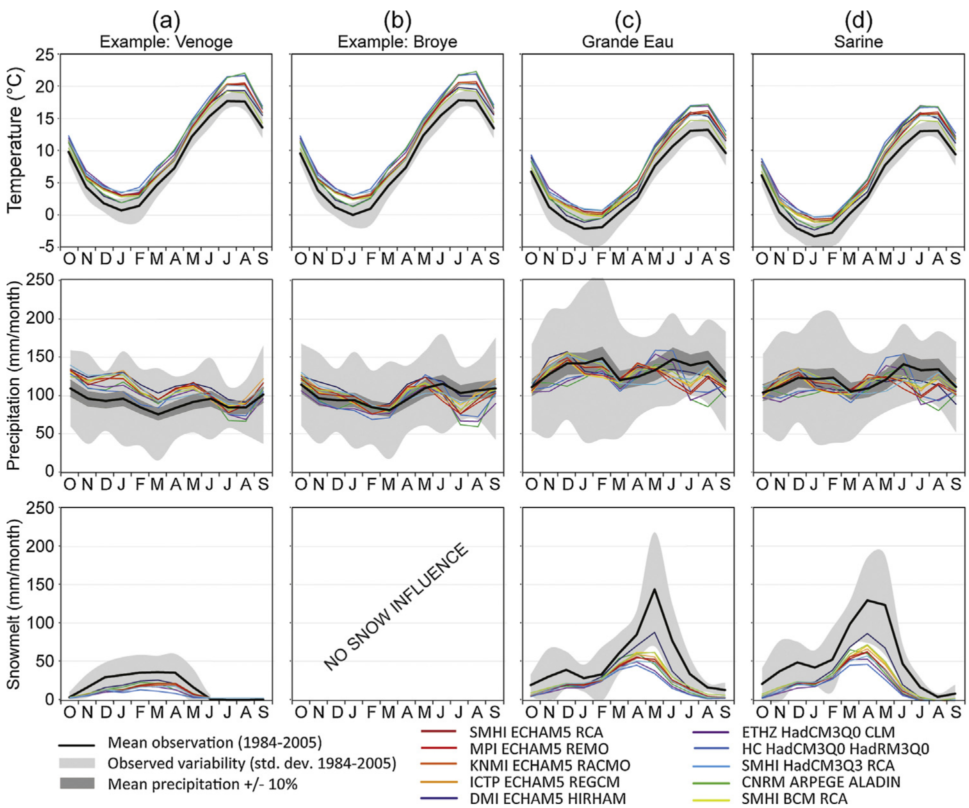


Fig. 4. Future climatic trends in the medium term (2050–2071) for catchments in the canton of Vaud under (a) nivo-pluvial regime, (b) pluvial regime, (c) transition nival regime and (d) alpine nival regime.

4.3. Future hydrological trends

According to the identified climatic trends, changes in seasonal runoff are most likely to occur. Future hydrological trends are here presented based on the clusters defined in the previous section.

In the Lake Geneva region, mean monthly river flows could increase from October to March and the mean high flow peak could occur in January, i.e., 2 months in advance compared to the mean observations (Fig. 5.1 and 5.3). Mean high flow values vary according to the GCM-RCM model chain. Scenarios based on KNMI-ECHAM5-RACMO (HC-HadCM3Q0-HadRM3Q0) project the highest (lowest) changes with a 50–70% (10–20%) increase. Over the Promenthouse and Venoge catchments, the mean high flow peak could exceed the mean observed values and reach the upper boundary of the observed variability range. At the Aubonne outlet, high flows are projected to remain lower than the mean high flow peak currently observed in April (5.9 m^3/s against 9.2 m^3/s on average; Fig. 5.2). During the rest of the year, river flows should remain close to current levels or decrease by 30–50%, notably during springtime (April and March).

Over the Swiss Plateau, nine out of ten scenarios project a decrease in seasonal runoff (Fig. 5.4–7). During autumn and winter, river flows should be reduced by 10–25%, according to the selected scenario, while during spring they could reach only half of the current resources. Nevertheless, the mean high flow peak should still occur in January, even for the Broye River. Indeed, for the latter, the mean high flow peak should move from March to January, i.e., occur 2 months earlier (Fig. 5.7). Finally, all scenarios project a 60–75% decrease in runoff during the summer season, reaching values close to the lower boundary of the current variability range (less than 0.5 m^3/s on average; Fig. 5.4–7).

In high altitude catchments, mean monthly river flows are projected to increase from October to February and decrease from March to September (Fig. 5.8–9). According to seven out of ten scenarios, a 35–50% increase in monthly runoff is projected at the Grande Eau outlet in autumn and winter (Fig. 5.8). During spring and summer, mean monthly river flows could decrease by 30–35%, exceeding the observed variability range in July and August. At the Sarine outlet, compared to the reference period, a 15–25% increase in seasonal runoff is projected from October to February and a 35–50% decrease during the second half of the year (Fig. 5.9). According to nine out of ten scenarios, two high flow peaks instead of one should characterize river flows. The first and still unseen high flow peak could occur in December or January (14–21 m^3/s, on average, according to the selected scenario) while the second one should take place one month earlier than usual, in April instead of May, with less amplitude (23–30 m^3/s according to the selected scenario instead of 40.4 m^3/s on average over the reference period). Regarding low flows, from June to August, river flows could reach water levels below the current variability range (Fig. 5.9).

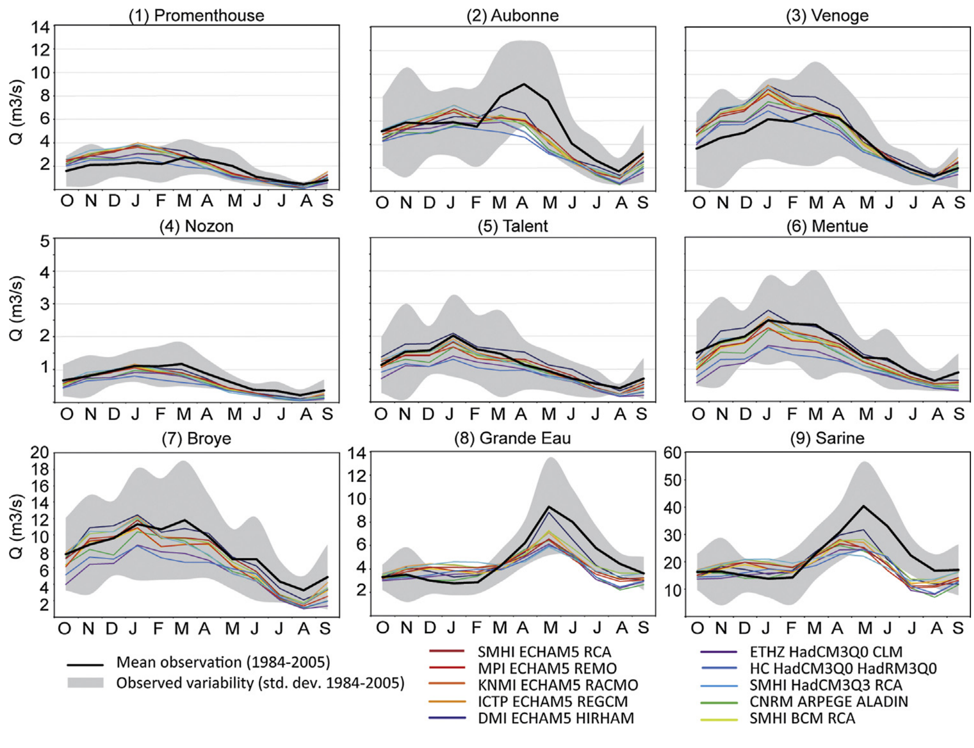


Fig. 5. Future hydrological trends in the medium term (2050–2071) for catchments in the canton of Vaud.

4.4. Changes in hydrological regimes and their causes

The projected climatic and seasonal runoff changes suggest some significant changes in hydrological regimes over the canton. Results are shown in Fig. 6. As the various scenarios project the same trends, a mean average of possible changes is presented in the figure to which an envelope was added to show the scenarios' variability.

In the medium term, hydrological regimes in the Lake Geneva region could no longer be qualified by two high flows between November and January and in March–April but by high flows from October to March with a maximum in January, and by more intense low flows from June to August (Fig. 6.1–3). Therefore, catchments of the area should move from a nivo-pluvial regime to a pluvial regime. This can be related to more rainfall from October to March and higher temperatures throughout the year leading to less snowfall and snowmelt, necessary to support low flow water levels.

Over the Swiss Plateau, hydrological regimes should remain unchanged (Fig. 6.4–7) although seasonal runoff should be lower than currently observed and low flows be more intense. This can be explained by lower precipitation and higher evapotranspiration rate with the rise of temperature, especially during the summer season.

According to the climatic and hydrological scenarios, the Grande Eau River should present more severe low flows due to higher temperature and unusual low precipitation. Constant river flows from September to February should be related to more rainfall and less snowfall. Contribution of snowmelt should still enhance a high flow peak in May but it should be relatively low compared to its current state. Therefore, in the medium term, the Grande Eau catchment should no longer be characterized by a transition nival regime but by a nival regime (Fig. 6.8).

At the Sarine outlet, two high flow peaks (December–January and April) as well as intense low flows from June to August should be recorded in the medium-term. Its hydrological regime should hence move from an alpine nival regime to a transition nival regime (Fig. 6.9). These changes should mainly be attributed to rising temperatures: rainfall would increase over snowfall leading to higher runoff volumes in autumn and winter, and less snowmelt would induce a lower high flow peak in spring. Finally, rising temperatures coupled to less precipitation during summer should enhance more intense low flows.

5. Discussion and conclusion

5.1. Summary and comparison with literature

This paper explores the impacts of climate change on water resources availability and on rivers' hydrological regimes in the canton of Vaud. The approach relies on a method often used to explore climate change and its impacts on water resources in Switzerland, i.e., the hydrological model PREVAH forced by Swiss climatic scenarios derived from GCM-RCM model chains. This paper aims to complement previous studies by focusing on the medium term and on a mountain area

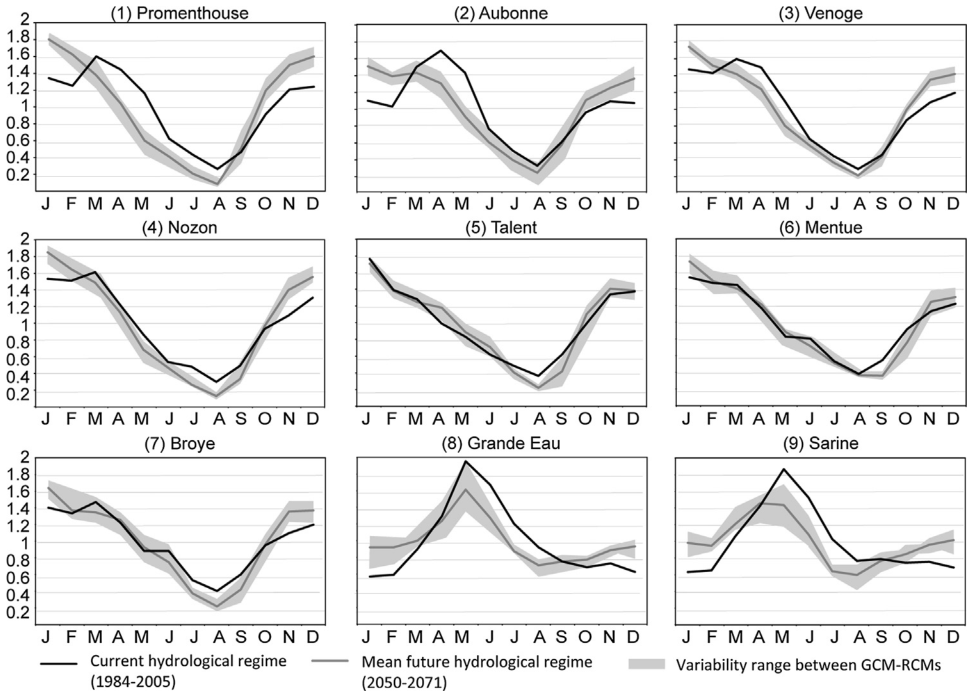


Fig. 6. Projected changes in hydrological regimes in the canton of Vaud by the medium-term (2050–2071), based on Pardé's coefficients (1933).

poorly explored up until now, even though vulnerable to climate change. By using the same tools, it enables comparisons with previous studies focusing on the short and long terms.

Currently, based on the selected catchments, water resources in the canton of Vaud amount to 19.2 km^3/year. Mid-altitude catchments (mean elevation above 700 m) are dominated by both rain- and snowfall whereas over the Swiss Plateau, the hydrological regime is rainfall based. In high altitudes (above 1500 m), river flows highly depend on snow- and ice-melt, defining regimes of the Grande Eau and Sarine catchments as transition nival and alpine nival, respectively. In the 2060 horizon, water resources could reach 14.1–17.8 km^3/year due to some significant hydro-climatic changes. By the medium term, the canton of Vaud should be affected by a 2–3 °C increase in temperature, even reaching +3–4 °C during summer, as well as by changes in precipitation distribution. Catchments of the Lake Geneva region and of the Swiss Plateau should be characterized by a pluvial regime, with mean maximum runoff in January and severe low flows from June to September. In mid-altitude catchments, this can be attributed to more precipitation with a higher liquid fraction during autumn and winter and less snowmelt. Over the Plateau, it would be function of increasing temperatures and decreasing summer precipitation. In alpine areas, low to no changes in precipitation distribution are projected but less snowmelt is simulated. The rise in temperature should increase the proportion of precipitation as rain and decrease winter snow accumulation leading to more severe low flows and a shift in flow seasonality, notably with mean maximum high flows in April, instead of May, currently over the Sarine River. The Grande Eau and the Sarine rivers should move toward a nival and transition nival regime, respectively. By the medium-term, hydro-climatic changes should then lead to less available freshwater resources in the canton of Vaud, especially during summer, and give rise to three different hydrological regimes, among which, one is currently not observed in the canton.

These results are coherent with previous national studies. No changes in hydrological processes were identified by national studies by the short-term, except a complete glacier retreat over the Grande Eau and Sarine catchments (Köplin et al., 2012). By the medium-term, our study highlights significant impacts of climate change on hydrological processes and water resources availability, and identifies possible evolution of hydrological regimes. The identified regimes in the 2060 horizon should remain likewise in the long term except over the Sarine catchment. Its hydrological regime should evolve toward a nival regime by the end of the century (FOEN, 2012a). Changes thus seem to follow a logical evolution pathway. It is nonetheless important to focus on the impacts of climate change in the medium term as changes identified up to now in the far future should already be visible by then.

This analysis also confirms the clusters defined by Köplin et al. (2012) over Switzerland based on hydro-climatological change signals, i.e., catchments with no clear changes, notably over the Swiss Plateau; and catchments with discernible changes in runoff as a function of precipitation change below 1000 m and temperature variability between 1000 m and 2500 m. Although it stays in the same order of magnitude, mean elevation limits can be adjusted over the canton of Vaud by stating that (i) below 700 m, no clear changes should be identified; (ii) between 700 m and 1500 m, rivers should move toward a pluvial regime because of changes in the solid-liquid fraction of precipitation; and (iii) above 1500 m, temperature variability should impact hydrological processes (shift and decrease of seasonal spring peak). López-Moreno and García-Ruiz (2004) and Bocchiola (2014) also identified a threshold close to the former, 1600 m in the Pyrenean Mountains and 1800 m in the Italian Alps, respectively. Both identified changes toward pluvial regimes below these altitudes due to less winter precipitation, less snow accumulation and higher evapotranspiration.

The earlier shift in high flows was also identified in several mid- and high altitude catchments in Italy (e.g., Confortola et al., 2015; Bocchiola, 2014), Western US (e.g., Hamlet et al., 2005; Adam et al., 2009; Elias et al., 2015) and in Canadian prairies (e.g., Gan, 2000) related to air warming and less snow accumulation. Our study thus joins these various regional studies to define a general consensus that where snowmelt is a key driver of hydrological regimes, significant shifts in the seasonal distribution of river flows are to be expected by the mid-21st century. More severe low flows are also an important issue for these areas and for catchments under pluvial regimes as it is during this period of time that water demands are highest, mainly for irrigation. This study thus provides a regional overview of how water resources availability could evolve by the 2060 horizon in the canton of Vaud and highlights when water issues could occur.

5.2. Assumptions and uncertainties framing the study

Prospective studies rely on future development hypothesis that condition the methodological core. Assumptions and uncertainties must then be addressed to frame the study, although weighing their influence on the results goes beyond the scope of this study.

A first uncertainty comes from the hydrological model and its capacity to represent hydrological variations. Effectiveness of the model was here assessed by three goodness-of-fit criteria, for which appropriate values were found. However, a large number of parameters reduces parameter uncertainty but increases equifinality (Her and Chaubey, 2015). Viviroli et al. (2009b) explored this aspect by comparing the PREVAH model iterative calibration with a Monte Carlo analysis with 50000 parameter sets generated randomly. They showed that their search algorithm identified Nash-Sutcliffe efficiency scores (NSE and NSEln) as high as Monte Carlo samples with a plausible behavior of baseflows. A small decrease in model performance was nonetheless observed when moving from calibration to validation periods. In the present assessment, efficiency scores improved between the two periods, supporting the capacity of the PREVAH model to catch a robust parameter set appropriately simulating the hydrological behavior of mountain catchments. In line with Bosshard and Zappa (2008), Viviroli et al. (2009b) also highlighted that PKOR and SNOKOR, scaling respectively rainfall and snowfall to compensate for errors in measurement and interpolation, were the most sensitive parameters, thus justifying treating them first in the calibration procedure. To further improve the calibration of these two parameters, one could apply a multi-criteria calibration with snowmelt sensitive scores and/or incorporate snow cover extent images (Addor et al., 2014). Moreover, most studies using the PREVAH model follow a regionalization process (e.g., Köplin et al., 2012; Addor et al., 2014), which often causes a wrong timing in the beginning of the snowmelt season (Zappa, 2002; Zappa and Kan, 2007). When working at the local scale, it is recommended to apply local calibration. This procedure was here applied over all catchments and enabled a better representation of observed runoff dynamics according to common efficiency criteria used with the various studies. The appropriate simulation of runoff volumes over each catchment during both calibration and corroboration phases also highlights that the PREVAH model is reliable to address water resources availability and explore water allocation or water stress. Furthermore, by using the PREVAH model, we aimed at using a reliable model in mountain environments and finding a robust parameter set for each catchment based on chosen goodness-of-fit functions, although subjective, in order to address water resources availability under climate change in a first instance, and further assess water stress risks (Milano et al., 2015), rather than finding a global optimum. By defining a set of parameters for each catchment, it is nonetheless assumed that the rainfall-runoff relationship and the bias between observed and simulated discharge identified over the reference period will remain stable in the future. The relevant item to bear in mind from this study is then the orders of magnitude of hydrological changes due to climate change. Another argument supporting this concluding remark is that anthropogenic activities and land-use were assumed a static property. Potential changes and effects on water resources were not considered..

Further uncertainties are related to climatic scenarios. The first uncertainty arises from the greenhouse gas emission scenario. The IPCC proposes several families of anthropogenic emission scenarios (IPCC, 2007) and projections of radiative forcing (IPCC, 2013). These story lines influence the evolution of climate change and its impacts on water resources. In this paper, the A1B emission scenario was chosen as it was the only one for which data had been post-processed for Swiss climatic stations. It was then voluntary to explore changes in water resources availability based on an intermediate emission scenario. However, the dominant source of uncertainty in climatic scenarios comes from the GCM-RCM model chains (see e.g., Wilby and Harris, 2006; Kay et al., 2009; Prudhomme and Davies, 2009; Bosshard et al., 2013; Addor et al., 2014). RCMs are useful to represent higher resolution atmospheric processes and consider the impacts of local topography yet they operate under boundary conditions set by GCMs and are unable to correct any biases deriving from it (Rummukainen, 2010). One way to validate RCMs is to compare their outputs for the control period. This task was carried within the CH2011 initiative (CH2011, 2011,1). The seasonal, interannual and geographic variability of temperature and precipitation were explored over Europe (Vidale et al., 2003; Jacob et al., 2007) and Switzerland (Fisher et al., 2011; Finger et al., 2012). The latter showed that all RCMs adequately simulated the annual and interannual climate cycle as well as the variability of local weather patterns. A tendency of all RCMs to simulate too cool and too wet rain events was also identified. However, it is not clear whether current climate conditions are reproduced for the correct reasons (Raisanen, 2007; Teutschbein and Seibert, 2010). Changes in climate main variables are linked to internal climate processes (e.g., energy budgets, convective processes) and measuring RCMs' performances as a whole is still poorly explored (Raisanen, 2007). To deal with this uncertainty, two procedures are recommended for hydrological impact studies: (i) apply a bias-correction method to correct both control and scenario runs; and (ii) include inter-model variability to evaluate RCM uncertainties (Wilby et al., 2000; Raisanen, 2007; Teutschbein and Seibert, 2010). These two measures were considered in this study. Climatic scenarios were downscaled according to the delta change method (Prudhomme and Davies, 2009; Bosshard et al., 2011; Fischer et al., 2011). This approach assumes that the temporal pattern of simulated series (i.e., occurrence, persistence and internal structure of meteorological events) remains the same as the observed series (Teutschbein and Seibert, 2010; Ruelland et al., 2012). Climatic variability is thus inherited from observed climate. This method was proved reliable when analyzing the evolution trends of water resources' volumes and seasonality but is judged inappropriate to explore year-to-year variability and changes in extreme events (e.g., heat waves, extreme precipitation events). Therefore, this study addresses changes in the monthly long-term mean in order to provide a first regional overview of the water situation in the canton of Vaud. In addition, climate change was explored according to the ten GCM-RCM model chains available, as different climatic scenarios might occur from one model to another due to their different capacity to consider and represent local scale processes (Tebaldi and Knutti, 2007). This approach showed that all models agreed on the climatic evolution trends as well as on the change signal, except for three models that appeared to be the most pessimistic over all catchments (CNRM-ARPEGE-ALADIN, ETHZ-HadCM3Q0-CLM and HC-HadCM3Q0-HadRM3Q0). However, their differences with other scenarios never exceeded 10%. Using several climatic models has the advantage of presenting a wide range of possible futures, a range of uncertainties and thus episodes that are most likely to occur or not. As an example, when looking at the hydrological scenarios, the higher variation range can be observed between December and March thus showing various possible futures, whereas the variation range is much smaller during the summer months (June, July and August). All models agree on the occurrence of more severe low flows in Western Switzerland in the 2060 horizon.

5.3. Prospects

Despite the aforementioned uncertainties, this study aims to bridge a gap in Swiss impact studies. It provides a quantitative assessment of how hydro-climatic conditions could evolve in Western Switzerland, and more specifically in the canton of Vaud. It shows that significant changes in runoff distribution might occur by the medium-term and that hydrological regimes are entitled to change. In a region where urbanization keeps increasing and where agriculture plays a major economic role, one can wonder whether water resources will still be able to meet future water demands.

Research should then move toward integrated studies including both climatic and anthropogenic changes. All activity sectors should be included in order to express possible water conflicts among users. A monthly time-step is also highly recommended to be able to consider the temporal variability of water resources and demands and thus highlight periods where water tensions are most likely to occur. Finally, applied at the cantonal scale, these studies could define the most vulnerable regions to water stress and support water allocation plans. This is the subject of a complementary paper (Milano et al., 2015).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.10.010.

References

Adam, J.C., Hamlet, A.F., Lettenmaier, D.P., 2009. Implications of global climate change for snowmelt hydrology in the twenty-first century. Hydrol. Process. 23, 962–972.
Addor, N., Rössler, O., Köplin, N., Huss, M., Weingartner, R., Seibert, J., 2014. Robust changes and sources of uncertainty in the projected hydrological regimes of Swiss catchments. Water Resour. Res. 50 (10), 7541–7562.
Arnell, N.W., Gosling, S.N., 2013. The impacts of climate change on river flow regimes at the global scale. J. Hydrol. 486, 351–364.
Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438 (17), 303–309.
Beniston, M., Stoffel, M., 2014. Assessing the impacts of climatic change on mountain water resources. Sci. Total Environ. 493, 1129–1137.
Bergström, S., 1976. Development and application of a conceptual runoff model for Scandinavian catchments. Bull. Ser. A 52, 134 pp.
Birsan, M.-V., Molnar, P., Burlando, P., Pfaundler, M., 2005. Streamflow trends in Switzerland. J. Hydrol. 314, 312–329.
Bocchiola, D., 2014. Long term (1921–2011) hydrological regime of Alpine catchments in Northern Italy. Adv. Water Resour. 70, 51–64.
Bosshard, T., Zappa, M., 2008. Regional parameter allocation and predictive uncertainty estimation of a rainfall-runoff model in the poorly gauged Three Gorges Area (PR China). Phys. Chem. Earth 33, 1095–1104.
Bosshard, T., Kotlarski, T., Ewen, T., Schär, C., 2011. Spectral representation of the annual cycle in the climate change signal. Hydrol. Earth Syst. Sci. 15, 2777–2788.
Bosshard, T., Carambia, M., Goergen, K., Kotlarski, S., Krahe, P., Zappa, M., Schär, C., 2013. Quantifying uncertainty sources in an ensemble of hydrological climate impact projections. Water. Resour. Res. 49, 1523–1536.
Buishand, T.A., 1984. Tests for detecting a shift in the mean of hydrologcial time series. J. Hydrol. 73, 51–69.
CH2011, 2011. Swiss Climate Change Scenarios CH2011. C2SM, MeteoSwiss, ETH, NCCR Climate and OcCC, Zurich. 88 pp.
CH2014, 2014. Towards Quantitative Scenarios of Climate Change Impacts in Switzerland. OCCR, FOEN, MeteoSwiss, C2SM, Agroscope, and ProClim, Bern, 136 pp.
Canton of Vaud, 2014. Veille hydrologique vaudoise. Département de la sécurité et de l'environnement. www.vhv.ch (accessed 01.15).
Ceppi, P., Scherrer, S.C., Fischer, A.M., Appenzeller, C., 2012. Revisiting Swiss temperature trends 1959–2008. Int. J. Climatol. 32, 203–213.
Confortola, G., Soncini, A., Bocchiola, D., 2015. 2013. Climate change will affect hydrological regimes in the Alps. A case study in Italy. J. Alp. Res. 101 (3) (accessed 01.15) http://rga.revues.org/2176.
Elias, E.H., Rango, A., Steele, C.M., Mejia, J.F., Smith, R., 2015. Assessing climate change impacts on water availability of snowmelt-dominated basins of the Upper Rio Grande basin. J. Hydrol. Reg. Stud. 3, 525–546.
FOEN—Federal Office for the Environment, 2012a. Effects of climate change on water resources and watercourses. Synthesis report on Climate change and hydrology in Switzerland (CCHydro project). Ed. by Federal Office for the Environment, Bern. Umwelt-Wissen 1217, 74 pp.
FOEN—Federal Office for the Environment, 2012b. Manage local water shortage in Switzerland. Report of the Federal Council in response to the postulate Water and agriculture. Tomorrow's challenges. 88 pp. (in French).
FOEN—Federal Office for the Environment, 2014. Observed discharge time series of Swiss rivers. www.bafu.admin.ch (accessed 01.15).
FOSD-ARE—Federal office for spatial development, 2013. Geographical distribution of the Swiss population (Facts and Figures series). http://www.are.admin.ch/dokumentation/01378/04466/index.html?lang=fr (accessed 01.15).
FSO—Federal Statistical Office, 2003. GEOSTAT Database Products. Licence No. G158000315, ©SFSO, Neuchâtel.
FSO—Federal Statistical Office, 2006. Agriculture in the Swiss cantons. Results from the regional accounts of 2005. FSO, Neuchâtel. 34 pp. (in French).
FSO—Federal Statistical Office, 2014. Statistical Atlas of Switzerland. Population density from 1850 to 2013. Federal population census. www.atlas.bfs.admin.ch (accessed 01.15).
Finger, D.C., Heinrich, G., Gobiet, A., Bauder, A., 2012. Projections of future water resources and their uncertainty in a glacierized catchment in the Swiss Alps and the subsequent effects on hydropower production during the 21st century. Water Resour. Res. 48, 20, W02521.pp.
Fischer, A.M., Weigel, A.P., Buser, C.M., Knutti, R., Künsch, H.R., Liniger, M.A., Schär, C., Appenzeller, C., 2011. Climate change projections for Switzerland based on a Bayesian multi-model approach. Int. J. Climatol. 32 (15), 2348–2371.
Gan, T.Y., 2000. Reducing vulnerability of water resources of Canadian prairies to potential droughts and possible climatic warming. Wat. Res. Manag. 14, 111–135.
Garen, D., Marks, D., 2001. Spatial fields of meteorological input data including forest canopy corrections for an energy budget snow simulation model. In: Dolman, A.J., Hall, A.J., Kavvas, M.L., Oki, T., Pomeroy, J.W. (Eds.), Soil–Vegetation–Atmosphere Transfer Schemes and Large Scale Hydrological Models, 270. IAHS Publ., pp. 349–353.
Graham, L.P., Hagemann, S., Jaunn, S., Beniston, M., 2007. On interpreting hydrological change from regional climate models. Clim. Change 81, 97–122.

Gurtz, J., Baltensweiler, A., Lang, H., 1999. Spatially distributed hydrotope-based modeling of evapotranspiration and runoff in mountainous basins. Hydrol. Process. 13, 2751–2768.
Gurtz, J., Zappa, M., Jasper, K., Lang, H., Verbunt, M., Badoux, A., Vitvar, T., 2003. A comparative study in modelling runoff and its components in two mountainous catchments. Hydrol. Process. 17, 297–311.
Hänggi, P., Weingartner, R., 2012. Variations in discharge volumes for hydropower generation in Switzerland. Water Resour. Manag. 26, 1231–1252.
Hamlet, A.F., Mote, P.W., Clark, M.P., Lettenmaier, D.P., 2005. Effects of temperature and precipitation variability on snowpack trends in the Western United States. J. Climate 18, 4545–4561.
Heimo, A., Konzelmann, T., Calpini, B., Rast, J., Tschichold, N., Grüter, E., 2005. SwissMetNet: renewal of the Swiss meteological networks. In: new developments and operational experience with surface observation technology. WMO-TECO-2005Conference, 8pp.
Her, Y., Chaubey, I., 2015. Impact of the numbers of observations and calibration parameters on equifinality, model performance, and output and parameter uncertainty. Hydrol. Process., http://dx.doi.org/10.1002/hyp.10487.
Hubacher, R., Schädler, B., 2010. Map 6.6: water balance of river basins in the 20th century. In: Weingartner R., Spreafico M. (Eds.): Hydrological Atlas of Switzerland (HADES). Federal Office for the Environment, Bern. www.hades.unibe.ch (accessed 01.15).
Hubert, P., Carbonnel, J.P., Chaouche, A., 1989. Segmentation des séries hydrométriques: application à des séries de précipitations et de débits de l'Afrique de l'ouest. J. Hydrol. 110, 349–367.
Huss, M., Farinotti, D., Bauder, A., Funk, M., 2008. Modelling runoff from highly glacierized alpine drainage basins in a changing climate. Hydrol. Process. 22, 3888–3902.
IPCC—Intergovernmental Panel on Climate Change, 2007. Climate change 2007: the physical science basis. In: SolomonQin, S.D.M., Manning, Z., Chen, M., Marquis, K.B., Averyt Tignor, M., Miller, H.L. (Eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, p. 2007.
IPCC—Intergovernmental Panel on Climate Change, 2013. Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
IRD—Institut de recherche pour le development, 2002. Khronostat. Software for statistical analysis of chronological series. http://www.hydrosciences.org/spip.php?article239 (accessed 01.15).
Jacob, D., Bärring, L., Christensen, O.B., Christensen, J.H., de Castro, M., Déqué, M., Girogi, F., Hagemann, S., Hirschi, M., Jones, R., Kjellström, E., Lenderink, G., Rockel, B., Sánchez, E., Scär, C., Seneviratne, S.I., Somot, S., van Ulden, A., van den Hurk, B., 2007. An inter-comparison of regional climate models for Europe: model performance in present-day climate. Clim. Change 81, 31–52.
Jasper, K., Calanca, P., Gyalistras, D., Fuhrer, J., 2004. Differential impacts of climate change on the hydrology of two alpine river basins. Clim. Change 26, 113–129.
Köplin, N., Viviroli, D., Schädler, B., Weingartner, R., 2010. How does climate change affect mesoscale catchments in Switzerland?—a framework for a comprehensive assessment. Adv. Geosci. 27, 111–119.
Köplin, N., Schädler, B., Viviroli, D., Weingartner, R., 2012. Relating climate change signals and physiographic catchment properties to clustered hydrological response types. Hydrol. Earth Syst. Sci. Discuss. 9, 3165–3202.
Köplin, N., 2012. Hydrological impacts of climate change in Switzerland during the 21st century. In: PhD Thesis. Institute of Geography, University of Bern, 111 pp.
Kay, A.L., Davies, H.N., Bell, V.A., Jones, R.G., 2009. Comparison of uncertainty sources for climate change impacts: flood frequency in England. Clim. Change 92, 41–63.
Kobierska, F., Jonas, T., Zappa, M., Bavay, M., Magnusson, J., Bernasconi, S., 2013. Future runoff for a partly glacierized watershed in Central Switzerland:a two-model approach. Adv. Water Resour. 55, 204–214.
Krause, P., Boyle, D.P., Bäse, F., 2005. Comparison of different efficiency criteria for hydrological model assessment. Adv. Geosci. 5, 89–97.
López-Moreno, J.I., García-Ruiz, J., 2004. Influence of snow accumulation and snowmelt on streamflow in the central Spanish Pyrenees. Hydrol. Sc. J. 49 (5), 787–802.
Lee, A.F.S., Heghinian, S.M., 1977. A shift in the mean level in a sequence of independent normal random variables—a Bayesian approach. Technometrics 19 (4), 503–506.
Lenderink, G., Buishand, A., van Deursen, W., 2007. Estimates of future discharges of the river Rhine using two scenario methodologies: direct vers delta approach. Hydrol. Earth Syst. Sci. 11 (3), 1145–1159.
Lubès-Niel, H., Masson, J.M., Paturel, J.E., Servat, E., 1998. Climatic variability and statistics: a simulation approach for estimating power and robustness of tests of stationarity. Revue des Sci. de l'eau 3, 383–408 (in French).
MandaTerre, 2013. Diagnosis of irrigation water needs in the canton of Vaud. Report established for the Service du développement territorial du canton de Vaud. 42 pp. (in French).
MeteoSwiss, 2008. Time series of meteorological variables. Federal Office for Meteorology and Climatology, Zurich. www.meteoswiss.admin.ch (accessed 01.15).
Middelkoop, H., Daamen, K., Gellens, D., Grabs, W., Kwadijk, J.C.J., Lang, H., Parmet, B.W.A.H., Schädler, B., Schulla, J., Wilke, K., 2001. Impact of climate change on hydrological regimes and water resources management in the Rhine basin. Clim. Change 49, 105–128.
Milano, M., Reynard, E., Köplin, N., Weingartner, R., 2015. Climatic and anthropogenic changes in Western Switzerland: impacts on water stress. Sci. Total Environ. 536, 12–24.
Morán-Tejeda, E., López-Moreno, J.I., Ceballos-Barbancho, A., Vicente-Serrano, S.M., 2011. River regimes and recent hydrological changes in the Duero basin (Spain). J. Hydrol. 404, 241–258.
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models, a discussion of principles. J. Hydrol. 10, 282–290.
OcCC—Organe consultatif sur les changements climatiques, 2007. Climate change and Switzerland 2050. Expected impacts on environment, society and economy. OcCC/ProClim, Bern, 168 pp.
OcCC—Organe consultatif sur les changements climatiques, 2008. Climate change is a fact –and now? The IPCC report and its consequences for Switzerland. OcCC, Bern. 47 pp. (in French and German).
OcCC—Organe consultatif sur les changements climatiques, 2012. Climatic objectives and emission reduction. Analysis and vision for a Swiss climate policy. OcCC, Bern. 63 pp. (in French and German).
Pardé, M.,1933. Fleuves et rivières. A. Colin, Paris. 224 pp.
Pellicciotti, F., Bauder, A., Parola, M., 2010. Effect of glaciers on streamflow trends in the Swiss Alps. Water Resour. Res. 46 (10), 16pp. W10522.
Pettitt, A.N., 1979. A non-parametric approach to the change-point problem. Appl. Statist. 28 (2), 126–135.
Poulin, A., Brissette, F., Leconte, R., Arsenault, R., Malo, J.-S., 2011. Uncertainty of hydrological modelling in climate change impact studies in a Canadian snow-dominated river basin. J. Hydrol. 409, 626–636.
Prudhomme, C., Davies, H., 2009. Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK. Part 2: future climate. Clim. Change 93, 197–222.
Raisanen, J., 2007. How reliable are climate models? Tellus 59A, 2–29.
Ruelland, D., Ardoin-Bardin, S., Collet, L., Roucou, P., 2012. Simulating future trends in hydrological regime of a large Sudano-Sahelian catchment under climate change. J. Hydrol. 424–425, 207–216.
Rummukainen, M., 2010. State-of-the-art with regional climate models. Wiley Interdiscip. Rev. Climate Change 1, 82–96.
SESA—Service des eaux, sols et assainissements, 2012. Report on water in the Vaud canton. Response to the postulates/interpellations Epars-Bory concerning water bodies' summer drying. Département de la sécurité et de l'environnement, Lausanne. 98 pp. (in French).

Schmidli, J., Frei, C., 2005. Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century. Int. J. Climatol. 25 (6), 753–771.
Serquet, G., Marty, C., Dulex, J.-P., Rebetez, M., 2011. Seasonal trends and temperatures dependence of the snowfall/precipitation-day ratio in Switzerland. Geophys. Res. Lett. 38, L07703, 5 pp.
Tebaldi, C., Knutti, R., 2007. The use of the multi-model ensemble in probabilistic climate projections. Philos. Trans. A Math Phys. Eng. Sci. 365 (1857), 2053–2075.
Teutschbein, C., Seibert, J., 2010. Regional climate models for hydrological impact studies at the catchment scale: a review of recent modeling strategies. Geogr. Compass 4 (7), 834–860.
USEPA—United States Environmental Protection Agency, 2004. Developing spatially interpolated surfaces and estimating uncertainty. Ed. by U.S. Environmental Protection Agency, EPA-454. R-04-004. 169 pp.
Uhlmann, B., Jordan, F., Beniston, M., 2013. Modelling runoff in a Swiss glacierized catchment—part I: methodology and application in the Findelen basin under a long-lasting stable climate. Int. J. Climatol. 33 (5), 1293–1300.
Viviroli, D., Weingartner, R., 2004. The hydrological significance of mountains: from regional to global scale. Hydrol. Earth Syst. Sc. 8 (6), 1016–1029.
Viviroli, D., Gurtz, J., Zappa, M., 2007. The hydrological modelling system PREVAH. In: Geographica Bernensia P40. Insitute of Geography University of Bern, pp. 89pp.
Viviroli, D., Zappa, M., Schwanbeck, J., Gurtz, J., Weingartner, R., 2009a. Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland—part I: modelling framework and calibration results. J. Hydrol. 377, 191–207.
Viviroli, D., Zappa, M., Gurtz, J., Weingartner, R., 2009b. An introduction to the hydrological modelling system PREVAH and its pre- and post-processing-tools. Environ. Model. Software 24, 1209–1222.
Weingartner, R., Aschwanden, H., 1992. Discharge regime—the basis for the estimation of average flows. Hydrological Atlas of Switzerland, Plate 5.2, Bern.
Wilby, R.L., Harris, I., 2006. A framework for assessing uncertainties in climate change impacts: low-flow scenarios for the river Thames, UK. Water Resour. Res. 42, 10, W02419.pp.
Wilby, R.L., Hay, L.E., Gutowski, J., r, Arritt, W.J., Takle, R.W., Pan, E.S., Leavesley, Z., Clark, G.H., MP, 2000. Hydrological responses to dynamically and statistically downscaled climate model output. Geophys. Res. Lett. 27 (8), 1199–1202.
Zappa, M., 2002. Multiple-response verification of a distributed hydrological model at different spatial scales. Ph.D thesis, Swiss Federal Institute of Technology, Zürich. Diss. ETH No. 14895. 167pp.
van der Linden, P., Mitchell, J. 2009. ENSEMBLES: climate change and its impacts. Summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, Exeter.
Zappa, M., Kan, C., 2007. Extreme heat and runoff extremes in the Swiss Alps. Nat. Hazards Earth Syst. Sci. 7 (3), 375–389.