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Climatic and anthropogenic changes in Western Switzerland: Impacts on water stress

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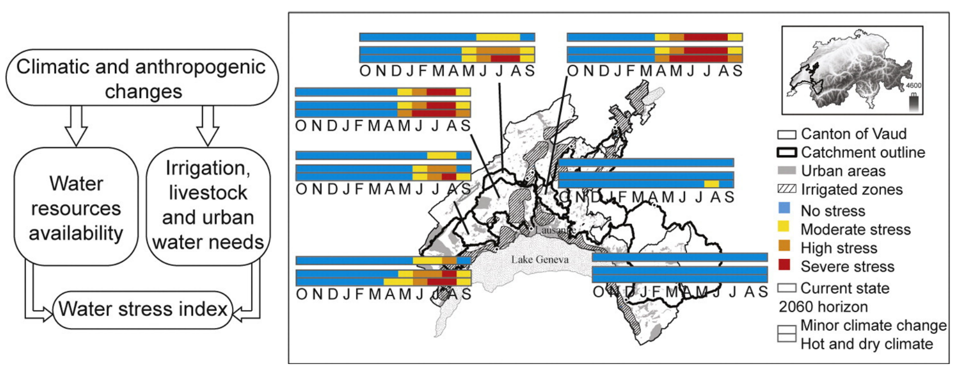
HIGHLIGHTS

- A cantonal vision of where and when water tensions are likely to occur is provided.
- Hydro-climatic and socio-economic changes are assessed by the mid-21st century.
- Water shortage episodes could become more frequent in western Switzerland.
- The Lake Geneva region should experience severe water stress during summer.

GRAPHICAL ABSTRACT



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ABSTRACT

Recent observed hydro-climatic changes in mountainous areas are of concern as they may directly affect capacity to fulfill water needs. The canton of Vaud in Western Switzerland is an example of such a region as it has experienced water shortage episodes during the past decade. Based on an integrated modeling framework, this study explores how hydro-climatic conditions and water needs could evolve in mountain environments and assesses their potential impacts on water stress by the 2060 horizon. Flows were simulated based on a daily semi-distributed hydrological model. Future changes were derived from Swiss climate scenarios based on two regional climate models. Regarding water needs, the authorities of the canton of Vaud provided a population growth scenario while irrigation and livestock trends followed a business-as-usual scenario. Currently, the canton of Vaud experiences moderate water stress from June to August, except in its Alpine area where no stress is noted. In the 2060 horizon, water needs could exceed 80% of the rivers' available resources in low- to mid-altitude environments in mid-summer. This arises from the combination of drier and warmer climate that leads to longer and more severe low flows, and increasing urban (+40%) and irrigation (+25%) water needs. Highlighting regional differences supports the development of sustainable development pathways to reduce water tensions. Based on a quantitative assessment, this study also calls for broader impact studies including water quality issues.

1. Introduction

In the past decades, there has been growing recognition that the impacts of climate change should modify the seasonal availability of water

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resources in a world where water demands are on an upward curve. At the global scale, the sensitivity of mid-latitude snow-dominated regions has been underlined (Barnett et al., 2005; Adam et al., 2009; Beniston, 2012). Mountain watersheds have shown early warnings of change in land surface hydrology. Since the late 1970s, a significant shrinkage of glaciers has been observed in high latitude and equatorial mountains (see e.g. Stewart, 2009; Peduzzi et al., 2010; Bolch et al., 2012; Buytaert and De Bièvre, 2012) as well as changes in precipitation and snowpack behavior in mid-elevated continental mountains (e.g. Knowles et al., 2006; Bocchiola, 2014; Morán-Tejeda et al., 2014; Pellicciotti et al., 2014a,b). A negative trend in snow accumulation and duration was indeed observed at medium altitudes (below 2700 m.a.s.l) in West-central Canada (Burn, 1994; Gan, 2000), the Western US (Lundquist et al., 2009; Stewart, 2009), the European Alps (Beniston, 2003; Coppola et al., 2014) and the Pyrenees (López-Moreno and García-Ruiz, 2004). This results from warmer temperatures that have increased the fraction of precipitation falling as rain rather than snow. Snowpacks act as reservoirs for water storage (Nijssen et al., 2001). Any further changes in snowpack volumes should strongly affect water availability in mountain environments (Adam et al., 2009; Barnett et al., 2005; de Jong et al., 2009). In the light of global warming, observed trends in medium altitudes are most likely to continue and at altitudes below 1700–1500 m, all snow cover could disappear (Stewart, 2009; Köplin et al., 2012). By the 2050s, rivers could exhibit seasonal shifts in streamflow, with higher flows during winter and a high flow peak coming about one month earlier in the year, and more severe and longer low flows in summer (see e.g. Stewart, 2009; Beniston and Stoffel, 2014; Morán-Tejeda et al., 2014; Pellicciotti et al., 2014b). Changes in seasonal water resources availability are of particular concern, as the ability to meet summer water demands could be reduced even in these “water-rich” regions (Fuhrer and Jasper, 2012).

The impacts of hydro-climatic changes on hydropower production have probably been the most explored water service in mountain environments (see e.g. Finger et al., 2012; Hänggi and Weingartner, 2012; López-Moreno et al., 2014; Kopytkovskiy et al., 2015). Reduced glacial melt water inputs and changes in water resource seasonality could alter water storage and flows, negatively affecting the potential hydroelectric production. In certain areas, like in the Western US or in the Alps for example, water managers and industries would have to choose between using water for hydroelectric power and releasing water for downstream water supplies or to sustain a river's ecology during summer (Middelkoop et al., 2001; Barnett et al., 2004; Leung, 2005). Satisfaction of irrigation water requirements has also been considered (see e.g. Piao et al., 2010; Fündel et al., 2013; Fuhrer et al., 2014). Warmer temperatures and projected changes in precipitation distribution in the mid-21st century should reduce soil moisture and increase crop evapotranspiration leading to additional water demands to maintain optimal crop yields. However, more severe low flows would limit water availability for irrigation purposes that would be in direct competition with other permanent water uses (e.g. domestic water use, fishery, ecosystem protection; Fuhrer and Jasper, 2012; Björnsen Gurung and Stähli, 2014). According to studies carried out in the Swiss Alps and in China, these pressures should be acute in rainfed rivers where irrigation water needs could exceed the available water resources compared to glacial-supported rivers where no water shortage should be noted (Piao et al., 2010; Fuhrer and Jasper, 2012; Fuhrer et al., 2014). Others put forward rising competition between upstream and downstream regions (Mul et al., 2011; Viviroli et al., 2011; Buytaert and De Bièvre, 2012). Any disturbance affecting water availability in headwaters would propagate to downstream areas exhibiting high urban water needs, thus enhancing a risk of water shortage. Finally, water use, notably for cooling purposes, might also be limited due to higher water temperatures (Middelkoop et al., 2001; Klug et al., 2012). Water quality is a major issue when it comes to water supply and environmental protection. Several studies have considered water quality and its related impacts on water resources availability or uses (see e.g. Murdoch et al., 2000; van Vliet and Zwolsman, 2008; Klug et al., 2012). However, the issue goes beyond the scope of this study and will not be addressed here. In summary, in light of hydro-climatic and anthropogenic changes, competitions among water users are most likely to increase in mountain areas. This calls for more integrated consideration of the interactions between hydro-climatic changes and various water users in mountain areas in order to assess pressures applied to water resources and their capacity to fulfill future water needs.

Such approach has been widely used at the global scale to identify the most vulnerable regions to climatic variability and anthropogenic pressures (e.g. Alcamo et al., 2007; Pfister et al., 2009; Arnell et al., 2011). However, a critical issue is that worldwide studies do not sufficiently account for regional development pathways and for seasonal changes in water needs and resources availability (Viviroli et al., 2011; Milano et al., 2013a; Sanches Fernandes et al., 2014). More detailed regional approaches are needed to understand the alignment between water supplies and demands and to provide more reliable prospective scenarios. This issue is still poorly explored in mountain areas. One reason might be that, until recently, hydro-climatic specificities at sub-continental scales were overlooked due to the low spatial resolution of models (Giorgi and Mearns, 1991; Beniston et al., 1994). Another reason could be the lack of data to describe the current water system, especially water uses that were poorly monitored until now (Bonriposi, 2013; Grouillet et al., 2015). Water use systems of mountain regions also often depend on factors lying outside the water and climate sectors, such as agricultural policies or tourism economy (e.g. Price, 1992; Fernandez et al., 2014). Few studies have analyzed the pressures arising from use upon mountain water resources. Special focus was laid on water deficits during dry years. Critical situations were identified during winter in alpine catchments that rely on artificial snowmaking and in August in rainfed catchments due to higher irrigation water needs and lower water levels (Vanham et al., 2009a,b; Fuhrer and Jasper, 2012; Fuhrer et al., 2014). Others tried to assess changes in water resources availability or consumption per capita on an annual basis, thus still overlooking seasonal differences (Buytaert and De Bièvre, 2012; Klug et al., 2012). The most integrated study in a mountainous context was recently carried in an Alpine touristic region in Switzerland (Reynard et al., 2014; Schneider et al., 2014). It considered the impacts of irrigation, urban and artificial snow water demands on water resources under climate change conditions. It highlighted the importance of glacial melt for water supply. In the mid-21st century, glacial melt should still supply enough water but its complete elimination during the second half of the century could enhance severe water supply issues. Although these studies do not use a water stress index to geographically express water use conflicts (see e.g. Collet et al., 2013; Milano et al., 2013a), they identify the range of factors that can influence water availability and use, and show the need to move towards better-integrated water resource management in mountainous regions.

This paper aims to provide a detailed regional overview of water stress in an area representative of mountain water-related issues. It will focus on both hydro-climatic and socio-economic drivers of water availability and use to the mid-21st century. The method relies on a regional integrated modeling tool initially developed in a Mediterranean context (Milano et al., 2013b) to which snow processes and seasonal variability have been added. The initial framework was judged useful to identify catchments and periods where water tensions are most likely to occur, and helpful in setting up regional sustainable development strategies (Milano et al., 2013b). Here, the focus is upon the canton of Vaud in Western Switzerland. It is characterized by densely populated areas along the shores of Lake Geneva, agricultural lowlands, and mid- to high-altitude mountains in its western (Jura Range) and eastern (Alps) borders. As such, it represents a clear example of an interdependent region, with a zone of plentiful water supply in the relatively under-populated mid and high altitude regions and a zone of high water demand in the relatively densely populated low altitude regions. This area has also been subject to an uprising issue in mountain environments: water shortage episodes (FOEN, 2012a). During the past decade, prohibition of water withdrawals and restriction of water supply have been more needed (1) in the mountains and watersheds of the Jura region due to lower groundwater levels in karstic aquifers; (2) in the Lake Geneva region and pre-alpine catchments due to growing water demands related to the recent development of irrigation practices to ensure crop yields and improve competitiveness; and (3) in pluvial catchments (e.g. Broye) due to lower precipitation volumes (Fündel et al., 2013; Kruse and Seidl, 2013; Fuhrer et al., 2014). These droughts highlighted increasing competition among water users and water management issues (SESA, 2012). Switzerland is a federal country characterized by the distribution of water management tasks between three levels: local municipalities (e.g. drinking water supply), cantons (e.g. protection against floods) and the federal state (e.g. hydrology monitoring). The country has no unified legislation on water and has not adopted an integrated water resource management. Finally, national scale studies have identified the Swiss mid- to lowlands as the area most prone to summer droughts and water shortage episodes by the mid-21st century (Fündel et al., 2013; Kruse and Seidl, 2013).

Assessing the possible evolution of water resources and demands in Western Switzerland could then serve as an example to other mountainous regions. A first study was carried out to better quantify water resources variability under climate change conditions in the canton of Vaud (Milano et al., under review). This paper attempts to meet two further objectives: (i) to analyze the spatial distribution and the temporal evolution of water needs by the medium term, and (ii) to assess the current and future pressures applied to water resources in the canton of Vaud, under climatic and/or anthropogenic changes.

2. Study area

The canton of Vaud, located in Western Switzerland, covers an area of 2822 km^2 (lakes excluded). It extends from the Jura Mountains (alt. max. 1677 m.a.s.l; Fig. 1) over the Swiss Plateau (400–600 m.a.s.l) to the high alpine areas (alt. max. 3200 m.a.s.l). It includes the borders of Lake Geneva – one of the largest European water reservoirs – Lake Neuchatel and Lake Murten. Different hydro-climatic profiles can be identified in the canton. In the Jura and the Alpine regions, the climate is cool and wet. Mean monthly temperatures vary between −1 °C and −5 °C during winter, and between 10 °C and 15 °C during summer (average over the 1983–2005 period). Mean precipitation varies between 115 and 200 mm/month. Nonetheless, changes in altitude and topography affect precipitation distribution and thus the timing and volume of snowpack development and depletion. This leads to different hydrological regimes (Weingartner and Aschwanden, 1992; Milano et al., under review). Rivers of the Lake Geneva Region with sources in the Jura Mountains are characterized by a nivo-pluvial regime. High flows occur during winter due to high precipitation and are sustained by snowmelt in spring. Low flows occur during the summer months due to high temperatures and evaporation (75–90 mm/month on average over the 1983–2005 period). Alpine rivers are characterized by transition nival to alpine nival regimes (Weingartner and Aschwanden, 1992; Milano et al., under review). As most of the precipitation falls as snow, river flows mostly depend on snowmelt that enhance high flows in May and June. Over the Plateau, climate can be described as mild and wet. Temperatures vary between 1 °C and 6 °C during winter, and between 16 °C and 19 °C during summer (average over the 1983–2005 period). Precipitation, mostly rainfall, remains more or less constant throughout the year (70–90 mm/month), although two maxima can be noted in May and August (90–120 mm/month). Rivers of the Plateau have a pluvial regime with river flows influenced by changes in precipitation but mostly by changes in evaporation due to temperature variability (Milano et al., under review). High flows can be identified from October to March, with peaks in February or March, and low flows from June to September (Weingartner and Aschwanden, 1992; Milano et al., under review). The geographic, climatic and hydrologic

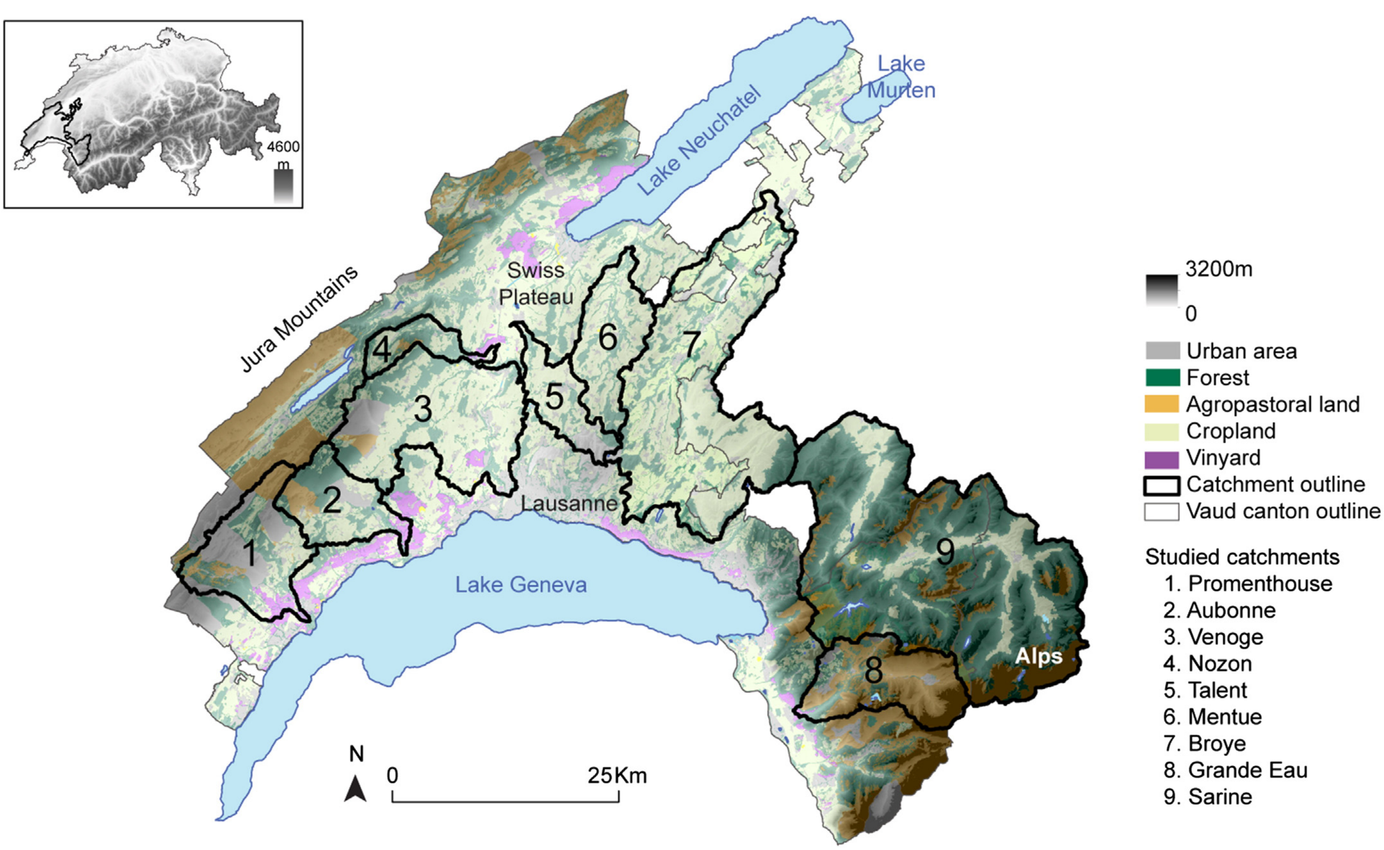

Fig. 1. Topography and land cover of the canton of Vaud.

properties of the canton then provide various water supply sources. During the past decade, on average, 60% of the canton's total water demands were supplied by rivers, 22% by lakes, 13% by groundwater resources and 5% by private springs (SGWA, 2004; MandaTerre, 2013).

The contrasted landscape of the canton also favors diversified anthropogenic activities (Fig. 1). The shores of Lake Geneva and Lake Neuchatel have experienced rapid population growth. Since the 1970s, the population has tripled in these areas related to urban and peri-urban development (FOSD-ARE, 2013). Agricultural lands in the littoral areas have been progressively abandoned in favor of expanding cities (Niwa et al., 2012). In 2012, the canton of Vaud was the third most populous canton of the country with 734,350 inhabitants. The plain and piedmont areas are mostly dedicated to agriculture. They cover 17% of the Swiss agricultural land (FSO, 2006). The main grown crops are wheat (20.5 km^2; MandaTerre, 2013), grasslands (14 km^2) and corn (8.7 km^2). Farmers rely on irrigation only for 5% of their croplands, mainly for vegetable farming, fruit trees, horticultural crops, berries, rhubarb and potatoes. However, the frequent droughts that affected the canton this past decade enhanced the development of this practice (MandaTerre, 2013). Permanent grasslands in the plain areas also promote cow, horse, pig and chicken breeding. Finally, in the Jura and Alps mountains, climate is convenient for permanent grassland thus supporting dairy cow breeding.

In order to explore freshwater availability, water needs and their evolution in the canton of Vaud by the 2060 horizon, all meso-scale catchments with a surface area of at least 30 km^2 and without major lake regulation were considered. Catchments also had to represent the hydrologic and geographic diversity of the canton, i.e. all four hydrological regimes present in the canton had to be considered as well as the different water users and land use practices identified in the littoral, lowlands and mountain areas. Nine catchments covering 67% of the canton's surface area were thus considered (Fig. 1).

3. Material and methods

3.1. Interaction between climate, freshwater resources and water needs

An integrated modeling approach was designed to define the current pressures applied to water resources in the canton of Vaud and grasp the relative influence of climatic and anthropogenic changes on water stress occurrence (Fig. 2). It is derived and modified from Milano et al. (2013b) who compared annual freshwater resource availability and annual water withdrawals for domestic and irrigation purposes through a water stress index in catchments of the Mediterranean basin. The initial framework was improved by implementing snow processes and seasonal variability in order to account for mountain hydrological processes, consider daily to monthly variations in freshwater availability and water needs, and identify both areas and seasons in which water use conflicts are most likely to occur. A new input was also the consideration of livestock water needs. This method was applied over each of the nine considered catchments.

Freshwater resources and water needs were estimated on a daily basis over the reference period 1984–2005 and the future period 2050–2071. For synthesis purposes, results were then aggregated at a monthly time-step. The reference period was chosen according to climatic data availability and its coverage of both wet and dry periods (see Milano et al., under review). Projections of climatic changes were based on the CH2011 initiative (CH2011, 2011). It established climatic scenarios exclusively for Switzerland (Bosshard et al., 2011) based on ten GCM-RCM model chains from the European ENSEMBLES project (van der Linden and Mitchell, 2009) forced with the A1B greenhouse gas emission scenario (IPCC, 2007). The impacts of climatic changes on the water resources of the canton of Vaud based on these ten GCM-RCM models were explored in a complementary assessment (Milano et al., under review). In this paper, for synthesis purposes, it was chosen to present the results based only on the KNMI-ECHAM5-RACMO and HC-HadCM3Q0-HadRM3Q0 models, which projected, respectively, the most optimistic and pessimistic hydro-climatic changes over the nine selected catchments. In this specific context, the former will refer to minor hydro-climatic changes while the latter will refer to the driest climate and most severe low flows simulations.

Monthly water needs were evaluated for the agricultural, livestock and urban sectors. For future projections, a business-as-usual scenario was considered. It was assumed that irrigated crops and surface areas would remain unchanged, yet the impacts of climate change on crops' water needs were explored. Livestock past evolution trends were carried on. Finally, the canton statistical office provided a continuous demographic growth scenario until 2040. The population growth rate was extrapolated until 2071.

3.2. Evaluation of freshwater resources availability

For each catchment, the semi-distributed and process-oriented hydrological model PREVAH (Viviroli et al., 2009) was run to simulate rivers' total runoff. In this section, the basic concepts of the model are explained. A synthesis on the calibration-validation procedure and on the data used is also made. For detailed information on the model structure, and on the datasets and calibration-validation procedure used please refer to Viviroli et al. (2009) and Milano et al. (under review), respectively.

The model is based on the HBV model structure (Bergström, 1976), using hydrological response units (HRU; Gurtz et al., 2003). This HRU structure enables a more spatially distributed representation of the catchment and a dynamic parameterization. Each catchment is divided

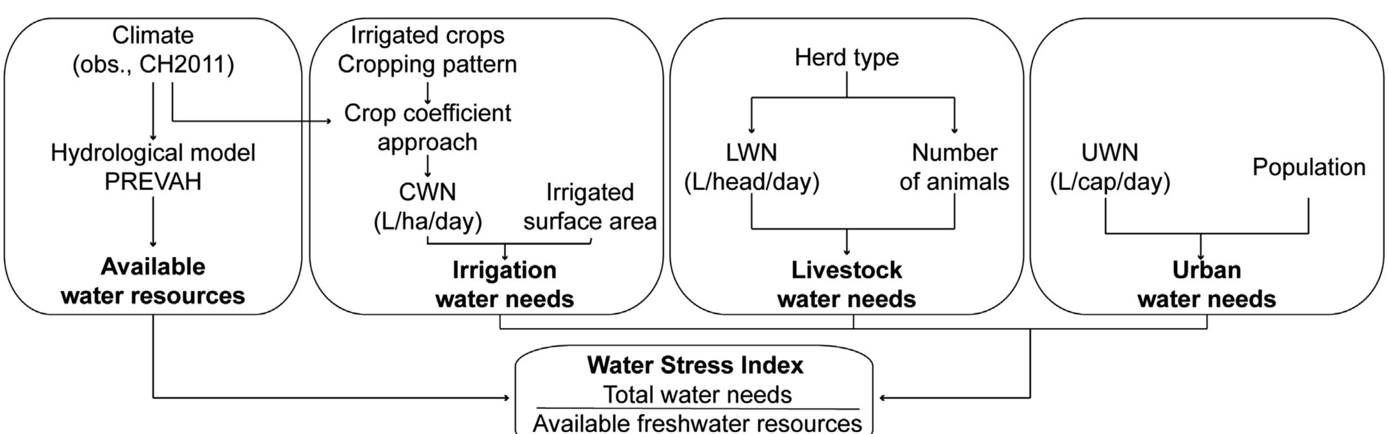

Fig. 2. Methodological approach. CWN — Crop unit water needs; LWN — Livestock unit water needs; UWN — Urban unit water needs.

into 100 m elevation zones for which surface and soil characteristics are defined. The different components of the hydrological cycle are also introduced through a series of modules. Runoff generation relies on three reservoirs and 12 tunable parameters. The soil reservoir produces surface runoff and interflow (quick and delayed runoff, respectively), governed by two distinct storage times, while two linear groundwater reservoirs produce baseflow (slow runoff) with a fast and a delayed component, defined by two other distinct storage times. Rapid, delayed and slow runoff contribution of each HRU of the considered catchment are summed to provide estimates of total discharge, i.e. available freshwater. For each considered catchment, the model was calibrated and validated against daily observed runoff series provided by the Federal Office for Environment (FOEN, 2014) and the canton of Vaud (2014). Simulations aimed at correctly representing the seasonal and low flow dynamics as well as monthly streamflow volumes. During the calibration and validation phases, the main features of annual discharge, notably low flows, were well captured and represented, and monthly volumes of available resources had narrow variation range (±9%; Milano et al., under review). The model was then judged reliable for exploring the spatial and temporal variability of water resources.

The model runs at an hourly time-step although daily to yearly data are allowed for input and output. In this study, daily meteorological data for each year of the reference period were used and collected from the automatic meteorological network of Switzerland (MeteoSwiss, 2008). Delta change signals from the CH2011 initiative (Bosshard et al., 2011; CH2011, 2011) were applied to daily temperature and precipitation series for scenario modeling. The model also needs physiographical information (elevation, mean slope, soil depth, soil water capacity, land use) to run. The latter were derived from Köplin et al. (2012), who acquired it from a digital elevation model, soil and land use maps provided by the Swiss Federal Statistical Office (FSO, 2003). This spatial information was considered constant through time.

3.3. Evaluation of water needs

3.3.1. Irrigation water needs

Daily irrigation water needs were evaluated for each catchment according to the crop coefficient approach (Allen et al., 1998; Fig. 2). This method relies on climatic data and cropping pattern. It considers that crops' irrigation water requirements are the volume of freshwater necessary to meet crops' evapotranspiration (ETc.), in addition to effective rainfall ($E_{rainfall}$; Eq. (1)). It assumes that no limitations are placed on crop growth or evapotranspiration (e.g. pests, diseases…). Irrigation water needs were then defined in this study as the daily volume of water required for crops' optimal growth.

$$IWR_i = (ETc_i - E_{rainfall}) \times IA_i \quad (1)$$

with

i	the considered crop
IWR	irrigation water requirement (mm/day)
ETc.	the crop's evapotranspiration under standard conditions (mm/day)
$E_{rainfall}$	effective rainfall (mm/day)
IA	irrigated surface area (ha).

For each time step and irrigated crop of a considered catchment, effective rainfall, i.e. the seasonal rainfall that can be used directly for crop production on site (Allen et al., 1998; Eq. (2)) is computed as well as the crop's evapotranspiration under standard conditions (ETc.; Eq. (3)) in order to define the crop's irrigation water requirements. To estimate ETc., the reference (or potential) evapotranspiration (ETP) is computed according to the Penman–Monteith equation (Penman, 1956) and corrected by a crop coefficient, Kc, depending on soil and crop's characteristics. Once irrigation water requirements are computed for each irrigated crop, they are summed to obtain estimates for the whole catchment.

$$E_{rainfall} = P_{TOTAL} - ETR \quad (2)$$

with

P_{TOTAL}	total precipitation (mm/day)
ETR	actual evapotranspiration (mm/day)

$$ETc_i = ETP \times Kc_i \quad (3)$$

with

ETP	reference (or potential) evapotranspiration (mm/day)
Kc	crop coefficient that varies according to the crop's growth stage (germination, development, mid-season, ripening).

For this assessment, the Federal Statistical Office provided utilized agricultural areas for each commune of the canton (FSO, 2013a) and the MandaTerre association provided details of the cultivated crops and their share of irrigated land under standard climatic conditions (MandaTerre, 2013). Crop coefficients and cropping patterns were collected from the FAO (Allen et al., 1998), Agroscope (Vullioud, 2005) and Aquastat (Frenken and Gillet, 2012) databases. Regarding climatic data over the reference and future periods, outputs from the hydrological model (interpolated precipitation over the catchment, ETP based on the Penman–Monteith equation and ETR) were used in order to be consistent and coherent between freshwater and water needs estimates.

3.3.2. Livestock water needs

Livestock water needs were defined as the volume of water required by farm animals for drinking purposes.

Livestock water needs (LWN) were computed for all the communes of the considered catchment by multiplying the livestock-specific water needs (L/head/day) by the number of cattle-heads (Fig. 2). Communes' values were then added to give estimates of LWN for each specific catchment.

Daily water requirements vary significantly among animal species, growth stage and food consumption (Ward and McKague, 2007). In this study, livestock specific water needs were defined according to several literature sources (Sautier, 2004; Ward and McKague, 2007; Collier and Lillywhite, 2011), assuming that all animals have reached adulthood and are given food with standard moisture content (Table 1). The Federal Statistical Office provided the number of cattle-heads in each commune from 1985 to 2012, on a yearly basis (FSO, 2013a). All listed livestock were considered and it was assumed that the number of animal heads did not evolve throughout the year. However, at this spatial scale, dairy cows were not distinguished from beef cows. This distinction is necessary as water requirements of dairy cows are five times higher than those of beef cows, due to their milk production (Table 1). Differences between dairy and beef cows were nonetheless available at the cantonal scale, according to different agricultural zones (mountains, hill slopes, meadows; FSO, 2013b). For each year,

Table 1
Livestock drinking water needs (according to Sautier, 2004; Ward and McKague, 2007; Collier and Lillywhite, 2011).

Livestock	Unit drinking water need (L/head/day)
Dairy cows	100
Beef cows	20
Horses	40
Sheep and goats	5.5
Pigs	7
Chickens	0.3
Other	0.4

the number of dairy cows per km^2 of agricultural zone was defined and applied to the communes. The number of beef cows was assumed to be the difference between the total number of cows (FSO, 2013a) and the deduced number of dairy cows. Regarding future estimates, current livestock-specific water needs (L/head/day) were supposed to remain unchanged in the 2060 horizon and past breeding evolution trends were carried on.

3.3.3. Urban water needs

Urban water needs were defined as the volume of water required for households, small businesses connected to the commune's water network and maintenance of the commune (e.g. road network, public gardens). It does not include auto-supplied industries.

Urban water needs were computed by multiplying the urban water use intensity (L/cap/day) by the local domestic population (Fig. 2).

The studied area covers more than 170 communes each of which have their own water supplier (Canton of Vaud, 2013). Annual urban water use intensity values were available only for 20 communes over the 1945–2012 period. These local values were compared to the annual national values (SGWA, 2013). Differences never exceeded 15%. The national urban specific water use intensity values were then judged appropriate for the canton of Vaud and it was decided to apply it to each commune over the reference period. Since the late 1980s, a net decrease in urban water needs has been observed in Switzerland, evolving from 445 L/cap/day in 1990 to 316 L/cap/day in 2012 (SGWA, 2013). This evolution can be attributed to long-term structural changes in industries, collective and individual behavior changes and development of water-saving devices (SGWA, 2013). For future estimates, a conservative approach would be to carry on decreasing past trends although it is unlikely to continue indefinitely with growing population and urban activities. It was then decided to consider past water-saving efforts and to apply the per-capita 2012 value for future simulations, assuming that constant progress in hydraulic efficiency would compensate growing water needs related to demographic growth and lifestyle changes. The Federal Statistical Office provided the results of the yearly population census from 1970 to 2012 for each commune (FSO, 2013c). Population was assumed to remain stable throughout the year. The canton of Vaud provided projections of annual population growth for each cantonal district up to 2040 (Statistique Vaud, 2011). These trends were extrapolated to the year 2071 and the share of the population living in each commune was assumed to remain as present.

3.4. Water stress

In order to express the exploitability of water resources, a water stress index (WSI) was computed. It is based on the ratio of monthly water needs to available freshwater resources, here considered as total discharge at the catchments' outlet (Eq. (4); Shiklomanov, 1991).

$$WSI = \frac{\textit{Total water needs}}{\textit{Available freshwater resources}} \times 100 \quad (4)$$

If WSI > 80%, the area studied faces severe water stress,
If 40% < WSI < 80%, the area studied faces high water stress,
If 20% < WSI < 40%, the area studied faces moderate water stress,
If WSI < 20%, the area studied faces no water stress.

This index expresses the intensity of anthropogenic pressures applied to river water resources: the higher the index, the higher the pressure. In case a water stress state is identified, it highlights that any additional water requirement might not be satisfied due to a lack of available freshwater in rivers. In this study, water stress occurrence relies on changes in freshwater resources and water needs which depend on both climatic and anthropogenic factors. In order to explore the impacts of these changes and to identify which factors should have the most influence, water stress was addressed first under anthropogenic changes, then under climate change and finally under both climatic and anthropogenic changes.

4. Results

4.1. Hydro-climatic changes

According to the two climatic scenarios based on the CH2011 initiative (Bosshard et al., 2011; CH2011, 2011), the canton of Vaud should be affected by a 2–3 °C temperature increase throughout the year and a 3–4 °C increase during summer by the 2060 horizon (Table 2). In the Lake Geneva region, a 10–30% increase in precipitation is projected with a higher fraction of liquid to solid precipitation, except during summer where a 10–20% decrease is projected. Over the Plateau and the Alps, low to no changes are projected throughout the year (±10%) except during summer (Table 2). From June to September, precipitation

Table 2
Projections of seasonal hydro-climatic changes by the 2060 horizon based on the regional climate models KNMI-ECHAM5-RACMO (optimistic) and HC-HadCM3Q0-HadRM3Q0 (pessimistic).

	Lake Geneva region	Swiss Plateau	Alpine area
	[Optimistic–pessimistic]	[Optimistic–pessimistic]	[Optimistic–pessimistic]
Temperature (°C)			
Autumn (OND*)	[1.8–2.5]	[1.8–2.7]	[1.9–2.7]
Winter (JFM*)	[1.9–2.9]	[2.1–3.0]	[2.1–2.6]
Spring (AMJ*)	[1.7–2.8]	[1.9–2.8]	[2.2–3.3]
Summer (JAS*)	[2.5–3.9]	[2.5–3.9]	[2.5–3.7]
Precipitation (%)			
Autumn (OND*)	[15–3]	[8–−9.5]	[10– −10]
Winter (JFM*)	[31– −3]	[12– −11]	[−2.5– −12.5]
Spring (AMJ*)	[5.5–7]	[1.5–4]	[0–10]
Summer (JAS*)	[−10– −20]	[−13.5– −25]	[−6.5– −19]
Snowmelt (%)			
Autumn (OND*)	[−77– −85]	[No snow influence]	[−60– −65]
Winter (JFM*)	[−65– −78]	[No snow influence]	[−35– −40]
Spring (AMJ*)	[−80– −95]	[No snow influence]	[−55– −70]
Summer (JAS*)	[No snow influence]	[No snow influence]	[−80– −90]
Discharge (%)			
Autumn (OND*)	[35–7.5]	[0– −22]	[225– −2]
Winter (JFM*)	[30– −2.5]	[−7– −36]	[30–15]
Spring (AMJ*)	[−25– −35]	[−18– −33.5]	[−25.5– −30]
Summer (JAS*)	[−10– −38]	[−35.5– −55]	[−21– −32.5]

* OND: October, November, December; JFM: January, February, March; AMJ: April, May, June; JAS: July, August, September.

should decrease by 20%. According to projections based on the most pessimistic model, precipitation could even decrease by 40% in August, falling below the observed variability range (not shown; Milano et al., under review). In the Alps, rainfall should also increase over snowfall leading to two to three times less snowmelt during spring and to almost none during summer (Table 2).

These climatic changes should lead to significant hydrological changes. Mean seasonal variations in runoff are presented in Table 2. In the Lake Geneva region, river flows should increase during autumn and winter (10–30%) and move towards more severe low flows (−10 to −40%). This is most likely explained by less precipitation and less snowmelt necessary to support low flows. Rivers in the Lake Geneva region should then move towards a pluvial hydrological regime (Fig. 3). Over the Swiss Plateau, river flows should remain near current levels according to the optimistic scenario, except during summer where a 35% decrease in discharge is projected (Table 2). According to the pessimistic scenario, river flows should decrease by 25–35% throughout the year and by 55% during summer, falling below the observed variability range in August (not shown; Milano et al., under review). Annual changes can be attributed to higher temperatures and thus higher evaporative capacity, while during summer it can also be explained by the projected decrease in precipitation. Finally, in Alpine areas, monthly river flows should increase from October to February (15–30%) and decrease from March to September (−25 to −30%). The decrease in snow accumulation and consequently in snowmelt should lead to more severe low flows and a lower high flow peak in May (not shown; Milano et al., under review). The mean high flow peak could even occur one month earlier at the Sarine outlet. The Grande Eau and Sarine rivers are then projected to move from transition nival and Alpine nival regimes to nival and transition nival regimes, respectively (Fig. 3).

4.2. Current water needs and evolution trends

Over the reference period, water needs are highest in the Lake Geneva region and over the Swiss Plateau (Fig. 4a). Water needs range between 7.2 Hm^3/year (Promenthouse catchment) and 21.7 Hm^3/year (Venoge catchment). The Aubonne, Venoge and Talent catchments are characterized by high irrigation water needs that represent 88%, 68% and 77% of the total water needs, respectively. The main irrigated crops are potatoes, vegetables, shrubs, apple trees and berries. In these catchments, water needs are more or less constant from October to March and start rising in April until reaching a maximum in July, related to irrigation practices during the warmest seasons. In July, water needs can represent up to 38% of the annual water needs (Fig. 4b). Other catchments, like the Promenthouse and Broye catchments, are characterized by high urban water needs, representing 80–95% of the total water needs. Over the Nozon and Mentue catchments, water needs are low (less than 1.5 Hm^3/year; Fig. 4a) and three-quarters of their total water needs come from the agricultural and urban sector, respectively. Total water needs are also low in Alpine catchments (less than 3 Hm^3/year; Fig. 4a). It is nonetheless in these catchments that livestock water needs are highest. They represent 10% of the total water needs compared to less than 1% in other catchments. In catchments of the Swiss Plateau and alpine areas, monthly variations are low as they are poorly affected by irrigation (Fig. 4b).

By the 2060 horizon, total water needs should increase over the whole canton (Fig. 4a). Highest water needs should remain in the Lake Geneva region (11.3–25.9 Hm^3/year) and over the Swiss Plateau (10.6–13.5 Hm^3/year; Fig. 4a). Annual Irrigation water needs are expected to increase between 40 and 60% in the most rural catchments (Aubonne, Venoge, Talent; Fig. 4a), with a marked rise in April and May (20–30%; Fig. 4b) in line with warmer and drier conditions. In other catchments, a regular 30–40% increase could affect monthly water needs (Fig. 4b), mostly due to an increase in urban water needs. On an annual basis, the latter should indeed increase by 30–40% in the canton, and could almost double over the Promenthouse (+77%) and Aubonne catchments (+90%; Fig. 4a). This is related to significant projected population growth. According to the scenario provided by the canton, the population could double in the littoral communes of the Promenthouse catchments and increase by 50–75% in mid- to low-land communes. In other communes, population is projected to increase by 25 to 50% by the medium term. Finally, livestock water needs could also significantly increase. Although volumes required to fulfill farm animals thirst will remain low compared to other sectors (less than 0.2 Hm^3/year; Fig. 4a), livestock water needs are expected to double to quadruple in the Lake Geneva region and be 6 times higher in the Plateau region compared to the reference period (Fig. 4a), in line with an increase in horse and beef cow breeding. Moreover, if past trends continue, a decrease in dairy cow breeding could be noted in alpine areas in the medium term, leading to a 10% and 30% decrease in livestock water needs over the Sarine and Grande Eau catchments, respectively (Fig. 4a).

4.3. Potential impacts of climatic and anthropogenic changes on water stress

Analysis of Fig. 5a shows a clear contrast between the East and the West of the canton. No pressures are currently applied to the rivers of eastern catchments and this should remain likewise in the medium-term. Reasons explaining this lack of water stress might be that alpine catchments benefit from abundant water resources thanks to high precipitation and snowmelt. Their steep topography also prevents urban sprawl and intensive farming. Regarding the Broye and Mentue lowland catchments, although a large part of their surface area is dedicated to

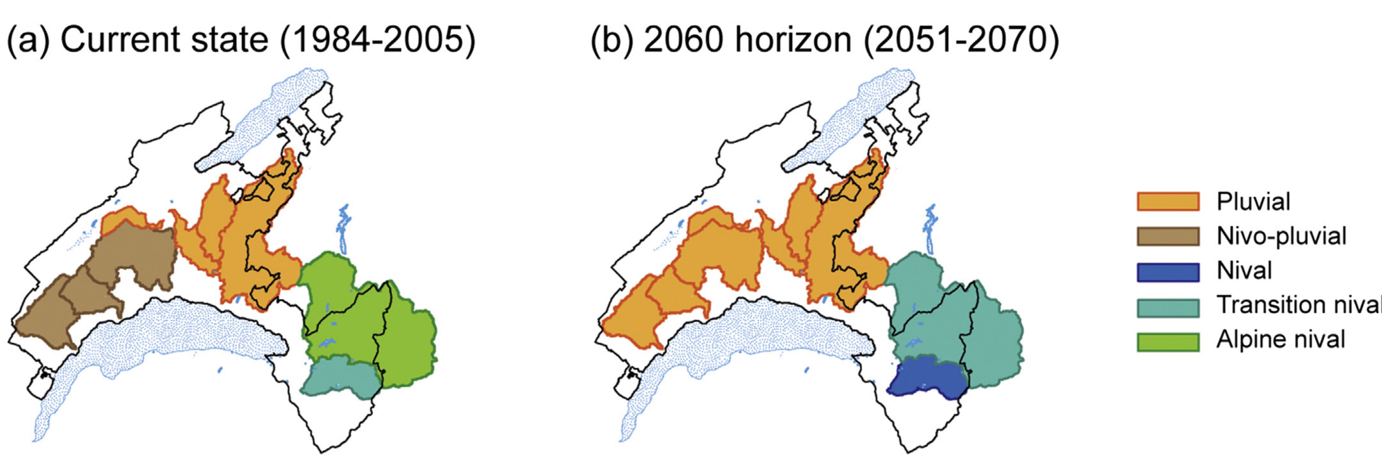

Fig. 3. Changes in hydrological regimes over the canton of Vaud by the 2060 horizon.

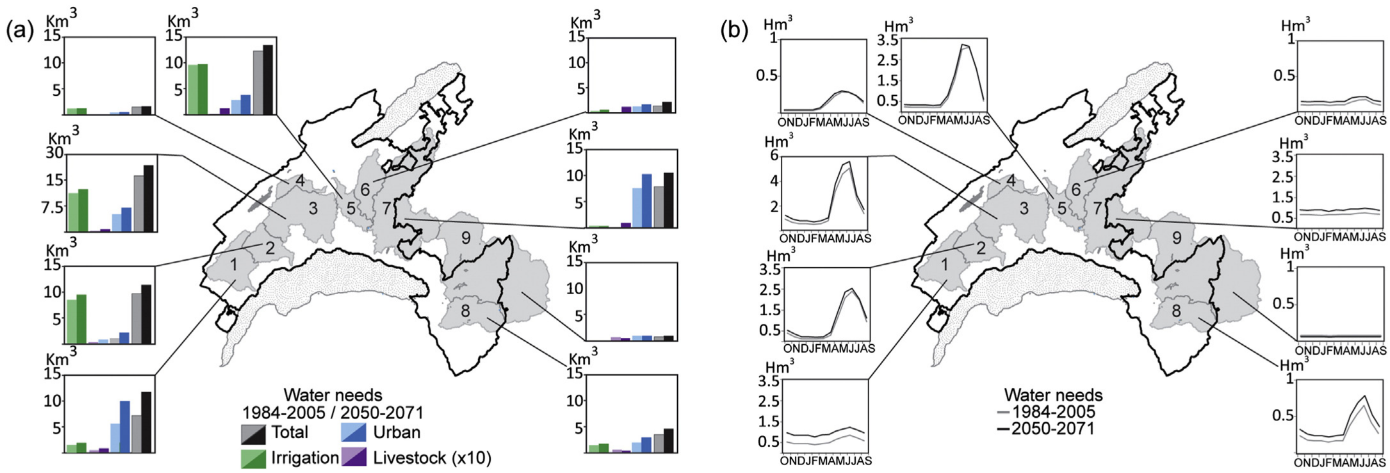

Fig. 4. Current and future water needs for each considered catchment: (a) annual water needs for each sector; (b) monthly distribution of total water needs. 1. Promenthouse; 2. Aubonne; 3. Venoge; 4. Nozon; 5. Talent; 6. Mentue; 7. Broye; 8. Grande Eau; 9. Sarine.

agriculture, irrigation water needs remain low due to high precipitation volumes during spring and summer (more than 100 mm/month). On the other hand, western catchments in the Lake Geneva region and over the Swiss plateau currently experience moderate water stress during the summer months (June, July, and August). Water needs amount to 30–40% of the available freshwater resources. This can be attributed to high urban water needs, especially over the Promenthouse, and high irrigation water needs. Severe water stress can even be noted in July and August over the Venoge and Talent catchments, notably due to the highest irrigation water needs computed in the area. During these two months, total water needs exceed 80% of the rivers' available freshwater.

In the 2060 horizon, if only anthropogenic changes are considered and rivers' water resources assumed to remain at their current level, all western catchments should experience moderate water stress starting in May (Fig. 5b). Over the Promenthouse, this period could even extend to September, and high to severe water stress could occur from June to August.

If the medium-term impacts of climate change alone are considered, all western catchments should experience moderate water stress starting in May as well as high (severe) water stress from June to August according to the optimistic (pessimistic) scenario (Fig. 5c). This relates to the projection of longer and more severe low flows. Over the Venoge and the Talent catchments, freshwater potential use should remain to its current state.

Finally, under both climatic and anthropogenic changes, moderate water stress could occur from May to September over all western catchments. Based on the optimistic hydro-climatic scenario, catchments

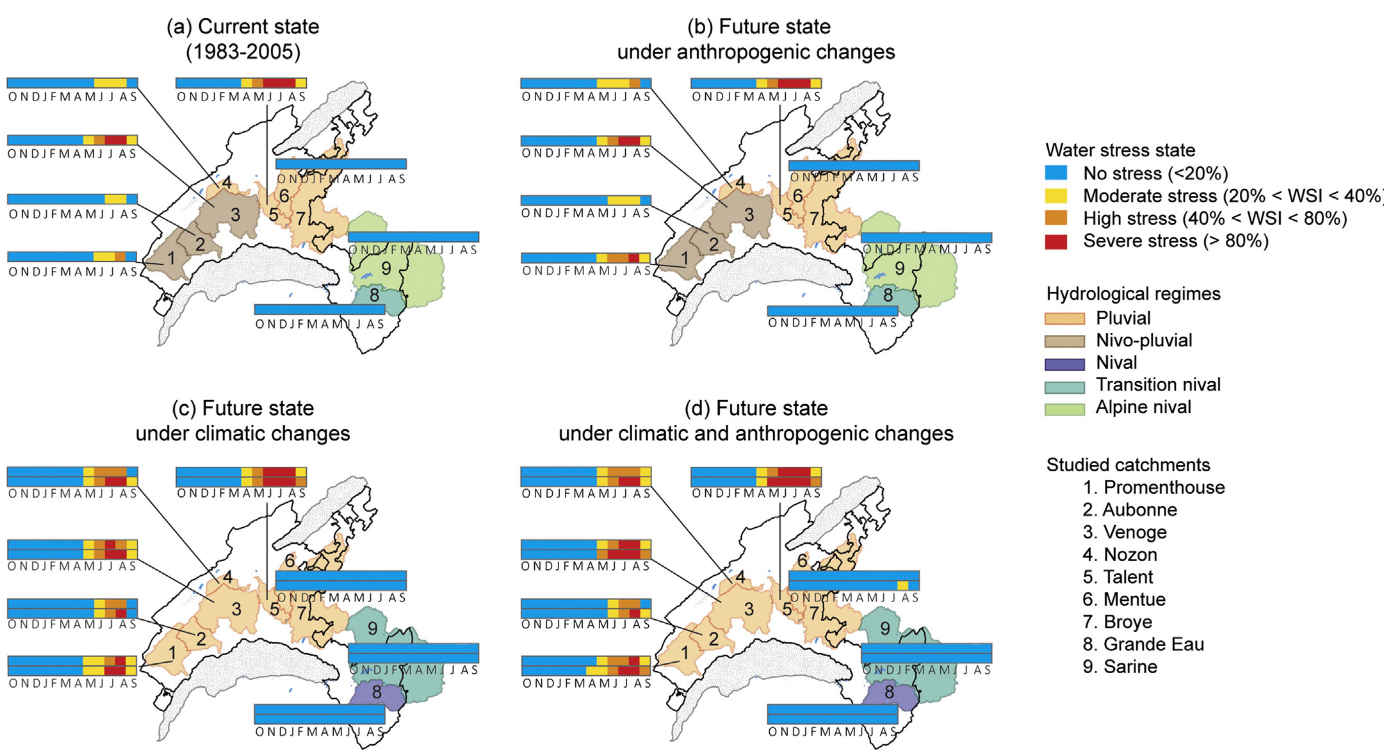

Fig. 5. Water stress in the canton of Vaud: (a) current situation (mean over 1983–2005); and possible evolution in the 2060 horizon (b) under anthropogenic changes; (c) under climatic changes based on KNMI-ECHAM5-RACMO (upper line) and HC-HadCM3Q0-HadRM3Q0 (bottom line) models projections; (d) under climatic and anthropogenic changes based on KNMI-ECHAM5-RACMO (upper line) and HC-HadCM3Q0-HadRM3Q0 (bottom line) models projections. N.B: A single and common line is presented for the Mentue and Broye catchments as they present the same results regarding current water stress and its possible evolution.

could experience high water stress from June to August, and the current water stress state could be maintained over the Venoge and Talent catchments (Fig. 5d). Under the worst-case scenario, water needs could exceed 80% of the rivers' available freshwater in July and August, and high water stress could occur in June and September. Over the Venoge and Talent catchments, severe water stress could occur from May to August and high water stress in April and September.

5. Discussion

5.1. Outcomes

The objectives of this study were (i) to provide a regional overlook of water stress risks in mountain environments and (ii) to identify the drivers affecting it. It focused on the canton of Vaud, a mountainous area with varied hydrological regimes, diversified water uses and increasing water needs due to urban sprawl and development of irrigation practices to save and ensure crop yields (MandaTerre, 2013). This region has already experienced water stress with local water shortage episodes during spring and summer in 2003 and 2011 (FOEN, 2012a; SESA, 2012). The originality of this work was then to adapt an integrated modeling framework to build a regional vision on potential water stress risks in mountain environments.

The outcome of this assessment is threefold. First, the applied modeling framework allowed efficient evaluation of long-term variations in water stress in hydrological systems undergoing climatic and water use variability. The former was derived from a Mediterranean analysis (Milano et al., 2013b). To better account for snow processes and topography, the regional conceptual rainfall-runoff model initially used was changed for a semi-distributed process-oriented hydrological model reliable in mountainous catchments (Gurtz et al., 1999). It was also decided to include water used by livestock and to explore water stress on a monthly basis rather than on an annual basis like suggested in the original method. The operability of the initial framework in a different context shows that it is an easy-to-use and scalable method that can be easily transferred to other geographic areas. Inputs required to run the integrated approach also seem to be available and accessible datasets. Finally, this framework offers a homogeneous and common method for all catchments. Comparison and identification of hot spots are then facilitated.

Second, the combination of hydro-climatic and socioeconomic data enabled identifying the respective and combined impacts of climate change and anthropogenic activities on water stress occurrence. In the 2060 horizon, anthropogenic changes should increase pressures applied to water resources during the summer season, especially in highly urbanized catchments. In the light of climate change, hydrological regimes will inevitably be impacted with an evolution towards a prevalence of pluvial regimes in mid- to low-land catchments. Streamflow dynamics should evolve towards longer and more severe low flows leading to an earlier start of the water deficit period. Combined to higher water requirements, water shortage could occur from May to September with water needs exceeding 80% of the rivers' available freshwater resources in mid-summer in the medium-term. Low to mid-altitude environments should then move towards more frequent local water stress episodes during summer by the medium term. These integrated results notably match agronomic studies, which highlight the vulnerability of rainfed rivers to fulfill irrigation water requirements during drought episodes (Piao et al., 2010; Fuhrer and Jasper, 2012). They also underline the importance of climate change in mid- to low-lands by the mid-21st century, complementing studies carried out in high Alpine areas that identified growing competitions among water users in mid-summer especially due to socio-economic changes (Reynard et al., 2014).

Finally, from a more local perspective, the assessment bridges a gap in Swiss knowledge. National studies focusing on climate change and its impacts on water resources identified Western Switzerland and the Alps as the most vulnerable areas of the country to significant seasonal variations in water resources availability and to summer droughts (Köplin et al., 2010; FOEN, 2012b; Fündel et al., 2013; Kruse and Seidl, 2013). Several case-specific studies have addressed the impacts of climate change on hydrological processes (see e.g. Huss et al., 2008; Uhlmann et al., 2013), on hydropower production in the Alps (see e.g. Finger et al., 2012; Hänggi and Weingartner, 2012), and on irrigation water requirements over the Swiss Plateau (Fuhrer, 2012; Fuhrer et al., 2014). None provided a regional vision of water resources vulnerability including both climatic and anthropogenic changes.

5.2. Limits and possible research improvements

This assessment relies on an integrative modeling framework, which combines hydro-climatic and socioeconomic data and tools. Each component is related to assumptions and uncertainties that must be addressed to qualify the results. However, weighing their influence on the results goes beyond the scope of the study.

The first assumption relates to climate modeling. When building climatic scenarios, the biggest uncertainty comes from the choice of climate models due to their different capacity to represent local scale processes (see e.g. Wilby and Harris, 2006; Bosshard et al., 2013). In a complementary study, hydro-climatic changes were explored based on the ten GCM-RCM model chains available for Switzerland (Milano et al., under review). It showed that all models agreed on hydro-climatic evolution trends and signals. For synthesis purposes, in this study, results were then based on two climate models, which project minor and major hydro-climatic changes, respectively. It enabled providing a range of uncertainty regarding the occurrence, length and severity of water stress events. Moreover, suggesting predefined and opposing scenarios is a recommended procedure to facilitate stakeholders exploring possible futures and to potentially suggest alternative scenarios (Rinaudo et al., 2013).

Uncertainties can also arise from the capacity of the hydrological model to represent hydrological seasonal and volumetric variations. The model was here calibrated and validated against observed runoff values. High efficiency values and visual inspection of the hydrographs proved the capacity of the PREVAH model to represent the seasonal dynamics and volumes of river discharge for the nine considered catchments (Milano et al., under review). It is nonetheless assumed that the rainfall-runoff relationship and the bias deriving from it over the reference period will remain the same in the future. The biggest uncertainty regarding water resources in this study comes from water supply sources. Just like in other regional or national studies (see e.g. Fuhrer and Jasper, 2012; Milano et al., 2013b), pressures applied to rivers were here explored. Freshwater resources were considered as the sum of rapid, delayed and slow runoffs. Other water supply sources were not considered although, during the past decade, 22% and 13% of the canton's water demands were supplied by lake and groundwater pumping, respectively (SGWA, 2004; MandaTerre, 2013). In addition, strong differences exist between regions. For example, in the Alpine communes of the canton, water used for irrigation exclusively comes from surface waters (MandaTerre, 2013). In the Promenthouse and Aubonne catchments, Lake Geneva supplies 70% of irrigation water needs while over the Venoge, they are only fulfilled with surface waters. In contrast, in the Lake Neuchatel area, rivers supply up to 70% of irrigation water needs, and the lake supplies the rest. The assumption regarding water supply was then constrained by (i) the will of applying a common method over all catchments to enable comparisons and highlight hot-spots, (ii) the various differences existing between areas and (iii) the lack of exhaustive data at the commune or district's scale. Water stress might then be overestimated, notably in the Lake Geneva region. This uncertainty advocates moving from regional to local scale studies considering local water supply networks.

Further limitations come from the water use scenario. First of all, it relies on water needs values, i.e. amounts of water required for crops' optimal growth, and for human and livestock welfare. These values tend to be higher than actual water demands or withdrawals (Döll, 2002; Calianno et al., 2014). Pressures applied to water resources might then have been overestimated. Moreover, although water needs were clustered by sector, and spatially analyzed and distributed, they were estimated based on a commonly used method (Fontanazza et al., 2014; Hutton and Kapelan, 2015). For each catchment, endogenous (e.g. irrigated crops and areas, past water use values) and exogenous (e.g. temperature, precipitation, population growth; livestock evolution) variables were identified to explain changes in past water needs. Their relationships were assumed to remain stable in the future and projected in the medium term. Such approach is commonly applied at global (e.g. Alcamo et al., 2007; Arnell et al., 2011) and regional (e.g. Menzel and Matovelle, 2010; Milano et al., 2013b) scales. It is considered useful and robust enough to size urban networks (Rinaudo, 2013), design and asset regional development pathways (Fontanazza et al., 2014; Makki et al., 2015), and highlight where and when water tensions are most likely to occur (Milano et al., 2013b). However, more information on water uses is required to better assess water needs and their evolution (Grouillet et al., 2015), and therefore ensure available water resources for water users and supply them with enough water of good quality (Fontanazza et al., 2014). Authors have suggested exploring and analyzing the historical evolution of past water demands (Grouillet et al., 2015; Makki et al., 2015). This step enables detecting behavioral changes and identifying drivers affecting the temporal dynamics and spatial disparities of water needs (Candelieri and Archetti, 2014; Grouillet et al., 2015). Knowledge on current water needs is thus improved, and the effects of socio-economic changes or local adaptation strategies on future water needs can be better implemented. Nonetheless, it is still an uneasy step for regional prospective studies due to the limited spatial and temporal metering coverage of water uses (Calianno et al., 2014; Hutton and Kapelan, 2015). Water needs were also explored based on a business-as-usual scenario. Considering alternative water use scenarios would enable analysis of the capacity of water management options to reduce water tensions. The elaboration of such scenarios based on participatory approaches with stakeholders and local users have already proven to be efficient and relevant to set adaptation strategies or development pathways (Rinaudo et al., 2013; Reynard et al., 2014; Schneider et al., 2014).

Finally limits come from the integrated modeling approach itself. The current framework provides mean monthly changes in water resources availability, water needs and water stress for each considered catchment in the mid-21st century. It is useful to offer a first diagnosis of where and when water tensions are most likely to occur under climatic and/or anthropogenic changes. It is an essential step for governments and public utilities considering implementing water-regulating strategies (Makki et al., 2015). Nonetheless, inter-annual variability is hidden. For example, according to our study, the Broye should not be subject to water stress in the medium-term, while studies focusing on dry years specifically identified that irrigation water requirements in this catchment could exceed 30% of the available freshwater resources in the near future (2036–2065; Fuhrer and Jasper, 2012; MandaTerre, 2013). One way to improve the analysis of catchments' current and future vulnerability to water stress could be to explore the year-to-year variability. This would imply (i) computing water requirements under standard and dry climatic conditions, given that information under such conditions are available (e.g. irrigated crops and surface areas; MandaTerre, 2013), (ii) detecting dry years from standard ones in the future, using a Standardized Precipitation Index (WMO, 2012) for example, and (iii) applying the appropriate water requirements each year. Nonetheless, this approach would require further statistical correction of future climatic scenarios to account for annual changes or changes in extremes (see e.g. van Pelt et al., 2012; Ragettli et al., 2013; Tramblay et al., 2013). Moreover, water stress was addressed based on water quantity issues but to provide a complete and thorough picture of possible water stress evolution, water quality issues should also be considered. Hydro-climatic changes (e.g. increasing air temperature and less runoff limits the dilution capacity of rivers; Murdoch et al., 2000; van Vliet and Zwolsman, 2008), terrestrial factors (e.g. changes in land use or urban-sprawl) and water users (e.g. water spillage) directly affect water quality. Available freshwater volumes might be of poor quality and thus be unavailable for water users. This could be a major issue in particular in highly irrigated areas (see e.g. Ducharne et al., 2007). Water stress analyses considering water resources availability both in terms of quantity and quality under climatic and anthropogenic changes are still poorly explored and documented (see e.g. Hughes et al., 2012; Wittmer et al., 2014; Bonsch et al., 2015; El-Khoury et al., 2015). New integrated modeling frameworks and studies, at both regional and local scales, should then move towards such assessments in order to provide complete overlooks and efficiently support decision-making.

6. Conclusion

The assessment of climatic and anthropogenic changes on water stress in Western Switzerland shows that water-rich regions like mountains can also be subject to local water deficits in mid-summer and that they are likely to occur on longer periods and become acute by the mid-21st century. From the analysis in this paper, the main driver increasing water stress is climate change. Warmer temperatures and changes in precipitation distribution should negatively affect snowpack development inducing higher winter flows and longer and more severe low flows. Water resources should then be reduced when water needs are already the highest. Moreover, the most vulnerable regions to water stress are low- to mid-altitude catchments, as rivers should move towards more rainfall-supported hydrological regimes. The impact of direct anthropogenic changes is more uncertain due to indefinite political and socioeconomic determinants and methodological assumptions. Despite these uncertainties, a warmer and drier climate is most likely to increase irrigation water requirements. Combined to urban sprawl and livestock development in lowlands, it will doubtlessly result in decreasing water availability for each sector and severe water tensions. Although carried under a conservative water use perspective, this study identified possible evolution trends and underlined geographic patterns. It is then useful to mobilize decision-makers, to guide them in formulating sustainable development pathways and to highlight the capacity of alternative strategies to reduce water tensions. Furthermore, this approach enabled identifying possible improvement for further integrated modeling assessments. From a regional perspective, additional efforts are required to address water resources availability by integrating both the quantitative and qualitative issue. This concern should also be addressed at the local scale. Local scale studies should also focus on the most vulnerable areas and move towards interdisciplinary approach in order to correctly apprehend water supply networks, factors affecting water uses and local water management rules. Developed in collaboration with local stakeholders, these integrated frameworks should correctly represent and address local water stakes, and thus support the development of sustainable pathways. The cantonal authorities promoted this kind of initiative when the results of the present study were presented.

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