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AUTHOR'S NOTE

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Introduction

1 From a hydrological perspective, the impacts of climatic and socio-economic changes on water resources have mainly been addressed through the lens of physical water scarcity, which highlights potential shortages but does not account for governance and adaptation processes. Several assessments were global and provided insights into the complex functioning of the hydro-social system (see e.g. Sivapalan *et al.*, 2012; Linton and Budds, 2014; Munia *et al.*, 2016) and helped identify areas where future water resources are most vulnerable to climatic and anthropogenic changes (see e.g. Alcamo et al., 2007; Wada *et al.*, 2011; Wieck and Larson, 2012; Mekonnen and Hoekstra, 2016). However, these studies relied on global political economy and water use scenarios that did not always fit local adaptive strategies, instruments and institutional frameworks (Gourbesville, 2008; Milano *et al.*, 2013). The spatial resolution of such studies and their simplification of socio-economic processes and demographic patterns were unable to grasp the complex socio-hydrological functioning of water systems at regional and local scales (Cook and Bakker, 2012). Regional and local scale studies were subsequently conducted to include the political and technical measures taken to avoid unsustainable exploitation of water resources (Lahmer *et al.*, 2001; Schneider and Homewood, 2013; Schneider *et al.*, 2015). These studies identified drivers likely to undergo local and rapid climatic and anthropogenic changes (see e.g. Fabre *et al.*, 2015; Wang *et al.*, 2016; Malek and Verburg, 2018) and assessed the capacity of local adaptation measures to reduce water scarcity (see e.g. Varela-Ortega *et al.,* 2011; Fabre *et al.*, 2016). These research advances are considered useful to involve and inform decision makers (Fant *et al.*, 2016). They are also in the thematic continuity regarding the appreciation of the emerging concept of water security (Cook and Bakker, 2012).

2 This concept emerged in the 1940s but has only come to the forefront of hydrological and social research, and of policy debates in the last two decades (Cook and Bakker, 2012; Garrick and Hall, 2014). It is a broad, conceptual, multi-dimensional framework that entails issues of ecosystem and human health, accounts for water quantity and quality issues, and questions existing water governance frameworks and processes (Grey and Sadoff, 2007; Savenije and van der Zaag, 2008; Bakker, 2012; Pahl Wostl *et al.*, 2013, 2016; Bolognesi and Kluser, 2018). It is understood as a key tool to address the multiple challenges associated with water management in the 21st century (UN Water, 2013). However, it is not a *ready-made* operational concept that can easily be applied, and multiple and incommensurate definitions exist that are used by both researchers and policy makers (Bakker, 2012; UN Water, 2013). Cook and Bakker (2012) called for narrowing the definition and focusing on issues of relevance in the first instance due to the innovative and interdisciplinary nature of the concept. In that respect, in this paper, it is assessed only from the hydrological perspective. Here, we define water security as “the capacity of a population to safeguard access to adequate quantities of water of acceptable quality for sustaining human and ecosystem health on a watershed basis, and to ensure efficient protection of life and property against water related hazards – floods, landslides, land subsidence and droughts” (UNESCO-IHP, 2012, p. 1). This definition frames the concept to the management of two sets of challenges:

extreme events such as floods, droughts and pollution issues, and the allocation of water to competing water users under climate change (Wheater, 2015; Young *et al.*, 2015). Research on water scarcity is viewed as a base research for water security assessment that provides data on resource-demand relationships and a primary way of measuring access to sufficient water (Cook and Bakker, 2012).

3 Currently, several indicators are used to evaluate water scarcity (Falkenmark *et al.*, 1989, Shiklomanov, 1991; Sullivan, 2002; Pedro-Monzonís *et al.*, 2015) but indicators that combine water resources, ecosystems and human health, and water governance arrangements are rare (Cook and Bakker, 2012; Bakker, 2012; Octavianti and Staddon, 2021). According to the literature, Lautze and Manthrithilake (2012) and Sun *et al.* (2016) recently developed the two first indexes to quantify water security in Asia, and Gain *et al.* (2016) suggested a first multi-criteria analysis framework based on the indicators of Goal 6 of Sustainable Development Goals to quantify water security at global scale. These studies aggregated different indicators and revealed the heterogeneous distribution of water security related to the sensitivity of countries to different physical and socio-economic indicators. The studies provide the first large scale analyses that go beyond water scarcity assessment, offer an initial assessment of the water security concept and suggest preliminary paths for quantifying water security. The authors still call for further studies as they had to rely on raw global data with different spatial details and of different quality, water resources availability is still poorly addressed from a qualitative point of view, the understanding of current institutional and policy regimes is too broad and indicators are weighted without sensitivity analyses or the involvement of stakeholders. Therefore, regarding its assessment, interpretation and index-based quantification, water security is still a concept under development.

4 As part of the special issue on “Water researchers in times of global change. What future for territories?”, this paper reflects on the conceptual and methodological evolution of water scarcity assessment based on four research projects undertaken in western Switzerland. Although Switzerland is often described as Europe’s water tower (Viviroli and Weingartner, 2004), the factors that affect the risk of present and future water scarcity in Switzerland are a major concern, as the country already experienced several water shortage episodes in the last decade. The most recent drought events (2003, 2011, 2015, 2018, 2019) were remarkably long and the highest summer temperatures were recorded since the beginning of meteorological measurements in 1864 (ProClim, 2005; Begert *et al.*, 2005; FOEN, 2016; Begert and Frei, 2018; FOEN, 2021). Rivers and some springs dried up during summer (FOEN, 2016; 2017; 2019). For the first time, cantonal authorities (the administrative bodies responsible for water distribution) called for water savings and farmers were allocated irrigation turns (FOEN, 2016). These episodes brought important water management issues to light, like the lack of water allocation priorities, the need to define good irrigation practices, and the need for drought prevention plans (FOEN, 2012a; Kruse and Seidl, 2013). The series of droughts also revealed “a moderate state of social capacities regarding drought risk management” (Kruse and Seidl, 2013, p. 3438). Several studies were launched to grasp the impacts of climate change on water resources and their related impacts on hydropower production (Hänggi and Weingartner, 2012; Gaudard *et al.,* 2013; Barry *et al.,* 2015 among others), the effects of alternative water policies on crop yields and farmers’ income (e.g. Finger and Lehman, 2012; Lehman et al., 2013; Lehman and Finger, 2014) and the impacts of land use or waste water treatment plants on water

quality (e.g. Ort *et al.,* 2009; Robinson *et al.*, 2014). Critical situations were identified in Alpine catchments where glacier melt could be reduced, thereby affecting the seasonal availability of water resources and altering water storage, in particular for the production of hydroelectricity (Finger *et al.*, 2012; Gaudard *et al.*, 2014; Lane and Nienow, 2019), but also in pre-Alpine catchments where water needs for irrigation could increase significantly (Vanham *et al.,* 2009; Fuhrer and Jasper, 2012; Fuhrer *et al.,* 2014). Western and southern Switzerland in particular will likely be prone to longer dry spells in summer (Schmidli and Frei, 2005; Scherrer *et al.,* 2016) and more intense low flows due to less snow storage and earlier snow melt (see e.g. Stewart, 2009; Beniston and Stoffel, 2014; Morán-Tejeda *et al.*, 2014; Milano *et al.,* 2015a). Coupled with anthropogenic changes such as population growth, increased irrigation and livestock raising in the lowlands, and the expansion of tourism, rivers in western Switzerland can no longer be considered as reliable water sources (FOEN, 2012b, 2021) and conflicts over water are likely to increase (Fuhrer and Jasper, 2012; Fuhrer *et al.*, 2014; Milano *et al.,* 2015b).

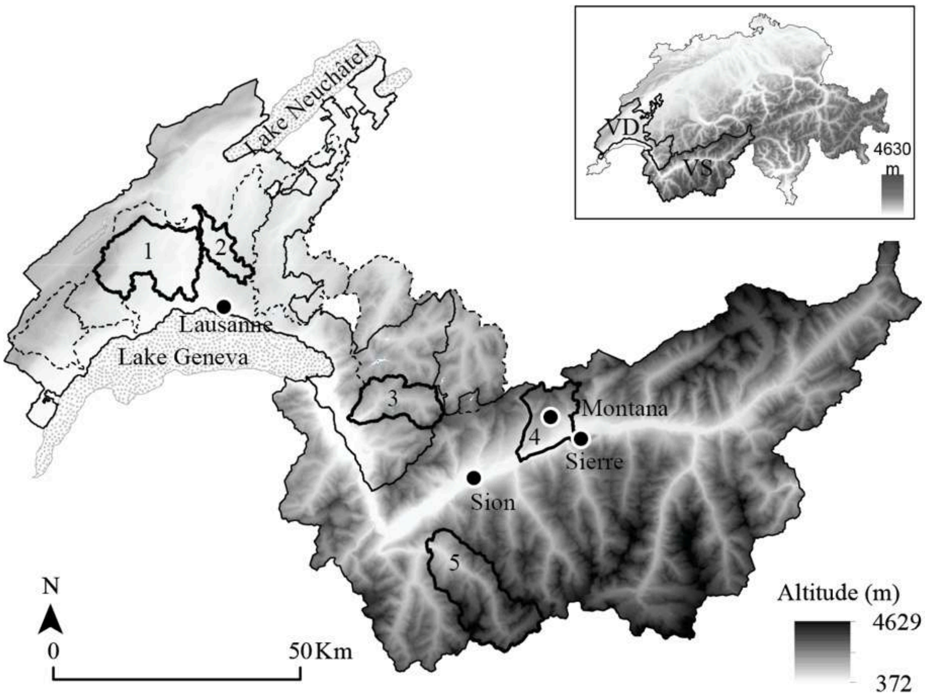
5 In that respect, two research projects[1] were created to develop integrated modeling frameworks and assess the risk of water scarcity in western Switzerland. Although their results regarding the occurrence of current and future water scarcity have already been published (Reynard *et al.,* 2014a; Milano *et al*., 2015a), this paper builds on these projects and provides new outcomes. In particular, the conceptual and methodological progresses and issues of water scarcity assessments are put forward in this paper. With the advances achieved in two other projects[2] that focused on water users and their territorial footprint in western Switzerland (Calianno *et al.*, 2018; Milano and Reynard, 2021), possible dimensions for a holistic approach to water scarcity are discussed together with the appropriate geographical scale to represent the relationships between water resources and water uses.

Case studies

6 The four research projects on which this paper draws focus on western Switzerland, more specifically on nine meso-scale catchments (38–637 km^2) of the canton of Vaud (Switzerland), the Crans-Montana-Sierre (CMS) area (130 km^2) and the municipality of Bagnes[3] (282 km^2) in the canton of Valais.

7 In the canton of Vaud, catchments extend from the Jura Mountains (alt. max. 1'677m.a.s.l.) over the Swiss Plateau (400–600m.a.s.l) to the high Alpine mountains (alt. max. 3'200m.a.s.l; Fig. 1). Mean annual temperatures range from 10°C to 4°C and mean annual precipitation vary from 865 to 2'020mm/year, from low to high altitudes (average for the 1984–2005 period; Milano et al., 2015b). The shores of Lake Geneva and Lake Neuchâtel are marked by strong urban and peri-urban development. Agricultural activities characterize the plains and piedmont, and account for 17% of Swiss agricultural land (FSO, 2006), while dairy cow breeding dominates in mountainous areas. In this paper, special attention is paid to the Venoge, Talent and Grande Eau catchments that are representative of hydro-climatic and anthropogenic stakes in the Lake Geneva Region, Plateau and Alpine areas of the canton of Vaud, respectively (Table 1).

Figure 1: Geographical location of the (1) Venoge, (2) Talent and (3) Grande Eau catchments, the (4) Crans-Montana-Sierre area and (5) the municipality of Bagnes



VD – canton of Vaud, VS – canton of Valais. The dashed lines show the borders of the catchments studied in the ICCARE-Vaud project (Milano et al., 2015a,b) but not presented in this paper.

8 The Crans-Montana-Sierre (CMS) area is located on the northern rim of the Rhone River valley (Fig. 1). It ranges from 519m.a.s.l in the Rhone River valley to 3'100m.a.s.l in the Bernese Alps mountains, and is partly covered by the Plaine Morte glacier (7.32km^2 in 2016; www.glamos.ch). Temperature and precipitation follow a steep vertical gradient (Table 1). The area benefits from a high level of sunshine and dry conditions in summer due to the climate barrier formed by the Swiss Alps. Vineyards thus predominate up to an altitude of about 800m. Above 800m, the CMS area is characterized by forests, grasslands and cattle raising. Higher altitudes (>1'400m.a.s.l) host one of the largest tourist resorts in Switzerland: Crans-Montana offers 40'000 beds and is very attractive for skiing in winter and golf and hiking in summer. Bagnes municipality (282km^2) is located on the southern rim of the Rhone River valley (Fig. 1) between 790 and 4'314m.a.s.l. From low to high altitudes, mean annual temperature ranges from 8 to ‑5°C and mean annual precipitation from 1'013 to more than 2'000mm, (MeteoSwiss, 2021). Bagnes municipality contains 68.8% of unproductive land (glaciers, lakes, areas with no vegetation or unproductive vegetation) and 0.2% of nature protected area, mainly at high altitudes, 18.6% of agricultural land and 11% of forests at mid-altitude, and 1.5% of urban area in the valley bottoms including the tourist resort of Verbier.

Table 1: Characteristics of the Venoge, Talent and Grande Eau catchments (canton of Vaud), the Crans-Montana-Sierre area and the municipality of Bagnes (canton of Valais)

	Canton of Vaud	**Canton of Valais**

	Venoge	Talent	Grande Eau	Crans-Montana-Sierre	Bagnes
Geographical context					
Area (km²)	231	62	134	130	282
Range of altitude (m.a.s.l)	382 – 1677	440 – 929	410 – 3'200	519 – 3'100	790 – 4'314
Hydro-climatic context (average over the 1984-2005 period in the Canton of Vaud; 1981-2010 in the CMS area; MeteoSwiss, 2016)					
Mean annual temperature (°C)	9.1	9.5	5.0	10.1 to -2.7	8 to -5
				(from valleys to mountain crests)	
Mean annual precipitation (mm)	1'075	1'175	1'587	672 to >2'500 1013 to >2'000 (from valleys to mountain crests)	
Mean runoff (m³/s)	4.1	1.1	4.8	5.3	2.03
Specific runoff (L/s/km²)	17.7	17.7	35.8	40.8	6.9
Land use (2013)					
Urban (%)	19	11	7	8	1.5
Forest (%)	2	21	16	28	11
Cropland and grassland (%)	77	68	75	27	18.6
Vineyard (%)	2	0	0	8	0
Other (ice and rock,%)	0	0	1	29	68.8

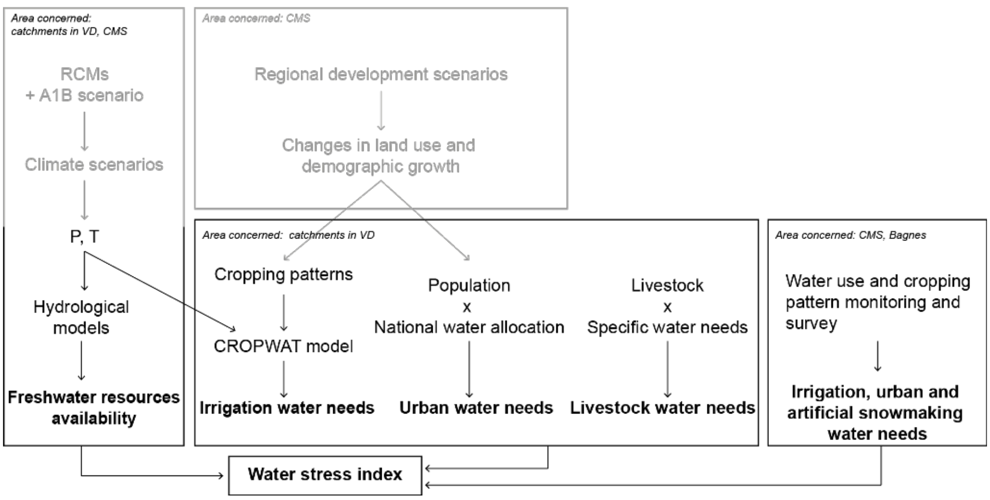
Material and methods

9 The *ICCARE-Vaud* and *MontanAqua* projects have been the subject of several scientific papers and reports in which the methods are described in great detail (Milano *et al.*, 2015a, b; Reynard *et al.*, 2014a; Weingartner *et al.*, 2014; Schneider and Rist, 2014; Schneider *et al.*, 2015). Only a summary of the methods is thus presented here. The PhD thesis (Calianno, 2018) and the *LABEAU* project were conducted in a second phase to extend knowledge on water uses.

An integrated and systemic modeling approach

10 In all four projects, hydrosystems were considered as a series of interrelated entities with natural, social and economic features (Chorley and Kennedy, 1971). In particular, an integrated and systemic modeling approach was developed to address interactions between climate, freshwater availability, freshwater withdrawals and water management options in the *ICCARE-Vaud* and *MontanAqua* projects (Fig. 2). Daily freshwater availability and water needs were estimated over a past reference period (1984-2005 for the canton of Vaud and 2006-2011 for the CMS area) and by mid-century (2050-2071 for the canton of Vaud and 2037-2041 for the CMS area). Results were aggregated at a monthly time step for synthesis purposes. Past daily meteorological data were collected from the automatic meteorological network of Switzerland and interpolated using the detrended inverse distance weighting method. For prospective modeling, delta change signals extracted from ten regional climate models forced with the IPCC A1B greenhouse gas emission scenario (Bosshard *et al.*, 2011; CH2011, 2011) were applied on daily temperature and precipitation series. For synthesis purposes and key messaging, the median hydro-climatic evolution is presented in this paper. Future water needs were estimated based on a business-as-usual scenario but also, in the CMS region, based on alternative land use scenarios co-constructed during focus groups with local water stakeholders (Schneider and Rist, 2014; Schneider *et al.*, 2015). Finally, water scarcity was quantified based on a water scarcity index, i.e. a ratio of monthly water needs to monthly available freshwater resources (Shiklomanov, 1991). This index expresses the intensity of pressure applied by water needs on available water resources: the higher the index, the greater the scarcity. In all four studies, water resources were evaluated based only on surface waters.

Figure 2: Methodological approach



In black: methodology core, in grey: additional data for future state assessment. P: Precipitation, T: Temperature

11 In support of these integrated modeling research projects, statistical analyses of water volumes measured daily at the outlet of the reservoirs of the drinking water distribution network in the municipalities of Montana and Bagnes were performed between January 2015 and December 2017. In Montana, these analyses were combined with statistical analyses of daily irrigation time series collected using metering devices

specifically installed for the project, as well as qualitative interviews with the drinking water department managers five winegrowers and one farmer. The purpose of these additional studies was to improve knowledge and methods related to water use quantification (Fig. 2).

Freshwater evaluation

12 In catchments in the canton of Vaud, available freshwater resources were considered as the daily contribution of rapid, delayed and slow runoffs modeled by the semi-distributed and process-oriented PREVAH model (Viviroli *et al.*, 2009). Further information on the model structure, and on the datasets and calibration-validation procedure used can be found in Viviroli *et al.* (2009) and Milano *et al.* (2015b), respectively.

13 Freshwater supply in CMS relies on the headwaters of the area, composed of springs and the Plaine Morte Glacier. Freshwater resources coming from the headwaters were modeled by the MontanAqua team using the Glacier Evolution Runoff Model (GERM) (Huss *et al.*, 2008) and the hydrological model Penn State Integrated Hydrologic Model (PIHM, Kumar, 2009). Further information on the structure and performance of the model can be found in Huss et al. (2008), Kumar (2009) and Kauzlaric (2015).

Evaluation of water use

14 In the canton of Vaud, water needs were considered as the sum of freshwater volumes required by irrigated agriculture, livestock farming and the domestic sector[4] and were projected based on a busines-as-usual scenario.

15 Irrigation water needs were evaluated according to the crop coefficient approach (Allen *et al.*, 1998). This method defines the volume of freshwater necessary to meet crop evapotranspiration in addition to rainfall, based on climatic data, cropping patterns and crop growth coefficients. These data were provided by the Federal Statistical Office (2013) and the MandaTerre (2013) association at the municipal level. For future projections, irrigated crops and surface areas were assumed to remain unchanged, but the impacts of climate change on crop water needs were explored. Further information on the model dataset and process can be found in Milano *et al.* (2015b).

16 Livestock water needs, i.e. the quantity of water required to water farm animals, were computed for each municipality by multiplying the specific water needs of each livestock species by the number of animals of the species concerned. Specific livestock water needs were defined using different literature sources (Sautier, 2004; Ward and McKague, 2007; Collier and Lillywhite, 2011) and the Federal Statistical Office provided the annual number of animals in each municipality (FSO, 2013). Past livestock trends were continued for future projections.

17 Urban water needs, i.e. water needs for households, businesses connected to the communal network and maintenance of the municipalities, were estimated for each municipality by multiplying the national unit per capita water allocation by the population of the municipality (SGWA, 2013; Canton of Vaud, 2013). Annual variations in unit water allocation and population were taken into account. For future estimates, it was assumed that water-saving efforts and progress in hydraulic efficiency would compensate for increasing water needs related to population growth. The 2012-unit

water allocation was used in future simulations. The canton of Vaud provided annual population projections (Statistique Vaud, 2011).

18 In the CMS area, water needs for the irrigation of agricultural plots and golf courses, the urban sector as well as for artificial snowmaking were evaluated from 2006 to 2011. They were estimated based on an intense documentary survey conducted in collaboration with the municipal administrations, technical managers, and the population, combined with the monitoring of several irrigation canals (Bonriposi, 2013). Water used for hydropower production was not included[5]. For future estimates, four different regional development scenarios were built with the support of a stakeholder group composed of politicians and local representatives of public administrations, associations and private companies (Schneider and Rist, 2014):

- business-as-usual scenario: the regional development of the CMS area relies on economic growth based on mass tourism and on the expansion of built-up areas. The population continues to increase while agriculture continues to decline. Water issues are assumed to be solved through technical measures.
- Stabilizing scenario: regional planning is improved by intercommunal collaboration. Four-season tourism is expanded, construction is restricted and agriculture remains a core economic activity. Water management aims to optimize water consumption by regulating water users and improving irrigation techniques.
- Moderate scenario: “soft” tourism and water saving efforts are promoted. Artificial snowmaking is abandoned and drip irrigation is adopted for vineyards.
- Shared strategy: this scenario was suggested by the stakeholders. It considers that the economic growth of the area is balanced by social needs (equity between citizens) and ecological considerations. Constructions of second homes is restricted. Four-season tourism is developed with an emphasis on agriculture and vineyards.

19 Each scenario was translated into changes in land-use and population growth with the support of the stakeholder group (Bonriposi, 2013). Based on these assumptions, future irrigation and urban water needs were evaluated using the same methods as those used in the canton of Vaud. For artificial snowmaking, the potential snow covered area supported by artificial snowmaking was first defined according to altitude and future air temperature, then multiplied by the unit water allocation for snowmaking (L/m^2).

Results

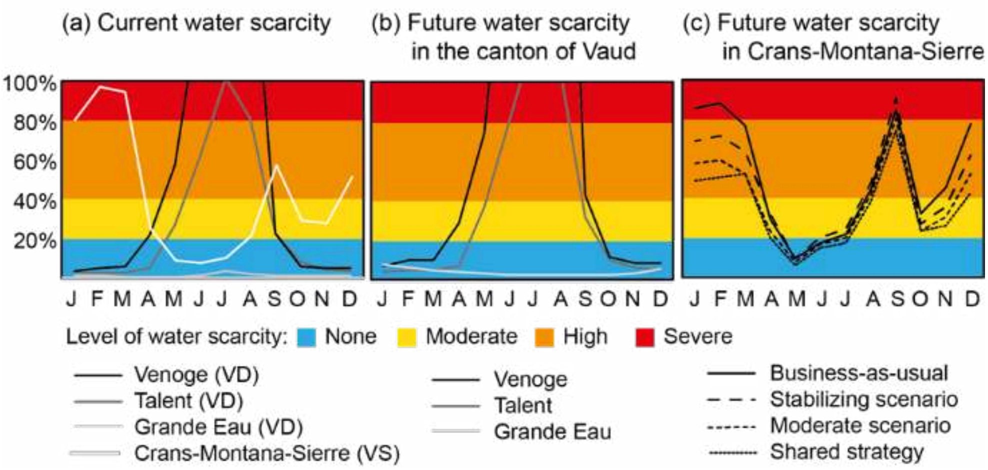
Future changes in water scarcity in western Switzerland

20 Currently, the highly irrigated Venoge and Talent catchments experience moderate water scarcity from May to September and severe water scarcity in July and August as total water needs exceed 80% of freshwater available in rivers (Fig. 3a). The Grande Eau pre-Alpine catchment does not suffer from water scarcity (Fig. 3a). The CMS area currently does not suffer from water scarcity in the summer season but is subject to moderate to high water scarcity over the rest of the year. Water scarcity is even defined as severe in the winter months (January–February–March) and in September (Fig. 3a).

21 By mid-century, under the business-as-usual scenario, the Venoge and the Talent catchments may experience moderate to high water scarcity in May and September and severe water scarcity from June to August (Fig. 3b). In particular, the needs for

water could exceed the freshwater available during these months. The Grande Eau catchment should continue to be spared water scarcity all year round (Fig. 3b). The CMS area could experience high to severe water scarcity from November to March and in August and September (Fig. 3c). However, alternative scenarios could prevent the region from experiencing severe water scarcity in winter as these scenarios could limit total water needs to 50-70% of the available freshwater resources. However, only the moderate scenario would prevent the region experiencing severe water scarcity in late summer, although water scarcity would still remain high. Finally, irrespective of the scenario, the region should not suffer from any water scarcity during the summer season.

Figure 3: Current and future water scarcity in catchments of the canton of Vaud and in the Crans-Montana-Sierre area based on the water scarcity index



Source: Shiklomanov, 1991

Causes of the risk of water scarcity in western Switzerland

Changes in freshwater availability

22 Currently, the risk of water scarcity in western Switzerland coincides with low flow. The river Venoge, which is representative of rivers flowing from the Jura Mountains to Lake Geneva, and the Talent, which is representative of rivers on the Swiss Plateau, are characterized by low flows during the summer season due to the end of snowmelt and less precipitation, respectively (Table 2; Fig. 4a). The pre-Alpine catchment Grande Eau and the headwaters of the CMS area are characterized with low flows in winter due to snow and ice accumulation (Table 2; Fig. 4d).

Table 2: Seasonal freshwater availability in four hydrosystems in western Switzerland

Catchment	Area (km^2)	Hydrological regime	Seasonal runoff (m^3/s)			
			JFM	AMJ	JAS	OND
Venoge (VD)	231	Nivo-pluvial	15.2	11	4.7	12.4

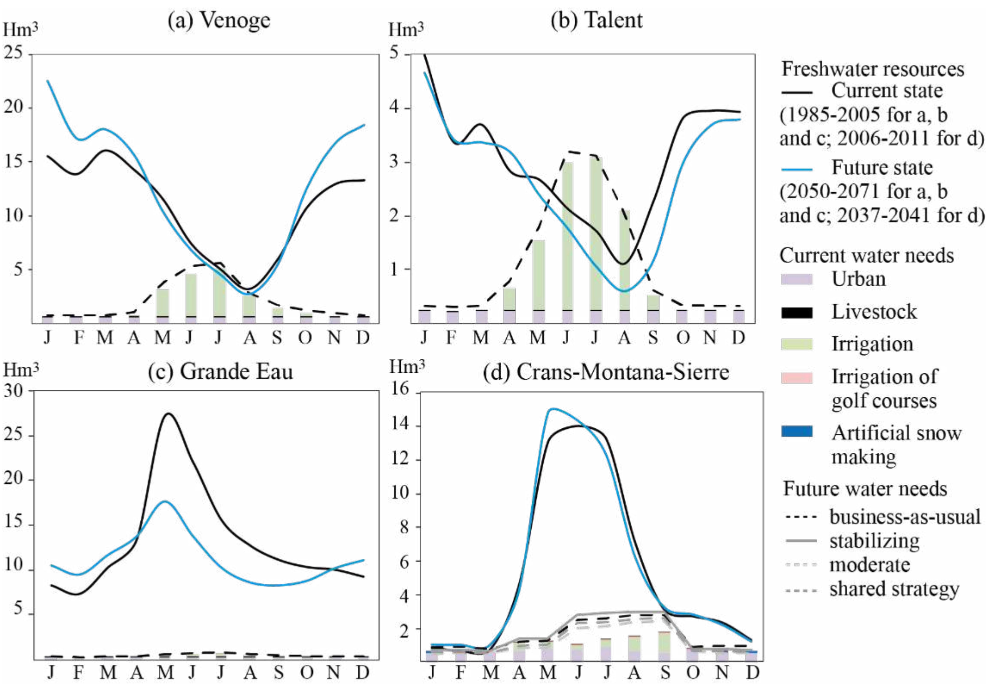
Talent (VD)	62	Pluvial	4.0	2.5	1.7	3.9
Grande Eau (VD)	134	Nival	8.6	20.8	13.1	9.8
Headwaters of CMS area (VS)	130	Nivo-glacial	0.74	10.6	7.8	2.1

Seasonal runoff is averaged over the 1984-2005 period for the Venoge, Talent and Grande Eau catchments (canton of Vaud – VD) and over the 2006-2011 period for the CMS area (canton of Valais – VS).

23 By mid-century, temperatures are expected to rise by 2–3 °C in western Switzerland throughout the year and by a further 1 °C in summer. Precipitation is projected to increase by 10–30% from October to May in the Lake Geneva Region and to decrease by 20–30% in summer over the Plateau and the Alps. In addition, up to 2'000 m a.s.l., rainfall should increase at the expense of snowfall as a result of rising temperatures (data not shown). Changes in the liquid-solid precipitation ratio should lead to less snow accumulation in winter and to a 56% reduction in ice volume in the Plaine Morte glacier (Huss et al., 2013).

24 Under climate change, low flows are expected to become more severe in the Venoge and Talent rivers with a 15% decrease in runoff due to less snowmelt in spring and changes in precipitation distribution (Fig. 4a and 4b). In Alpine catchments, river flows should increase from October to February (+20% in the Grande Eau; Fig. 4) and decrease from March to September (-30%) due to changes in snow accumulation. Yet the higher ice melt related to the glacier retreat could offset changes in the liquid-solid precipitation ratio (Huss *et al.*, 2013), maintaining river flows near their current level all year round (± 10% in the CMS area; Fig. 4d)[6].

Figure 4: Changing trends in water resources in western Switzerland



25 Current availability of freshwater resources and water needs and future changes under climate change by mid-century in the (a) Venoge, (b) Talent and (c) Grande Eau catchments, and (d) in the CMS area. *Results are based on ten regional climate models but for the purpose of readability and key messaging, median water resources availability and needs are presented here.*

Future changes in water needs in western Switzerland

26 Currently, total water needs are highest in the Venoge and Talent catchments (21.7Hm^3/year and 12.3Hm^3/year, respectively) due to high irrigation water needs that amount to nearly three-quarters of the total water needs (Fig. 4a and b). In the Grande Eau catchment, total water needs are low (3.6Hm^3/year). Finally, in the CMS area, total water needs amount to 10.9Hm^3/year. Its domestic sector uses the most water (59%) followed by the irrigation of agricultural plots and golf courses (37.7%) and artificial snowmaking (3.3%; Fig. 4d). In all four study areas, water needs are constant between October and March, and start increasing in April when irrigation practices begin (Fig. 4). Production of snow in the CMS area is seasonal and occurs between November and February.

27 By mid-century and under a business-as-usual scenario, total water needs are expected to increase by 10-20% in the Venoge and Talent catchments (Fig. 4a and b). Annual urban water needs are expected to increase by 40% and livestock water needs to quadruple - although water needs would remain low in this sector compared to other sectors (0.1Hm^3/year) - and irrigation water needs are expected to remain high. In the Grande Eau catchment, total water needs are expected to increase by 35% mainly due to a 35-40% increase in urban and agricultural water needs (Fig. 4c). In the CMS area, under the business-as-usual scenario, total water needs are expected to increase by 24% due to an increase in water needs by the domestic sector (+35%), for golf course irrigation (+8%) and for artificial snow making (+77%; Fig. 4d). However, the reduction in the agricultural surface area could lead to a 15-20% decrease in the need for irrigation water.

28 Under a stabilizing scenario, however, total water needs could increase by 19% in the CMS area due to a 10-25% increase in urban and irrigation water needs and a 19% decrease in artificial snowmaking, owing to a decrease in the area and length of the periods of artificial snowmaking (Fig. 4d). On the other hand, if water saving efforts were made by domestic users, irrigation practices were improved, and artificial snowmaking were abandoned, as assumed in the moderate scenario, total water needs could decrease by 13%. Finally, total water needs could remain at their current level if the development of the CMS area is balanced. Changes assumed under the shared scenario would increase urban water needs (+8%) and irrigation of golf courses (+6%) but reduce artificial snowmaking (-19%).

Assessing water demand

29 The monitoring of water uses in the municipalities of Montana and Bagnes over several years highlighted water consumption patterns and seasonal differences. The biggest seasonal changes in water use are found in the tourist resorts of Montana and Verbier, as well as in hotels and secondary homes. The most significant peaks occur during the end-of-year holidays, the February winter holidays and between mid-July and mid-

August. Very intense peaks in water distribution to main homes are related to abrupt activation of spas and/or watering the garden. In Montana, watering gardens can account for as much as 40% of domestic water use between June and August. Calianno *et al.* (2018) thus suggest defining *water use regimes* that mirror hydrological regimes. Based on this concept, the seasonal water use regime of the two mountain tourist resorts studied here includes two high seasons (winter and summer) and two low seasons (spring and fall).

30 We also compared the irrigation water needs simulated by the CROPWAT agronomic model with data resulting from monitoring conducted in the municipality of Montana (Calianno, 2018). The model tends to overestimate actual water use because it simulates the optimal amount of water needed by the crop, which does not correspond to the quantities actually delivered to the plants by the irrigators. Simulated water needs were 10 to 19 times higher than measured irrigation amounts (Calianno, 2018). These results underline the importance of analyzing irrigation practices to be sure the model parameters match the real practices.

Discussion

Dimensions to be taken into account when assessing water scarcity

31 This paper is based on the assessment of water scarcity in several catchments in western Switzerland characterized by different hydrological regimes and seasonal water users and trends. Like previous regional studies, it underlines the fact that such assessments are useful to identify the areas and seasons most prone to water scarcity and to address the capacity of adaptation strategies to reduce the risk. In western Switzerland, the period most vulnerable to water scarcity is during low flows: either in summer in the Lake Geneva and Plateau regions (and in Alpine regions by mid-century) due to high irrigation and urban water needs, or in winter in Alpine areas due to urban water needs during the tourist high season and artificial snowmaking.

32 Based on these analyses, four main conclusions can be drawn regarding water scarcity assessment. The first is the need to consider both hydro-climatic and anthropogenic factors when exploring possible future changes in water systems. In catchments in the canton of Vaud, population growth, irrigation practices and changes in livestock rearing practices should increase both water needs and pressure on water resources, while climate change should lead to longer and more intense low flow periods, reducing available water resources when water needs are highest. Water scarcity could continue over a longer period of time by mid-century. In the CMS area, freshwater resources should remain near their current level at mid-century, mainly thanks to the contribution of glacier melt to summer runoff. Water scarcity would then be caused by changing water needs and the degree of the severity would depend on water management options. Climatic and anthropogenic changes have cumulative effects that must be taken into account when exploring possible water management plans.

33 A second conclusion is the need for an appropriate time scale to guarantee the risks of water scarcity are properly understood and to build realistic socio-economic scenarios. Most regional studies explore water scarcity on an annual basis (e.g. Menzel and Matovell, 2010; Buytaert and De Bièvre, 2012; Klug *et al.*, 2012; Milano *et al.*, 2013), thereby masking intra-annual temporal variations. For example, the CMS area does not

experience any water scarcity on an annual basis but our monthly analysis showed that conflicts concerning water could arise during the winter season and are expected to arise in late summer by mid-century. Seasonal or monthly analysis of water scarcity hence help identify the length of water scarcity episodes, i.e. periods when conflicts are most likely to occur. This issue was also covered by Mekkonnen and Hoekstra (2016) at the global scale. These authors reported that 3.97 billion people currently experience severe water scarcity for at least one month per year, whereas when they used an annual approach, they only identified 2.7 billion people. They argue that studies carried out on an annual basis thus underestimate water scarcity and the number of people affected. Building scenarios with stakeholders also underlines the importance of the choice of time scale. Water shortage in the CMS area is most likely to happen by the end of the century due to the complete melting of the Plaine Morte glacier by 2080 (data not shown, Huss *et al*., 2013; Kauzlaric, 2015). However, it was difficult for the stakeholders to build realistic regional development scenarios after 2050 due to the speed of territorial changes and the uncertainties of economic development (Reynard *et al*., 2014b). Water scarcity assessment should thus focus on potential short or medium term changes.

34 A third conclusion concerns the spatial scale. Specific studies of water demands in the municipalities of Montana and Bagnes revealed different water use dynamics and typologies between sectors and types of housings. It thus seems necessary to stop assessing water demand at the regional (Saulnier *et al*., 2011; Coll *et al.,* 2015), catchment (Milano *et al*., 2013; Fabre *et al.,* 2015), municipal (Bonriposi, 2013; Leroy, 2015; Calianno, 2018) or matrix scale (Vanham *et al*., 2011), and to move towards the assessment of *water use basins*. This concept, which was suggested by Calianno *et al.* (2018), aims to map the spatial footprint of water users and describe the spatial distribution of water demands within a municipality or region. Adding the concept of *water use regime* would make it possible to characterize the temporal intra-annual distribution of water demands. The combination of water resources and water demand and their spatial and temporal distribution targets high-resolution computing of water scarcity and the identification of *water scarcity hot spots*, i.e. places and periods with high water stress. We believe that such an approach will support dynamic water demand management, and hence facilitate planning of storage infrastructure.

35 A fourth conclusion is the added value of working with local stakeholders and water managers. The assessment and modeling of future water needs and potential stress will be dynamic as long as anthropogenic changes and adaptation measures are taken into account. To give an example, in the canton of Vaud, water needs were only explored using a business-as-usual scenario even though water use practices are highly likely to change (e.g. through the expansion of drip irrigation). In addition, water managers in the canton of Vaud expressed interest in expanding their water supply, e.g. by pumping water from Lake Geneva in the case of a water shortage (General Directorate for the Environment of the canton of Vaud, personal communication, May 13th, 2015). Changing one or more of these variables would have a direct impact on future water scarcity. Based on the experience of the MontanAqua project, building alternative water use scenarios with local stakeholders makes it possible to explore water management strategies that are likely as well as their capacity to reduce conflicts over water. Several authors have highlighted the benefits in involving stakeholders (Carr *et al.,* 2012; Fabre *et al.,* 2016; Gain and Giupponi, 2015; Stanghellini and Collentine, 2008; among others). It is an opportunity for researchers to learn more about water

management and policy as well as any environmental problems the study area is facing and to understand the drivers of some water needs (e.g. irrigation practices; Calianno, 2018). It is also an opportunity for stakeholders to listen to different opinions and share ideas or information in a structured and organized framework (Schneider *et al*., 2015). We agree with Wheater (2015, p. 27), who states "stakeholder engagement is a necessity, not an option". We also believe that stakeholder engagement better guarantees the implementation of scientific results.

Reducing uncertainties and moving from water scarcity to water security

36 Water scarcity assessments rely on hydro-climatic and socio-economic data and tools that have their own assumptions and uncertainties and consequently affect the results. The aim of this paper is not to weigh their influence on the results but to highlight the methodological progress that is still required. We would like to underline two types of uncertainty: hydro-climatic uncertainty linked to the lack of knowledge about future change, and methodological uncertainty linked to the difficulty of assessing the needs of different water users.

37 The best handled uncertainties are certainly those related to hydro-climatic scenarios. On one hand, several climate models are often used to present a range of possible trends and signals. In this study, 10 RCMs were considered but we decided to present a median result for synthesis purposes. On the other hand, we selected hydrological models with high efficiency values to describe seasonal dynamics and the volumes of runoff (Kauzlaric, 2015; Milano *et al.,* 2015b). Uncertainties mainly arise from only focusing on the quantity of water, likely missing water quality-related concerns. Indeed, freshwater resources may be of poor quality, and consequently be unavailable for water users, which can also lead to water scarcity. In agreement with van Vliet *et al.* (2017), Vanham *et al.* (2018) and Octavianti and Staddon (2021) , we argue that water scarcity assessments should now focus on the availability of freshwater resources of acceptable quantity *and* quality for users in each sector. To our knowledge, two main approaches are currently under development. One relies on the blue, green and grey water footprint concept (Liu *et al.,* 2016). It aims to account for actual water consumption, control water pollution and maintain environmental flows for good ecological habitat conditions. However, the final index is composed of three components rather than a single value, which requires mastery of the water footprint concept to apply the method and interpret the results (Zeng *et al*., 2013; Liu *et al*., 2016). The other method adds to the water scarcity index (Shiklomanov, 1991) the extra amount of water necessary to dilute a pollutant and to reach its legal threshold (e.g. water temperature, salinity; van Vliet *et al*., 2017; Jones and van Vliet *et al.,* 2018). This is a step forward in water scarcity assessment but still requires considering multiple parameters simultaneously. The availability of data is a further challenge to incorporating water quality in water scarcity assessments. Data on water quality vary among regions, even within the same country, and often has a broader time-step than runoff series (Liu *et al*., 2017).

38 Further uncertainties concern the estimation of water needs, which are often higher than actual water demand, because they are based on generic assumptions and often lacks a comprehensive knowledge of their spatial and temporal dynamics (Wada *et al*.,

2011; Grouillet *et al.,* 2015). This is mainly due to scarce data series on water demands recorded with high temporal resolution due to a lack of local monitoring strategy (Calianno, 2018; Calianno *et al*., 2018). Most assessments regularly use estimations or proxy data, which has two downsides: (1) monthly variations related to seasonal changes (e.g. due to tourism) are hidden, and (2) the growth stage and local discrepancies are not emphasized. The use of agronomic models also tends to overestimate water needs (Calianno, 2018). It is thus urgent to progress from these conventional econometric methods to dynamic models that couple quantitative and qualitative data (House-Peters and Chang, 2011; Qi and Chang, 2011; Rinaudo, 2015). This entails analyzing individual and social behaviors to identify water use practices or regimes (Calianno *et al.,* 2018) and to identify feedback between key variables in the system (Candelieri and Archetti, 2014; Grouillet *et al*., 2015; Makki *et al*., 2015). In this way, the identification and spatial and temporal assessment of the economic, social and environmental factors that influence water uses is improved and can support the development of prospective water demand models (Schleich and Hillenbrand, 2009; House-Peters and Chang, 2011; Gössling *et al*., 2012; Romano *et al*., 2014).

39 In addition to the aforementioned methodological progresses, the hydrological perspective of water scarcity ignores the social values and institutional context of water management (Buchs and Milano, 2014; Wheater, 2015; Gain *et al*., 2016). Research on water security needs to be more holistic, in particular by integrating the ecological dimension of water, and putting more emphasis on governance issues. This calls for interdisciplinary research to address both hydrological and social water management challenges (Wheater, 2015; Gain et al., 2016; Octavianti and Staddon, 2021). Indeed, water security must be considered as a holistic framework that accounts for five main dimensions (Grey and Sadoff, 2007; Savenije and van der Zaag, 2008; Lautze and Manthrithilake, 2012; Bakker, 2012; Pahl-Wostl *et al*., 2013, 2016): (i) environmental health – the spatial and temporal availability of water resources in terms of both quantity (including hydraulic disturbances) and quality, as well as measures taken to restore rivers and protect aquatic ecosystems, (ii) the human dimension – the spatial and temporal variability of water users and environmental standards, their needs and their effects on the quantitative and qualitative availability of water resources, (iii) the physical and natural infrastructure – the ability of water users to have sustainable access to water, sanitation and hygiene networks and services, (iv) the economic environment – the productive use of water to sustain economic growth in the food production, industry, and energy sectors of the economy, (v) the social and institutional environment – the institutional framework and policy-making process and the capacity of societies to build resilient communities that can adapt to change and to reduce the risk of natural disasters.

Conclusion

40 This paper builds on several research projects conducted to assess water scarcity and water needs in western Switzerland. It emphasizes, on the one hand, the fact that the most vulnerable period to water scarcity in western Switzerland is during low flows, i.e. in summer in the Lake Geneva and Plateau regions and in winter in Alpine areas. On the other hand, it defines the requirements for and challenges to future research on water scarcity, and from a broader perspective, the integration of water scarcity in the water

security concept. Integrated hydrological studies on water scarcity currently correctly integrate hydro-climatic and socio-economic changes and test the capacity of plausible adaptation strategies to reduce conflicts over water with the support of stakeholder involvement. However, two main challenges remain: (1) hydrological approaches must better integrate the geographical dimension of territories, in particular to better grasp the different spatial and temporal dynamics and typologies of water users, and (2) interdisciplinary research is required to assess water resources in terms of both quantity and quality, and to include social and governance processes in modeling exercises, in order to provide a comprehensive and easy-to-use water security index.

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NOTES

1. *MontanAqua* (2010-2014), financed by the Swiss National Foundation, and *ICCARE-Vaud* (2013-2015), financed by the University of Lausanne.
2. *Quantifier les usages de l'eau en territoire touristique de montagne* (2013-2018), PhD thesis financed by the University of Lausanne (Calianno, 2018), and *LABEAU : Mise en place d'un observatoire des usages de l'eau à l'échelle régionale* (2020-2021), financed by the University of Lausanne, the BlueArk innovation pole and ALTIS SA water company.
3. The municipalities of Bagnes and Vollèges merged on 1st January 2021 to form the commune of Val de Bagnes. Our study focused on the municipality of Bagnes before the fusion.
4. In the canton of Vaud, hydropower is mainly run-of-river production and is highly regulated by long-term concessions. Artificial snow production is restricted to Alpine catchments, which

are not considered in this study. These two water users were hence not taken into account in this study.

5. As this use is strictly regulated by long-term concessions (and therefore does not influence the water needs of specific groups of stakeholders), it was not included in our calculations of the current and future water needs.

6. After 2060, the glacier will be too small to continue having a positive impact on river flows.

ABSTRACTS

Water security is an emerging concept, whose assessment and quantification are under development, and of which water scarcity can be considered as a basic research need. This paper draws on four research projects conducted by the authors in western Switzerland and has five key messages: (i) scenarios that account for both hydro-climatic and socio-economic changes are necessary to grasp their respective impacts on water scarcity; (ii) the spatial and temporal resolution of integrated models need to be adapted to the issue tackled; (iii) the involvement of stakeholders in co-producing future water demand scenarios and testing the capacity of plausible adaptation strategies to reduce water tensions is needed to increase the plausibility of modelled situations; (iv) hydrological approaches must evolve towards a geographical integration of territories, in particular to better grasp the different water users, and (v) interdisciplinary research is necessary to assess both the quantity and quality of water resources, and to include both social and governance processes in modelling. Rooted in a comprehensive perspective, the authors argue that such methodological developments would help move towards a dynamic and prospective view of water security.

La sécurité hydrique est un concept émergent, dont l'évaluation et la quantification sont en cours de développement. La quantification du stress hydrique peut être considérée comme une recherche de base pour la sécurité hydrique. Cet article s'appuie sur quatre projets de recherche menés par les auteurs en Suisse occidentale permettant de délivrer cinq messages clés : (i) des scénarios tenant compte à la fois des changements hydro-climatiques et socio-économiques sont nécessaires pour saisir leurs impacts respectifs sur la pénurie d'eau ; (ii) la résolution spatiale et temporelle des modèles intégrés doit être adaptée à la question traitée ; (iii) l'implication des parties prenantes pour coproduire des scénarios de demande en eau future et tester des stratégies d'adaptation permettant de réduire les tensions hydriques est nécessaire afin d'augmenter la plausibilité des situations modélisées ; (iv) les approches hydrologiques empiriques doivent évoluer vers une intégration géographique des territoires, notamment pour mieux appréhender les différents usagers de l'eau, et (v) des recherches interdisciplinaires sont nécessaires pour évaluer les ressources en eau en termes de quantité et de qualité, et pour inclure les processus sociaux et de gouvernance dans les exercices de modélisation. Dans une perspective globale, nous pensons que de tels développements méthodologiques permettraient d'évoluer vers une vision dynamique et prospective de la sécurité hydrique.

INDEX

Mots-clés: stress hydrique, sécurité hydrique, Suisse occidentale, enjeux, perspective hydrologique
Keywords: water scarcity; water security; Western Switzerland; challenges; hydrological perspective

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