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Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes

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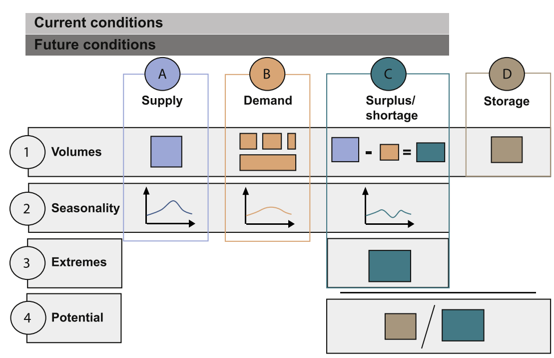
HIGHLIGHTS

- Estimation of water supply, demand, and surplus/shortage for Switzerland
- Assessment of the potential of reservoirs and lakes for alleviating summer shortages
- Future alleviation potential only slightly higher than today under normal conditions
- Increase or decrease of alleviation potential under extreme conditions
- Catchment-scale storage capacity often not sufficient to cover water shortages

GRAPHICAL ABSTRACT



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ABSTRACT

In Alpine regions, future changes in glacier and snow cover are expected to change runoff regimes towards higher winter but lower summer discharge. The low summer discharge will coincide with the highest water demand for irrigation, and local and regional water shortages are expected to become more likely. One possible measure to adapt to these changes can be the extension of current uses of artificial reservoirs and natural lakes to the provision of water for the alleviation of water shortage. This study assesses the potential of reservoirs and natural lakes for the alleviation of water shortages in a nationwide analysis in Switzerland. To do so, we estimated water supply and demand under current and future conditions both under normal and extreme runoff regimes for 307 catchments. Water demand was assessed for various categories including drinking water, industrial use, artificial snow production, agriculture, ecological flow requirements, and hydropower production. The aggregated supply and demand estimates were used to derive water surplus/shortage estimates. These were then compared to the storage capacity of reservoirs and natural lakes within a catchment to determine the potential for alleviating summer water scarcity. Our results show that water shortage is expected mainly in the lowland region north of the Alps, and less in the Alps. In this lowland region, the potential of natural lakes for alleviating water scarcity is high. This potential is lower in the Alps where it is expected to increase or decrease under future conditions depending on the region of interest. Catchments with a high storage capacity can potentially contribute to the alleviation of water shortage downstream. We conclude that a spatial mismatch between water scarcity and storage availability exists since water stored in reservoirs on the southern side of the Alps is often not available for the use on the northern side.

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1. Introduction

Water is required for fulfilling multiple water needs including but not limited to irrigation, livestock feeding, drinking and industry water supply, hydropower production, tourism, ecology, and thermal cooling. In Europe, the demand for water is particularly high in summer when more water is needed for irrigation and cooling. Current runoff regimes in Alpine catchments meet such high seasonal water demands because their runoff also peaks in the summer months. This summer runoff peak is owed to runoff contributions from snow- and glacier melt, which are of particular importance in dry years (Huss, 2011; Stahl et al., 2016; Jenicek et al., 2018). Indeed, the development of a hydrological drought is strongly influenced by the storage capacity of a catchment, the latter being composed of snow and glaciers but also soil, groundwater, lakes, and reservoirs (Van Loon, 2015). Snow and glaciers, two natural storages, are expected to decline in the future due to a warming climate leading to glacier retreat and a reduction in winter snow cover (Farinotti et al., 2016; Marty et al., 2017; Beniston et al., 2018). These changes are projected to cause a shift in the seasonality of Alpine runoff regimes, with increased discharge in winter and spring but a decrease in summer and fall, while the total runoff volume is expected to remain relatively stable (Bernhard and Zappa, 2012; Addor et al., 2014). This decrease in summer discharge might be challenging with respect to water management since it coincides with a high water demand from the agricultural sector. This temporal mismatch between seasonal water availability and demand might lead to seasonal and local water shortages, especially in late summer (Weingartner et al., 2014). It might be even larger if droughts become more severe and occur more often (Bernhard and Zappa, 2012).

Water shortages can have socio-economic and ecological consequences such as restrictions in industrial production due to a limited availability of water for cooling, restrictions in shipping due to low river levels, or constraints in the water use in households and the tourism industry. In addition, water shortages might lead to increased fish mortality due to high water temperature and an insufficient water quality due to reduced dilution effects (Sabater et al., 2018). The alleviation of water shortages is crucial for reducing such associated negative effects. One option for alleviating water shortages in summer would be to maintain the favorable, current runoff regime with the highest runoff in the summer months. This could be achieved by substituting the reduced melt contributions from snow and glaciers by contributions from other types of storages. It has been suggested that artificial reservoirs, as those currently used for hydropower production, could be used for preserving similar runoff regimes as today by storing water in winter and spring and releasing it later in the year (Barnett et al., 2005; Biemans et al., 2011; Farinotti et al., 2016). Today, artificial reservoirs are mostly used for hydropower production as they allow for a shift of electricity production from summer, when inflow is high, to winter, when the electricity demand is highest (Schaefli et al., 2019). This situation might alter in future. In Switzerland, most concessions for hydropower water use expire until 2050 (Thut et al., 2016). This offers the chance to rethink current management practices, the modification of which might be beneficial in order to adapt to climate and socio-economic change (Dorchies et al., 2014). In the future, reservoirs may be operated to provide services beyond electricity generation, including irrigation, water supply, flood protection, modulation of runoff regimes, recreational activities, navigation, and fishery (Branche, 2015; Schleiss, 2016). Such multi-purpose reservoirs could at least partially take the role of natural storages such as snow and glaciers, by storing winter precipitation and releasing water in summer (Viviroli et al., 2011; Thut et al., 2016). A major challenge with multi-purpose reservoirs, however, is sharing water among competing users (Branche, 2015; Nazemi and Wheater, 2015; Andrew and Sauquet, 2017), especially during droughts (Labadie, 2004).

Water resources assessments often focus on natural water availability, and often neglect water demand and storage in reservoirs. This is unfortunate as they should be considered together (Viviroli et al., 2011; Nazemi and Wheater, 2015) due to the potential role of reservoirs in alleviating water scarcity in summer (Buytaert et al., 2017). To date, only few studies have jointly considered water demand and reservoir storage. Adam et al. (2007) developed a method for the estimation of potential contributions of reservoirs to long-term changes in seasonal streamflow. Loukas et al. (2007) modeled not only water availability but also reservoir operation and water demand to evaluate the sustainability of water resources management strategies in two catchments in Greece. Haddeland et al. (2006) have studied the impacts of reservoirs on continental surface water fluxes. The question is, however, whether such reservoirs have the capacity to eventually buffer projected seasonal shifts in runoff regimes. This has been investigated by Barnett et al. (2005) who compared simulated annual runoff to the capacity of existing reservoirs for the world's largest river basins. However, they did not investigate whether the storage capacity was sufficient to cover existing water demand. Biemans et al. (2011) went into this direction by estimating the impact of reservoirs on irrigation, and found that reservoirs contribute significantly to irrigation water supply.

In this study, we assess the potential role of reservoirs and lakes in alleviating water shortages. We do so by comparing reservoir storage capacity with water shortage for current and future climate conditions. We assume that water shortage can be alleviated efficiently if the ratio between storage and shortage is large. However, if this ratio is small, then the shortage exceeds the storage capacity, and there is little potential for alleviation. A similar concept has been applied by Anghileri et al. (2016) who defined stress situations as cases when reservoir capacity was small and water demand was high. In order to define the potential of reservoirs for alleviating summer water scarcity under current and future conditions, we address the following questions:

1. What is the spatial and temporal distribution of water shortage under current and future i) normal and ii) extreme climate conditions?
2. How do these water shortages differ for current and future climate conditions?
3. Where and to what degree is the regional storage capacity of artificial reservoirs and natural lakes sufficient for bridging current and future summer water shortages?

According to Clarvis et al. (2014), augmenting the integration and comprehensiveness of reservoir and lake management for adaptation purposes will be particularly important in an Alpine context. We conduct a nationwide analysis in Switzerland focusing on spatial patterns rather than individual case studies. This becomes possible thanks to a spatially comprehensive dataset of 307 medium-sized catchments in Switzerland at a comparably fine spatial resolution. This is anticipated to provide a comprehensive picture and is therefore distinct from existing studies that focus on individual reservoirs or catchments. Such as spatial overview is necessary to identify regions where reservoirs, existing or newly built, might take an important role in alleviating water scarcity.

2. Methods and material

2.1. Assessment framework

We addressed the questions listed in the previous section in a framework consisting of the four elements A) water supply, B) water demand, C) water surplus/shortage, and D) storage capacity (Fig. 1). For each of these elements, we 1) computed total volumes averaged over the whole year and 2) assessed the seasonality over the year. In the case

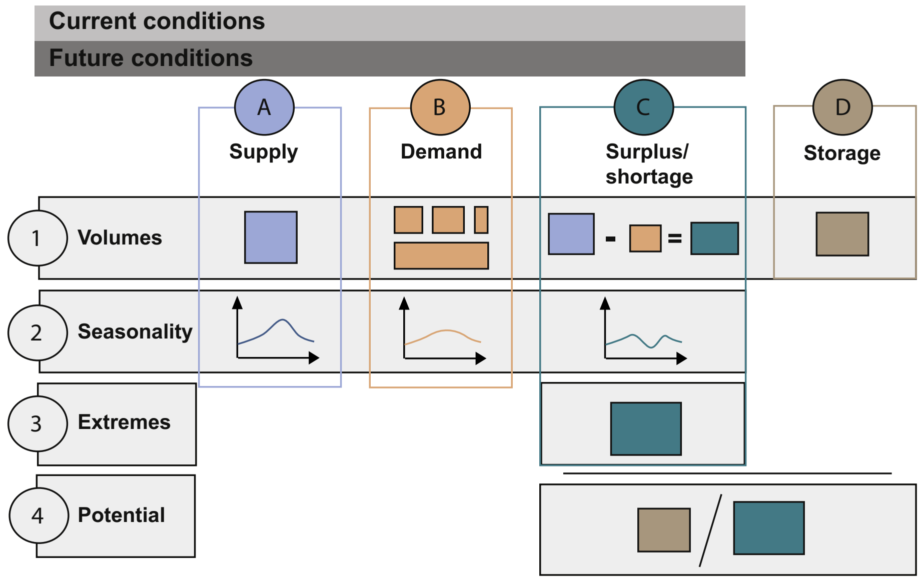

Fig. 1. Study framework: The four elements A) water supply, B) water demand, C) water surplus/shortage, and D) storage capacity are analyzed with respect to 1) volume and 2) seasonality. They are used to assess 3) extremes and 4) the potential of natural lakes and reservoirs for alleviating water shortages.

of water scarcity, we estimated extreme water scarcity by applying a univariate frequency analysis on simulated summer water shortages. The potential of reservoirs and lakes for alleviating summer water shortage was subsequently computed as the ratio between storage at the catchment scale and water shortages which were estimated to occur under normal and extreme discharge conditions.

2.2. Study area

The study was performed on a comprehensive and spatially complete dataset consisting of 307 medium-sized catchments in Switzerland (Fig. 2) (Federal Office for the Environment FOEN, 2015). Brunner et al. (2018) have shown that nationwide water scarcity assessments should focus on a catchment-scale rather than a regional scale if the variability in physiographical and meteorological catchment characteristics is large.

The variation in topography, precipitation sums and seasonality, as well as other catchment characteristics leads to various runoff regimes including glacial, nival, and pluvial regimes (Blanc and Schädler, 2014). Spatial variability exists not only in the natural water supply but also in the demand for water, owing to differences in land use, population density, degree of urbanization, industry density, and other factors. Water is used for agricultural purposes (roughly $400\,10^6\,m^3$ per year or 0.028 mm/d), household water supplies (ca. $500\,10^6\,m^3$ or 0.033 mm/d), for industry water supplies ($1.1\,10^9\,m^3$ or 0.076 mm/d), and for cooling nuclear power plants ($1.6\,10^9\,m^3$ or 1.108 mm/d) (Federal Office for the Environment FOEN, 2014). The demand for water does not only vary in space; it also varies temporally, owing to seasonal differences in temperature which affect cooling, or to differences in evapotranspiration which affect irrigation (Björnsen Gurung and Stähli, 2014). The variety of both hydrological and land-use conditions makes this dataset a representative case study for addressing the research questions presented in Section 1. The methods described in the subsequent sections, especially the computation of the potential of reservoirs and lakes for alleviating summer water

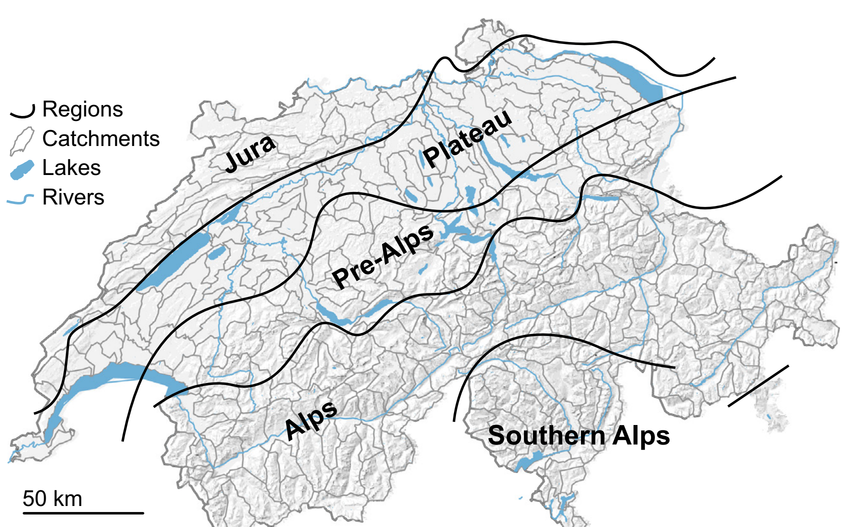

Fig. 2. Map of Switzerland with 307 catchments and the five main geographical regions: Jura, Plateau, Pre-Alps, Alps, and Southern Alps.

scarcity, are not restricted to this dataset but can be applied to other study regions.

2.3. Water supply

We used runoff time series simulated with the hydrological model PREVAH (Viviroli et al., 2009b) to quantify water supply in the 307 catchments in Switzerland (Fig. 2) at a daily temporal resolution. Using even finer temporal resolution was found to be of little added value in water shortage assessments (Brunner et al., 2018). Water transfers between regions were not considered because local supply was compared to local demand.

PREVAH is a conceptual process-based model consisting of several sub-models which represent different parts of the hydrological system. These include interception storage, soil water storage and depletion by evapotranspiration, snow accumulation and melt, glacier melt, groundwater, runoff and baseflow generation, discharge concentration, and flow routing. PREVAH has been chosen as it was shown to reliably simulate the water balance of Switzerland (Zappa and Pfaundler, 2009; Speich et al., 2015) and because it has previously been adopted for climate impact studies (Köplin et al., 2010). A gridded version of the model (Speich et al., 2015) at a spatial resolution of 500 m was set up for Switzerland. The high resolution is needed to capture the variations of discharge regimes, which are observed for regions with distinct physiographical and meteorological characteristics.

For the calibration, runoff time series from 140 mesoscale catchments covering the different runoff regimes were used. The model calibration was conducted over the period 1984–1996. Verification was performed with periods 1980–1983 and 1997–2009, using (i) volumetric deviation (Viviroli et al., 2007) and (ii) benchmark efficiency (Schaefli and Gupta, 2007) as objective functions. The calibration and validation procedures are described in detail in Köplin et al. (2010). The parameters for each model grid cell were derived by regionalizing the parameters obtained for the 140 catchments with a procedure based on ordinary kriging (Viviroli et al., 2009a; Köplin et al., 2010).

The calibrated and validated model was then driven with daily meteorological data including precipitation, temperature, relative humidity, radiation, and wind speed, representing both reference and future climate conditions. The reference period comprised the years 1981–2010 while the future period lay at the end of the century (2071–2100) when the projected changes in runoff are expected to be most noticeable. The two reference periods were used as they are commonly adopted in climate impact studies (World Meteorological Organization, 2015). The transient forcing meteorology for future climate was derived from the CH2018 climate scenarios (National Centre for Climate Services, 2018). They are based on the EURO-CORDEX initiative (Jacob et al., 2014; Kotlarski et al., 2014) which reflects the most recent climate model developments and contains transient simulations based on greenhouse gas forcing. The scenarios are based on representative concentration pathways (RCP) (Moss et al., 2010; van Vuuren et al., 2011) and a regional downscaling approach based on quantile mapping. For a more detailed description of quantile mapping approaches, refer to Themeßl et al. (2012) or Gudmundsson et al. (2012). The meteorological data was derived for the 39 model chains in the ensemble, which provide temperature, precipitation, relative humidity, radiation, and wind speed, for various meteorological stations in Switzerland. For a full list of the model chains used, refer to Table A.1 in the appendix. The use of the set of chains allows for the consideration of uncertainties coming from the choice of both (i) emission scenarios and (ii) global and regional climate models (GCMs and RCMs). Addor et al. (2014) have shown that the choice of the GCMs and RCMs is an important source of uncertainty in hydrological climate impact assessments while the choice of the hydrological model and thus the technique used for spatial data interpolation are less important.

The meteorological data were interpolated to a 2×2 km grid using detrended inverse distance weighting The scheme uses elevation-dependent regression, and spatially interpolates the residuals of that regression with inverse-distance weighting (Viviroli et al., 2009b). During the model run, PREVAH reads the meteorological grids and further downscales the data to the computational grid of 500×500 m using bilinear interpolation. For temperature, a moist-adiabatic lapse rate of $-0.65\,^{\circ}$C/100 m was additionally used. This indirectly allows for the consideration of local topographic effects. This two-steps procedure has been introduced to cope with the large amount of data needed to run PREVAH for 119 years in transient mode for 39 scenarios.

Future glacier extents were obtained from simulations with a glacier evolution model. Two different approaches were used for short and long glaciers, with a threshold set at 1 km glacier length. Glacier lengths were taken from the Randolph Glacier Inventory version 6.0 (RGI Consortium, 2017), and refer to the year 2003. For short glaciers, the future glacier evolution was modeled with the global glacier evolution model (GloGEM; Huss and Hock, 2015). In GloGEM, glacier changes were simulated from a retreat parameterization that relies on observed glacier changes (Huss et al., 2010). For long glaciers, GloGEMflow (Zekollari et al., 2018) was used. GloGEMflow is a new, extended version of GloGEM with an added dynamic ice flow component. This new model was extensively validated over the European Alps, by relying on observed surface velocities and glacier changes and by comparing the future projected glacier changes to those resulting from detailed projections from detailed 3-D modeling studies focusing on individual glaciers (e.g. Jouvet et al., 2011; Zekollari et al., 2014). The simulated glacier extents were transformed from the GloGEM(flow) 1D model grid to the 2D PREVAH model grid by conserving the area of each elevation band.

For illustration purposes, we chose the results of three climate model chains among the 39 available ones. We identified climate chains leading to *wet*, *medium*, and *dry* hydrological conditions, respectively. These conditions were assessed on the period 2070–2100 using three discharge characteristics, namely, mean discharge, the 5% quantile of discharge, and seven day lowflow. These characteristics were computed for the results of each of the 39 model chains, and ranked across the chains. The chain leading to *dry* hydrological conditions was identified as the one with the lowest rank across the three characteristics, the chain leading to *wet* conditions as the one with the highest rank, and the chain leading to *medium* conditions as the one with mean ranks across the chains. The characteristics of the model chains are listed in Table 1.

The daily, simulated runoff series resulting from the 39 model chains were used to compute a mean runoff regime over (i) the period 1981–2010, representing current normal runoff conditions and (ii) the period 2071–2100, representing future normal runoff conditions. The simulated series were also used to extract extreme runoff regimes for current and future conditions. The year 2003 was chosen to represent very dry conditions at present (Beniston, 2004; Rebetez et al., 2006; Schär et al., 2004; Zappa and Kan, 2007) for current conditions and the year with the minimum monthly flow was chosen to represent dry conditions in future. These regimes were used, together with the water demand estimates, to estimate water surpluses/shortages.

Table 1
Summary of the three climate chains considered for illustrating dry, medium, and wet conditions: global circulation model (GCM), regional climate model (RCM), representative concentration pathway (RCP), and type of grid resolution (Resolution).

Conditions	GCM	RCM	RCP	Resolution
Dry	MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	8.5	EUR-44
Medium	ICHEC-EC-EARTH	SMHI-RCA4	4.5	EUR-44
Wet	ICHEC-EC-EARTH	DMI-HIRHAM5	4.5	EUR-11

2.4. Water demand

In this study, we focused on both net and gross water abstraction from surface water because they both provide important information on water stress (Vanham et al., 2018). Net water abstraction comprises consumptive water uses only, while gross water abstraction includes non-consumptive uses such as hydropower production (Liu et al., 2017). Water demand was estimated for various water use categories including 1) drinking water (domestic and tourism), 2) industry (second and third sector), 3) artificial snow production, 4) agriculture (irrigation and livestock), 5) ecological flow requirements, and 6) hydropower production. The estimation procedures for the considered water demand categories are described in the subsequent paragraphs. For drinking water, industry, agriculture, and ecology, they are the same as in Brunner et al. (2018).

1) Drinking water. We considered both drinking water demand from households and from the tourism sector. Drinking water demand from households was estimated by multiplying the water use rate of 142 l per person and day (Freiburghaus, 2015) with the number of inhabitants per catchment (Swiss Federal Statistical Office FSO, 2017) as in Loukas et al. (2007). The drinking water demand from households was assumed to be constant over the year. Drinking water demand for tourism was estimated in a similar way by multiplying the same water use rate by the number of overnight stays (Swiss Federal Statistical Office FSO, 2015b) per catchment. The estimated annual water demand for tourism was attributed to the winter (December–February) and summer season (June–September) which were considered to be most relevant for tourism.

2) Industry. Industrial water demand was estimated by multiplying the water use rate per employee with the number of employees per catchment (Swiss Federal Statistical Office, 2018). The second (manufacturing) and third sector (services) were treated separately by using two different water use rates: 148 m^3 per employee and year for the second sector and 85 m^3 per employee and year for the third sector (Freiburghaus, 2009). The industrial water demand was assumed to be constant over the year.

3) Artificial snow production. In Switzerland, artificial snow is produced in the winter season to support winter tourism. The water demand for this purpose was estimated by multiplying ski run area with the mean water demand per area (1200 m^3 per hectare Teich et al., 2007). Ski run areas were derived by multiplying ski run lengths obtained by MySwitzerland (2018) and provided by the skiing regions with an average piste width of 30 m (Iseli, 2015).

4) Agriculture. Agricultural water demand was derived from water demand for livestock feeding and irrigation. Livestock water demand was computed by multiplying the water use rate per unit of livestock (110 l per day; Freiburghaus, 2009) with the number of livestock per catchment (Swiss Federal Statistical Office FSO, 2015a), in line with Wada et al. (2016). The livestock water demand was assumed to be constant over the year. The irrigation water demand, which represents the difference between the crop water requirement and effective precipitation (Allen et al., 1998) was computed using time series derived by the hydrological model described in the previous section. Crop water requirement was defined as the potential evapotranspiration computed using the Penman-Monteith equation (Allen et al., 1998). Effective precipitation, which represents the portion of rainfall that contributes to meet crop water demand (Patwardhan et al., 1990), was estimated using the current precipitation index, which describes the current catchment wetness. It is defined as a continuous function of precipitation which accumulates on rainy days and exponentially decays during the recession periods of no rainfall (Smakhtin and Masse, 2000). To characterize the exponential decay, we here used a recession coefficient of 0.7. Irrigation water demand is seasonally variable but withdrawal for irrigation was restricted to the spring and summer months (April to September).

5) Ecology. Ecological flow requirements were considered by using a threshold flow value corresponding to the 95% quantile of daily discharges as prescribed by Swiss legislation (Aschwanden and Kan, 1999). The ecological flow requirement was assumed to be constant over the year. We did not consider further specific needs, e.g. for sustaining protected wetlands or the avoidance of hydro peaking.

6) Hydropower. We only considered storage hydropower and neglected run-of-river hydropower plants since they can usually not be actively regulated (Schaefli, 2015). The water demand for hydropower production was estimated for each storage reservoir within Switzerland and then aggregated to basin-wide water demand. The monthly water demand was estimated by multiplying the monthly percentage change in storage content with the storage capacity of the reservoir, and by subsequently adding the monthly natural inflow to the reservoir. The monthly percentage changes in storage content were derived using monthly storage content curves provided by the Swiss Federal Office of Energy (2017) for four large regions, being the cantons (i) Valais, (ii) Grisons, (iii) Ticino, and (iv) the aggregated remaining cantons. The monthly inflows were computed based on the catchment runoff simulated with the hydrological model PREVAH (see previous section), which was adjusted proportionally to the catchment area contributing to reservoir inflow. Locally, water used for hydropower production becomes unavailable for other uses since it is diverted from the natural channel. It becomes usable again downstream of the location where the water is released after electricity production (Johnson, 2009).

The seasonal values were explicitly estimated for drinking water in the tourism sector, irrigation, and hydropower water demand. For the remaining demand categories, the seasonal values were derived from the annual values distributing them equally across all seasons. This is because historical records on sectoral water withdrawals are sparse, and restricted to the annual scale (Huang et al., 2018).

2.5. Future water demand

For calculating future water demand, we considered changes in the demand related to population growth and changes in the hydrological conditions. Drinking water demand was estimated using population projections provided by the Swiss Federal Statistical Office FSO (2016). Industry water demand was kept at the current level since no projections are available for this sector. Artificial snow production was estimated taking into account that skiing areas below a certain altitude threshold will disappear due to unprofitability (Uhlmann et al., 2009; Fischer et al., 2011) and assuming that the water consumption per hectare will increase to 1500 l (upper limit provided by Teich et al., 2007). The altitude threshold was set to 2000 m a.s.l. because temperature has a more important impact on snow below altitudes around 1500–2000 m a.s.l. than on those above (Beniston, 2012). Water demand for livestock feeding was kept at the current level while water demand for irrigation was estimated using potential evapotranspiration representing future climate conditions. Future hydropower demand was computed with future reservoir inflows. Changes in production patterns were not considered due to the high uncertainty (Gaudard et al., 2014; Ranzani et al., 2018). Total catchment water demand was estimated by aggregating the demand estimates from the different demand categories.

2.6. Water surplus and shortage

Water surplus or shortage were estimated by computing the difference between the water supply and the total water demand estimates both at an annual and at a monthly resolution. A water surplus resulted if this difference was positive and a water shortage if it was negative.

Normal, i.e. mean monthly water surplus/shortage was computed using mean runoff conditions over the time period of interest. In contrast, *extreme* monthly water surplus/shortage was estimated using an annual hydrograph representing extreme runoff conditions. For current conditions, we used the hydrograph of the year 2003, which represents a very dry year. For future conditions, we used the hydrograph comprising the minimum monthly flow (i.e. the minimum flow over the whole time series) within all future time series. Summer water shortage was computed as the aggregated water shortage in the months June to September. Extreme summer water shortage was estimated using univariate frequency analysis on the cumulative shortages of the months June to September. For future conditions, we used the water shortage estimates combined from all 39 climate model chains, and fitted a Generalized Extreme Value (GEV) distribution. The distribution was not rejected at a level of significance of 0.05 by a Anderson–Darling goodness-of-fit test following Chen and Balakrishnan (1995). We used the fitted GEV distribution to derive water shortage estimates corresponding to return periods of 10 and 100 years, which are the return periods commonly used for planning purposes.

2.7. Storage capacities

We focused on reservoir storage capacity and distinguished between two types of reservoirs: natural lakes and artificial reservoirs. Currently, the latter are mainly used for hydropower production. In the following, we will refer to these two types of reservoirs just as lakes and reservoirs.

- Lakes: For the largest lakes (>0.5 Mm^3), we used volume estimates provided by the Swiss Federal Office for the Environment (FOEN). The storage capacity of the remaining lakes was computed by multiplying the mean lake depth, defined by using the isolines of the digital elevation model for Switzerland (Federal Office of Topography swisstopo, 2018), with the lake surface area.
- Reservoirs: The storage capacity of hydropower reservoirs in Switzerland was provided by the Swiss Federal Office for Energy (BFE) (Panduri and Hertach, 2013).

We assumed that the total storage capacity of different reservoirs in a catchment was available in a single, virtual reservoir (Loukas et al., 2007; Ahn et al., 2016; Garrote et al., 2018). The total storage capacity was computed by aggregating the capacities of the two reservoir types.

2.8. Potential of reservoirs and lakes for alleviating summer water scarcity

The potential of reservoirs and lakes for alleviating summer water scarcity was estimated as the ratio between storage capacity and water shortage estimates derived for normal and extreme conditions (10-year and 100-year estimates). A large storage-shortage ratio represents a high potential for alleviating local water scarcity, while a small ratio represents situations where catchments either have a low storage capacity or where high shortages are expected. The assessment was performed at a catchment-scale, where local shortages were compared to local storage capacities. Catchments with storage capacities that are higher than estimated shortages might, however, also contribute to the alleviation of water shortages in catchments downstream. This possibility was not accounted for.

3. Results

3.1. Current water supply, demand, and shortage

The runoff regimes in Switzerland are influenced by different factors depending on the region (see Fig. 3 for four example

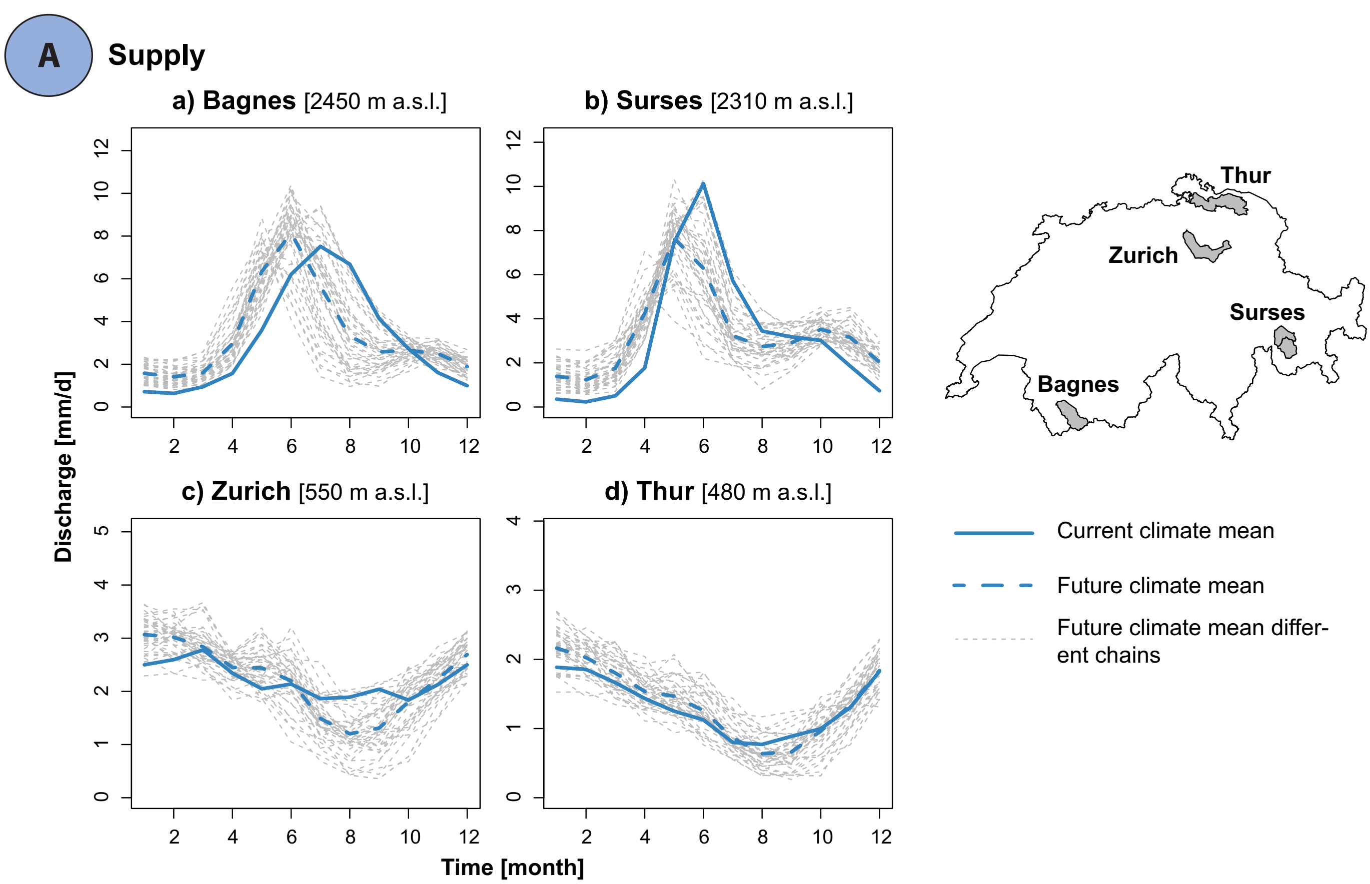

Fig. 3. Hydrological mean regimes under current (bold line) and future (dashed lines) climate conditions for four example catchments: a) Bagnes, b) Surses, c) Zurich, and d) Thur (map to the right). The grey lines represent mean regimes computed from the 39 climate chains available. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

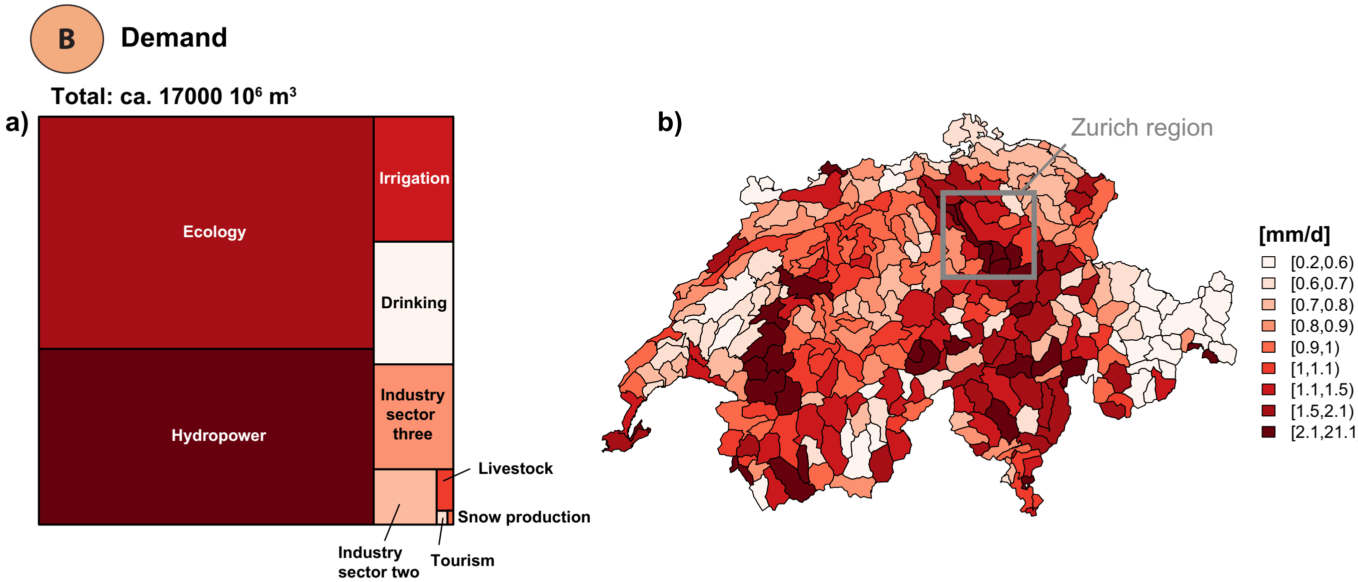

Fig. 4. a) Annual estimated water demand over all catchments for the considered water-demand categories, and (b) spatial distribution of the water demand over all categories. The grey box indicates a region with a comparably high water demand: Zurich region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

catchments). Alpine regions (e.g. Bagnes and Surses) are influenced by glacier- and/or snow melt, and are therefore characterized by runoff regimes with high runoff in spring and summer and low runoff in winter. In contrast, runoff regimes in the Plateau region (e.g. Zurich and Thur) are influenced mainly by rainfall, and characterized by low runoff in summer and higher runoff in winter.

Estimated current water demand varies between categories. Over all catchments, annual water demand is estimated to be highest for

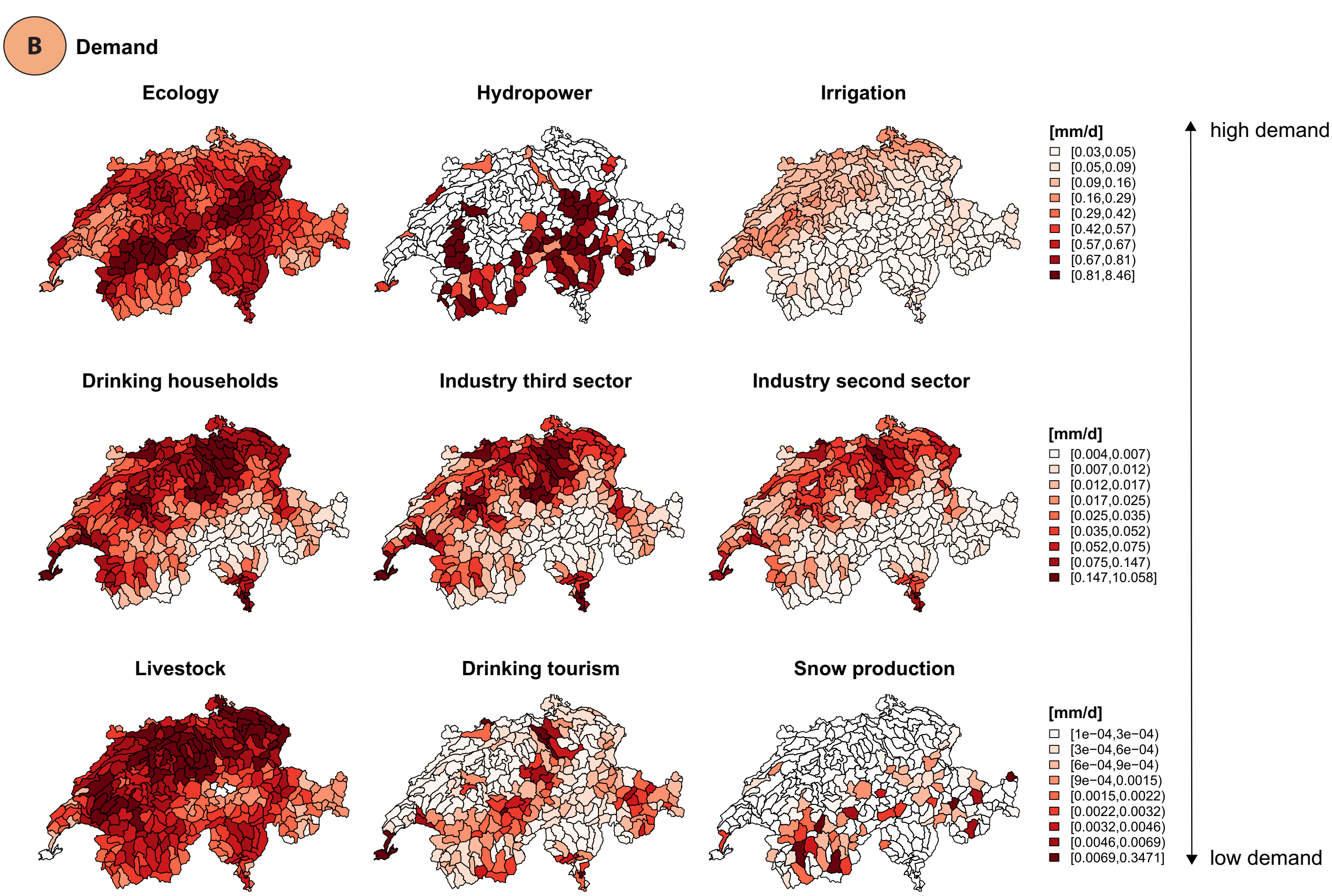

Fig. 5. Estimated annual water demand for the 307 catchments. Categories are sorted in order of decreasing water demand. Note that the three rows have different color scales due to the large differences in magnitude. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

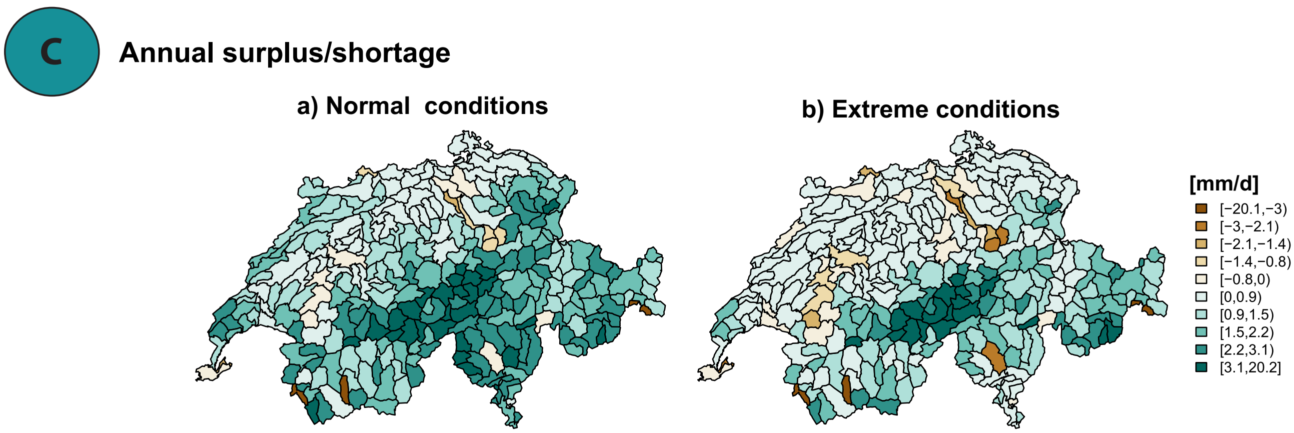

Fig. 6. Annual water shortage/surplus estimates for a) current mean conditions (1981–2010) and b) extreme conditions represented by the year 2003. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ecological flow requirements (ca. 8000 10^6 m^3) and for hydropower production (ca. 6000 10^6 m^3) (Fig. 4 b). Water demand for irrigation (ca. 1000 10^6 m^3) and drinking (ca. 1000 10^6 m^3) are much lower but still substantial. The water demand decreases in the following order: ca. 900 10^6 m^3 for industry sector three, 360 10^6 m^3 for industry sector two, 70 10^6 m^3 for livestock feeding, 15 10^6 m^3 for drinking and tourism, and 8 10^6 m^3 for snow production. The water demand does not only vary according to the categories but also in space (Fig. 4b). The overall water demand is highest in the Plateau region, especially in the region Zurich (grey square Fig. 4b). The spatial pattern is quite diverse for the different water demand categories (Fig. 5). Ecological flow requirements are dependent on the natural flow conditions and therefore highest in the regions with comparably high discharges such as the Alps and Southern Switzerland. Water demand for hydropower production is mainly restricted to the Alps, the Pre-Alps, and the Southern Alps, where most hydropower reservoirs are located. In contrast, livestock and irrigation water demand are highest in the Plateau region because of the comparably flat terrain suitable for agriculture. Water demand for drinking and industry are highly dependent on the population density and the number of employees, respectively, and are therefore highest in the densely populated areas in the Swiss Plateau. Drinking water demand for tourism is highest in the Alps, where the mountain resorts are located, and in the large cities in the Plateau which also attract tourism. The locations of the mountain resorts also appear in the spatial distribution of demand for snow production, which is restricted to the Alps.

The high water demand in the Plateau region is reflected in the low water surplus estimates for current conditions. The estimates are lower in the Plateau region than in the Alps (Fig. 6). Estimated water shortage is higher for the extreme year 2003 (Fig. 6b) than for average conditions (Fig. 6a).

Under normal conditions, hardly any region is expected to be affected by water shortage on an annual scale. However, under extreme conditions, a few catchments in the Plateau region are expected to be affected by water shortage. This is also the case for some regions in the Alps. If the water shortage estimates are averaged over all months, only a few regions are affected. This is different for monthly water shortage estimates, as shown for April, August, and December (Fig. 7).

Under current normal conditions, monthly estimates indicate local water shortages in only a few catchments in the Alps and the Plateau region. This can mainly be explained by hydropower water demand. In contrast to normal conditions, extreme conditions are expected to lead to local water shortages in most catchments in the Plateau region in summer. Water shortages are also expected in a few regions in the Alps in winter.

The storage capacity of both natural lakes and artificial reservoirs is distributed heterogeneously (Fig. 8). The largest natural lakes are located in the Pre-Alps and Western Switzerland, while the storage

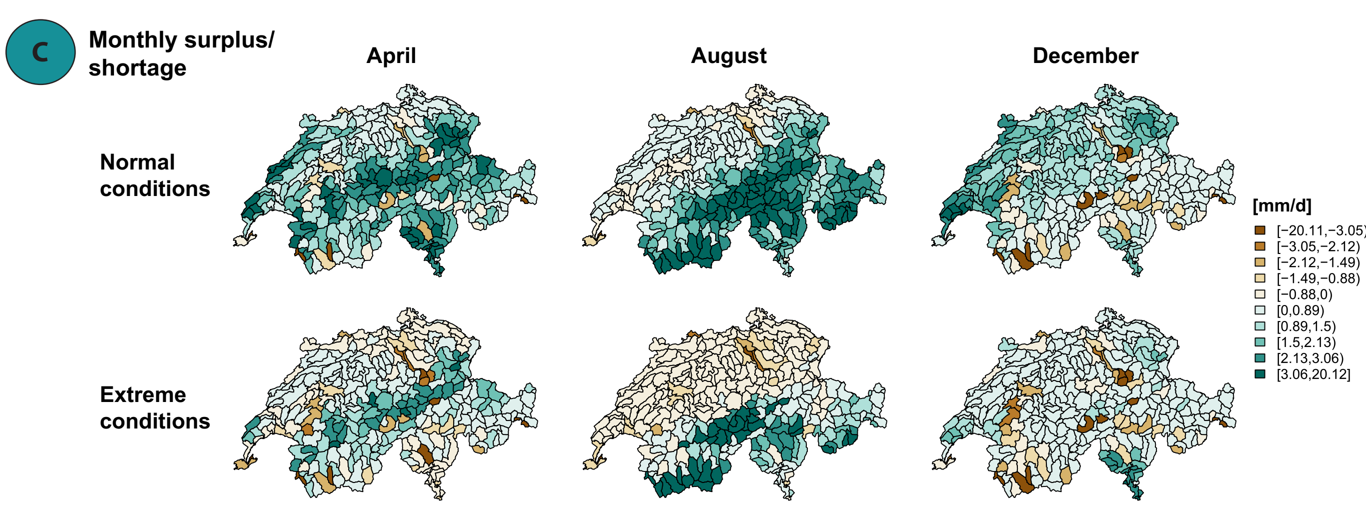

Fig. 7. Monthly water shortage/surplus estimates for the months April (left panels), August (middle panels), and December (right panels) considering normal (upper panels) and extreme water supply conditions (lower panels). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

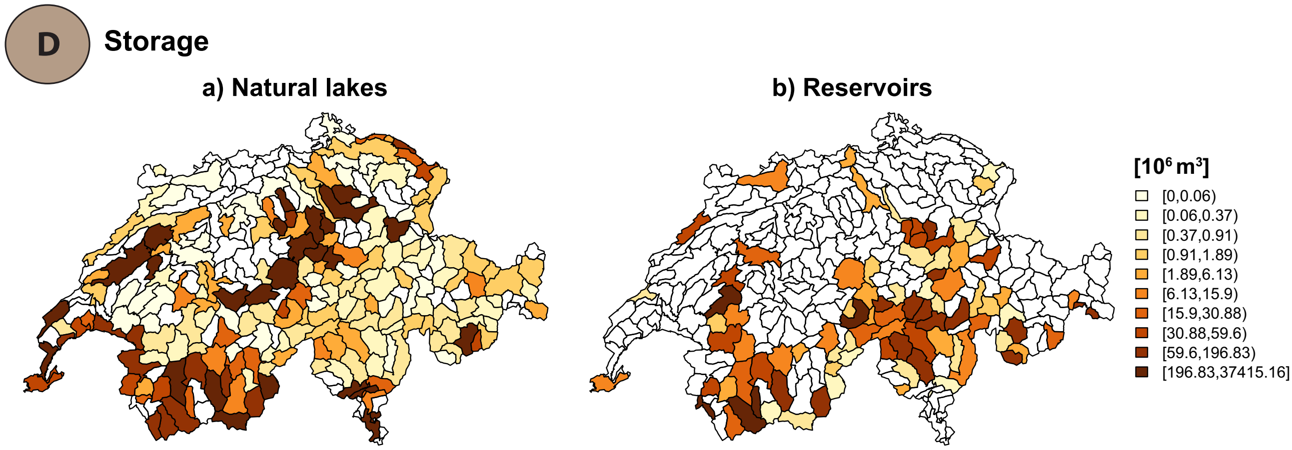

Fig. 8. Storage capacities for natural lakes (a) and hydropower reservoirs (b).

capacity of reservoirs is highest in the Alps and the Southern Alps. The storage capacities in catchments in the Plateau region are rather low compared to the Alps except for catchments with a natural lake.

3.2. Future water supply, demand, and shortage

The hydrological regime is expected to be modified under future climate conditions both for melt-dominated and rainfall-dominated catchments (Fig. 3). The maximum runoff of the hydrological regime of the melt-dominated catchments (e.g. Bagnes and Surses) is expected to be shifting from summer to spring, which results in a future surplus of water in winter, an earlier melt season, and a deficit in summer. A regime shift is also expected for the rainfall-dominated regimes whose winter runoff is increased while the summer lowflows become more intense.

Future water demand was assumed to remain at the current level for industry, livestock feeding, tourism, and ecology. On the other hand, it was estimated to increase for drinking water in households due to population increase, and in irrigation due to a projected increase in potential evapotranspiration. Future water demand for snow production was estimated to increase in catchments maintaining snow production in future, and to reduce to zero in the remaining catchments. The future water demand was found to remain approximately stable for hydropower production due to the small annual changes in reservoir inflow. Remember that production patterns were assumed to remain constant.

Fig. 9 shows annual water surplus/shortage estimates for current and future conditions.

For visualization purposes, the future conditions are summarized by three climate model chains representing dry, medium, and wet conditions. On an annual scale, hardly any water shortages are expected under normal conditions, independently of the model chain. Under extreme conditions, however, water shortage estimates are more severe in future than currently, even for wet conditions. Similarly as under current conditions, water shortage estimates vary over the year (Fig. 10). In the melt-dominated regions, water shortages are estimated to occur in winter, when runoff is lowest. In rainfall-dominated regions, instead, water shortages are estimated to occur in summer. These shortages are expected to be more severe under future than under current climate conditions.

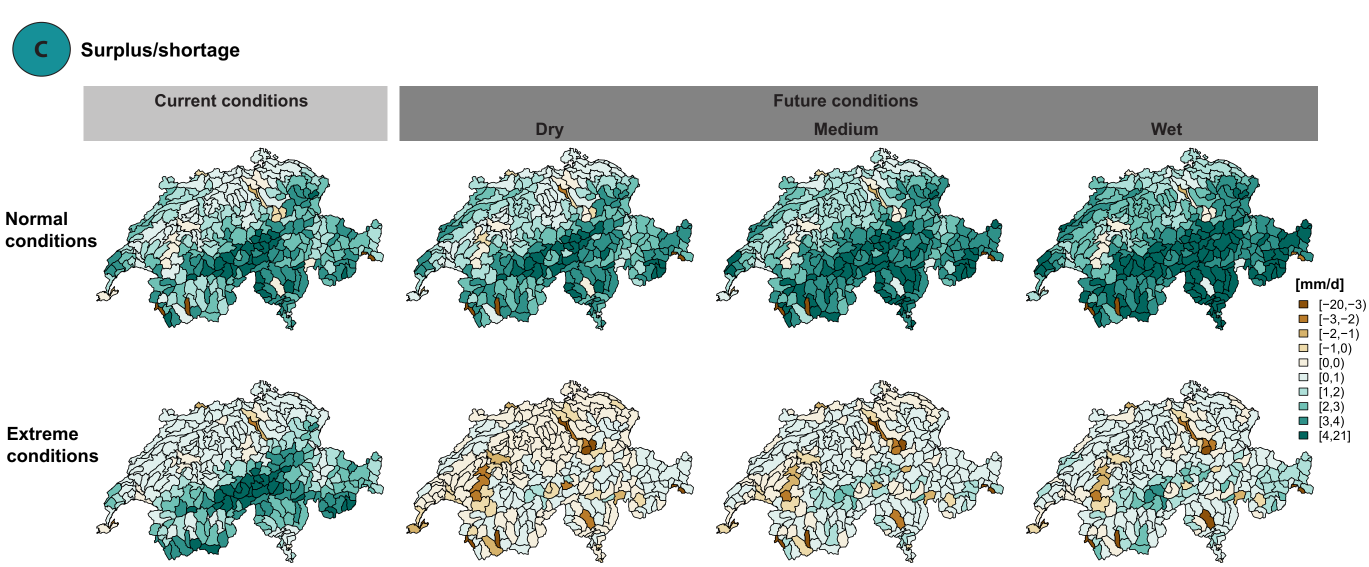

Fig. 9. Annual water shortages/surplus estimates for current and future normal (upper panels) and extreme (lower panels) climate conditions. The future conditions are represented by three climate model chains: dry, medium, and wet. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

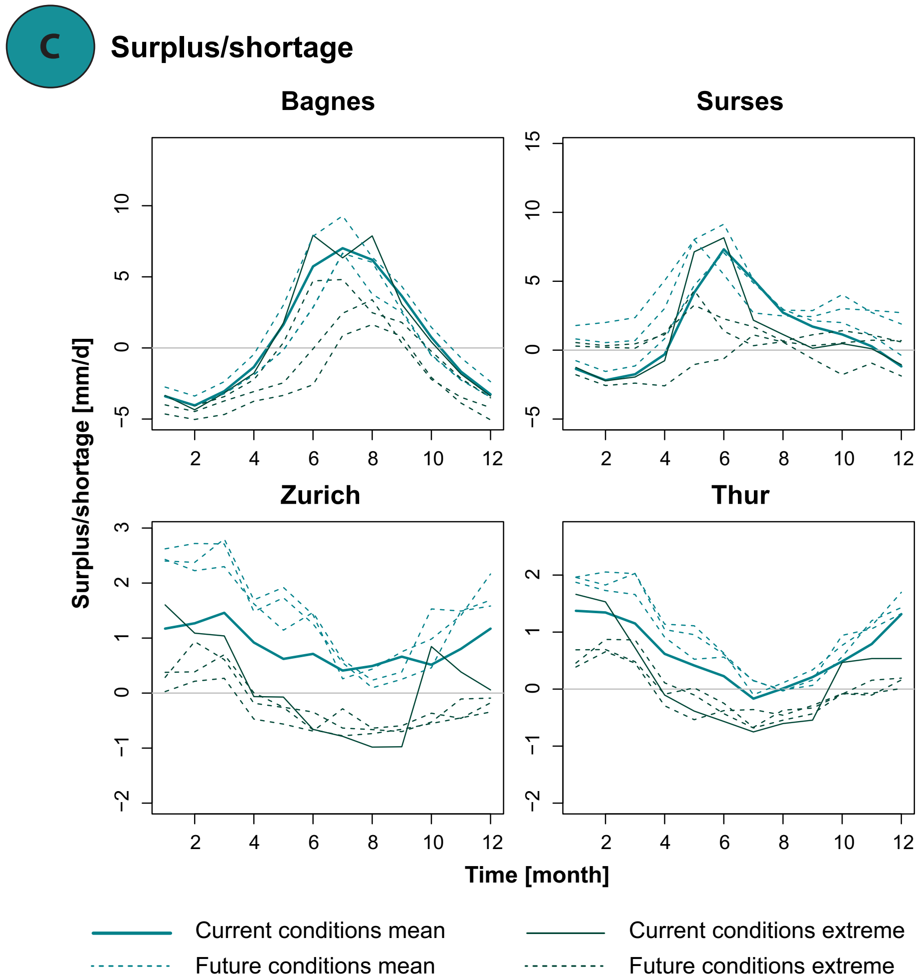

Fig. 10. Seasonal water shortages for current (bold lines) and future (dashed lines) normal (light green) and extreme (dark green) climate conditions. Future estimates are given for the three example model chains representing dry, medium, and wet conditions (Table 1). The catchments are those for which the location is given in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In melt-dominated catchments (i.e. mainly in the Alps), the differences between current and future conditions are more noticeable for extreme than for normal conditions.

The Plateau region, where the water demand is highest (Fig. 4), is expected to be affected most by water shortages (Fig. 7). This is especially in the summer months, when water demand for irrigation is highest. For further analyses, we therefore focused on the months June to September. Fig. 11 shows mean and extreme summer shortage estimates for return periods of 10 and 100 years under current and future conditions.

While the mean shortage estimates are relatively similar for current and future conditions, there are significant differences between the 10- and 100-year estimates. The catchments in the Plateau region are more severely affected by water shortage under future conditions, and a few regions in the Alps may also be impacted when considering shortage estimates with a high return period (i.e. a low recurrence frequency).

3.3. *Potential of reservoirs and lakes for the alleviation of summer water shortages*

Water shortage situations can potentially be alleviated by using water stored in natural lakes and artificial reservoirs. The estimated potentials are displayed in the upper two panels of Fig. 12. Under current and future mean conditions, only a few catchments in the Plateau region are expected to experience water shortage. For these catchments, the potential of reservoirs for the alleviation of water scarcity is relatively small, and storage capacities are limited to regions with large natural lakes (Fig. 8). In the latter regions, lakes have a high potential for the alleviation of summer water scarcity. For dry summers with a return period of 10-years under future conditions, a few regions in the Alps have a significant reservoir potential for alleviating shortages — in addition to the catchments in the Plateau region. For a summer water shortage with a return period of 100 years, the potential is maintained in the catchments of the Plateau with large natural lakes, but is reduced in some regions in the Alps where the increased shortage can not be covered entirely by existing storage capacities. However, some regions in the Southern Alps show a high potential for alleviating water scarcity through reservoirs not affected by water shortage under less extreme conditions. The lower panel in Fig. 12 shows that the potential of reservoirs and lakes for alleviating summer water scarcity in future can both increase or decrease. While the differences in current and future potential are rather small for mean conditions, they can be large under extreme conditions.

The potential in the Lake region (brown box in Fig. 12), for example, decreases under future conditions because of an increase

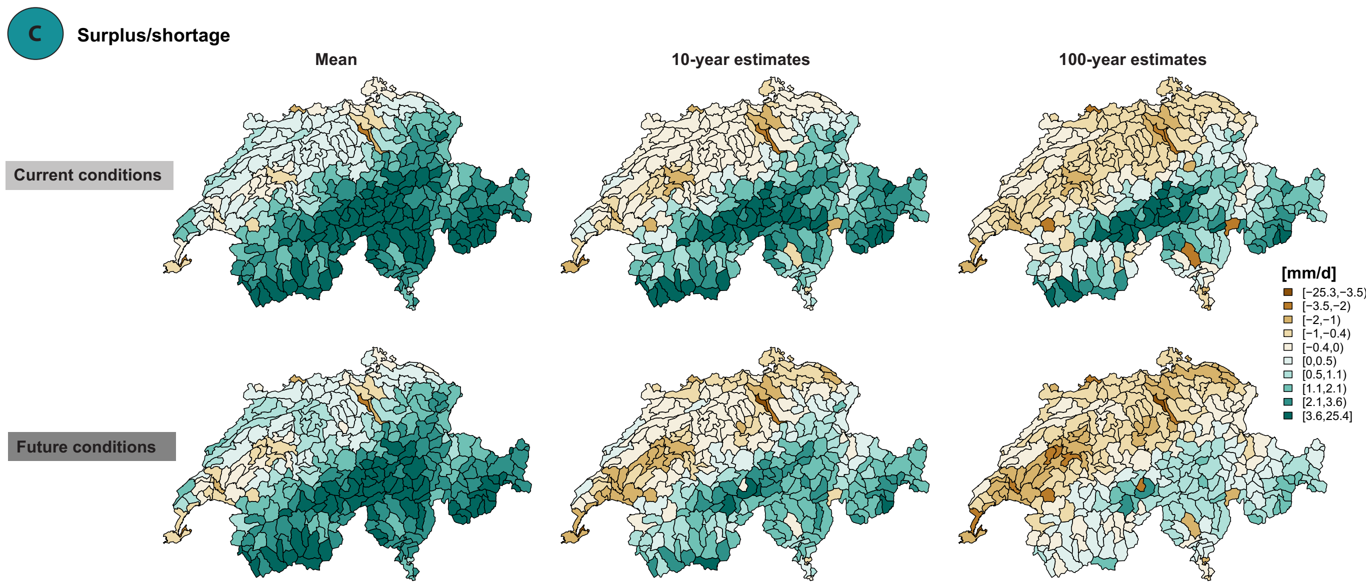

Fig. 11. Mean and extreme summer (June–September) water shortage/surplus estimates under current (upper panels) and future (lower panels) conditions. The displayed values were calculated by combining all 39 climate model chains. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

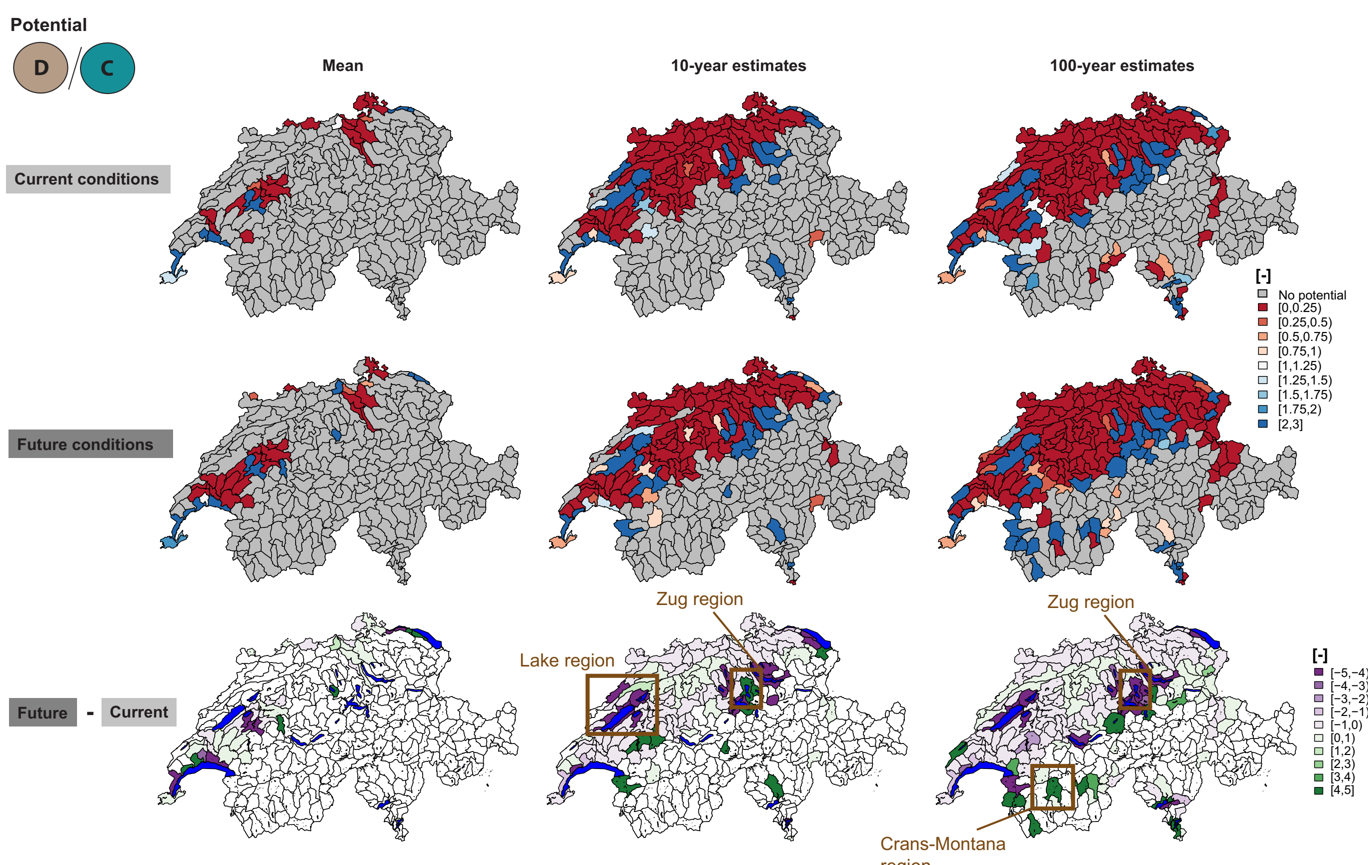

Fig. 12. Storage/shortage-ratio for the summer period (June–September) for current (upper panels) and future mean and extreme conditions (10-year and 100-year water shortage estimates). Regions with a ratio larger than one are colored in blue (surplus), those with a ratio smaller than one in red (deficit), and regions without shortage in white. The lowest panels show the difference in the potential for future and current conditions. Catchments with a higher future than current potential are colored in green, those with a lower future than current potential in purple. Illustration regions are marked by brown boxes and lakes are depicted in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in water shortage, even though the potential is still large. In contrast, the potential of reservoirs in the Crans-Montana region increases because the region includes a few reservoirs but is only affected by water scarcity under extreme future conditions. Also in the Zug region, the reservoir potential increases in the future, since it is affected by water shortage only in the future. On the contrary, the region has a decreasing potential in the future under very extreme conditions (100-year event) because future shortage becomes larger compared to current shortage.

4. Discussion

The expected shifts in runoff regimes lead to an increase in water availability in winter but to a decrease in summer. This is not ideal with respect to the seasonality of irrigation water demand, which is highest in summer when potential evapotranspiration is high. In contrast, the expected regime shifts are potentially beneficial for hydropower production via both run-of-river and storage power plants. This is because water supply and high energy prices would coincide, prices being highest in winter due to heating requirements. Note, however, that energy demand might increase in summer due to cooling requirements (Gaudard et al., 2014). The additional water that becomes available in winter can potentially be stored in reservoirs, and released in the season it is needed. The seasonal lack of water can therefore partially be alleviated by reservoirs and regulated lakes. In addition to the seasonal mismatch between water availability and demand, there is a spatial mismatch between water supply and demand. Catchments in the Plateau generally have a higher water demand than those in the Alps. However, water availability shows the opposite pattern, with high availability in the Alps and rather low availability in the Plateau region. It must be noted, however, that this spatial distribution will in practice be solved by water flowing from the Alps towards the Plateau, where it can contribute to satisfy water demands.

The Plateau is the region mainly affected by water scarcity. This is because more runoff is generated in the Alps, where higher annual precipitation is found. While annual water demand is hardly higher than annual water supply, seasonal water demand can exceed local water supply both locally and regionally. Water shortage is highest in summer, and enhanced by extremely low runoff conditions. When considering hydropower as a water demand, even catchments in the Alps can experience water scarcity under current and future conditions, especially in winter and spring when natural runoff is low for melt-dominated regimes but the demand for hydropower is highest. It is noteworthy that winter water scarcity hardly becomes apparent due to the use of hydropower reservoirs which enable hydropower companies to store water in the Alps during the water-abundant summer, and to release it in winter. This strategy is already now used for alleviating water shortage.

Our analysis has shown that reservoirs and natural lakes can also help to alleviate summer water scarcity. The potential is highest in regions where large natural lakes are located in places with water scarcity. In addition, potential for water scarcity alleviation also exists in regions where both water demand for hydropower production and seasonal storage of water in hydropower reservoirs are large. While this potential is not very different in future than at present for average conditions, it can significantly differ under extreme conditions. Some regions were shown to have an increased future potential when they become affected by water scarcity. Other regions had a lower potential because they are less affected by water scarcity under current conditions than in future. If the storage capacity of a region exceeds the volume needed to cover local water scarcity, the water might also be used in other regions. This might, however, be associated with (high) transportation costs and/or environmental damage. In some cases, not the whole storage capacity can be used for the alleviation of water scarcity since the reservoirs are not necessarily connected to the regions with the highest water scarcity. The reservoirs in the south-western part of Switzerland (Valais) or the Southern Alps are for instance hydrologically not connected to the Plateau region.

Water scarcity issues can be either considered from a water supply or demand perspective (Montanari et al., 2013). Using existing reservoirs in a multi-purpose framework is only one measure for alleviating water scarcity, thereby addressing the supply side of the problem. Another measure is the use of groundwater resources which have a high but currently not fully exploited potential (Sinreich et al., 2012). In regions with high expected shortage but low natural water availability, new reservoirs could be constructed which collect rainwater in winter to be used for irrigation in summer. Other measures rather address the demand side in times of water scarcity. Potential measures include the choice of drought-resistant crop types, improved irrigation techniques, public awareness campaigns, efficient cooling techniques, etc. Multi-purpose reservoirs would ideally complement such measures, but can probably not replace them due to the spatial differences in storage availability and water demand. In a scenario analysis, Hao et al. (2015) showed that combining reservoir management with a reduction in irrigation water demand by altering the cropping system and improving irrigation techniques is much more effective than building additional reservoirs. Last but not least, it is crucial to note that water quality can significantly influence the availability of water resources (Lissner et al., 2014). Water quality should be considered together with water availability and infrastructure.

This study provides decision makers with an overview of regions where reservoirs and natural lakes might play a role in the alleviation of water scarcity. Its results are not directly transferable to the scale of an individual community because water-demand estimates were derived using input data at rather coarse spatial resolution. If similar analyses are conducted at a community scale, data on water demand should be collected locally, and complemented with qualitative techniques such as surveys and interviews. Depending on the location of the reservoir of interest, other types of water demands not considered in this analysis might be important. Volpi et al. (accepted for publication) have for example shown that reservoirs can have a positive effect on flood attenuation. In catchments with nuclear power plants or important industrial facilities, thermal cooling needs to be taken into account. In the case of reservoirs with a large surface, evapotranspiration from that surface should be accounted for (Loukas et al., 2007).

Water management becomes crucial at the local scale as well. To identify suitable operation modes for a multi-purpose reservoir, as opposed to a hydropower reservoir, optimal management options would need to be identified (Schaefli, 2015). This can be achieved by minimizing the adverse effects of water shortage, or by maximizing the economic benefits of the water resource system (Anghileri et al., 2011; Nazemi and Wheater, 2015). Hendrickx and Sauquet (2013) have shown that an earlier filling of the reservoir is necessary in winter to support minimum downstream flow in summer. According to Kellner and Weingartner (2018), the suitability of a multi-purpose reservoir needs to be assessed individually. They conclude that the use of multi-purpose reservoirs might not in every case be the best solution, and rather propose water-systems well connected by infrastructure.

5. Conclusions

The region mostly affected by summer water scarcity in Switzerland is the Plateau, where a relatively high demand meets a relatively low natural water supply. There, catchments with natural lakes might profit from water scarcity alleviation through nearby reservoirs and natural lakes. Our results have shown that storage capacity can be several times larger than estimated water scarcity. Reservoirs and lakes allow for a seasonal shift of water from the season with water abundance to the season with water shortage. This study has shown that the future potential of reservoirs and natural lakes for alleviating summer water shortage at the catchment scale will be slightly larger than under current normal conditions. This is because water shortage only weakly increases. However, this potential is expected to change under extreme future conditions. The potential will increase in regions which have a substantial storage capacity in reservoirs and/or lakes, and which are not affected by water shortage under extreme current conditions but might be under extreme future conditions. On the contrary, the potential will decrease in regions which are suffering from water scarcity under current extreme conditions but even more under future conditions. In contrast to catchments with a potential for the alleviation of summer water scarcity, many catchments with water shortage do not have enough storage capacity to fully cover water shortages. These regions might still profit from inflow from other catchments or from reservoirs and lakes located upstream. However, additional infrastructure might be needed to transport water from places with a high water availability to places with a high water demand. Due to high infrastructure costs and environmental damage, alternative measures, addressing the demand side of the water shortage problem might be necessary.

Author contributions

MB, MS, and AB set up the study design. HZ and DF created the future glacier masks. MZ did the hydrological model simulations. MB did the water demand estimation, conducted the analyses, produced the figures, and wrote the first draft of the manuscript. The manuscript was revised by AB, MS, HZ, and DF, and edited by MB.

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A. Appendix

Table A.1
Summary of the 39 climate chains used in this study: Global climate model (GCM), regional climate model (RCM), representative concentration pathway (RCP), and type of grid resolution.

GCM	RCM	RCP	Resolution
ICHEC-EC-EARTH	DMI-HIRHAM5	2.6	EUR-11
ICHEC-EC-EARTH	DMI-HIRHAM5	4.5	EUR-11
ICHEC-EC-EARTH	DMI-HIRHAM5	8.5	EUR-11
ICHEC-EC-EARTH	SMHI-RCA4	2.6	EUR-11
ICHEC-EC-EARTH	SMHI-RCA4	4.5	EUR-11
ICHEC-EC-EARTH	SMHI-RCA4	8.5	EUR-11
MOHC-HadGEM2-ES	SMHI-RCA4	4.5	EUR-11
MOHC-HadGEM2-ES	SMHI-RCA4	8.5	EUR-11
MPI-M-MPI-ESM-LR	SMHI-RCA4	4.5	EUR-11
MPI-M-MPI-ESM-LR	SMHI-RCA4	8.5	EUR-11
MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	8.5	EUR-44
ICHEC-EC-EARTH	CLMcom-CCLM5-0-6	8.5	EUR-44
MOHC-HadGEM2-ES	CLMcom-CCLM5-0-6	8.5	EUR-44
MIROC-MIROC5	CLMcom-CCLM5-0-6	8.5	EUR-44
MPI-M-MPI-ESM-LR	CLMcom-CCLM5-0-6	8.5	EUR-44
ICHEC-EC-EARTH	DMI-HIRHAM5	2.6	EUR-44
ICHEC-EC-EARTH	DMI-HIRHAM5	2.6	EUR-44
ICHEC-EC-EARTH	DMI-HIRHAM5	4.5	EUR-44
ICHEC-EC-EARTH	DMI-HIRHAM5	8.5	EUR-44
ICHEC-EC-EARTH	DNMI-RACMO22E	4.5	EUR-44
ICHEC-EC-EARTH	DNMI-RACMO22E	8.5	EUR-44
MOHC-HadGEM2-ES	DNMI-RACMO22E	2.6	EUR-44
MOHC-HadGEM2-ES	DNMI-RACMO22E	4.5	EUR-44
MOHC-HadGEM2-ES	DNMI-RACMO22E	8.5	EUR-44
CCma-CanESM2	SMHI-RCA4	4.5	EUR-44
CCma-CanESM2	SMHI-RCA4	8.5	EUR-44
ICHEC-EC-EARTH	SMHI-RCA4	2.6	EUR-44
ICHEC-EC-EARTH	SMHI-RCA4	4.5	EUR-44
ICHEC-EC-EARTH	SMHI-RCA4	8.5	EUR-44
MOHC-HadGEM2-ES	SMHI-RCA4	2.6	EUR-44
MOHC-HadGEM2-ES	SMHI-RCA4	4.5	EUR-44
MOHC-HadGEM2-ES	SMHI-RCA4	8.5	EUR-44
MIROC-MIROC5	SMHI-RCA4	2.6	EUR-44
MIROC-MIROC5	SMHI-RCA4	4.5	EUR-44
MIROC-MIROC5	SMHI-RCA4	8.5	EUR-44
MPI-M-MPI-ESM-LR	SMHI-RCA4	2.6	EUR-44
MPI-M-MPI-ESM-LR	SMHI-RCA4	4.5	EUR-44
MPI-M-MPI-ESM-LR	SMHI-RCA4	8.5	EUR-44
NCC-NorESM1-M	SMHI-RCA4	2.6	EUR-44
NCC-NorESM1-M	SMHI-RCA4	4.5	EUR-44
NCC-NorESM1-M	SMHI-RCA4	8.5	EUR-44

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