Stochastic System Dynamics Modelling for climate change water scarcity assessment on a reservoir in the Italian Alps

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Abstract

Water management in mountain regions is facing multiple pressures due to climate change and anthropogenic activities. This is particularly relevant for mountain areas where water abundance in the past allowed for many anthropogenic activities, exposing them to future water scarcity. Here a stochastic System Dynamics Modelling (SDM) was implemented to explore water scarcity conditions affecting the stored water and turbined outflows in the S.Giustina reservoir (Province of Trento, Italy). The analysis relies on a model chain integrating outputs from climate change simulations into a hydrological model, which output was used to test and select statistical models into a SDM for replicating turbined water and stored volume within the S.Giustina dam reservoir. The study aims at simulating future conditions of the S.Giustina reservoir in terms of outflow and volume as well as implementing a set of metrics to analyse volume extreme conditions.

Average results on 30-years slices of simulations show that even under the RCP4.5 short-term scenario (2021-2050) future reductions for stored volume and turbined outflow are expected to be severe compared to the 14 years baseline (1999-2004, 2009-2016; -24.9% of turbined outflow and -19.9% of stored volume). Similar reductions are expected also for RCP8.5 long-term scenario (2041-2070; -26.2% of turbined outflow and -20.8% of stored volume), mainly driven by the projected precipitations having a similar but lower trend especially in the last part of the 2041-2070 period. At monthly level, stored volume and turbined outflow are expected to increase for December to March (outflow only), January to April (volume only) depending on scenarios and up to +32.5% of stored volume in March for RCP8.5 2021-2050. Reductions are persistently occurring for the rest of the year from April to November for turbined outflows (down to -56.3% in August) and from May to December for stored volume (down to -44.1% in June). Metrics of frequency, duration and severity of future stored volume

values suggest a general increase in terms of low volume below the 10th, 20th percentiles and a decrease of high volume conditions above the 80th and 90th percentiles. These results point at higher percentage increases in frequency and severity for values below the 10th percentile, while volume values below the 20th percentile are expected to last longer. Above the 90th percentile, values are expected to be less frequent than baseline conditions, while showing smaller severity reductions compared to values above the 80th percentile. These results call for the adoption of adaptation strategies focusing on water demand reductions. Months of expected increases in water availability should be considered as periods for water accumulation while preparing for potential persistent reductions of stored water and turbined outflows. This study provides results and methodological insights that can be used for future SDM upscaling to integrate different strategic mountain socio-economic sectors (e.g., hydropower, agriculture and tourism) and prepare for potential multi-risk conditions.

Introduction

Mountains serve as "water towers" providing freshwater to a large portion of the global population (IPCC, 2014, 2018; Kohler et al., 2014; United Nations, 2012; Viviroli et al., 2007). Climate change affects mountain environments more rapidly than many other places, with impacts on glaciers, snow precipitation, water flows and on the overall supply of water (Viviroli et al., 2011; Barnett et al., 2005). These impacts call for the need to shift water management towards more sustainable and adaptive practices. Adaptation delays and unpreparedness to water availability changes can spread consequences across multiple systems, from natural ecosystems to anthropogenic activities relying on water (van den Heuvel et al., 2020; Mehran et al., 2017a; Fuhrer et al., 2014; Xu et al., 2009).

The European Alps are among those mountain regions where water abundance in the past allowed for the development of activities with intensive water use such as large hydropower plants and irrigated agriculture, making them susceptible to future impacts regarding reduced water availability (Beniston and Stoffel, 2014; Majone et al., 2016; Permanent Secretariat of the Alpine Convention, 2009). That is, in many Alpine regions the socio-ecological systems are unprepared for water scarcity and hence the impacts of water shortage can be more severe (Di Baldassarre et al., 2018).

Previous studies have assessed the hydrological processes involved in mountain environments, looking at the overall hydrological dynamics (Bellin et al., 2016) or specifically assessing topics such as glacier melt and runoff (Huss and Hock, 2018; Farinotti et al., 2012), and snowpack dynamics (Etter et al., 2017; Wever et al., 2017). However, the interplay connecting natural processes and socio-economic activities calls for further research. There is a need to implement methodologies with the ability to unravel this complexity in order to effectively tackle climate-related water issues.

System Dynamics Modelling (SDM) is a methodology used to improve the understanding of complex systems and their dynamic interactions. It makes use of four main modelling elements: (i) stocks (system state variables) – 'accumulating' material (e.g. water in a reservoir); (ii) flows (variable's rate of change) –moving material into and out of stocks (e.g. river inflows and outflows), (iii) converters - parameters influencing the flow rates (e.g. temperature variable acting to alter evaporation from a water body) and (iv) connectors – as arrows transferring information within the model (e.g. linking the

65   monthly effects on reservoir' water discharges; Sterman et al., 2000). The combination of these elements is applied to represent temporal changes in system elements accounting for endogenous and exogenous influences on system behaviour. This concept encourages a system thinking approach, splitting large systems into sub-systems and progressively increasing their interactions and complexity (Gohari et al., 2017; Mereu et al., 2016). SDMs can combine different metrics and indices, improving models by adding social, economic and environmental sectors (Terzi et al., 2019). Moreover, SDM can implement a graphical

70   interface, supporting the visualization of interactions and feedback loops during participatory approaches.

While SDM was developed to improve industrial business processes (Forrester, 1971), it has been successfully applied to model human and natural resources interactions (Meadows et al., 2018). Moreover, SDM applications span a wide range of problems, from climate change risk assessments (Duran-Encalada et al., 2017; Masia et al., 2018), water management issues (Davies and Simonovic, 2011; Gohari et al., 2017), disasters studies (Menk et al., 2020; Simonovic, 2001, 2015), water-energy-

75   food nexus studies (Sušnik et al., 2018; Davies and Simonovic, 2008) and applications fostering participatory modelling (Malard et al., 2017; Stave, 2010). SDM has therefore been proved to be a useful tool to study complex interactions and dynamic behaviour in a wide variety of complex systems (Ford, 2010).

However, SDM also shows some limitations, such as (i) the limited spatial representation since it works with lumped regions, although recent research has coupled SDM to GIS to account for spatially explicit system dynamics (Neuwirth et al.,

80   2015; Xu et al., 2016); (ii) the ease of creating complex what-if scenarios that can be difficult to validate, but which can be useful to explore systems behaviour under potential futures; (iii) the fact that applications usually account for deterministic expert-based assumptions on existence and type of variable's interactions (Mereu et al., 2016; Sahin and Mohamed, 2014; Sušnik et al., 2013), although statistical analysis of trends and interactions are crucial under uncertain climate change and risk assessments and recent analyses have been used for probabilistic SDM output (Sušnik et al., 2018).

85   These limitations call for methodological improvements. The combination of statistical methods with SDM represent a valuable integration to overcome the current limitations involved in deterministic expert-based assumptions of variables interactions and dependencies. Existing studies already considered the need to implement variables statistical testing within SDM (Taylor et al., 2009; Ford, 2005) and this application allows to test and investigate variables interactions under future uncertain of water availability conditions and explore potential impacts, water disputes and crises.

90   This study focused on the S.Giustina reservoir in the Noce catchment, Province of Trento, Italy, due to its important function for hydropower production and regulating water availability downstream. While water has always been recognized as abundant in the province, temperature increase, loss of glacier mass volume and decreased snow precipitation during winter are among the causes of reduced summer discharge and water availability both in mountain areas and downstream. At the same time, numerous activities have flourished in the Noce catchment such as increasing hydropower plants, agricultural

95   production, urbanisation, industrial activities and more intense tourism all demanding large water amounts to satisfy their needs. Tensions for water allocation have recently arisen asking for a fair use of the resource among different actors, and at the same time (e.g. orchards irrigation coinciding with rising tourist water demand). In particular, associations and civil society groups (e.g. local association for the Noce river safeguard: https://nocecomitato.wordpress.com/) were established at provincial

level showing their concerns about ecological impacts of further exploitation (i.e. hydropower plants). For these reasons,
100 current conditions and future climate change projections leading to critical levels of low and high stored volume and turbined
outflows for hydropower production in the S.Giustina dam reservoir were assessed. Indices for frequency, duration and severity
of the reservoir's critical states and its reduced water availability are explored and discussed. By doing so, the aim is to develop
and demonstrate a stochastic SDM as an effective tool to assess climate change impact of water scarcity in one of the main
reservoirs in the north-east of the Italian Alps supporting its adaptation planning. Such results could inform water operators,
105 local and provincial authorities fostering a discussion on the implementation of climate change adaptation strategies in line
with the Water Framework Directive (European Parliament & Council, 2000).

1 Case study

The Noce river (Province of Trento, Italy) in the south-eastern part of the Alps (Figure 1) is a tributary of the Adige River,
the second longest river in Italy. The Noce river basin is a typical Alpine basin with an overall area of 1367 km^2 and an average
110 discharge of 33.8 m^3/s at the basin closure. It is characterized by intensive anthropogenic activities including hydropower
plants in the upper part of the catchment relying on glacier melting, to intensive apple orchards shaping the landscape of valley
bottoms. It also hosts a significant number of tourists with peaks of water demands during winter and summer time for sport
activities (i.e. skiing, hiking and kayaking). The hydropower sector is the main water user (77.8% of the licensed water
withdrawals is allocated to small hydropower plants with a nominal capacity <3MW) followed by agriculture (16.4%),
115 domestic uses (4%), fish-farming (0.9%), industry (0.4%), snowmaking (0.3%) and others (0.2%; Provincia Autonoma di
Trento, 2018).
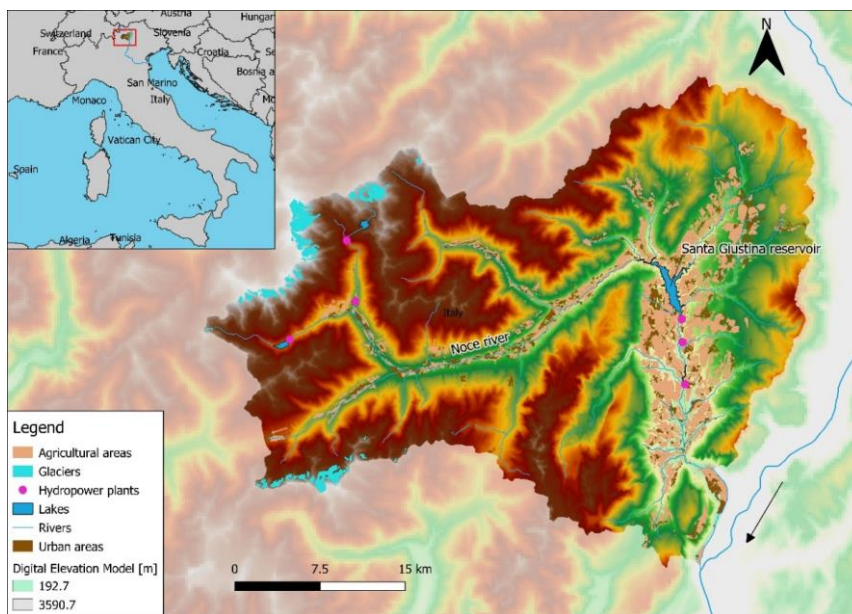
Figure 1 - Noce river basin and main characteristics. The black arrow specifies the Adige River flow direction.

Water has always been considered abundant in most regions in the Alps and only recent events of water scarcity in 2015 and 2017 raised wider concerns about water quantity and quality (Stephan et al., 2021; Chiogna et al., 2018; Hanel et al., 2018; Laaha et al., 2017). Within this context, climate change effects at regional level have already been recognized acting on the current water balance and triggering multiple impacts on a wide range of economic activities relying on water use (La Jeunesse et al., 2016; Zebisch et al., 2018).

In the Noce river basin, the S. Giustina reservoir provides a large buffer for water resources regulation. The reservoir has a storage capacity of 172 Mm^3 (equal to a maximum net available volume of 152.4 Mm^3), the largest reservoir volume within the Trentino-Alto Adige region. It was built in the 1940's and 1950's for hydropower purposes. Nowadays, the reservoir has a multipurpose function, producing a large amount of energy (i.e. installed power of 108 MW), and regulating water flow for downstream users and providing water for irrigation. Moreover, the local water use plan (Provincia Autonoma di Trento, 2006) established from 2009 onwards a minimum ecological flow threshold ranging from 2.6 to 3.7 m^3/s (the only water flow downstream the dam) according to each month of the year to continuously sustain fluvial ecosystems.

2. Methods and exploited material

This study focuses on a refinement of SDM applications implementing a stochastic assessment of variable interactions for validation of uncertainties and trends in the field of risk assessment. Conceptual diagrams of system variable interactions were elaborated using the Stella software (https://www.iseesystems.com/) while statistical correlations, dependencies and tests were analysed in R (Duggan, 2016; R Core Development Team, 2019). This combination contributes to improving SDM analysis accounting for the uncertainty and variability associated with past and future water flow data.

The methodological approach here presented is composed of 5 sequential phases, from (1) the SDM set-up, (2) the analysis of SDM variables' interactions, (3) SDM model calibration and validation on historical observations (4) the integration of future projections in the SDM and test of statistical significance changes to the baseline and finally (5) the characterization of future low and high stored water critical conditions through a MonteCarlo sampling approach. Each of the stages is described in this section.

2.1 System dynamics modelling set-up and input data

The SDM was set-up integrating multiple sources of data (e.g. observations, modelled values and climate projections) to replicate past and to simulate future S.Giustina turbined water and stored reservoir volume. The model chain considered for this objective consists of 3 main modules, namely climate projections in box 1, hydrological model in box 2 and the SDM in box 3 (Figure 2).
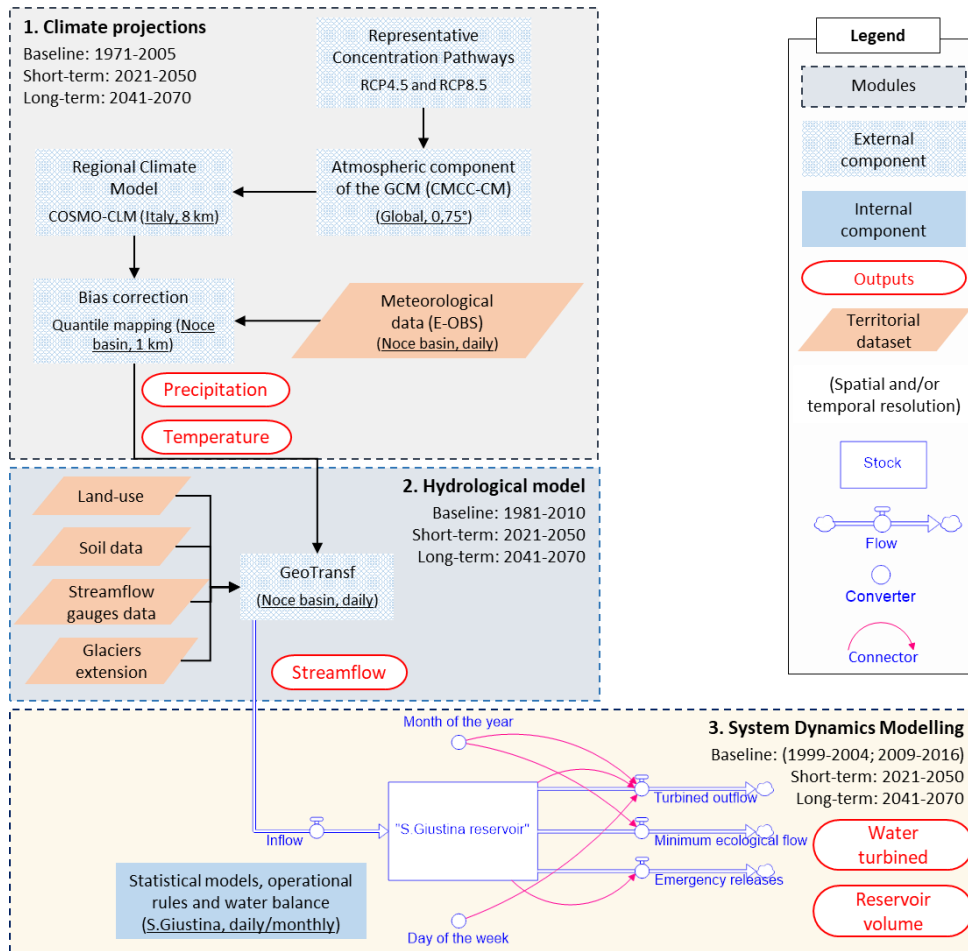
Figure 2 - Models' chain considered in this study. Box 1 includes the climate modelling used as input for the hydrological model simulation of water streamflow in box 2. Box 3 contains the SDM components of stock (S.Giustina reservoir), flows (inflow and three outflows), converters (month of the year, day of the week) and connectors (red arrows) considered to simulate stored water in the reservoir and the turbined outflow for hydropower production considering a baseline from 1999 to 2016 with a data gap from 2005 to 2008. Sources: adapted from Pham et al., 2018; Ronco et al., 2017.

The climate projections provide information stemming from global climate models downscaled to regional level, and bias corrected through the quantile mapping method (Maraun, 2016; Teutschbein and Seibert, 2012) using the downscaled daily E-OBS dataset at 1 km resolution (Cornes et al., 2018) to better simulate climate local conditions. The regional climate model COSMO-CLM (Climate Limited-area Modelling) was selected for its spatial resolution of $0.0715° × 0.0715°$ ($≈ 8km×8km$) allowing local level climate impact assessment (Rockel and Geyer, 2008). Such model information was developed by the CLM community and provided by Euro-Mediterranean Centre on Climate Change (CMCC) as an external component for the application to the Noce catchment (Bucchignani et al., 2016). In the case of climate data from COSMO-CLM, precipitation and temperature baseline data were available from 1971 to 2005, they were also used to characterize the Noce catchment

climatology and compare the baseline with future conditions of precipitation and temperature for the two Representative Concentration Pathways (RCPs).

Temperature and precipitation daily data were used as input to the physically-based model "GeoTransf" (external component, Bellin et al., 2016) together with topographical information to replicate streamflow conditions of the Noce river (box 2 in Figure 2). These two boxes were obtained from simulations developed from the OrientGate project (http://m.orientgateproject.org/) and used as an input to focus on the S.Giustina reservoir through the SDM (box 3 in Figure 2). GeoTransf was calibrated and validated on past daily water flow data in the case study area considering a baseline time range from 1981 to 2010 with a performance of Nash-Sutcliffe efficiency coefficient of 0.88 for calibration and 0.73 for validation at the S.Giustina control section (Bellin et al., 2016). GeoTransf provides a description of the water flow within the Noce alpine river catchment relying on precipitation and temperature data (from box1), land use and soil type (http://pguap.provincia.tn.it/#), streamflow gauge data (https://www.floods.it/) and on glacier extension (https://webgis.provincia.tn.it/). Water withdrawals for anthropogenic uses were modelled within GeoTransf at sub-catchment level accounting for their licensed number and the physical constraints from the existing water infrastructures. Moreover, GeoTransf was applied with COSMO-CLM precipitation and temperature scenarios from 2021 until 2070 over the Noce catchment to assess future conditions of river discharge at local level for the RCPs 4.5 and 8.5 (Bucchignani et al., 2016). While climate was considered as the only drivers of change in future simulations, anthropogenic water withdrawals were assumed at their maximum physical discharge in order to account for possible future increases of water demands from sectors such as domestic and agricultural needs, sectors recognised to lead possible increases in demand (Bellin et al., 2016; La Jeunesse et al., 2016).

The stochastic SDM relied on the inflow values from GeoTransf applications as one input variable. Other input variables were initially considered and tested as other variables data in the SDM to replicate water turbined and stored volume (excluded to the modelling, further information reported in the Supplementary material). The baseline simulation period was constrained by the reservoir volume data availability over 14 years with a range 1999-2004 and 2009-2016, and a data gap from 2005 to 2008. For this reason, the SDM was forced with past observations of inflow to S.Giustina (with data available for the period 1981-2016) and with GeoTransf values for future simulations due to the limited temporal overlap of past GeoTransf values (over 1981-2010) with observations of the S.Giustina stored volume (1999-2004; 2009-2016, Table 1). The SDM was run at a daily time resolution to replicate the different outflow's regulations (e.g. minimum ecological flow and emergency outflows). Finally, simulations were aggregated to monthly values being a suitable time resolution for supporting reservoir volume management over long periods considering climate change effects (Solander et al., 2016).

Table 1 - Selected variables within the SDM (box 3 in Figure 2) for the S.Giustina reservoir.

Data type	Variable name	Time range	Source
Inflows to S.Giustina [m^3/s]	Inflows	1981-2016	

S.Giustina outflows for hydropower use [m³/s]	Outflow	1981-2016	Province of Trento – Agency for water resource and energy
S.Giustina volume [Mm³]	Volume	1999-2004 2009-2016	
Minimum ecological flow [m3/s]	MEF	1999-2016	
Emergency releases [m3/s]	Releases	1981-2016	

2.2 Variables' interaction analysis

This analysis aims to statistically describe the existence and type of interactions among the systems variables. For the simulations of turbined outflows different statistical models and variables interactions were tested and recursively implemented to simulate the stored water in S.Giustina applying the reservoir water balance equation.

195   2.2.1 Hydropower outflows

The simulation of turbined outflows from the S.Giustina reservoir for hydropower production considered regressions of different input variables (e.g. inflow, hydroelectric energy market price, temperature, precipitation and water outflows from an upstream dam reservoir) and statistical models, including linear regressions and more flexible generalized additive models. After an initial exploratory data analysis, the variables hydroelectric energy market price, temperature, precipitation and water

200   outflows from an upstream dam reservoir were rejected based on criteria of (i) data availability to the maximum target time period, (ii) correlations among the explanatory and response variables and (iii) the selection of the most parsimonious model. Further information on input variables, their tested combinations for model selection and link to the open code is reported in the Supplementary material.

The best regressions for each model type are reported in Table 2. The "lme4" package in R (Bates et al., 2015) was applied

205   for linear mixed effects models while the "mgcv" package in R (Wood, 2017; Wood and Scheipl, 2020) for the generalized additive models. Model #2 in Table 2 was selected as the best regression for its performance of 0.75 adjusted-R^2 and 16.57 Mm³ RMSE at monthly scale (daily scale of 0.42 adjusted-R^2 and 0.95 Mm³ RMSE). In particular, the linear mixed effect model showed its ability to account for weekday and monthly variations as important variable to capture weekly and seasonal reservoir management while showing lower proneness to overfit calibration data compared to flexible non-linear models. The

210   model simulated water diverted to the turbines (Q_{out}) as a function of water flowing into the reservoir (Q_{in}), the volume state in the previous day ($V(t-1)$, through the "lag" operator to shift the time series back by 1 time step), the day of the week and the month of the year. As fixed effect the water flowing into the reservoir and the volume in the previous day were here considered accounting for the linear relation with the water turbined. As a random effect to capture differences among different groups, day of the week and month of the year were selected to account for the recurrent water volume variations occurring

215   according to the day of the week group and months group (distinguished by vertical bars in linear mixed effect models). By

doing so, it was possible to describe the reservoir water volume combining the GeoTransf model outputs with statistical analysis aiming to explore the reservoir volume vulnerability to future changing conditions.

Table 2 - Best of each model type and their performance indicators (R2 and the root mean square error, RMSE) on monthly resolution and at daily resolution in brackets. The best selected model is reported in bold. The syntaxes follow that from the R packages "lme4" (for the linear mixed effects model), "mgcv" (for the generalized additive models) with the "bs" term set to "re" refer to the random-effect in the generalized additive mixed model; "s" is the function used in definition of smooth terms within the gam model formulae. Full list of tested models and their features is reported in the Supplementary material.

Model types	#	R syntax	Monthly resolution (daily)	
			Adjusted-R^2	RMSE ($\cdot 10^6$)
Multi-linear model	1.	lm(Outflow ~ Inflows + lag(Volume))	0.63 (0.35)	19.86 (1.03)
Linear mixed effect model	**2.**	**lmer(Outflow ~ Inflows + lag(Volume)+ (1|weekday) + (1|month))**	**0.75 (0.42)**	**16.57 (0.95)**
Generalized additive model	3.	gam(Outflow ~ s(Inflows) + s(lag(Volume)))	0.61 (0.50)	20.31 (1.07)
Generalized additive mixed model	4.	gam(Outflow ~ s(Inflows) + s(lag(Volume)) + s(weekday, bs="re")+s(month, bs="re"))	0.65 (0.54)	19.27 (1.02)

2.2.2 Reservoir volume

Simulated outflow values were used at each time step to replicate the volume stored through the water balance equation Eq. (1):

$$\frac{dV(t)}{dt} = Q_{in}(t) - Q_{out}(t) - Q_{mef}(t) - Q_{rels}(V) \tag{1}$$

where Q_{in} is the water flowing into the reservoir, Q_{out} the water diverted to the turbines, Q_{mef} the minimum ecological flow released and Q_{rels} the water outflow for emergency flood releases. In particular, Q_{mef} was set to 2.1 m3/s in case of simulations before 2004 while equal to 2.6 m3/s for January-March and December, 3.68 m3/s for April-July, October and November, 3.2 m3/s for August and September from 2009-2016 (http://pguap.provincia.tn.it/#). Moreover, the same values of minimum ecological flow were set in future simulations assuming no changes in minimum discharges for the ecological flow in the future. A simplified operational rule was implemented for emergency releases from flood gates considering the maximum daily emergency discharge value of 168.5 m3/s in case of daily stored volume greater than or equal to 159.3 Mm3.

2.3 Model calibration and validation

The statistical model for turbined water was calibrated and validated over 5061 days of available data for the baseline period, representing a total of 14 years from 1999 to 2004 and from 2009 to 2016. A forward time-window approach was applied as a cross-validation technique to better estimate model fitting (i.e. based on training data) and predictive performance

(i.e. based on temporally independent test data) using root mean square error (RMSE). The applied methodology is based on multiple separations of training and testing data sets. Within the first repetition, the predefined model setups (i.e. turbined outflows models) is calibrated using a subset of the original data that relates to the first 3650 days of available data. The derived relationships are then tested using both training data (i.e. fitting performance) and the data set that relates to the remaining (not yet) considered days (i.e. predictive performance). The following 1410 repetitions are based on the same procedure, but on increasingly larger training data sets (i.e. consecutively adding 1 day within the forward time-window approach). The mean value for RMSE was calculated considering all 1411 repetitions over the increasingly larger data set providing a more robust estimation of model performance and its variability using multiple temporally independent subsets of the original data (Hastie et al., 2009; Kohavi, 1995; Tashman, 2000; Varma and Simon, 2006). This methodology allows to overcome some limitations of common one-fold non-temporal validation methods (splitting of training and test data randomly; e.g. hold-out validation) associated with data temporal dependencies (i.e. autocorrelation) and an arbitrary choice of training and validation subsets. A major advantage of such multi-fold partitioning strategies is the possibility to exploit all the available data for the generation of the final prediction model.

2.4 Future projections and statistical testing

Future water inflow to the reservoir (coming from the GeoTransf application) were used to simulate future turbined outflow and volumes stored in the S.Giustina reservoir. GeoTransf simulations considered unchanged maximum water withdrawals in the Noce catchment in the future and although possible variations in the future may affect river water flows this set-up provided a conservative assumption accounting for future water demand increases, such as from domestic and agricultural needs, in future scenarios. Moreover, integrated downscaled COSMO-CLM climate scenarios were considered (Bellin et al., 2016; Bucchignani et al., 2016). Such climate projections have been demonstrated to well represent climate forcing variables (i.e. precipitation and temperature) over Alpine regions (Montesarchio et al., 2013).

The RCP4.5 and 8.5 scenarios were selected according to the IPCC AR5 (IPCC, 2014). Simulations stretched over two 30-year time horizons to represent short-term (2021-2050) and long-term (2041-2070) future climate conditions, affecting the Noce river flow, and the S.Giustina reservoir management.

Differences between the future and baseline simulated water turbined and volumes stored were statistically tested through the Wilcoxon Rank Sum test, a non-parametric test selected since it allows to deal with non-normally distributed, unpaired groups of data (Hollander and Wolfe, 1973). It was implemented to test whether future predicted values of stored volume were significantly different than the baseline and rejecting the null hypothesis (i.e. same tendencies among the tested groups) in case of a p-value ≤ 0.05.

2.5 Future critical conditions characterization

This study explored and analysed critical conditions of low and high future stored volume considering the 10th, 20th and 80th, 90th percentile thresholds calculated from water stored from the baseline (1999-2004, 2009-2016). Such thresholds

provided a symmetrical reference of extreme conditions and were already identified in previous studies as significant levels to assess critical states in hydrological studies (Yilmaz et al., 2008). Considering these thresholds, a set of different metrics were calculated to characterize frequency, duration and severity of future critical volume conditions (Table 3) based on existing metrics used to describe extreme events (Vogt et al., 2018). In particular, frequency was considered in relative terms as the ratio of the overall number of months below or above the selected threshold used to define the level of volume critical conditions over 14 years, hence describing yearly conditions of extreme events. Maximum duration was described considering the maximum number of consecutive months below or above the selected thresholds. The severity metric describes the accumulated deficit/surplus of simulated volume values with respect to the total volume stored over a 14-year window (relative severity). This last metric provides information on the fraction of the total stored volume in deficit or surplus as average annual severity.

Table 3 - Metrics implemented to characterize extreme events of low and high volume stored in the S.Giustina reservoir for RCP4.5 and 8.5 future projections, adapted from Vogt et al., 2018.

#	Metrics	Unit	Description
1	Relative frequency	Months/year	Number of months below or above the selected thresholds used to define the level of volume critical conditions over a 14-year period
2	Maximum duration	Months	Maximum number of consecutive months below or above the selected thresholds used to define the level of volume critical conditions
3	Relative severity	%	Computed as the sum of the differences, in absolute values, between simulated volume values and the selected thresholds over the total stored volume and 14-year period. $S_i = \dfrac{\sum |V_i| < \text{Threshold}}{\sum V_i \cdot 14}$

Moreover, a Monte Carlo approach was implemented to account for the uncertainty related to the simulations in future conditions. The water balance equation considered the lower and upper turbined outflow from the prediction bands to generate a range of simulated volume values. A set of 1000 replications of 30 years-length per each future climate scenario were generated by randomly sampling from the simulated volume values and their prediction bands. In addition, for each replication a subset was iteratively extracted considering a time-window of 14 years moving progressively at a monthly time step along the simulated 30 years of future volume. Extreme conditions metrics of relative frequency, maximum duration and relative severity were calculated on the subset at each iteration. This procedure allowed to compare the calculated metrics of each subset replication with the 14 years of available data for the baseline volume (1999-2004, 2009-2016). By doing so, it was possible to account for the uncertainty related to the modelling and providing a wider range of low and high future volume values for a more robust characterization of their conditions.

3 Results

3.1 Baseline period

The linear mixed-effect model was used to replicate observations of turbined water outflows from the S.Giustina reservoir (Figure 3). The model was run at a daily time step and values aggregated and reported at monthly resolution. The model gave an R^2 = 0.75, and mean RMSE of 16.57 Mm^3. Figure 3 shows the modelled and real values, with y-scale ranging from 0% (i.e. no turbined water) to 100% (i.e. maximum turbined water of 176 Mm^3·month^{-1} for 31 days of full turbine operations). Coloured bands outline areas above or below the percentile values defining critical thresholds that were considered throughout the analysis.
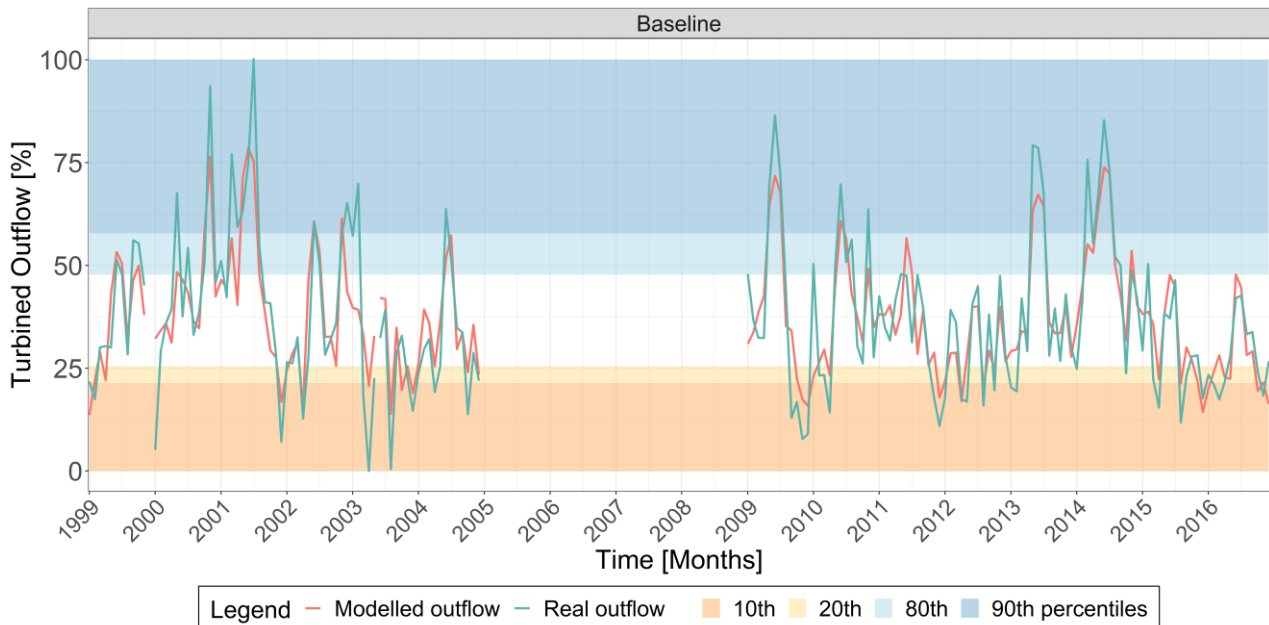
Figure 3 - S.Giustina water diverted to the turbines from 1999 to 2016. Modelled values (red line) and real (green line). Adjusted-R2= 0.75, mean RMSE= 16.57 Mm3. Coloured bands outline areas of values lower than the 10th, 20th and greater than the 80th and 90th percentiles.

The modelled turbined water was then used in the iterative implementation of the water balance equation together with the operational rules for the minimum ecological flow and the emergency releases. Figure 4 shows the modelled and real volume ranging from 0 to 100% of stored volume (equal to 159.3 Mm^3, maximum volume allowed for flood prevention), where the simulation of the stored volume resulted in a R^2 = 0.60, and mean RMSE of 19.74 Mm^3·month^{-1}. In Figure 3 and 4 the general behaviours of real turbined outflows and stored water were replicated by the regression models. Some specific very high and low conditions were not completely represented or missed due to abrupt changes in the reservoir management, such as the 2001 summer peak of turbined outflows in Figure 3, due to persistent inflows to S.Giustina forcing dam managers to turbine

at the maximum outflow for 23 days consecutively, as well as the low values in spring 2003 in Figure 4, when the S.Giustina reservoir was emptied due to construction works on a penstock.
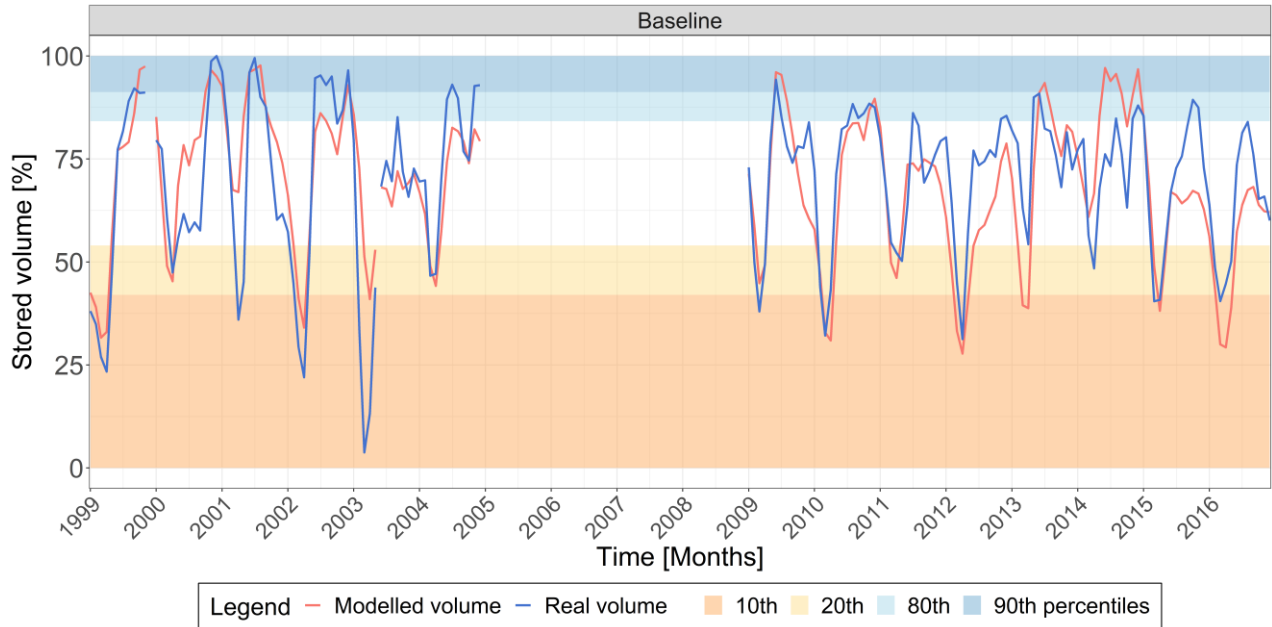
Figure 4 - S.Giustina stored volume values from 1999 to 2016, modelled values (red line) and real (blue line). Adjusted-R^2= 0.60, RMSE= 19.74 Mm3. Coloured bands outline areas of values lower than the 10th, 20th and greater than the 80th and 90th percentiles.

3.2 Future projections and statistical testing

Future GeoTransf model results forced by the COSMO-CLM climate projections depict a situation of general decreases in precipitation and water inflowing to the reservoir (Table 4 and Figure 5). In particular, changes in RCP4.5 are rather similar for short- and long-terms, whereas changes are larger in the long-term for RCP8.5 compared to short-term. These results are consistent with the precipitation trends from COSMO-CLM projections with RCP8.5 showing higher values of total precipitation in the short-term but a higher decrease on the long-term compared to RCP4.5 (Bucchignani et al., 2016). In RCP8.5, inflow, outflow and volume reductions are lower for the short-term future compared to the baseline (-7.8, -11.5, -10.2%) and are associated with the only case of precipitation increase (+1.4%) pointing to the increase of evapotranspiration due to the relatively larger increase in temperature (+29.4%). In the long-term, results show the greatest increase of temperature (+58.8%), reduction of precipitation (-4.3%) as well as for inflow, outflow and volume (-21.3, -26.2, -20.8 %).

Table 4 - Average values of temperature and precipitation (COSMO-CLM projections), water inflow to the S.Giustina reservoir, turbined outflow, stored volume (simulations) and their percentage differences compared to baseline values. †Baseline period for climate data goes from 1971 to 2005, while for water inflow and volume stored spans over 14 years of 1999-2004 and 2009-2016.

	Baseline	RCP4.5				RCP8.5			
	†	2021-2050		2041-2070		2021-2050		2041-2070	
Variable	Value	Value	Δ [%]	Value	Δ [%]	Value	Δ [%]	Value	Δ [%]

Temperature [°C]	5.1	6.5	+27.5	7.5	+47.1	6.6	+29.4	8.1	+58.8
Precipitation [mm/year]	1495.1	1433.6	-4.1	1391.5	-6.9	1516.3	+1.4	1430.7	-4.3
Inflow [Mm3/month]	71.5	57.4	-19.7	58.3	-18.5	65.9	-7.8	56.3	-21.3
Turbined outflow [Mm3/month]	64.1	48.2	-24.8	48.7	-24	56.7	-11.5	47.3	-26.2
Stored volume [Mm3]	109.6	87.8	-19.9	88.2	-19.5	98.4	-10.2	86.8	-20.8

A summary overview of future conditions for inflow, turbined water and stored volume is reported in Figure 5. For all variables, four coloured bands representing areas lower than the 10th, 20th and greater than the 80th and 90th percentile are reported as reference allowing to compare the 30-year time slices. Values show a generalized decrease into the 20th and 10th percentile thresholds of the long-term RCP8.5 scenario. This trend is clearly visible for future water inflow, while values larger than boxplots whiskers can be identified in all inflow scenarios and hence pointing to single future conditions greater than baseline maximum recorded values (Figure 5 A). Future turbined outflows show boxplot values with the lowest interquartile range expected to reach 10th percentile conditions. Consistently with the results from Table 4, volume values show significant reductions already for RCP4.5 with interquartile levels below with the 20th calculated from baseline (i.e. 1999-2004 & 2009-2016). These results were further investigated through the application of the Wilcoxon Rank Sum Test (Table 5), which provide more quantitative insights on the statistical significance of changes considering the whole 30-yeas of data for the baseline and the four scenarios (Figure 5) as well as considering monthly averaged values (Figure 6 and Figure 7). While p-values considering the whole time series are below the 0.05 threshold of significance, monthly averages for short-term RCP8.5 scenario (2021-2050) provided non-significant results both for stored volume and turbined outflow.

Table 5 – Summary of the Wilcoxon Rank Sum Test application to stored volume and turbined outflow for the 4 scenarios compared to the baseline (1999-2004, 2009-2016). P-values are reported for the test considering the whole time series of future and baseline values and on paired monthly averages. Symbol '*', '', '***', '****' refer to significant p-value ≤ 0.05, ≤ 0.01, ≤ 0.001 and ≤ 0.0001.**

		On the whole time series	On monthly averages
Compared scenarios	**Variable**	**P-value**	**P-value**
RCP4.5 2021-2050 vs Baseline	Stored volume	2.203e-15****	0.016*
	Turbined outflow	3.737e-12****	4.883e-4***
RCP4.5 2041-2070 vs Baseline	Stored volume	2.275e-16****	0.034*
	Turbined outflow	8.676e-12****	0.009**
RCP8.5 2021-2050 vs Baseline	Stored volume	1.120e-06****	0.092
	Turbined outflow	0.003**	0.095
RCP8.5 2041-2070 vs Baseline	Stored volume	5.006e-18****	0.012*
	Turbined outflow	1.381e-13****	0.007**

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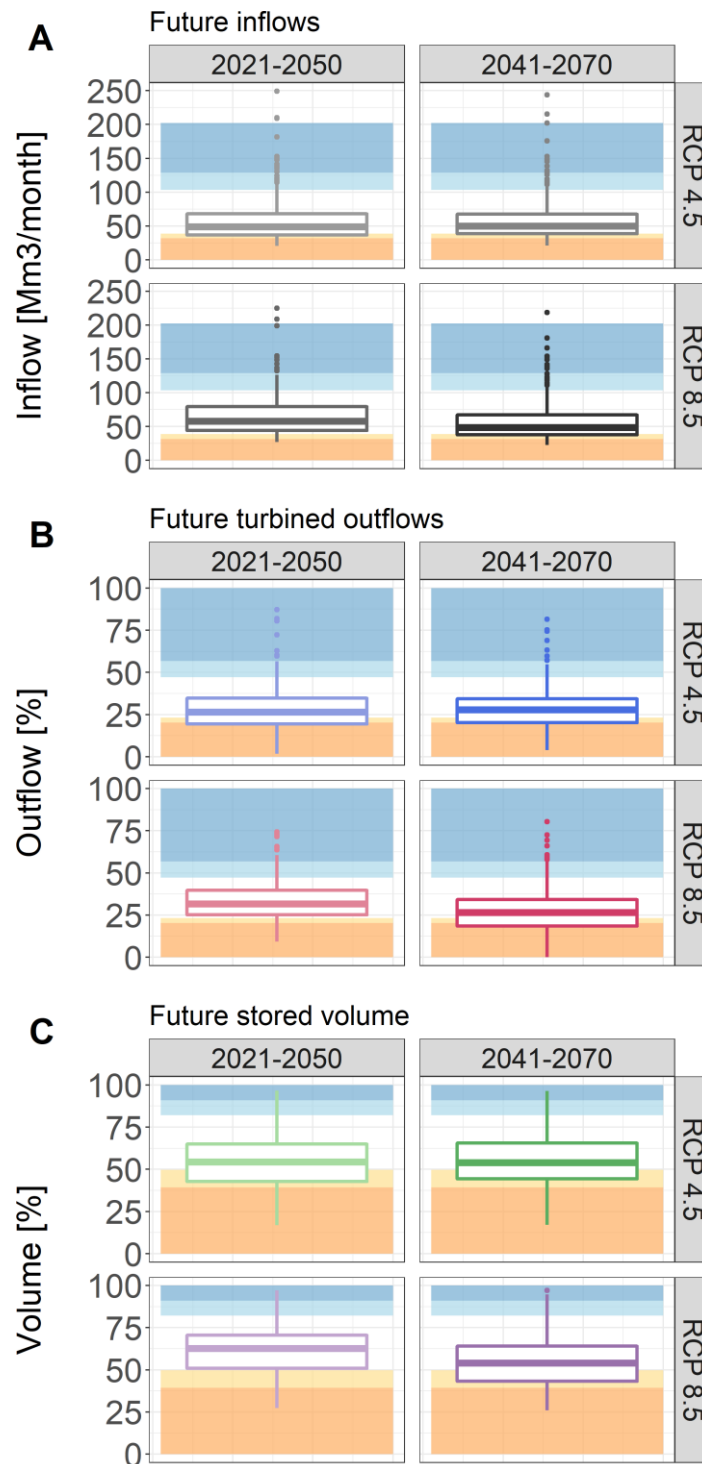
Figure 5 - 30-years slice boxplots for future projections of: A simulated water inflow to the S.Giustina reservoir, B simulated water turbined and C simulated future water volume stored in the S.Giustina reservoir. Coloured bands outline areas of baseline values lower than the 10th, 20th and greater than the 80th and 90th percentiles using the same colours as in Figure 4.

Results of future turbined outflows are reported in Figure 6 with values averaged for each month over the 30-year
350   simulation and compared to the baseline (i.e. percentage change). Negative reductions of outflows for all scenarios are reported
for spring and summer, starting in April and until September with differences up to -56.3% in August for the RCP4.5 long-
term scenario. All climate scenarios agree on a water flow reduction during November reaching a minimum of -33.5% of
turbined outflow for RCP8.5 long-term scenario. In all other months, scenarios depict varying conditions of water flow. In
particular, short-term RCP4.5 depicts conditions of negative differences for every month of the year. Increased number of
355   positive differences are predicted for long-term RCP4.5 during January (+5%) and December (+5.3%). Short-term RCP8.5
shows larger positive differences during January (+10.3%), February (+1.8%), March (+2.9%), October (+0.8%) and
December (+6.5%). Long-term RCP8.5 projects a negative trend from April until the end of the year reaching persistent
negative conditions in summer down to -55.5% in August, overlapping with the summer electricity peak loads and calling for
particular attention (Terna, 2019). Nevertheless, small but positive values are expected for January (+0.7%), February (+1.4%)
360   and March (+3.7%), when the winter electricity peak load usually occurs (Terna, 2019).
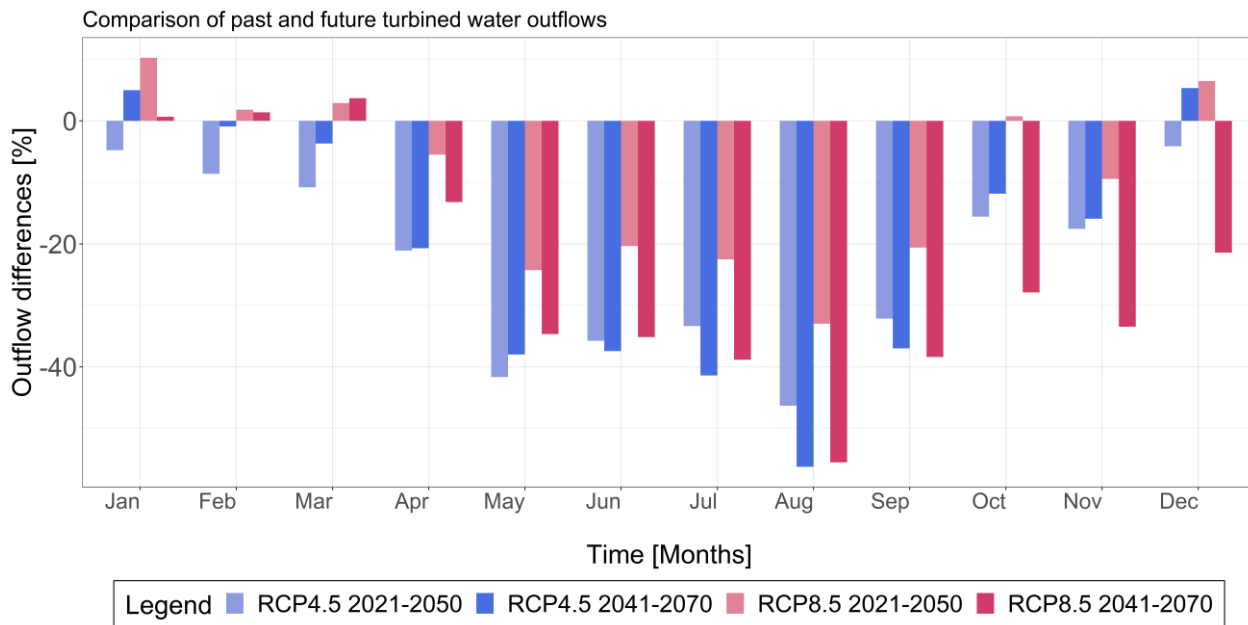
Figure 6 - Percentage change of turbined water outflows [%] comparing the 4 climate scenarios to the baseline at monthly level

Comparative results with the baseline for monthly average over the 30-year simulation are reported for the stored volume
in Figure 7. All climate scenarios agree on the general volume decrease from May until the end of the year. Short- and long-
365   term RCP4.5 depicts conditions of minimum peaks in May (-43.8 and -40.6%) and June (-44.1 and -41.9%), while long-term
RCP8.5 shows less negative minimum values although persistent negative values in November and December lower than the
other scenarios (-26.8 and -19%). Scenarios agree on the positive variation during February and March with a maximum
increase of +32.5% for the RCP8.5 short-term case. However, scenarios disagree in terms of stored volume for January, with
RCP4.5 scenarios representing a positive variation both in the short- and long-term cases (+1.4 and +2.2%), while the RCP8.5

370 short-term case depicts a positive variation (+7.3%) but a negative one for the long-term (-7.1%). Conditions in April are reversed with RCP4.5 short-term depicting a decrease (-8.3%) and RCP8.5 increases for short- and long-term cases (+5.5% and +3.5%).
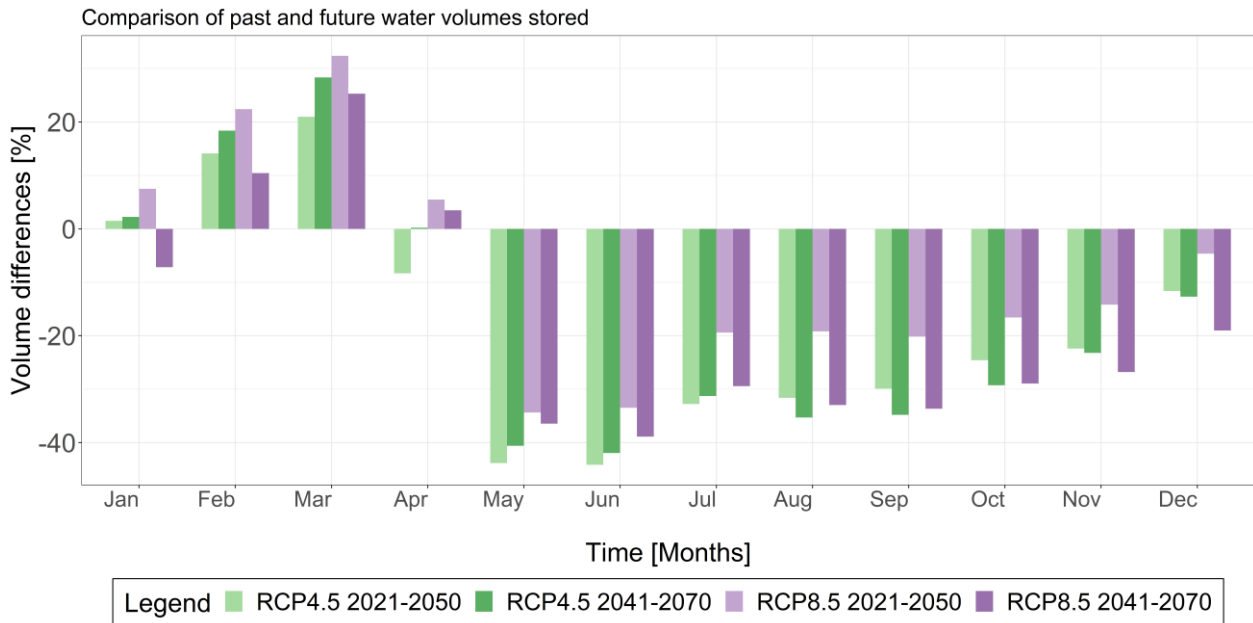
Figure 7 - Percentage change of volume [%] comparing the 4 climate scenarios to the baseline at monthly level

375 Months of positive variation and scenarios disagreement provide important information on the timing of potential reservoir management adaptation, while the small volume increases are insufficient to counterbalance persistent volume reductions. Short-term RCP8.5 shows the most favourable conditions of water volumes, depicting positive differences in January (+7.3%), February (+22.5%), March (+32.5%) and April (+5.5%).

3.3 Future critical conditions characterization

380 Critical conditions of stored reservoir water volumes (both high and low) were explored to further understand how climate change may impact on long-term reservoir's vulnerability. A set of different metrics were calculated to characterize frequency, duration and severity of future critical volume conditions considering values lower than the 10th, 20th and higher than the 80th and 90th percentiles of stored volume (Figure 8 and Figure 9). The metrics were calculated from 1000 replications per scenario randomly sampled from the simulated future volume values and their prediction bands. Reductions showed to have similar
385 trends across the metrics between the 10th and 20th as well as between the 80th and 90th percentiles with the 4 future scenarios having statistically significant differences compared to the baseline.

Boxplots for low volume conditions (Figure 8) show increasing average values for all metrics and scenarios compared to the baseline: conditions of low volume are expected to become more frequent, having a longer maximum duration and larger severity. In particular, for both values lower than the 10th and 20th percentile, short-term RCP4.5 shows the highest average

390 increase. Relative frequency and relative severity are expected to have an higher increase for average values below the 10th percentile (+157% for frequency, from 1.64 to 4.21 months/year and +250% for severity, from 0.2 to 0.7%) compared to values below the 20th percentile (+105% for frequency, from 2.86 to 5.86 and +300% for severity, from 0.3 to 1.2%), while maximum duration is expected to have an higher increase for values below 20th percentile (+100%, from 5 to 10 months) compared to values below the 10th percentile (+75%, from 4 to 7 months). These results point to events of low volume conditions below

395 the 10th percentile to be more frequent and with higher severity, while low volume events below the 20th percentile to last for longer time in the case of the most extreme events. RCP8.5 in the short-term depicts less negative conditions for both thresholds in line with results in Figure 6. For values below the 10th percentile: +40% in relative frequency (from 1.64 to 2.29 months/year), +0% in maximum duration (4 months) and +50% in relative severity (from 2 to 3%). For values below the 20th percentile: +38% in relative frequency (from 2.86 to 3.93 months/year), +20% in maximum duration (from 5 to 6 months) and

400 +67% in relative severity (from 0.3 to 0.5%).
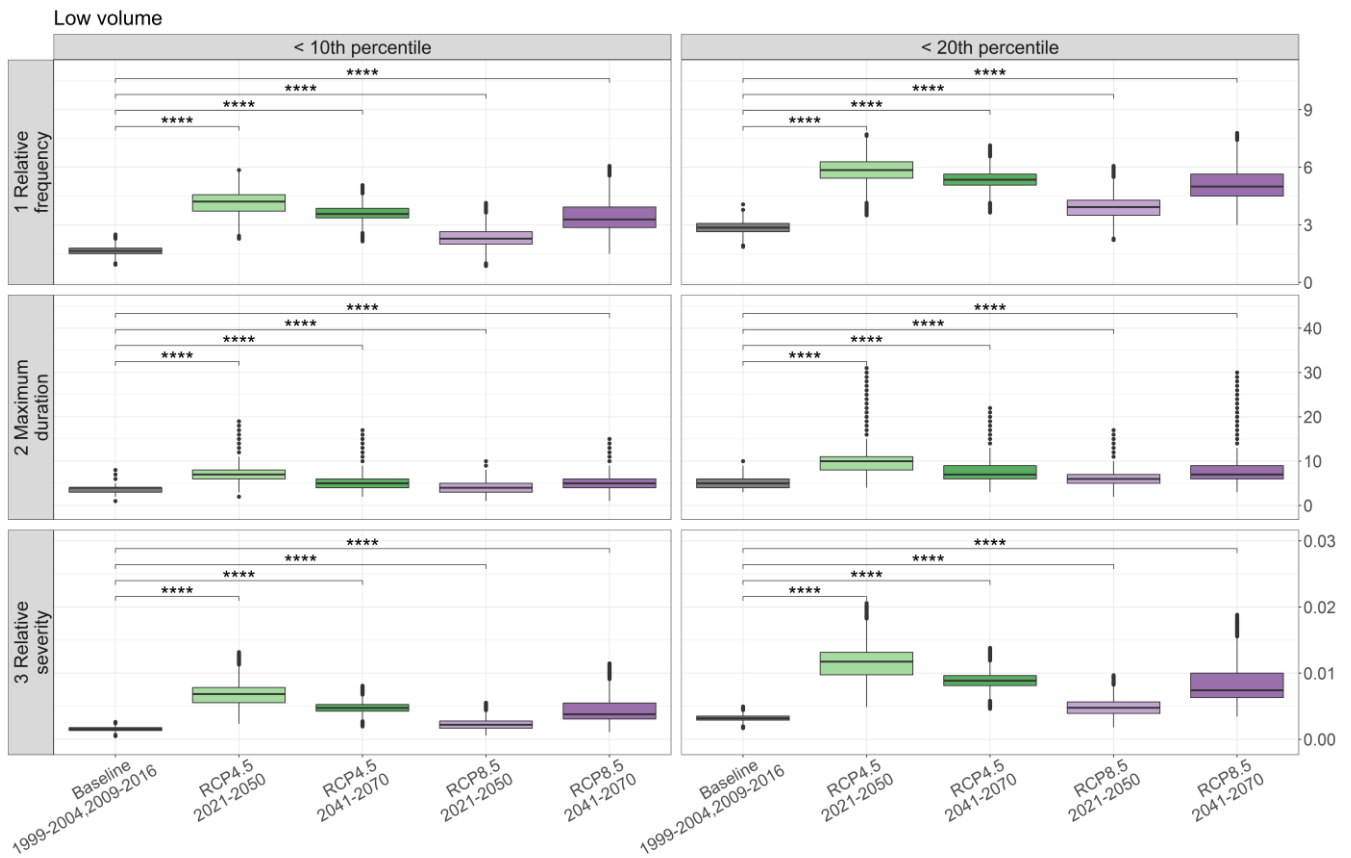
Figure 8 – Boxplots of relative frequency, maximum duration and relative severity metrics calculated from volume values lower than the 10th and 20th percentiles. The simulated volume values used for the metrics calculation resulted from the Monte Carlo approach by randomly sampling from the volume prediction bands. Symbol '**' refers to p-value ≤0.0001.**

405   For values lower than the 20th percentile, a larger number of values outside the boxplots whiskers are depicted for all scenarios and especially towards higher number of months for relative frequency as well as maximum duration and relative severity, hence pointing to potential single conditions of lower volume stored in the future with respect to the represented median. These results point to the possibility of the most extreme water scarcity conditions lasting longer than one hydrological year and pointing at chronic consequences of low stored volume, especially considering short-term RCP4.5 (maximum values

410   of 19 months and 31 months for values below the 10th and 20th percentile) and long-term RCP8.5 (maximum values of 15 and 30 months for values below the 10th and 20th percentile) where the outliers highest values are expected.

     Boxplots for high volume conditions (Figure 9) also show a generalized decrease in all metrics of high stored volume for all scenarios and for both thresholds. Long-term RCP4.5 and RCP8.5 scenarios depict conditions of higher percentage reductions for relative frequency (-75% for both scenarios) and maximum duration (-60% for both scenarios) above the 90th

415   percentile compared to the 80th percentile (-68% in relative frequency and -50% in maximum duration for both scenarios). On the contrary, relative severity reductions are expected to be higher for RCP8.5 for values above the 80th percentile (-97%) compared to the 90th percentile (-80%). Above the 90th percentile, values are expected to be less frequent than baseline conditions, while showing smaller severity reductions compared to values above the 80th percentile. Short-term RCP8.5 predicts a smaller decrease in all metrics in comparison with the other scenarios with -48% of relative frequency (from 3.14 to

420   1.64 months/year), -50% of maximum duration (from 6 to 3 months) and -75% in relative severity (from 0.4 to 0.1%) for values above the 80th percentile compared to the baseline, as well as -56% of relative frequency (from 2.29 to 1 months/year), -60% of maximum duration (from 5 to 2 months) and -68% of relative severity (from 0.3 to 0.08%) for values above the 90th percentile compared to the baseline. A summary table with median, maximum, minimum and standard deviation values for low and high volume conditions is provided in the Supplementary material.
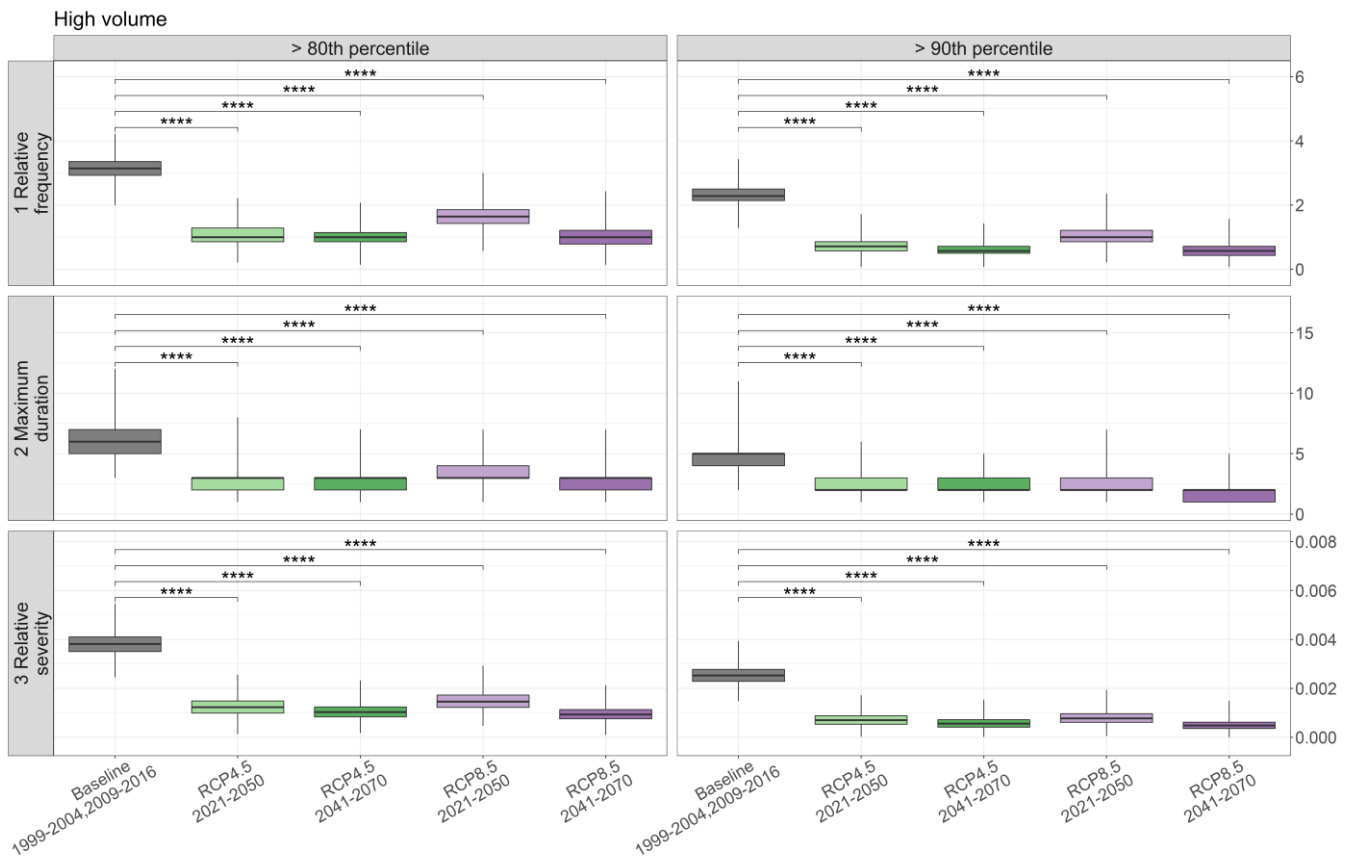
Figure 9 - Boxplots of relative frequency, maximum duration and relative severity metrics calculated from volume values greater than the 80th and 90th percentiles. The simulated volume values used for the metrics calculation resulted from the Monte Carlo approach by randomly sampling from the volume prediction bands. Symbol '**' refers to p-value ≤0.0001.**

4 Discussion

The analysis considered the water flowing into the S.Giustina reservoir, and modelled using the GeoTransf hydrological model, as a key variable influencing the turbined water and hence the stored volume. A stochastic approach considered the simulated turbined outflows and its predictions bands as the main source of uncertainty to explore a wide range of possible outcomes in terms of turbined outflow and stored volume values.

Results show how the amount of water flowing into the reservoir is deeply affecting both turbined outflows and hence the stored water, which are expected to reduce in the future even under the short-term RCP4.5 scenario (-25.9%). In the case of long-term scenarios high reductions are also expected (-24% for RCP4.5 and -26.3% for RCP8.5).

Moreover, results on monthly averages provide useful information on the timing of possible consequences coming from reservoir operations and climate change effects. Considering those months of positive variation of volume (i.e. January, February, March and April, depending on the considered scenario) and turbined water outflows (i.e. December, January,

440 February and March, depending on the considered scenario) provides insights on the need to plan adaptation and operational strategies to improve the management of the S.Giustina reservoir. Months of positive water volume changes need to be considered as periods of preparation to worsening conditions. Strategies of earlier water accumulation should be considered to face the persistent reductions throughout the last part of spring, summer, autumn and part of winter. Such a strategy could prevent downstream conditions of water shortages, while also preparing for reductions in turbined water for hydropower uses,

445 especially during summer and winter months of high electricity peak loads. These results are in line with other findings in the Alps showing the need for earlier reservoir water accumulation during winter to prevent downstream conditions of water shortages during summer (Brunner et al., 2019; Hendrickx and Sauquet, 2013). Although positive percentage variations are expected to be lower and for fewer months than negative cases, earlier water accumulation strategies potentially reducing water scarcity conditions need to acknowledge and avoid flood events exacerbation. Additional storage for flood prevention

450 needs to be ensured and managed together with the Civil protection department to prevent potential downstream floods. Negative stored volume variations are supported by the generalized trends of future water scarcity conditions characterized by an increase in frequency, maximum duration and severity of low stored volumes for values lower than the 10th and 20th percentiles and for both RCP4.5 and 8.5. These results point at higher percentage increases in frequency and severity for values below the 10th percentile, while volume values below the 20th percentile are expected to last longer in case of the most extreme

455 events. At the same time, high volume conditions decrease in terms of frequency, duration and severity with higher reductions for volume above the 90th percentile compared to the percentage decrease for events above the 80th percentile. Only in case of relative severity, reductions are expected to be higher for values above the 80th percentile compared to those above the 90th percentile for long-term RCP4.5 and 8.5 scenarios. Above the 90th percentile, values are expected to be less frequent than in baseline conditions, while showing smaller severity reductions compared to values above the 80th percentile. Within this

460 context, the calculation of a set of metrics in terms of low and high volume conditions through a Monte Carlo approach considering a moving window of data (Figure 8 and Figure 9 allowed to generate a set of possible future volume time series derived from the simulation prediction bands. By doing so, the analysis prevented any potential bias associated with limited data and provided statistically tested information on increases of low volume and reductions of high volume values showed as boxplots for S.Giustina over four 30-years climate scenarios.

465 In general, the results suggest exacerbated risks to reservoir operation due to persistent stored volume and turbined outflow reductions in late spring and summer, autumn, and early winter that can potentially lead to chronic consequences lasting more than one hydrological year and hence threatening water supply security, hydropower production, and ecosystem services in the valley.

4.1 Limitations of the study

470 The applied SDM is mainly considering outputs from the GeoTransf applications integrating the COSMO-CLM climate projections. However, several assumptions and limitation in this study are noted.

Accounting for the GeoTransf application means relying on a very accurate water streamflow within the catchment (Bellin et al., 2016), but also considering the COSMO-CLM climate model for future projections. A wider range of inflow values driven by a set of climate models could provide a larger set of results that can be used for further stochastic analysis of turbined water and stored volume. Nevertheless, the climate model has been demonstrated to well represent conditions in mountain regions (Montesarchio et al., 2013) and differently from other climate models depicts general conditions of decreased precipitation over the catchment (Table 4). Hence it provides conservative information on possible impacts on streamflow and volume management. The results from the GeoTransf application assumed a conservative condition of upstream water use set at the maximum licensed withdrawals values. This information was kept unchanged for future scenarios, although possible variations in the future (e.g. from agricultural and touristic uses) may affect river water flows.

Moreover, the presented study considered precipitation, water flow and volume trends over a 30-year period considering their monthly average values, important for long-term large reservoir management. For this reason, conditions of high volume with a very short duration might have been potentially underrepresented.

The statistical models are an effective tool to replicate past observations of water volume and turbined water outflows. Applying such a regression to future conditions of predictors, reservoir management in terms of turbined outflow as well as minimum ecological flows was assumed to be stationary over time. Nevertheless, such a constraint is justified by the high uncertainty associated to future changes in hydropower production patterns affected by societal conditions (e.g. energy price fluctuations; Gaudard et al., 2014; Ranzani et al., 2018). Moreover, the minimum ecological flow was always set to the values established by law, although critical conditions in water availability (e.g. streamflow) may lead to extraordinary changes in minimum flow which can affect the stored volume as well as the turbined outflow.

Finally, the selected models considered few tested and selected variables. Although other variables play important roles within the management of the reservoir at different temporal resolution (e.g. hourly energy market price), the simulation on monthly aggregated values supported the objective of analysing long-term variations of stored volume for the large S.Giustina reservoir.

5 Conclusions

The SDM well represents the overall behaviour of the system in terms of turbined outflow (water demand) and future conditions of reduced water availability over a 30-year period. Changes in water availability can deeply affect the actual turbined water, which plays a strategic role in the economy of the province, as in the whole Alpine region. Moreover, reduction in the water streamflow can have consequences in terms of ecological hazards and water supply quality downstream of the reservoir. The S.Giustina reservoir plays a crucial role in buffering water variations in the Noce catchment and downstream. Due to its size, type and position it is strategic for hydropower regulation and hydrologically disconnecting upstream with downstream river flow.

The modelling chain from climate change projections to the hydrological model water flow output and their use into the stochastic SDM provided to be a quick and effective tool to explore trends conditions of the S.Giustina reservoir volume and turbined outflows.

Results of both stored volume and turbined outflow suggest that even under RCP4.5 in the short-term scenario reductions in terms of volume and turbined outflow will be severe with monthly average reductions for outflow and volume values respectively from April and May onwards and persisting throughout the year. This period of negative variations should be considered for the adoption of adaptation strategies focusing on water demand reduction, while considering months of expected increases in water availability as preparation periods, implementing strategies of earlier reservoir water accumulation while preparing for persistent conditions of lower availability compared to the baseline period. Such a strategy could prevent downstream conditions of water shortages during summer, autumn and part of winter, while also preparing for reductions in turbined water for hydropower especially during summer and winter months of high electricity peak loads. Adaptation strategies should consider the results on generalized future conditions with increase in frequency of months, maximum number of consecutive months and relative severity for all scenarios of low volume below 10th and 20th percentiles. Consistently with these projections, frequency, duration and severity metrics for high volume events below 80th and 90th percentiles are expected to decrease. These results call for adaptation strategies of coordinated actions across those socio-economic sectors relying on abundant water demands (e.g. for agriculture) to face more frequent and longer periods of higher reduction of stored volume compared to the past.

Future model expansions will include water demand from multiple human activities (e.g. agriculture and domestic) and their effects on water availability reduction from upstream to downstream. By doing so, SDM models can support the understanding of criticalities connected to unsustainable water demands and anticipate critical conditions, to inform dam managers and local authorities on the timing and importance of climate change adaptation strategies. Moreover, the use of open codes and libraries for the assessment of variables interactions through statistical models make SDM transferrable to other cases at interregional / transnational scale in combination with available water flows datasets and open hydrological models (e.g. Copernicus, LISFLOOD model).

Finally, this analysis sheds light on the need to consider future changes in water availability and their consequences on already existing human activities relying on abundance water resources, and hence unprepared to quickly adapt to future climate impacts. Results should be considered in future plans to change S.Giustina management practices to reduce climate change impacts on reservoir operations. The findings presented reinforce the Alpine 'water tower' region's vulnerability to supply water and ensure its use for power production. This is the first step for more comprehensive water scarcity assessments in order to provide policy-makers with information in line with the European Water Framework Directive on potential adaptation strategies to gain systemic leverage effects on sustainable water management and climate change adaptation in the Alps (Alpine convention, 2013; European Commission, 2018, 2021).

Code availability

The source code for data processing and analysis developed in this study is freely available at https://github.com/Sterzi/SGiustina_future_SDM.

Author contribution

Stefano Terzi: conceptualization, data curation, formal analysis, methodology, software, validation, visualization, writing – original draft preparation. **Janez Susnik**: conceptualization, formal analysis, methodology, writing – review & editing; **Stefan Schneiderbauer**: visualization, supervision, writing – review & editing; **Silvia Torresan**: visualization, supervision, writing – review & editing, **Andrea Critto**: supervision, writing – review & editing.

Competing interests

The authors declare that they have no conflict of interest.

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References

Alpine convention: Guidelines for Climate Change Adaptation at the local level in the Alps, , 44, 2013.

Di Baldassarre, G., Wanders, N., AghaKouchak, A., Kuil, L., Rangecroft, S., Veldkamp, T. I. E., Garcia, M., van Oel, P. R., Breinl, K. and Van Loon, A. .: Water shortages worsened by reservoir effects, Nat. Sustain., 1(November), 617–622, doi:10.1038/s41893-018-0159-0, 2018.

Barnett, T. P., Adam, J. C. and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438(7066), 303–309, doi:10.1038/nature04141, 2005.

Bates, D., Mächler, M., Bolker, B. M. and Walker, S. C.: Fitting linear mixed-effects models using lme4, J. Stat. Softw., 67(1), doi:10.18637/jss.v067.i01, 2015.

Bellin, A., Majone, B., Cainelli, O., Alberici, D. and Villa, F.: A continuous coupled hydrological and water resources

management model, Environ. Model. Softw., 75, 176–192, doi:10.1016/j.envsoft.2015.10.013, 2016.

Beniston, M. and Stoffel, M.: Assessing the impacts of climatic change on mountain water resources, Sci. Total Environ., 493, 1129–1137, doi:10.1016/j.scitotenv.2013.11.122, 2014.

Brunner, M. I., Björnsen Gurung, A., Zappa, M., Zekollari, H., Farinotti, D. and Stähli, M.: Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes, Sci. Total Environ., 666, 1033–1047, doi:10.1016/j.scitotenv.2019.02.169, 2019.

Bucchignani, E., Montesarchio, M., Zollo, A. L. and Mercogliano, P.: High-resolution climate simulations with COSMO-CLM over Italy: Performance evaluation and climate projections for the 21st century, Int. J. Climatol., 36(2), 735–756, doi:10.1002/joc.4379, 2016.

Chiogna, G., Skrobanek, P., Narany, T. S., Ludwig, R. and Stumpp, C.: Effects of the 2017 drought on isotopic and geochemical gradients in the Adige catchment, Italy, Sci. Total Environ., 645, 924–936, doi:10.1016/j.scitotenv.2018.07.176, 2018.

Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M. and Jones, P. D.: An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets, J. Geophys. Res. Atmos., 123(17), 9391–9409, doi:10.1029/2017JD028200, 2018.

Davies, E. and Simonovic, S. P.: Global water resources modeling with an integrated model of the social-economic-environmental system, Adv. Water Resour., 34(6), 684–700, doi:10.1016/j.advwatres.2011.02.010, 2011.

Davies, E. G. R. and Simonovic, S. P.: An Integrated System Dynamics Model for Analyzing Behaviour of the Social-Economic-Climatic System: Model Description and Model Use Guide, Department of Civil and Environmental Engineering, The University of Western Ontari., 2008.

Duggan, J.: System Dynamics Modeling with R, Springer International Publishing, Switzerland., 2016.

Duran-Encalada, J. A., Paucar-Caceres, A., Bandala, E. R. and Wright, G. H.: The impact of global climate change on water quantity and quality: A system dynamics approach to the US-Mexican transborder region, Eur. J. Oper. Res., 256(2), 567–581, doi:10.1016/j.ejor.2016.06.016, 2017.

Etter, S., Addor, N., Huss, M. and Finger, D.: Climate change impacts on future snow, ice and rain runoff in a Swiss mountain catchment using multi-dataset calibration, J. Hydrol. Reg. Stud., 13(February), 222–239, doi:10.1016/j.ejrh.2017.08.005, 2017.

European Commission: Commission Staff working document Evaluation of the EU Strategy on adaptation to climate change Accompanying- Accompanying the document Report from the Commission to the European Parliament and the Council on the implementation of the EU Strategy on adapt, SWD(2018) 460 Final, 1–65, 2018.

European Commission: Forging a climate-resilient Europe - the new EU Strategy on Adaptation to Climate Change., 2021.

European Parliament & Council: DIRECTIVE 2000/60/EC, Anal. Proc., 21(6), 196, doi:10.1039/AP9842100196, 2000.

Farinotti, D., Usselmann, S., Huss, M., Bauder, A. and Funk, M.: Runoff evolution in the Swiss Alps: Projections for selected high-alpine catchments based on ENSEMBLES scenarios, Hydrol. Process., 26(13), 1909–1924, doi:10.1002/hyp.8276, 2012.

Ford, A.: Statistical Screening Analysis of System Dynamics Models, Island Press, USA., 2005.

Ford, A.: Modelling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems (2nd Edition)., Isl. Press, 400, 2010.

Forests, R.: Random Forests 15.1, Elements, 27(2), 587–604, doi:10.1007/b94608, 2001.

Forrester, J. W.: World dynamics, Wright-Allen Press., 1971.

Fuhrer, J., Smith, P. and Gobiet, A.: Implications of climate change scenarios for agriculture in alpine regions - A case study in the Swiss Rhone catchment, Sci. Total Environ., 493, 1232–1241, doi:10.1016/j.scitotenv.2013.06.038, 2014.

Gaudard, L., Romerio, F., Dalla Valle, F., Gorret, R., Maran, S., Ravazzani, G., Stoffel, M. and Volonterio, M.: Climate change impacts on hydropower in the Swiss and Italian Alps, Sci. Total Environ., 493, 1211–1221, doi:10.1016/j.scitotenv.2013.10.012, 2014.

Gohari, A., Mirchi, A. and Madani, K. D. E. of C. C. A. S. for W. R. M. in C. I.: System Dynamics Evaluation of Climate Change Adaptation Strategies for Water Resources Management in Central Iran, Water Resour. Manag., 31(5), 1413–1434, doi:10.1007/s11269-017-1575-z, 2017.

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., Kyselý, J. and Kumar, R.: Revisiting the recent European droughts from a long-term perspective, Sci. Rep., 8(1), 1–11, doi:10.1038/s41598-018-27464-4, 2018.

Hastie, T., Tibshirani, R. and Friedman, J.: The Elements of Statistical Learning, Springer., 2009.

Hendrickx, F. and Sauquet, E.: Impact du changement climatique sur la gestion de l'eau dans le bassin de l'Ariége, Hydrol. Sci. J., 58(5), 976–993, doi:10.1080/02626667.2013.788790, 2013.

van den Heuvel, L., Blicharska, M., Masia, S., Sušnik, J. and Teutschbein, C.: Ecosystem services in the Swedish water-energy-food-land-climate nexus: Anthropogenic pressures and physical interactions, Ecosyst. Serv., 44(August 2019), doi:10.1016/j.ecoser.2020.101141, 2020.

Hollander, M. and Wolfe, D. A.: Nonparametric statistical methods, Wiley, New York., 1973.

Huss, M. and Hock, R.: Global-scale hydrological response to future glacier mass loss, Nat. Clim. Chang., 8(2), 135–140, doi:10.1038/s41558-017-0049-x, 2018.

IPCC: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change., 2014.

IPCC: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, 2018.

La Jeunesse, I., Cirelli, C., Aubin, D., Larrue, C., Sellami, H., Afifi, S., Bellin, A., Benabdallah, S., Bird, D. N., Deidda, R., Dettori, M., Engin, G., Herrmann, F., Ludwig, R., Mabrouk, B., Majone, B., Paniconi, C. and Soddu, A.: Is climate change a threat for water uses in the Mediterranean region? Results from a survey at local scale, Sci. Total Environ., 543, 981–996, doi:10.1016/j.scitotenv.2015.04.062, 2016.

Kohavi, R.: A Study of Cross-Validation and Bootstrap for Accuracy Estimation and Model Selection, Int. Jt. Conf. Artif. Intell., (0), 0–6, 1995.

Kohler, T., Wehrli, A. and Jurek, M.: Mountains and climate change: A global concern, Sustainabl., edited by Centre for Development and Environment, Swiss Agency for Development and Cooperation, and Geographica Bernensia, Bern, Switzerland., 2014.

Laaha, G., Gauster, T., Tallaksen, L. M., Vidal, J. P., Stahl, K., Prudhomme, C., Heudorfer, B., Vlnas, R., Ionita, M., Van Lanen, H. A. J., Adler, M. J., Caillouet, L., Delus, C., Fendekova, M., Gailliez, S., Hannaford, J., Kingston, D., Van Loon, A. F., Mediero, L., Osuch, M., Romanowicz, R., Sauquet, E., Stagge, J. H. and Wong, W. K.: The European 2015 drought from a hydrological perspective, Hydrol. Earth Syst. Sci., 21(6), 3001–3024, doi:10.5194/hess-21-3001-2017, 2017.

Majone, B., Villa, F., Deidda, R. and Bellin, A.: Impact of climate change and water use policies on hydropower potential in the south-eastern Alpine region, Sci. Total Environ., 543, 965–980, doi:10.1016/j.scitotenv.2015.05.009, 2016.

Malard, J. J., Inam, A., Hassanzadeh, E., Adamowski, J., Tuy, H. A. and Melgar-Quiñonez, H.: Development of a software tool for rapid, reproducible, and stakeholder-friendly dynamic coupling of system dynamics and physically-based models, Environ. Model. Softw., 96(October 2017), 410–420, doi:10.1016/j.envsoft.2017.06.053, 2017.

Maraun, D.: Bias Correcting Climate Change Simulations - a Critical Review, Curr. Clim. Chang. Reports, 2(4), 211–220, doi:10.1007/s40641-016-0050-x, 2016.

Masia, S., Sušnik, J., Marras, S., Mereu, S., Spano, D. and Trabucco, A.: Assessment of Irrigated Agriculture Vulnerability under Climate Change in Southern Italy, Water, 10(2), 209, doi:10.3390/w10020209, 2018.

Meadows, D. H., Meadows, D. L., Randers, J. and Behrens, W. W.: The limits to growth, Universe Books, New York., 2018.

Mehran, A., AghaKouchak, A., Nakhjiri, N., Stewardson, M. J., Peel, M. C., Phillips, T. J., Wada, Y. and Ravalico, J. K.: Compounding Impacts of Human-Induced Water Stress and Climate Change on Water Availability, Sci. Rep., 7(1), 1–9, doi:10.1038/s41598-017-06765-0, 2017.

Menk, L., Neuwirth, C. and Kienberger, S.: Mapping the Structure of Social Vulnerability Systems for Malaria in East Africa, Sustainability, 12(12), 5112, doi:10.3390/su12125112, 2020.

Mereu, S., Sušnik, J., Trabucco, A., Daccache, A., Vamvakeridou-Lyroudia, L., Renoldi, S., Virdis, A., Savić, D. and Assimacopoulos, D.: Operational resilience of reservoirs to climate change, agricultural demand, and tourism: A case study from Sardinia, Sci. Total Environ., 543, 1028–1038, doi:10.1016/j.scitotenv.2015.04.066, 2016.

Montesarchio, M., Manzi, M. P., Cattaneo, L. and Mercogliano, P.: Performance Evaluation of a Regional Simulation with COSMO-CLM in the Alpine Space, SSRN Electron. J., (July), doi:10.2139/ssrn.2195316, 2013.

Neuwirth, C., Hofer, B. and Peck, A.: Spatiotemporal processes and their implementation in Spatial System Dynamics models, J. Spat. Sci., 60(2), 277–288, doi:10.1080/14498596.2015.997316, 2015.

Permanent Secretariat of the Alpine Convention: Water and water management issues - Report on the State of the Alps Alpine Signals - Special Edition 2., 2009.

Pham, V., Sperotto, A., Torresan, S., Acua, V., Jorda-capdevila, D. and Rianna, G.: Coupling scenarios of climate and land – use change with assessments of potential ecosystem services at the river basin scale, 2018.

Provincia Autonoma di Trento: PGUAP - Piano Generale di Utilizzazione delle Acque Pubbliche. Trento, 2006.

Provincia Autonoma di Trento: Provincia Autonoma di Trento - Agenzia provinciale per le risorse idriche e l'energia, [online] Available from: http://www.energia.provincia.tn.it/ (Accessed 6 July 2021), 2018.

665 R Core Development Team: A language and environment for statistical computing., , 1, 2019.

Ranzani, A., Bonato, M., Patro, E. R., Gaudard, L. and De Michele, C.: Hydropower future: Between climate change, renewable deployment, carbon and fuel prices, Water (Switzerland), 10(9), 1–17, doi:10.3390/w10091197, 2018.

Rockel, B. and Geyer, B.: The performance of the regional climate model CLM in different climate regions, based on the example of precipitation, Meteorol. Zeitschrift, 17(4), 487–498, doi:10.1127/0941-2948/2008/0297, 2008.

670 Ronco, P., Zennaro, F., Torresan, S., Critto, A., Santini, M., Trabucco, A., Zollo, A. L., Galluccio, G. and Marcomini, A.: A risk assessment framework for irrigated agriculture under climate change, Adv. Water Resour., 110, 562–578, doi:10.1016/j.advwatres.2017.08.003, 2017.

Sahin, O. and Mohamed, S.: Coastal vulnerability to sea-level rise: A spatial-temporal assessment framework, Nat. Hazards, 70(1), 395–414, doi:10.1007/s11069-013-0818-4, 2014.

675 Simonovic, S. P.: Systems Approach to Management of Disasters, edited by Wiley., 2001.

Simonovic, S. P.: Systems approach to management of disasters: methods and applications, J. Integr. Disaster Risk Manag., 5(2), 70–83, doi:10.5595/idrim.2015.0099, 2015.

Solander, K. C., Reager, J. T., Thomas, B. F., David, C. H. and Famiglietti, J. S.: Simulating human water regulation: The development of an optimal complexity, climate-adaptive reservoir management model for an LSM, J. Hydrometeorol., 17(3),

680 725–744, doi:10.1175/JHM-D-15-0056.1, 2016.

Stave, K.: Participatory system dynamics modeling for sustainable environmental management: Observations from four cases, Sustainability, 2(9), 2762–2784, doi:10.3390/su2092762, 2010.

Stephan, R., Erfurt, M., Terzi, S., Žun, M., Kristan, B., Haslinger, K. and Stahl, K.: An Alpine Drought Impact Inventory to explore past droughts in a mountain region, , (March), 1–25, doi:10.5194/nhess-2021-24, 2021.

685 Sterman, J. D., Burr Ridge, B., Dubuque, I., Madison, I. and New York San Francisco St Louis Bangkok Bogota Caracas Lisbon London Madrid Mexico City Milan New Delhi Seoul Singapore Sydney Taipei Toronto, W.: Business Dynamics Systems Thinking and Modeling for a Complex World., 2000.

Sušnik, J., Vamvakeridou-Lyroudia, L. S., Savić, D. A. and Kapelan, Z.: Integrated modelling of a coupled water-agricultural system using system dynamics, J. Water Clim. Chang., 4(3), 209–231, doi:10.2166/wcc.2013.069, 2013.

690 Sušnik, J., Chew, C., Domingo, X., Mereu, S., Trabucco, A., Evans, B., Vamvakeridou-Lyroudia, L., Savić, D. A., Laspidou, C. and Brouwer, F.: Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate nexus: The SIM4NEXUS approach, Water (Switzerland), 10(2), doi:10.3390/w10020139, 2018.

Tashman, L. J.: Out-of Sample Tests of Forecasting Accuracy: A Tutorial and Review, Int. J. Forecast., 16, 437–450, 2000.

Taylor, T. R. B., Ford, D. N. and Ford, A.: Improving model understanding using statistical screening, Syst. Dyn. Rev., 26(41),

695 73–87, doi:10.1002/sdr, 2009.

Terna: Dati generali, , 1–9 [online] Available from: https://download.terna.it/terna/1-DATI

GENERALI_8d8e26126475683.pdf, 2019.

Terzi, S., Torresan, S., Schneiderbauer, S., Critto, A., Zebisch, M. and Marcomini, A.: Multi-risk assessment in mountain regions: A review of modelling approaches for climate change adaptation, J. Environ. Manage., 232(1), 759–771,

700 doi:10.1016/j.jenvman.2018.11.100, 2019.

Teutschbein, C. and Seibert, J.: Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods, J. Hydrol., 456–457, 12–29, doi:10.1016/j.jhydrol.2012.05.052, 2012.

United Nations: The Future We Want: Outcome document of the United Nations Conference on Sustainable Development, Rio de Janeiro, Brasil., 2012.

705 Varma, S. and Simon, R.: Bias in error estimation when using cross-validation for model selection, BMC Bioinformatics, 7, 1–8, doi:10.1186/1471-2105-7-91, 2006.

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M. and Weingartner, R.: Mountains of the world, water towers for humanity: Typology, mapping, and global significance, Water Resour. Res., 43(7), 1–13, doi:10.1029/2006WR005653, 2007.

Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor,

710 M. I., López-Moreno, J. I., Lorentz, S., Schädler, B., Schreier, H., Schwaiger, K., Vuille, M. and Woods, R.: Climate change and mountain water resources: Overview and recommendations for research, management and policy, Hydrol. Earth Syst. Sci., 15(2), 471–504, doi:10.5194/hess-15-471-2011, 2011.

Vogt, J. V., Naumann, G., Masante, D., Spinoni, J., Cammalleri, C., Erian, W., Pischke, F., Pulwarty, R. and Barbosa, P.: Drought Risk Assessment and Management. A conceptual framework., 2018.

715 Wever, N., Comola, F., Bavay, M. and Lehning, M.: Simulating the influence of snow surface processes on soil moisture dynamics and streamflow generation in an alpine catchment, Hydrol. Earth Syst. Sci., 21(8), 4053–4071, doi:10.5194/hess-21-4053-2017, 2017.

Wood, S. and Scheipl, F.: gamm4: Generalized Additive Mixed Models Using mgcv and lme4, 2020.

Wood, S. N.: Generalized Additive Models : An Introduction with R, Gen. Addit. Model. An Introd. with R, Second Ed., 1–

720 476, doi:10.1201/9781315370279, 2017.

Xu, D., Song, A., Tong, H., Ren, H., Hu, Y. and Shao, Q.: A spatial system dynamic model for regional desertification simulation - A case study of Ordos, China, Environ. Model. Softw., 83, 179–192, doi:10.1016/j.envsoft.2016.05.017, 2016.

Xu, J., Grumbine, R. E., Shrestha, A., Eriksson, M., Yang, X., Wang, Y. and Wilkes, A.: The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods, Conserv. Biol., 23(3), 520–530, doi:10.1111/j.1523-

725 1739.2009.01237.x, 2009.

Yilmaz, K. K., Gupta, H. V. and Wagener, T.: A process-based diagnostic approach to model evaluation: Application to the NWS distributed hydrologic model, Water Resour. Res., 44(9), 1–18, doi:10.1029/2007WR006716, 2008.

Zebisch, M., Vaccaro, R., Niedrist, G., Schneiderbauer, S., Streifeneder, T., Weiss, M., Troi, A., Renner, K., Pedoth, L., Baumgartner, B. and V, B.: Rapporto sul clima - Alto Adige 2018, Eurach Research., 2018.

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