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Stochastic system dynamics modelling for climate change water scarcity assessment of a reservoir in the Italian Alps

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Supplementary material

Several input variables were considered and tested to replicate past values of S.Giustina turbined outflows. Beyond the four variables reported in Table 2 for the linear mixed effect model (inflow , volume, weekday and month), outflows from an upstream dam reservoir (i.e. Careser), temperature, precipitation and the national single energy price (PUN) were initially considered and tested as predictors (Table S1).

Table S1 – Summary table with all tested variables, unit, temporal coverage and their data source. * Data for temperature and precipitation considered the closest weather station (#T0236) to the S.Giustina reservoir.

#	Variable	Variable name	Unit	Temporal coverage	Source and link
1	Inflows to S.Giustina [m^3/s]	Inflow	[$m^3 \cdot s^{-1}$]	1981-2016	Province of Trento – Agency for water resource and energy
		GeoTransf	[$m^3 \cdot s^{-1}$]	1981-2010	GeoTransf hydrological model (Bellin et al., 2016)
2	S.Giustina outflows for hydropower	Outflow	[$m^3 \cdot s^{-1}$]	1981-2017	Province of Trento – Agency for water resource and energy
3	S.Giustina volume	Volume	[Mm^3]	1999-2004 2009-2017	
4	Upstream dam reservoir (Careser) outflows for hydropower	Outflow Careser	[$m^3 \cdot s^{-1}$]	1990-2013	
5	Temperature*	Temp	[°C]	1986-2017	Province of Trento – Weather service https://www.meteotrentino.it/index.html#!/content?menuItemDesktop=111
6	Precipitation*	Prep	[mm]	1986-2017	
7	National Single energy Price (PUN)	PUN	[€·MWh^{-1}]	2004-2017	Energy market operator http://www.mercatoelettrico.org/En/download/DatiStorici.aspx

In details, variables selection was based on a stepwise procedure considering three criteria: (i) data availability to the maximum target time period, (ii) a correlation matrix was here implemented to check for correlation among the explanatory variables and response and (iii) the selection of the most parsimonious model. For the prediction of turbined outflows the variables

Inflow, Temperature and Volume_lagged (i.e. volume time series shifted back by 1 day time step) were the most correlated variables. Following the above reported criteria, since the outflow from an upstream dam reservoir and the national single energy price have a limited temporal overlap down to 6 years in combination with volume and inflow to simulate the response variables, they were not further considered in modelling. Moreover, given the correlation between Inflow and Temperature (Figure S1) and the principle of selecting the most parsimonious models, the variable Inflow was selected and Temperature not further considered for predicting Outflow values.

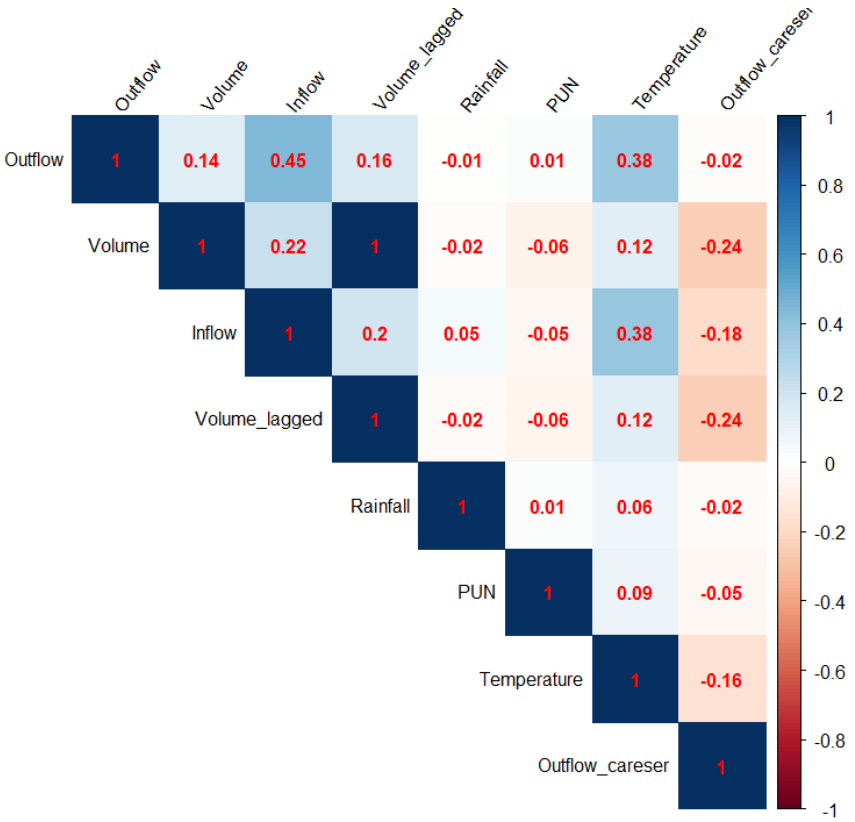

Figure S1 – Correlation matrices displaying positive correlations in blue and negative correlations in red color. Color intensity is proportional to the correlation coefficients reported within each square.

Here a summary of the best models implemented and tested is reported. Starting from the variables shown in Table 1, a stepwise procedure for model testing was implemented for each model type. Moreover, a moving window approach for the assessment of model performance indicators (i.e. R-squared and RMSE) allowed to evaluate the model performances considering an increasing set of training and testing datasets.

Table S2 - Summary table with best developed and tested regressions for each model type for predicting turbined water outflow from the S.Giustina reservoir at daily time step as combination of the selected variables. Best models for each model types reported in bold and the finally selected model is reported in bold and italics.

			Daily resolution		Monthly resolution	
Models type	**#**	**Formulas**	**R^2**	**RMSE ($\cdot 10^6$)**	**R^2**	**RMSE ($\cdot 10^6$)**
Multi-linear model	1.	lm(Outflow ~ Inflows)	0.33	1.05	0.56	22.15
	2.	lm (Outflow ~ lag(Inflows))	0.08	1.24	0.56	24.12
	3.	lm (Outflow ~ Inflows + Volume)	0.34	1.03	0.56	21.70
	4.	lm (Outflow ~ lag(Inflows) + Volume)	0.10	1.22	0.51	23.77
	5.	**lm (Outflow ~ Inflows + lag(Volume))**	**0.35**	**1.03**	**0.63**	**19.86**
	6.	lm (Outflow ~ lag(Inflows) + lag(Volume))	0.10	1.21	0.50	23.72
Linear mixed effect model	7.	lmer (Outflow ~ Inflows + (1|weekday)+ (1|month))	0.41	0.97	0.67	19.63
	8.	lmer (Outflow ~ lag(Inflows) + (1|weekday) + (1|month))	0.23	1.13	0.59	21.78
	9.	lmer (Outflow ~ Inflows + Volume + (1|weekday) + (1|month))	0.41	0.96	0.67	18.96
	10.	lmer (Outflow ~ lag (Inflows) + Volume + (1|weekday) + (1|month))	0.26	1.10	0.59	21.05
	11.	***lmer (Outflow ~ Inflows + lag(Volume) + (1|weekday) + (1|month))***	***0.42***	***0.95***	***0.75***	***16.57***
	12.	lmer (Outflow ~ lag(Inflows) + lag(Volume) + (1|weekday) + (1|month))	0.27	1.09	0.60	20.90
	13.	gam(Outflow ~ s(Inflows))	0.44	1.12	0.56	21.60

Generalized additive model	14. gam(Outflow ~ s(lag(Inflows)))	0.19	1.36	0.58	22.64
	15. gam(Outflow ~ s(Inflows) +s(Volume))	0.49	1.08	0.60	20.42
	16. gam(Outflow ~ s(lag(Inflows)) + s(Volume))	0.25	1.31	0.57	21.76
	17. **gam(Outflow ~ s(Inflows) + s(lag(Volume))**	**0.50**	**1.07**	**0.61**	**20.31**
Generalized additive mixed model	18. gam(Outflow ~ s(Inflows) + s(weekday, bs="re") +s(mo, bs="re"))	0.47	1.09	0.57	21.41
	19. gam(Outflow ~ s(lag(Inflows)) +s(weekday, bs="re") +s(mo, bs="re"))	0.30	1.26	0.59	21.98
	20. gam(Outflow ~ s(Inflows) + s(Volume) +s(weekday, bs="re") +s(mo, bs="re"))	0.53	1.03	0.64	19.43
	21. **gam(Outflow ~ s(Inflows) + s(lag(Volume)) +s(weekday, bs="re") +s(mo, bs="re"))**	**0.54**	**1.02**	**0.65**	**19.27**

Table S3 - Summary of future stored volume metrics for baseline and the 4 considered climate change scenarios

Stored volume < 10th percentile						
Scenarios	Variable	Baseline 1999-2004, 2009-2016	RCP4.5 2021-2050	RCP4.5 2041-2070	RCP8.5 2021-2050	RCP8.5 2041-2070
1 Relative frequency	Median	1.64	4.21	3.57	2.29	3.29
	Maximum	2.5	5.86	5.07	4.14	6.07
	Minimum	0.93	2.29	2.14	0.86	1.5
	Standard dev	0.264	0.577	0.402	0.456	0.726
2 Maximum duration	Median	4	7	5	4	5
	Maximum	8	19	17	10	15
	Minimum	1	2	2	1	1
	Standard dev	1.032	1.779	1.432	1.272	1.824

3 Relative severity	Median	0.002	0.007	0.005	0.002	0.004
	Maximum	0.003	0.013	0.008	0.006	0.012
	Minimum	0.001	0.002	0.002	0.0006	0.001
	Standard dev	0.0003	0.002	0.0007	0.0007	0.002

Stored volume < 20th percentile

Scenarios	Variable	Baseline	RCP4.5 2021-2050	RCP4.5 2041-2070	RCP8.5 2021-2050	RCP8.5 2041-2070
1 Relative frequency	Median	2.86	5.86	5.36	3.93	5
	Maximum	4.07	7.71	7.14	6.07	7.79
	Minimum	1.86	3.5	3.64	2.21	3
	Standard dev	0.337	0.62	0.429	0.527	0.77
2 Maximum duration	Median	5	10	7	6	7
	Maximum	10	31	22	17	30
	Minimum	3	4	3	2	3
	Standard dev	1.256	2.519	1.796	1.699	2.752
3 Relative severity	Median	0.003	0.012	0.009	0.005	0.007
	Maximum	0.005	0.021	0.014	0.010	0.019
	Minimum	0.002	0.005	0.005	0.002	0.003
	Standard dev	0.0005	0.002	0.001	0.001	0.003

Stored volume > 80th percentile

Scenarios	Variable	Baseline	RCP4.5 2021-2050	RCP4.5 2041-2070	RCP8.5 2021-2050	RCP8.5 2041-2070
1 Relative frequency	Median	3.14	1	1	1.64	1
	Maximum	4.21	2.21	2.07	3	2.43
	Minimum	2	0.21	0.14	0.57	0.14
	Standard dev	0.326	0.296	0.231	0.339	0.295
2 Maximum duration	Median	6	3	3	3	3
	Maximum	12	8	7	7	7
	Minimum	3	1	1	1	1
	Standard dev	1.414	0.897	0.989	0.973	0.929

3 Relative severity	Median	0.004	0.001	0.001	0.001	0.0001
	Maximum	0.005	0.003	0.002	0.003	0.002
	Minimum	0.002	0.0001	0.0002	0.001	0.0001
	Standard dev	0.0004	0.0004	0.0003	0.0004	0.0003

Stored volume > 90th percentile

Scenarios	Variable	Baseline	RCP4.5 2021-2050	RCP4.5 2041-2070	RCP8.5 2021-2050	RCP8.5 2041-2070
1 Relative frequency	Median	2.29	0.71	0.57	1	0.57
	Maximum	3.43	1.71	1.43	2.36	1.57
	Minimum	1.29	0.07	0.07	0.21	0.07
	Standard dev	0.284	0.222	0.181	0.266	0.2
2 Maximum duration	Median	5	2	2	2	2
	Maximum	11	6	5	7	5
	Minimum	2	1	1	1	1
	Standard dev	1.197	0.824	0.918	0.861	0.848
3 Relative severity	Median	0.003	0.0007	0.0006	0.0008	0.0005
	Maximum	0.004	0.0002	0.002	0.002	0.001
	Minimum	0.001	0.00005	0.00002	0.00005	0.000006
	Standard dev	0.0004	0.0003	0.0002	0.0003	0.0002