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Original scientific paper

Analysis of Climate Change Impact on Water Supply in Northern Istria (Croatia)

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Abstract: This paper analyses impacts of climate change and anthropogenic pressure on groundwater resources in the Mirna river catchment used for water supply in Northern Istria (Croatia) up to 2050. Using Regional Climate Models simulations and hydrologic model, the future average annual and the characteristic (in critical period) water resource availabilities were calculated. Current and five future water demand scenarios were analysed. Water Exploitation Index (WEI) and modified Characteristic Water Exploitation Index (CWEI) were calculated. In 2050, the analysed springs will be subject to climate change consequences, with more extreme changes and intense variations. The WEI for average conditions indicates little risk of unmet future water demand. Considering seasonal variability, the future CWEIs indicates strong risk for most future water demand scenarios and overexploitation for water demand increases over 20%. The 2012 drought, more extreme than any considered future scenario, was also examined.

Keywords: climate change; drinking water supply; water resources availability

1 INTRODUCTION

The Mediterranean basin, including the Adriatic Sea region, is a region that is very sensitive to climate change and anthropogenic impacts [1]. According to Xoplaki et al. [2], since the 1970s, the mean annual temperatures in the Mediterranean region have increased by 0.1 °C per decade, and precipitation has decreased by 25 mm per decade. Temperatures are expected to increase by 1.5-2.5°C, and precipitation is expected to decrease by 5% to 20% up to 2050 [3], which could significantly decrease (30-50%) freshwater resources throughout the Mediterranean basin. In the Adriatic region, the decrease of 15% of freshwater is expected in northern Italy and the Balkans [3]. Climate changes cause more frequent drought and flood occurrence. On the other hand, an increase in water demand is expected due to increasing urbanisation, agricultural production and tourism activities, increasing the withdrawal of and pressures on regional water resources [4]. Changes in land use potentially affect the available water resources too (e.g. increased intercepted precipitation in case of enlarging the forest area [5]).

Water resource and supply vulnerability and risk assessments, water scarcity estimates and drought analyses due to climate change impacts are necessary for avoiding future water crises and preparing adaptation measures to mitigate the consequences of such crises [6,7].

Numerous studies have investigated the impact of climate change on water resources worldwide (e.g. [8]); many have also analysed the impacts of human activities on water resources (e.g. [9]). Recently, more research has been conducted to simulate the impacts of climate change on water resources in future. This can be done by using various methodologies [10]: coupling Global Circulation Models (GCMs) with hydrologic models through downscaling techniques, coupling high-resolution Regional Climate Models (RCMs) with hydrologic models and using hypothetical scenarios as inputs to hydrologic models. Coupling high-resolution RCMs with hydrologic models has frequently been used to model the climate change impacts on hydrological regimes and water resources in the mid- to long-term future in Europe [11, 12].

Regardless of the methodology used to simulate climate change, the impact of climate change on the water resources in the Mediterranean has been confirmed in different studies [13-15]. Based on scenarios of varying future temperature and precipitation to analyse the changes in groundwater recharge and in agricultural water demand for the West Bank of the Mediterranean basin, Mizyed 15] concluded that the groundwater recharge could decrease by up to 50%.

Water supply system and sources vulnerability due to climate change are analysed by researchers in the Monterrey Metropolitan Area of northern Mexico [7] and on Mexico City [16]. However, only a small number of papers have investigated mitigation measures and adaptive strategies for drinking water supply [4, 17].

Impact of climate change on water resources used for drinking water supply in the Adriatic region has been investigated within the DRINKADRIA project [18, 19].

This paper presents the investigation of the climate change impacts and the anthropogenic pressure on groundwater resources in the river Mirna catchment that are used for drinking water supply in Northern Istria (Croatia, Northern part of the Adriatic sea region) to give the basis for preparation of adaptation and mitigation strategies up to year 2050. Analysing the impacts of climate change on water resource availability consists of using RCMs to simulate the change in temperature and precipitation up to 2050. Then, based on the results from climate modelling, a hydrological model is applied to calculate the future average annual water resource availability and characteristic renewable water resources availability (critical period), which are compared to past availability to estimate the changes.

Water demand analysis was conducted for the present demand and for five future water demand scenarios. To estimate the water resource vulnerability in Northern Istria, the Water Exploitation Index (*WEI*) was calculated [20]. However, to encompass the strong seasonal variability of the water demand and water resource availability, a modified Characteristic Water Exploitation Index (*CWEI*) was also used.

The 2012 drought, which was more extreme than any considered future scenario, was also examined.

2 STUDY AREA

The river Mirna catchment is the largest drainage basin and watercourse in the Istria peninsula and covers approximately 700 km^2 (Fig. 1).

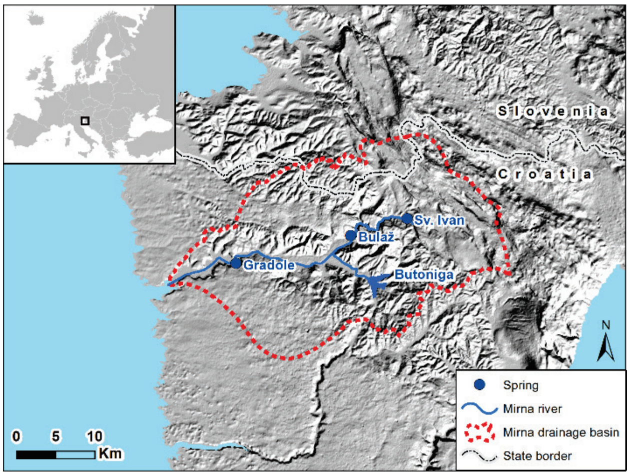

Figure 1 Mirna River catchment and location of springs Sv. Ivan, Bulaž and Gradole and Butoniga reservoir

The area of Istrian Peninsula is spreading over 3476 km^2, of which 2820 km^2 administratively belongs to Istria County. The Mirna catchment area belongs to the periphery of the Adriatic Carbonate platform. This geological structure includes carbonate and clastic deposits with stratigraphic ranges from the Upper Jurassic to the Eocene. The parts of the Istrian Peninsula where the surface watercourses are developed are mostly composed of flysch. The northern and northeastern parts of Istria are characterized by significant structural disturbances of the high carbonate massif of Mt Učka and Mt Ćićarija. The central and southeastern parts of Istria belong to the Pazin flysch basin, while the northwestern edge of this area belongs to the Trieste flysch basin. The Buje carbonate anticline rises between these basins, while the western and southwestern parts belong to the western Istrian carbonate anticline. The Mirna River formed its course between the abovementioned structures and partly through a valley area composed of an alluvial deposit reaching deep below sea level, thus retarding groundwater flow.

Groundwater emerges from the aquifer, in the form of several significant karst springs in the Mirna catchment at a contact point between the karst hinterland and the alluvial deposits. These springs are Sv. Ivan in the upper Mirna course (45°24'03.2" N 13°58'39.5" E), Bulaž in its middle course (45°22'46.5" N 13°53'17.4" E), and Gradole in its lower course (45°20'37.9" N 13°42'10.9" E) (Fig. 1).

The already observed manifestations of climate change are predicted to intensify in this area, where the majority of run-off goes underground, and karst springs are the main water supply resource [21].

Approximately 50% of the Mirna water balance (11.3 m^3 s^{-1} estimated at the river mouth) is accounted for by the Sv. Ivan (0.82 m^3 s^{-1}), Gradole (2.1 m^3 s^{-1}) and Bulaž (1.4 m^3 s^{-1}) springs, as well as by several other minor springs (e.g., Tombazin) that are not under the official hydrological monitoring programme [22].

During prolonged dry periods, water flowing from the karst springs is almost the only inflow to the Mirna River. The area of the Mirna catchment is most significant in terms of the available groundwater and surface water resources included in the water supply system of Istarski vodovod (Water Utility of Istria), the largest of the three water supply companies in Istria County.

Using spring water for water supply adds pressure to the water resources and the ecosystem of the Mirna River, particularly during the extremely dry years that are becoming increasingly more frequent. The coastal area that is supplied by these springs mostly host tourist activity, leading to increased water demand in the summer months, when the spring yield is the lowest.

Severe dry events during the last several decades (e.g., 1986-89, 2002-03, and 2011-12) have shown that the exploitable water resources available in Istria within the constructed water supply systems are at the limit of meeting the current needs. A potential solution is to better optimise the provision of seasonal water reserves from the Butoniga reservoir (45°19'57.8" N 13°55'25.3" E), which also lies in the Mirna catchment (Fig. 1). This reservoir has a volume of approximately 20 million m^3, 8 million m^3 of water is used for water supply annually.

Due to the proximity of the individual spring catchments and the close occurrences of both wet and dry periods, the water balance characteristics of these three most significant spring water intakes in this area (i.e., Sv. Ivan, Gradole and Bulaž) are presented and analysed in the aggregate in this paper (Fig. 2).

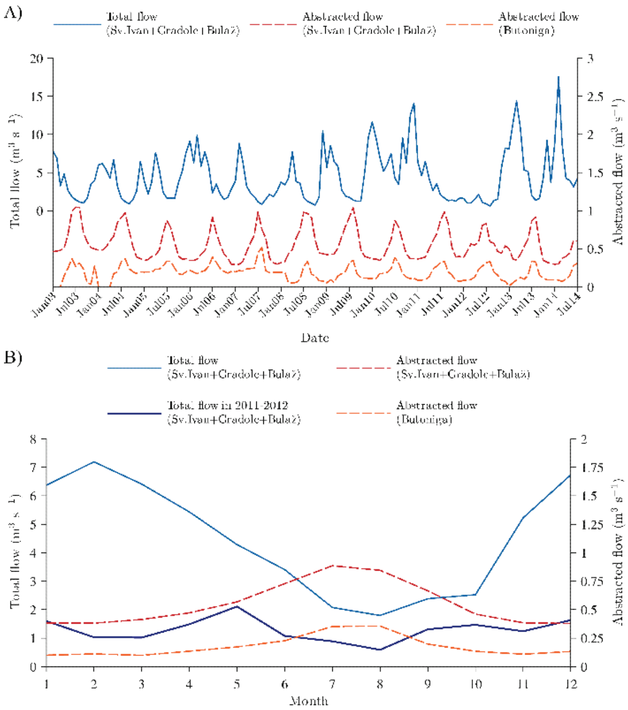

Figure 2 Distribution of: a) the average monthly discharge and abstracted flow of Sv. Ivan, Gradole and Bulaž springs and Butoniga reservoir (2003-2014); b) Inter-annual distribution of the total discharge and water pumping of Sv. Ivan, Gradole and Bulaž springs and Butoniga reservoir (2003-2014) with the inter-annual distribution of the total discharge in the extremely dry 2011-2012

Data used for this research (overflow and abstracted water quantities at selected springs that were used for estimation of springs yield) are provided by Croatian Meteorological and Hydrological Service based on their monitoring system.

During dry summer periods, approximately 3.57 million tourists (as registered during 2015) are visiting − dramatically increasing the permanent population of approximately 210 000. The increased water demand during summer is affected not only by tourist activities but also by the demand for water to irrigate private lawns and community parks.

These springs are highly sensitive to climate change and droughts that can significantly reduce the available water balance of these springs. The year 2012 was particularly critical as the area experienced a low water event with a return period of between 100 and 200 years [23].

3 METHODOLOGY

3.1 Methodology for Analysing the Impact of Climate Change on Water Resources

The methodology used to assess the impact of climate change on water resources in the analysed area of Northern Istria was described in detail by Rubinić and Katalinić [24].

The proposed model uses a runoff estimation based on a spatial distribution of the annual rainfall and air temperature in the GIS environment. The localized measurements at specific points are distributed over the entire basin area using point-weighted averages. The Langbein [25] and Turc [26] empirical expressions were used for this purpose. The choice of an appropriate runoff distribution was based on a comparison of data from basins with available observations of climatological indicators and measured discharges. The Turc method was used for regional hydrological water balance assessment for karst basins [27], but in this case study the Langbein method was chosen as the most appropriate for the analysed karstic springs located in the Mirna river catchment [28]. This concurs with an established practice in regional hydrological approach of using empirical models that are calibrated based on the results of hydrological observations during the period of 1961-2013 [27-29].

The approach used here is based on the analysis of the historical climatological and hydrological data (1961-2013) to generate the data for the period of 2014-2050. Using these models along with the spatial assessment of the annual rainfall and the average annual air temperatures in the analysed basin and determining the basin surface area using hydro-geological methods, it is possible to define the spatial distribution of the actual annual rainfall, i.e., the rainfall that infiltrated into the karst aquifer basin.

In the process of modelling, both point and spatially distributed data for the annual rainfall and the average annual air temperatures were used. Pazin, the main climatological station located in the central part of the Istrian Peninsula, was selected as the reference station, and the historically recorded data from the period of 1961-2013 were analysed. The spatial distributions of the average annual air temperature and precipitation for the reference time period of 1961-1990 were also used. Estimations of the average annual air temperature and precipitation for the time period of 2014-2050 were based on the available data from the main climatological station.

Then, the impacts of climate change on hydrological characteristics, the average annual discharge and the lowest average monthly discharges, were estimated. The modelling of the annual runoff is based on the acceptable correlation ($r = 0.85$) between average annual and lowest average monthly discharges of the analysed springs in the Mirna river basin. This correlation was determined from the regression analysis of available historical data and discharge measurements in the period of 1961-2013. Additionally, the generated data series of the lowest average monthly discharges were determined, which usually represent a critical factor in securing the water availability during an increased seasonal water supply demands in the analysed area that is characterized by strong tourism activities.

Due to the high uncertainty in estimation of future climate characteristics three climate models were used. The discharge data were generated by regional climate models REGCM3 [30], ALADIN [31] and PROMES [32]. The selected RCMs were forced by the observed and predicted concentrations of the greenhouse gases (GHGs) based on several scenarios, including the IPCC's (Intergovernmental Panel on Climate Change) A1B scenario of the GHGs emissions for the period after 2001. The initial and boundary data for each RCM were provided from different global climate models (GCMs): the ECHAM5 GCM data were used to force REGCM3, ALADIN was forced by the Arpege GCM and PROMES was forced by the HadCM3Q GCM [33].

A homogeneity assessment of the results based on the historical time series and on the two chosen models was performed using the Wilcoxon test [34]. The trend analysis was conducted, both in terms of a common approach based on linear correlation and also by using the Theil-Sen's estimator [35, 36]. Testing the significance of trends was carried out using nonparametric Man-Kendall's test [37, 38].

3.2 Methodology for Estimation of the Water Exploitation Index

The Water Exploitation Index (*WEI*) was applied to estimate the water resource vulnerability. *WEI* is a ratio of the average annual total water demand to the average annual available water resources and is often used to assess water stress at a national level based on total water use and the average annual water availability [20]. However, such an analysis cannot fully reflect the stress at a local level, e.g., river basins or systems of karst springs. Furthermore, because the original *WEI* is based on mean annual data, it does not account for seasonal variations in water demand or availability. Seasonal variations are especially important in coastal Mediterranean regions, such as Northern Istria, where the domestic, tourist and agricultural water demand peak coincides with minimum water resources availability in summer. Considering these specific concerns, the original formula was modified here for local analysis and critical periods.

Water Exploitation Index (*WEI*) was computed to assess the average annual conditions as a ratio of the Average Water Demand (*WD*) to the Average Water Resources (*WR*):

$$WEI = WD/WR \tag{1}$$

The Characteristic Water Exploitation Index (*CWEI*) was used to assess the vulnerability of water resources considering the strong seasonal variability in Northern Istria. In particular, the characteristic water demand focused on August, which is a typical summer month characterized by very high temperatures and low precipitation along with increased tourism and agricultural water needs. *CWEI* is defined as the ratio of the Characteristic Water Demand (*CWD*) to the Characteristic Water Resources (*CWR*):

$$CWEI = CWD/CWR \tag{2}$$

Water demands and resources in Northern Istria were assessed using a simplified approach based on the statistical analysis of the observed hydrological data (i.e., abstracted and total flow) from Sv. Ivan, Gradole and Bulaž springs as well as the Butoniga reservoir. Average Water Demand (*WD*) was computed as the long-term mean annual abstracted flow, whereas Characteristic Water Demand (*CWD*) was computed as the long-term mean August abstracted flow, from Sv. Ivan, Gradole and Bulaž springs, and the Butoniga reservoir. Water resources were based mainly on the measured total flow from the Sv. Ivan, Gradole and Bulaž springs. The main issue was accounting for the water reserves in the Butoniga reservoir. Clearly, omitting these quantities from the resource analysis would overestimate the *WEI* and *CWEI*. However, the Butoniga reservoir does not have any external inflow other than direct precipitation. Therefore, two water resources scenarios were evaluated: scenario 1 was used to estimate water resources by considering total flows only at the Sv. Ivan, Gradole and Bulaž springs (WR_1 and CWR_1), and scenario 2 considered total flows at the springs and the abstracted flow from the Butoniga reservoir (WR_2 and CWR_2). The average water resources (WR_1 and WR_2) were computed as the mean annual total flow, whereas the characteristic water resources (CWR_1 and CWR_2) were computed as the minimum mean monthly total flow.

In addition to the long-term statistical data, the extremely dry year of 2012 was examined in more detail to determine how these results match long-term projections. Both the average Water Exploitation Index WEI^{2012} (2012 calendar year and hydrological year) and the Characteristic Water Exploitation Index $CWEI^{2012}$ (the critical month of August 2012) were considered.

For the original method [39], $WEI < 0.1$ indicates no stress, while $WEI > 0.4$ indicates severe stress. Although this classification is reasonable for average conditions at a national level, when considering characteristic water conditions at a local level, these thresholds are too rigorous. Both Alcamo et al. [40] and Smakhtin et al. [41] recognized that these threshold values are too low, and they defined slightly higher boundaries. This work used a similar classification that was proposed in a CC-WaterS project that considered climate change and its impacts on water supply in South-eastern Europe: $WEI < 0.50$ indicates low risk, $0.5 \le WEI < 0.7$ indicates possible difficulties, $0.7 \le WEI < 1.0$ indicates strong risk, and $WEI \ge 1.0$ is considered to be unsustainable [33].

4 RESULTS AND DISCUSSION

4.1 Impact of Climate Change on Water Resources

Results of the generated minimum average monthly discharge according to the three climatological models and their future estimates based on the historically available aggregate average monthly discharge from the springs Sv. Ivan, Gradole and Bulaž for the period of 1961-1990 are presented in Fig. 3.

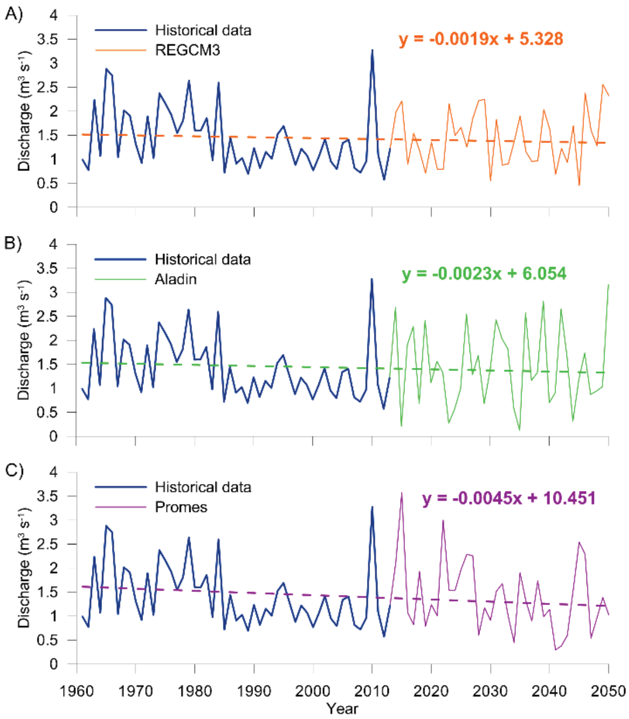

Figure 3 Historical time series and projected time series of the total lowest average monthly discharge of Sv. Ivan, Gradole and Bulaž springs generated using different climate models for 1961-2050 with accompanying trends: A) REGCM3, B) ALADIN, and C) PROMES models

The trends show that on a longer timescale and 2050, a decreasing trend in the selected characteristic discharge is expected to continue. More importantly, considering the water availability of the analysed springs, the trends suggest a possibility for a more frequent occurrence of the extremely low values of the lowest average monthly discharges.

However, each of the applied models gives different scenarios for the future changes and different slopes of these trends. According to the implemented Mann-Kendal test, the trend for the entire analysed series of historical data and projected values for the future (up to 2050), at the significance level of 5%, there is no apparent decrease of mean annual flow rates according to results obtained by the use of REGCM3 (*P*-value 0.216) and the ALADIN model (*P*-value 0.101), while in the results using PROMES, such a trend (P-value 0.031) was established. This statistically significant trend (Fig. 3) for the discharges generated by the PROMES model amounts to 0.45 $m^3 s^{-1}$ over 100 years.

In other words, the PROMES model predicts a decrease of the lowest average monthly discharges for almost a third of the measured historical data.

The homogeneity of the historical and generated time series of inflows based on REGCM3, ALADIN and PROMES models results was analysed using the Wilcoxon test. According to the results of this test, analysed series of historical (for the 30-year reference series 1961-1990, as well as in the case of a more complete historical series from 1961 to 2013) and generated future data (30-year series 2021-2050, or in the case of a more complete sequence analysis of 2014-2050), are mutually homogeneous in all analysed cases.

This analysis shows also that the lowest non-homogeneity was recorded for the REGCM3 model. This model is usually used in the wider region of the analysed Croatian localities and it has been used for the longest for climate predictions caused by climate change [42]. The results of these models were used as input values in hydrological models, with which hydrological changes in the water regime of water resources were generated in other areas of Croatia [27, 33].

Tab. 1 presents the relationship between the projected lowest average monthly discharge for the future periods and the historical inflows, which were determined using measured historical data, as well as the generated data based on measured annual rainfall and temperatures.

The comparison also analysed the relationship between two characteristic 30-year periods, i.e., the reference historical period of 1961- 1990 and the projected period of 2021-2050, as well as the entire available historical period of 1960-2013 and the entire projected period of 2014-2050.

The average values of the minimum average monthly discharge from the end of the generated period (2021-2050) are significantly lower than the corresponding values from the 30-year historical period (1961-1990) in the inflow series for the entire climate models used. For the discharge generated using the REGCM3 model, this difference is the smallest with a discharge decrease of 8.6%, while for the discharge generated using the PROMES model, this difference is the largest with a decrease of 15.6%. However, more prominent differences are expected regarding an increase of the discharge variability, as well as a more frequent occurrence of the lower average monthly discharges, generated by the ALADIN model (66.9%). Similar results are found when the data generated by the selected climate models for the period 1914-2050 are compared to the historical data from 1961-2013. This is also true when the generated data in a characteristic 30-year period (2021-2050) is compared to the historical data from 1961-1990. Possible differences in the occurrence of the minimal values generated by all three climate models are even more pronounced and amount up to 80%.

Table 1 Statistical analysis of the measured and generated aggregate lowest average monthly discharge from Sv. Ivan, Gradole and Bulaž springs, expressed as a percentage relative to the historical series, 1961-1990 and 1961-2013, (Note: *Avg* - average, *SD* - standard deviation, *Cv* - coefficient of variation, *Max* - maximum, and *Min* - minimum)

	Avg (m^3s^{-1})	*SD* (m^3s^{-1})	*Cv*	*Max* (m^3s^{-1})	*Min* (m^3s^{-1})
Measured historical discharges					
1961-1990	1,60	0,65	0,41	2,88	0,70
1961-2013	1,41	0,64	0,45	3,28	0,57
Historical discharges generated from the measured precipitation and temperatures					
1961-2013	1,42	1,07	0,75	5,06	0,18
Historical discharges generated by the climate models (1961.-2013.)					
REGCM3	1,42	0,72	0,51	3,14	0,27
ALADIN	1,42	0,69	0,49	3,81	0,38
PROMES	1,41	0,71	0,50	3,75	0,41
Comparison of the future discharges generated by the climate models and the measured historical discharges					
2021-2050/1961-1990	(%)	(%)	(%)	(%)	(%)
REGCM3	−8,6	−8,2	0,43	−11,3	−35,4
ALADIN	−11,6	23,5	39,8	9,6	−82,1
PROMES	−15,6	4,6	23,9	4,1	−57,4
2014-2050/1961-2013	(%)	(%)	(%)	(%)	(%)
REGCM3	2,5	−8,3	−10,5	−22,0	−21,5
ALADIN	2,5	29,8	26,7	−3,6	−78,3
PROMES	−0,62	17,2	17,9	8,9	−48,3
Comparison of the historical and future discharges generated by the climate models					
2021-2050/1961-1990	(%)	(%)	(%)	(%)	(%)
REGCM3	2,6	−19,0	−21,1	−18,7	64,7
ALADIN	−2,8	5,8	8,9	−17,1	−66,9
PROMES	−9,0	−12,7	−4,0	−19,9	−42,8
2014-2050/1961-2013	(%)	(%)	(%)	(%)	(%)
REGCM3	2,3	−18,9	−20,7	−18,7	64,7
ALADIN	2,1	19,2	16,7	−17,1	−66,9
PROMES	−0,7	4,5	5,2	−4,8	−28,3

However, a decrease of the average discharges is found only in the data series generated by the ALADIN model (−9%), and only for the period closer to the middle of the 21st century.

When the generated data for the future period of 2014-2050 are compared to the historical data from the period of 1961-2013, the analysed maximum values of the lowest average monthly discharge show different results: according to the PROMES and ALADIN models, they could even increase by 4.1% and 9.6%, respectively, while according to the REGCM3 model, they could decrease by 11.3%. In addition, the variability of the analysed lowest average monthly discharge is expected to increase.

If the generated and historical data of the lowest average monthly discharge after 2014 and until the end of 2013 are compared, smaller discharge differences and variabilities are obtained. The reason for this could be the change of dynamics, i.e., the gradually increasing impacts of climate change on discharge, or because climate change has already somewhat manifested in the historical and generated periods that were not covered by the selected 30-year reference period (1991-2020).

4.2 Water Exploitation Index

The results of the hydrological analyses were used to assess the potential impacts of climate change, i.e., a general decrease in discharge based on the exploitation of water for water supply needs. For this purpose, the Water Exploitation Index was calculated for Northern Istria, considering average (annual) and characteristic (monthly) hydrological conditions. In addition to the current water resources (1991-2014), past values (1961-1990) and several future predictions (2021-2050) from the three climate models (i.e., REGCM3, ALADIN and PROMES) were considered. Similarly, in addition to the current water demand (1991-2014), several future (2021-2050) scenarios were considered with varying increases in the current water demand of up to 25% with increments of 5%. These increases were estimated from the long-term population projections and planned accommodation capacities for tourists. According to the Croatian census [43], the total population in the Istria County increased from 206 344 in 2001 to 208 055 in 2011, which amounts to 0.08% per year. This increase is largely attributed to the immigration from other parts of the country and is not expected to rise in the future [43, 44]. Considering a linear continuation of this trend, the population by 2050 is estimated to reach 215 000 (a 3.2% increase). The accommodation capacities, on the other hand, are expected to increase from 210 000, which were available in 2001, to 285 000 by 2050 [42], which amounts to a 35.7% increase. Therefore, if these ambitious plans are realised, the population and accommodation capacities will together reach 500 000 by the year 2050, and the total water demand is estimated to increase up to 25%. It should be stressed that a decrease of the water demand could also be feasible if a different approach to water demand management issued (i.e. green infrastructure, grey water reuse, artificial aquifer recharge, better management of the water supply losses, an increased water supply efficiency in general, etc.) but this is not analysed in this paper.

Tab. 2 shows the estimated *WEI* and *CWEI* for Northern Istria.

Table 2 *WEI* and *CWEI* for Northern Istria

Average annual conditions			WR_1 (WR_2) (m^3 s^{-1})				
			Past 1961-1990	Present 1991-2014	Future 2021-2050		
					REGCM3	ALADIN	PROMES
			4.8 (4.897)	4.299 (4.396)	4.64 (4.737)	4.5 (4.597)	4.83 (4.927)
WD (m^3 s^{-1})			$WEI_1 = WD/WR_1$ ($WEI_2 = WD/WR_2$)				
1991-2014		0.71	0.15 (0.15)	0.16 (0.16)	0.15 (0.15)	0.16 (0.16)	0.14 (0.14)
Future	5%	0.73	0.15 (0.15)	0.17 (0.17)	0.16 (0.15)	0.16 (0.16)	0.15 (0.15)
Future	10%	0.77	0.16 (0.16)	0.18 (0.17)	0.17 (0.16)	0.17 (0.17)	0.16 (0.16)
Future	15%	0.80	0.17 (0.16)	0.19 (0.18)	0.17 (0.17)	0.18 (0.17)	0.17 (0.16)
Future	20%	0.84	0.17 (0.17)	0.19 (0.19)	0.18 (0.18)	0.19 (0.18)	0.17 (0.17)
Future	25%	0.87	0.18 (0.18)	0.20 (0.20)	0.19 (0.18)	0.19 (0.19)	0.18 (0.18)
Characteristic monthly conditions			CWR_1 (CWR_2) (m^3 s^{-1})				
			Past 1961-1990	Present 1991-2014	Future 2021-2050		
					REGCM3	ALADIN	PROMES
			1.6 (1.809)	1.176 (1.385)	1.46 (1.669)	1.41 (1.619)	1.35 (1.559)
CWD (m^3 s^{-1})			$CWEI_1 = CWD/CWR_1$ ($CWEI_2 = CWD/CWR_2$)				
1991-2014		1.13	0.71 (0.63)	0.96 (0.82)	0.78 (0.68)	0.80 (0.70)	0.84 (0.73)
Future	5%	1.19	0.74 (0.66)	1.01 (0.86)	0.82 (0.71)	0.84 (0.74)	0.88 (0.76)
Future	10%	1.25	0.78 (0.69)	1.06 (0.90)	0.85 (0.75)	0.88 (0.77)	0.92 (0.80)
Future	15%	1.30	0.82 (0.72)	1.11 (0.94)	0.89 (0.78)	0.92 (0.81)	0.97 (0.84)
Future	20%	1.36	0.85 (0.75)	1.16 (0.98)	0.93 (0.82)	0.97 (0.84)	1.01 (0.87)
Future	25%	1.42	0.89 (0.78)	1.21 (1.02)	0.97 (0.85)	1.01 (0.88)	1.05 (0.91)

Average Water Demand (*WD*) was calculated as the mean annual abstracted flow from the Sv. Ivan, Gradole and Bulaž springs and the Butoniga reservoir in the period of 1991-2014 (with future increases of 5-25%). Average Water Resources were calculated as the mean annual total flow at the Sv. Ivan, Gradole and Bulaž springs (WR_1), and as the sum of WR_1 and the mean annual abstracted flow from Butoniga reservoir (WR_2), in the past (1961-1990), present (1991-2014), and future (2021-2050), as predicted by three climate models: REGCM3, ALADIN and PROMES. Characteristic Water Demand (*CWD*) was computed from the mean August abstracted flow from the Sv. Ivan, Gradole and Bulaž springs as well as the Butoniga reservoir; whereas, Characteristic Water Resources were computed as the minimum mean monthly flow observed at all three springs (CWR_1), and as the sum of CWR_1 and the mean August abstracted flow from the Butoniga reservoir (CWR_2) for the past, present and future scenarios. When evaluating *WEI* using the CC-WaterS [33] thresholds, the *WEI* values are similar and suggest a very low risk even if the future water demand increases by 25%.

When the original [39] boundary values are considered, all the *WEI* values indicate moderate water stress. For past water resources, $CWEI_1$ indicates a strong risk for all water demand scenarios. When present water resources are considered, $CWEI_1$ indicates a strong current risk and an overexploitation of the karst springs for all future demands.

For future water resources, all climate models predict higher $CWEI_1$ values than the past ones, suggesting a strong risk for most future water demand scenarios and overexploitation for increases in water demand over 20% or 25%, depending on the climate model. The results for present water resources that indicate even stronger risks than any future scenario are somewhat misleading, because the present scenario includes an extremely dry event that occurred in August 2012. Future modelled scenarios, clearly, do not anticipate an occurrence of such a strong drought in the period 2021-2050.

To separately evaluate this extremely dry event from 2012, when a first-degree water restriction was declared in the Istria County, and the karst springs were exploited to their maximum capacity, the WEI^{2012} for the calendar and hydrological year and the $CWEI^{2012}$ for August were additionally evaluated.

Water Demand (WD^{2012}) was calculated as the mean 2012 abstracted flow from the Sv. Ivan, Gradole and Bulaž springs and the Butoniga reservoir, whereas the water resources were calculated as the mean 2012 total flow at the three springs (WR_1^{2012}), and the sum of the WR_1^{2012} and the 2012 abstracted flow from the Butoniga reservoir (WR_2^{2012}). Characteristic Water Demand (CWD^{2012}) was calculated as the mean August 2012 abstracted flow from the three springs and the Butoniga reservoir, whereas the Characteristic Water Resources (CWR^{2012}) were calculated as the mean August 2012 total flow at the three springs (WR_1^{2012}) or the sum of WR_1^{2012} and the abstracted flow from the Butoniga reservoir (WR_2^{2012}).

From the results presented in Tab. 3, the hydrological year (possible difficulties) was much more critical than the calendar year (low risk).

Furthermore, $CWEI_1^{2012}$ > 1.0 for August indicates overexploitation and an unsustainable situation.

Table 3 *WEI* for the extremely dry year of 2012 in Northern Istria

Period	WD^{2012} (m^3 s^{-1})	WR_1^{2012} (WR_2^{2012}) (m^3 s^{-1})	WEI_1^{2012} (WEI_2^{2012})
January 2012 - December 2012	0.71	2.20 (2.35)	0.32 (0.30)
October 2011 - September 2012	0.72	1.28 (1.45)	0.57 (0.50)
Period	CWD^{2012} (m^3 s^{-1})	CWR_1^{2012} (CWR_2^{2012}) (m^3 s^{-1})	$CWEI_1^{2012}$ ($CWEI_2^{2012}$) (m^3 s^{-1})
August 2012	1.01	0.59 (1.01)	1.71 (1.00)

This event is clearly characterized by a much longer return period than any future scenario considered here. Nevertheless, such events are not isolated and could be expected again in the future.

5 CONCLUSIONS

This paper shows that the analysed Northern Istria region, i.e., the Sv. Ivan, Gradole, and Bulaž springs in Mirna river catchment, has risks of unwanted consequences of climate change and that until the year 2050, even more extreme changes can be expected.

Different models for forecasting changes in climate indicators result in different scenarios of the impact of such changes on the selected water balance indicators. Even the most conservative REGCM3 climate model projected that the lowest monthly discharge in the analysed springs during the period of 2021-2050 could be approximately 8.6% lower than the average of the 30-year period of 2021-2050 and that the extreme minimums could be up to 35.4% lower with far more extreme variations and a potential for even drier years than the extremely dry 2011-12 season. The projections of the other two models used in this paper, ALADIN and PROMES, suggest even more pronounced differences and significantly lower average and extremely low values of the lowest average monthly discharge. All the trends show a decrease in the analysed discharge and therefore the water resources available for water supply.

The WEI results for Northern Istria for average conditions (the mean annual abstracted flow from the Sv. Ivan, Gradole and Bulaž springs, with and without the Butoniga reservoir), using the CC-WaterS [33] thresholds, indicate that there is a very low risk of not meeting future water demands even if they increase by 25%. Similarly, when the original [39] boundary values are considered, all of the values indicate moderate water stress.

Considering the seasonal variability in Northern Istria, the *CWEI* for past water availability indicates a strong risk for all water demand scenarios. For the current water resources, *CWEI* indicates a strong current risk; however, any future increases in water demand would result in overexploitation of the karst springs if the Butoniga reservoir is not included. The predicted *CWEI*s for future water resources are also higher than the past ones, suggesting a strong risk for most future water demand scenarios and overexploitation for increases in water demand greater than 20%.

The extreme dry event that occurred in the summer of 2012 was also examined; the *WEI* for 2012 and the *CWEI* for August 2012 were also calculated. The results clearly show that the hydrological year (possible difficulties) was much more critical than the calendar year (low risk). Furthermore, the *CWEI* for August indicates overexploitation and an unsustainable situation that resulted in a first-degree water restriction that was declared in the Istria County in 2012 when the karst springs were exploited to their maximum capacity. This event was more extreme than any estimated future scenario. Nevertheless, such events are not isolated and could be expected again in the future. It can also be concluded that using water from the Butoniga reservoir in addition to the water from Sv. Ivan, Gradole and Bulaž springs to meet the water demand during critical periods lowers the *CWEI* by as much as 19%.

Sustainable water resource management requires optimization of the use and also the reduction of excessive exploitation of available water resources. Therefore, to ensure the required water supply quantities and the functionality of the water supply system in Istria in the given climate scenarios and their hydrological consequences, it is essential to develop adequate scenarios of management and structural responses for the spatial and temporal allocation of available resources in cases that are far more unfavourable than the current scenario.

The methodology presented in this paper can be applied to other water resources and locations where the seasonal character in water resources availability and water demand is present. It can be used for longer periods estimation (e.g. until 2100) which gives the possibility to decision makers to better prepare adequate management and structural responses.

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