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Analysis of extreme precipitation indices in the Marche region (central Italy), combined with the assessment of energy implications and hydrogeological risk

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Abstract

Extreme weather events are increasingly affecting the climate of our planet and they cause natural disasters that are often dangerous to human life. Furthermore, the management of extreme events is very important and can be mitigated by artificial reservoirs, such as those existing in the region. From this point of view, the management of extreme events would become an opportunity for development linked to the production of energy through artificial reservoirs. The aim of this study is to assess the changes of these phenomena, in a small area of central Italy (Marche region), calculating 11 extreme precipitation indices from 1961 to 2017. The analysis shows an extremisation of rain events, with an increase in indices CDD, CWD and R99. However the innovativeness of this research lies in the spatialization of these extreme indices, through areal interpolations performed by GIS software. The territorial assessment of extreme precipitation events has revealed significant local countertrends, useful for hydrogeological protection, water resource management and energy production.

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Keywords: Extreme indices; Geographic information systems (GIS); Precipitation

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1. Introduction

In the last decades, the public attention is increasingly focusing on extreme events because they are harmful for human activity. Extreme events, however, also have other implications, such as those related to the storage of water resources [1], also depending on the energy that reservoirs can produce. In this context there were studies that have

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analyzed the European situation by means of climate modeling to assess the future variation of precipitation that seems to be characterized by the alternation of more frequent extreme events and extended dry spells [2]. Instead, other authors have calculated extreme climatic indices similar to this study, to assess climate change, on a large scale, in order to verify the extreme climate change over vast areas of the World [3]. However, the analysis of extreme climatic events is much more frequently assessed on a small scale because of the large amount of data that needs to be analyzed and because of the variability of local atmospheric dynamics. Although regional studies agree on the increase in extreme events, they show a wide variability in intensity across the Mediterranean basin [4,5]. In Italy the available studies are very detailed and show an increase of extreme events of precipitation throughout the peninsula [6,7]. The indices considered in this study are all precipitation extreme indices of the list developed by the joint CCI/CLIVAR/JCOM expert team on climate change detection and indices (ETCCDI) [8,9]. In particular, the extreme indices used for precipitation are 11 and they were calculated within a period from 1961 to 2017. The period 1961–2017 was chosen because it includes two standard normal periods 1961–1990 and 1991–2020, thus allowing a comparison with other regions of the world. A total of 91 rain gauges with complete data were considered, covering an area of about 9400 km^2. The lack of an adequate survey on extreme rainfall in central Italy, particularly on the Adriatic coast (Marche region), determines the need of this study. In addition, the presence in this region of valuable crops very sensitive to climate change and especially to extreme events contributes to increasing the need for knowledge and prevention [10–12]. Similarly, for the mitigation of hydrogeological risk, it is essential to have the possibility of containing the effects of extreme precipitation events. This determines a central role for the artificial reservoirs and consequently the predisposition of appropriate countermeasures would lead to increased energy production, avoiding precautionary emptying.

2. Method

Daily data of precipitation were collected from 91 rain gauges in the Marche region from 1961 to 2017 and by four different institutions: experimental geophysical observatory of Macerata, civil protection of Marche region, ISPRA (Higher Institute for Environmental Protection and Research) and functional center of Umbria region. Completeness controls detected 4 weather stations (Osimo, Novafeltria, Offida and San Martino) below the minimum amount of rainfall data, these locations were removed immediately from the survey. Subsequently the remaining 87 rain gauges were validated [13] and homogenized [12,14]. To obtain the 11 extreme indices and their trends, the statistical software R has been used [15], through the RClimDex package developed and maintained by Zhang and Yang [16], and adopted by the ETCCDI. The following 11 extreme indices were calculated [17]:

1. CWD = Maximum number of consecutive rainy days with precipitation greater than 1 mm.
2. CDD = Largest number of consecutive days without rain (less than 1 mm) in the period j.
3. PRCP = Sum of the daily precipitation i in the period j (usually annual) (mm).
4. R10 = Number of days with precipitation greater than 10 mm (days)
5. R20 = Number of days with precipitation greater than 20 mm (days).
6. R95 = Daily precipitation amount in period i greater than 95th percentile of precipitation during the study period (mm).
7. R99 = Daily precipitation amount in the period greater than 99th percentile of precipitation in the study period (mm).
8. R1 = Total amount of rainy days (days).
9. RX1 = monthly maximum 1-day precipitation amount (mm).
10. RX5 = monthly maximum 5-day precipitation amount (mm).
11. SDII = Simple daily intensity index, annual amount of precipitation divided by the rainy days of the year (mm).

The above extreme indices were analyzed with the Mann–Kendall test [18,19] to evaluate the presence of trends in each weather station. In fact the Mann–Kendall test assess the null hypothesis H0 in which the observations are randomly distributed, against the alternative one H1 in which it is detected a trend that can be increasing or decreasing. The p-value for the test has been set with a significance level of $p = 0.05$ (95%), the smaller is the p-value, the more likely it is that the null hypothesis is false. To evaluate the magnitude of the trend, the Sen's slope estimator [20,21], which provides the slope of the trend line, was used. Furthermore some maps were performed using Geographic Information Systems (GIS) software, in particular Arc Map 10.6 with the package Geostatistical Analyst. Therefore the detected trends were studied with the kriging interpolation method which was chosen because of the best minimization of errors compared with other methods [12,22], assessing the cross validation on the basis of 5 statistical indicators (mean error, root mean square error, average standard error, mean standardized error and root mean square standardized error) [12]. In addition, a pilot project for the evaluation of the energy production of artificial reservoirs has been studied. The project was for the lake of Polverina, the dam was built in 1967 and has a storage volume of 5,800,000 cubic meters of water. The water from the reservoir through a 8800 m long pressure tunnel ends in a piezometric well from which a steel pipeline feeds the vertical axis Francis turbines of the two generating units with a power of 14,823 KW each. The lake has never been dredged and therefore in addition to the natural sedimentation, we want to assess from satellite maps landsat if there was a decrease or an increase in the area occupied by water.

3. Results

3.1. Extreme indices

The extreme indices for all rain gauges were graphically reported with the trend line that allows to assess the spatial variations on the maps. To summarize the observations the graph (Fig. 1) shows in percentage the number of rain gauges with a negative or positive trends, and if they are significant or not.

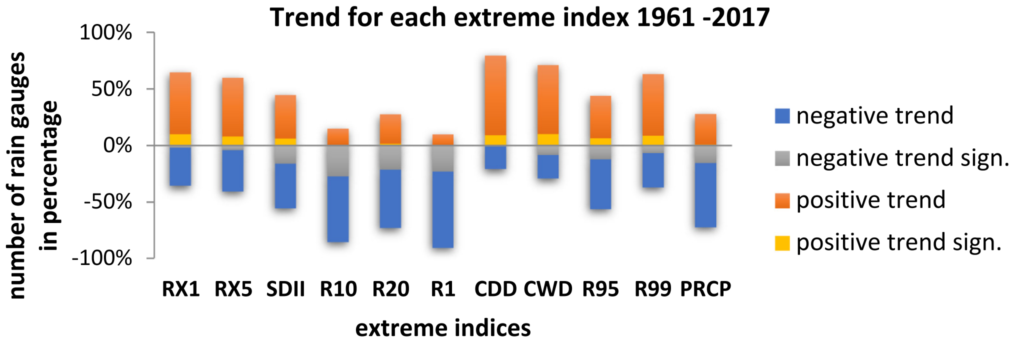

Fig. 1. Graphical summary of the trends of each extreme index over the period 1960–2017.

From the graph (Fig. 1) the indices with negative trends for number of weather stations are the following: total precipitation, number of rainy days with rain greater than 1 mm, number of rainy days with rain greater than 10 mm and number of rainy days with rain greater than 20 mm. The indices that have an equal or almost equal number of rain gauges with a positive and negative trend are SDII and R95. Instead RX1, RX5, CDD, CWD and R99 have a majority of rain gauges with a positive trend.

Table 1. Number of rain gauges with positive, negative, positive significant and negative significant trends; average of rain gauges trend and average of rain gauges with a significant trend.

Rain gauges	RX1	RX5	SDII	R10	R20	R1	CDD	CWD	R95	R99	PRCP
Positive trend	54	51	43	17	29	11	68	65	40	56	28
Negative trend	33	36	44	70	58	76	19	22	47	31	59
Positive trend sign	10	8	7	1	2	0	9	11	7	9	1
Negative trend sign	2	4	18	33	24	26	1	9	13	7	16
Average trend	0.08	0.09	0.00	−0.10	−0.03	−0.17	0.07	0.02	−0.04	0.30	−1.74
Average trend sign	0.37	0.34	0.00	−0.21	−0.09	−0.38	0.17	0.03	0.01	1.13	−5.99

Table 1 shows the exact percentages and averages of each individual extreme index. Total precipitation has 67% of the rain gauges with a negative trend and as many as 18% of these have a trend considered significant (significant trend for the positive 1%), testifying to a generalized drop in rainfall over sixty years. Similarly, the number of rainy days is emblematic, which, especially for rainfall greater than 1 mm and 10 mm, show a negative trend of 80% or more of the weather stations; while rainy days with rainfall greater than 20 mm present a negative trend, but that is reduced to 67% of the total of rain gauges, although the significant is around 30% for both indices previously treated (R10 mm, R20 mm). It can be deduced that rainy days decrease for low quantities of rain and normalize for higher quantities. Among the indices that have an undefined trend and are equally distributed as number of rain gauges, there are: the rain intensity index (SDII) and the number of days with cumulative precipitation greater than the 95th percentile of the daily amount (R95). The SDII is in a situation of almost perfect equality between the rainfall stations with a negative trend and those with a positive one, although it shows a prevalence of significant negative weather stations (20%) against the 8% of the positive ones; obviously this could testify to either a decrease in rainfall or an increase in rainy days from 1961 to 2017. As for the R95, there is a very slight prevalence of rain gauges where this index decrease. The indices in which most weather stations show a growth are: the maximum value of the daily cumulative precipitation (RX1), the maximum value of the 5-day cumulative precipitation (RX5), the maximum number of consecutive days with precipitation greater than 1 mm (CWD), the period of consecutive days of drought with precipitation less than 1 mm (CDD). The maximum value of cumulated precipitation has a positive trend from 1961 to 2017 for most of the rainfall sensors considered, both for RX1 and for RX5 testifying to the increase in maximum monthly precipitation. As for the CWD, the general trend is on average increasing, although the significant one is almost equal for number of weather stations (increasing 12% and decreasing 10%). Finally, the last index treated is the period of consecutive days of drought (CDD), in this case the rising trend is overwhelming and equal to 78%, while the weather stations with a significant positive trend are 10% of the total, however many if compared to the meager 1% of rain gauges with a decreasing one.

By averaging the extreme indices of each rain gauge, it is possible to provide some important assessment about climate change in the last 60 years. In fact, the decrease in total precipitation (PRCP) is generalized in the entire area, with an average decrease rate of 1.74% in 60 years (between all weather stations), even if calculating the average only among the weather stations with a significant trend, the decrease in precipitation reaches 6%. Nevertheless, for each extreme index, there are some rain gauges in countertrend (Fig. 2) that highlight the importance of cartographic representations that allow you to appreciate on the map the various territorial clusters [23].

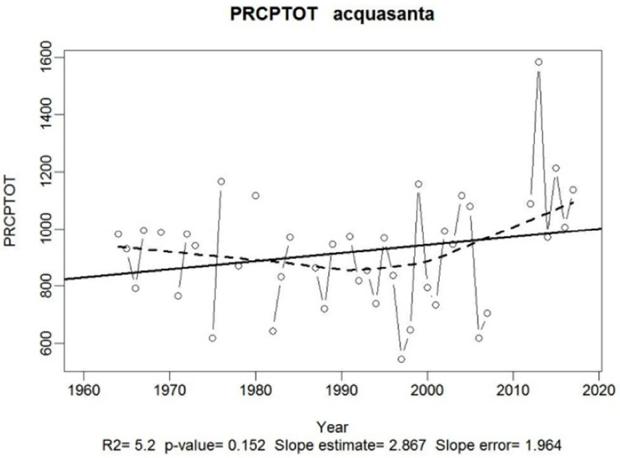

Fig. 2. Example of a rain gauge with a significant countertrend for total precipitation, compared to the other ones; the continuous line represent the linear regression (trend); the dashed line represent the polynomial regression.

The increase in the number of days with cumulative precipitation greater than the 99th percentile of the daily amount (R99) is also significant and of a certain consistency, as it increases by 1.13% for rain gauges with a significant trend and by 0.3% if the average includes all the weather stations. This analysis allowed an accurate evaluation of the extreme climate indices of each rain gauge, however, despite the exhaustive general discussion, this analysis does not provide clear indications about local conditions and areas affected by countertrends. In this context, the interpolation maps are indispensible because they allow the representation of clear and immediate results, favoring a spatial analysis of the study area. In this brief analysis an explanatory map of the total precipitation trend has been reported (Fig. 3(a)); this map clearly shows a generalized decline of precipitation in the entire region from 1961 to 2017, even if the presence of a dominant trend does not perfectly summarize the situation that can be locally different, as shown in Fig. 3(a). In fact, the increase in rainfall is mainly located in the central-southern coastal area, with some small areas in the interior to the north and in the center of the Marche region. Moreover,

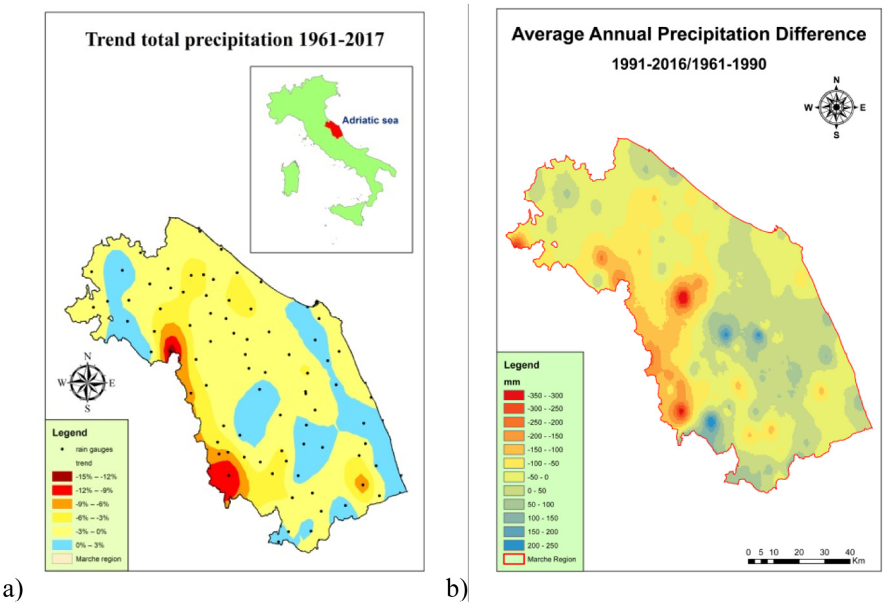

Fig. 3. (a) Trend map of total precipitation index (PRCP) from 1961 to 2017; (b) average annual precipitation difference 1991–2016/1961–1990 [23].

observing the comparison in the literature [23] of the precipitation values of the 2 climatological standard normal (1991–2020 and 1961–1990), it is possible to note how in some cases the more pronounced growth and decrease trends typical in the last period (1991–2016) have been weakened since the previous standard period (1961–1990).

3.2. *Energy and reservoirs*

The extreme indices have very significant effects both on the production of electricity and on the management of the water level from artificial lakes. Satellite maps were used to assess the variation in the territory occupied by water for the lake of Polverina. It is very interesting to note that there has been a constant reduction in the area occupied by water from 1972 to the present day (Fig. 4). This decrease was originated by the constant sedimentation that led to an advancement of the land emerged.

Analyzing the surface of the lake, from 0.64 square kilometers in 1972, it went from 0.53 in 1992, to 0.47 in 2012, to 0.42 in 2019.

4. Conclusions

From this in-depth analysis it follows that in the period 1961–2017 there is a prevalence of rain gauges affected by a decreasing trend in rainfall and rainy days (PRCPTOT, R1, R10, R20), while there is a tendency to increase extreme precipitation, rainy periods and dry periods (RX1, RX5, CWD, CDD, R99). Thus over the last 60 years there was a decrease in precipitation amounts and in the number of days of precipitation, with an increase of the days of drought and for the amount of extreme precipitation, which are responsible for the calamitous events. This situation is similar to many other analyses [24–26], although unlike almost all the surveys, a spatial report of the extreme indices is available, which allows the improved management of the phenomena. The spatialization of each index also highlights possible clusters in the area ensuring a more accurate assessment. On the other hand, with regard to the analysis of reservoirs, it is essential to be prepared for extreme events. The capacity of the reservoirs is fundamental and so is the capacity of the artificial reservoirs, as they guarantee a clean supply of energy. It follows that constant maintenance is necessary to ensure the correct capacity at all times. In conclusion, this analysis allows a very targeted management of the territory, which as a result can be easily differentiated both from the point of view of risk, accumulation of water resources and related energy, generating savings with more focused interventions.

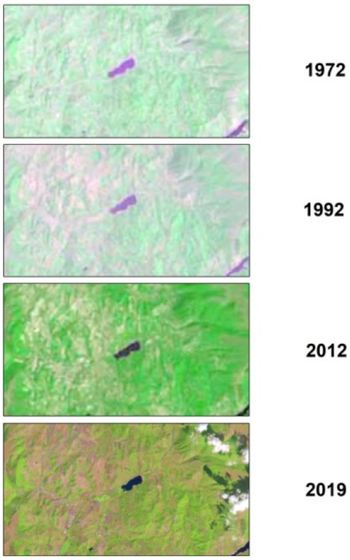

Fig. 4. Variations in different periods (1972, 1992, 2012, 2019) in the size of Polverina lake through landsat satellite images.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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