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Climatic variability and its impact on rainfall extremes and urban runoff design in Tuscany

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Abstract The distinct role of errors in the extremal statistics used to infer design storms of any duration and any return period and trend in the extremal time series are analysed to derive uncertainties affecting the estimates of the design storms. Several extremal time series collected at gauges in Tuscany, Italy, are considered. The Generalized Extreme Value (GEV) distribution is employed to compute the design storms, and the uncertainties in the estimates are derived through the maximum likelihood method. Design storms are then computed for several consecutive 30-year moving time windows (step of one year) to evaluate intrinsic (*climatological*) uncertainties in the series. The climatological uncertainties in the evaluations are connected to trends and oscillations affecting general circulation features, tentatively expressed by the North Atlantic Oscillation (NAO) index. The hydrological consequences of climate variability are shown to have a major impact on the design of hydraulic works in an urban drainage network.

INTRODUCTION

The Earth's climate is warming and is thought likely to warm in the future, as a result of changes in atmospheric CO_2 and other trace gases (Houghton *et al.*, 1990). This global warming should lead to changes in annual or seasonal precipitation. Groisman & Easterling (1994) studied the annual precipitation and snowfall changes over Canada, Russia and USA; trend analysis confirmed previous results (Diaz *et al.*, 1989; Vinnikov *et al.*, 1990) about precipitation increases in northern extratropics. Assessment of potential impacts on climate of global warming was generally focused on mean conditions, even at the regional scale (Fowler & Hennessy, 1995).

Beyond the concrete underlying reasons, some researchers (e.g. Sonechkin *et al.*, 1996) have found that most of the current climate evolution consists of pumping up and not shifting of the atmospheric system, i.e. an increase of atmospheric variability.

Recently, it was a general opinion that any climate change will lead first of all to changes in the frequency and intensity of extreme events such as floods and droughts; this was supported by some enhanced-greenhouse simulation studies analysed in terms of changes in precipitation intensity (Mearns *et al.*, 1984). Gordon *et al.* (1992), simulating an enhanced greenhouse with the four atmospheric-layer GCM of the Australian Scientific and Industrial Research Organisation (CSIRO4), observed an increase in average precipitation intensity much more widespread and spatially coherent than the increase in total precipitation. Etkin (1995) observed that changes in the monthly patterns of tornado occurrence in Canada correlate well with mean monthly temperature anomalies, concluding that tornado frequency might well increase with climate warming.

Extreme rainfall regimes can be described by means of the associated design storms. The large-scale circulation features underlying the occurrence of excessive rainfall events are very complex and can be only tentatively identified unless very complex analyses are performed on circulation patterns.

In this work the role of statistical techniques and climatic shifts and variations are investigated in respect of the uncertainties affecting the estimated design storms at several sites in Tuscany, Italy, and the consequences in terms of hydraulic design are stressed. Climatic shifts and variations are tentatively expressed by the series of the North Atlantic Oscillation (NAO) index, which preliminary analyses have shown to have a distinct effect on the average and extreme regional climatic features.

STUDY AREA

The Tuscany region (Fig. 1) is characterized by an extreme heterogeneity in morphological and climatic features varying from the plain areas near the coastline and around the main river valleys to the hilly and mountainous areas (Appennine and other chains). Climate regimes are several and their distribution (from the Mediterranean to the temperate warm and cool) follows the latitude and elevation gradients and the distance from the sea.

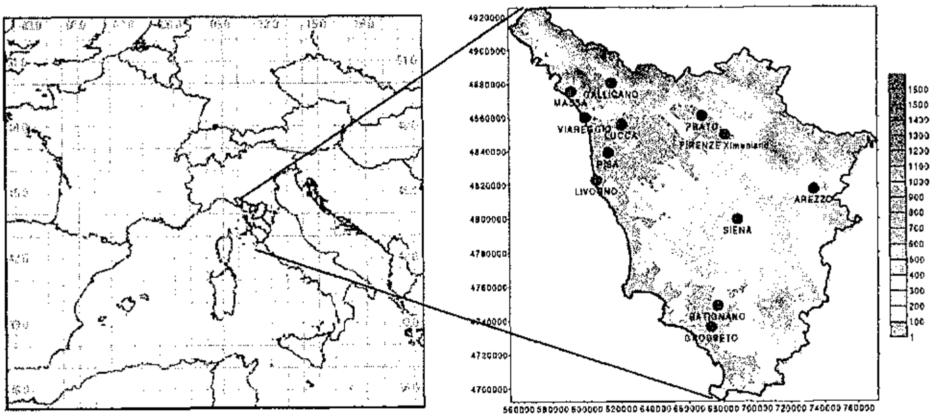

Fig. 1 Tuscany in Europe and a Digital Terrain Model of Tuscany. The points indicate the 12 raingauges used.

MATERIALS AND METHODS

Annual extreme rainfall time series with duration 1 and 3 h at 12 raingauges from the network of the Italian National Hydrographic Service (Fig. 1) have been used to study the time fluctuations of the series in the period 1935–1994 (Table 1).

Table 1 List of raingauges time series utilized in the work.

Raingauge station	Time series	Coordinate Utm x	Coordinate Utm y	Elevation (m)	Basin
Arezzo	1935–1992	733980	4817170	277	Arno
Batignano	1951–1992	677040	4748740	163	Ombrone
Firenze	1935–1993	681580	4849500	75	Arno
Gallicano	1935–1992	615380	4880055	186	Serchio
Grosseto	1935–1992	672990	4736055	6	Ombrone
Livorno	1935–1995	606140	4822595	3	Calambrone
Lucca	1935–1994	620990	4855580	20	Serchio
Massa	1935–1995	591800	4875450	65	Frigido
Pisa	1935–1992	613017	4838671	3	Arno
Prato	1935–1993	668480	4860647	74	Arno
Siena	1935–1993	688975	4799420	380	Ombrone
Viareggio	1945–1994	599770	4859630	3	Versilia

Utm: Universal Transverse Mercator.

The first analysis carried out on the extremal time series concerns the detection of an increasing or decreasing trend by means of the Mann-Kendall rank non-parametric test for trend (Kendall & Ord, 1990), at the 5% significance level. This analysis is preliminary and generally not conclusive: when the null hypothesis is accepted it is reasonable to exclude the occurrence of a definite trend in the time series.

A more powerful technique is the derivation of the design storms for varying time samples (Keim & Muller, 1992). Extreme rainfall series derived from data collected at four selected gauges (for the two main Tuscany basins, Arno and Ombrone) are processed by means of the Generalized Extreme Value (GEV) distribution (Kottegoda & Rosso, 1997). Design storms and associated statistical uncertainties for each raingauge, characterized by the duration of 3 h and return period of 15 years, are derived using a 30-year moving time window, leading to a time series of design storms and associated estimate errors.

The hypothesis that some part of the time variations of the frequency and magnitude of extreme events can be explained on the basis of the changes in atmospheric variability is tentatively checked by means of the comparison of the time series of extreme rainfalls against the time series of the standard deviation of the NAO index during several consecutive time periods.

The NAO index is evaluated as the normalized difference of sea level pressures in Iceland and Gibraltar, Spain (Hurell, 1995); this feature of the large-scale atmospheric circulation has often been shown to distinctly affect the Mediterranean climate.

RESULTS

The Mann-Kendall test for trend applied to the 1 and 3 h duration annual extreme rainfall time series at 12 selected raingauges suggests the occurrence of a trend only for three gauges: Firenze (increase), Batignano (decrease in 3 h) and Siena (decrease), while at the other gauges no trends are detected. This test of course accounts for any event, and the lowest one weights just as the highest one (Table 2).

On the other hand, the analysis of the time series of design storms (15 years return period and 3 h duration) collected at those gauges suggests an increasing trend for three of them (Firenze, Pisa and Grosseto) and above all an increase in the amplitude of the uncertainties of the estimated design storms (dotted lines in Fig. 2). The statistics leading to the design storms accounts almost only for the highest events and this consideration explains the discrepancy in the results.

The role of the NAO index variability is evaluated by means of a comparison between the standard deviation of the NAO index itself computed using a 30-year moving time window and the times series of extreme rainfalls (3 h duration) and design storms (15 years return period and 3 h duration) at Firenze (Fig. 3). In this Figure, the 30-year moving time window of NAO index variability and design storms are shown centred on the fifteenth year specified by the abscissa to underline the relationship with the extreme rainfalls.

Table 2 Results of Mann-Kendall test for trend applied to the extreme rainfall series.

Site	Duration	Value of z	Significance level (Upper threshold: 0.05)	Series with significant trend
Arezzo	1 h	−0.10	0.28	No
	3 h	−0.007	0.93	No
Batignano	1 h	−0.15	0.14	No
	3 h	−0.22	0.03	Yes (decrease)
Firenze	1 h	0.2	0.02	Yes (increase)
	3 h	0.18	0.03	Yes (increase)
Gallicano	1 h	−0.14	0.10	No
	3 h	−0.08	0.37	No
Grosseto	1 h	0.1	0.29	No
	3 h	0.11	0.23	No
Livorno	1 h	−0.076	0.41	No
	3 h	−0.0013	0.98	No
Lucca	1 h	−0.02	0.74	No
	3 h	0.04	0.63	No
Massa	1 h	−0.07	0.41	No
	3 h	−0.021	0.8	No
Pisa	1 h	0.04	0.65	No
	3 h	0.05	0.56	No
Prato	1 h	−0.0007	0.99	No
	3 h	−0.0002	0.98	No
Siena	1 h	−0.23	0.008	Yes (decrease)
	3 h	−0.19	0.03	Yes (decrease)
Viareggio	1 h	0.0009	0.92	No
	3 h	−0.02	0.82	No

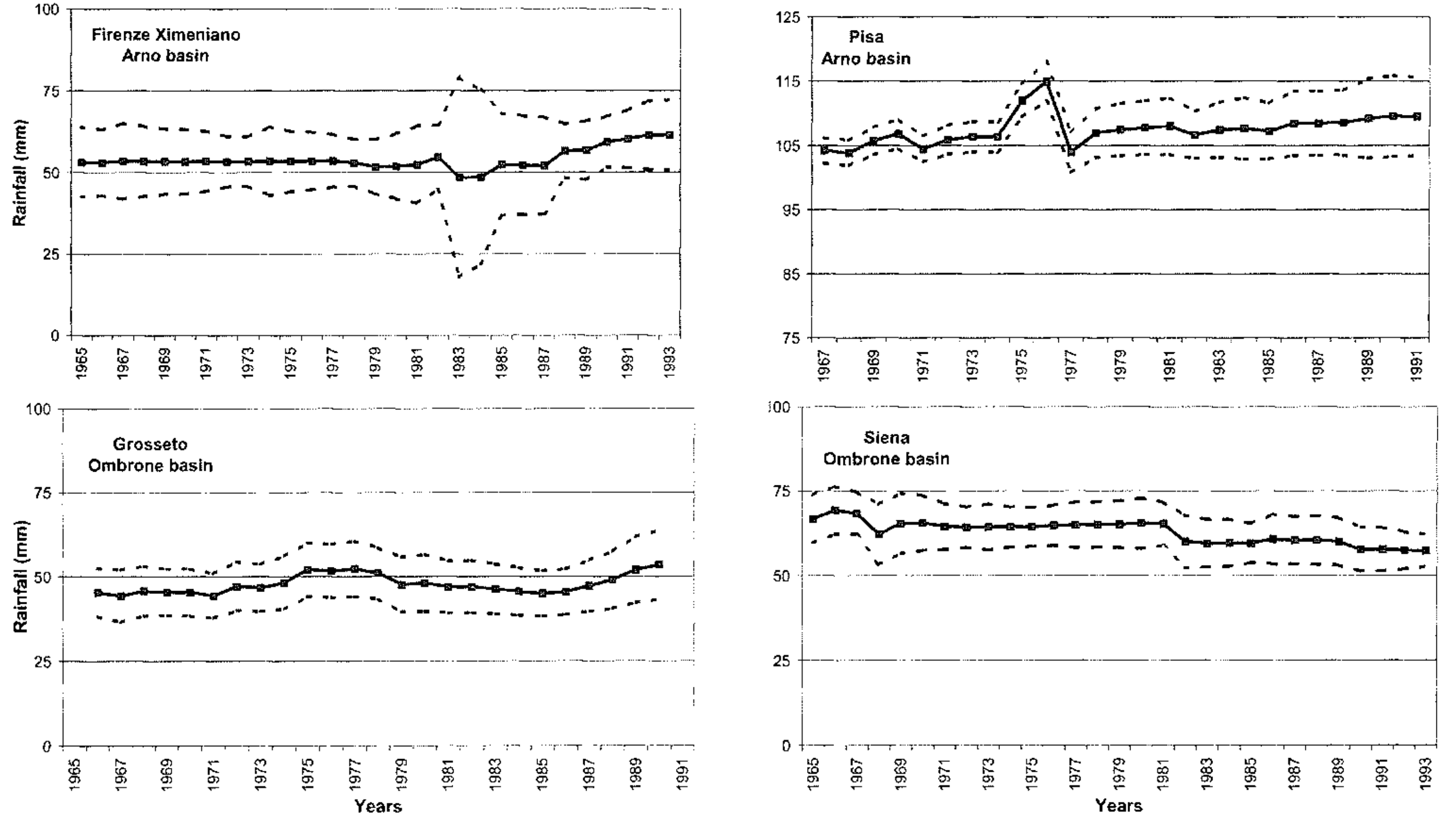

Fig. 2 Design storms time series and uncertainties (dotted lines) at 3 h duration, 15-year return period using a 30-year moving window at four raingauges in Tuscany.

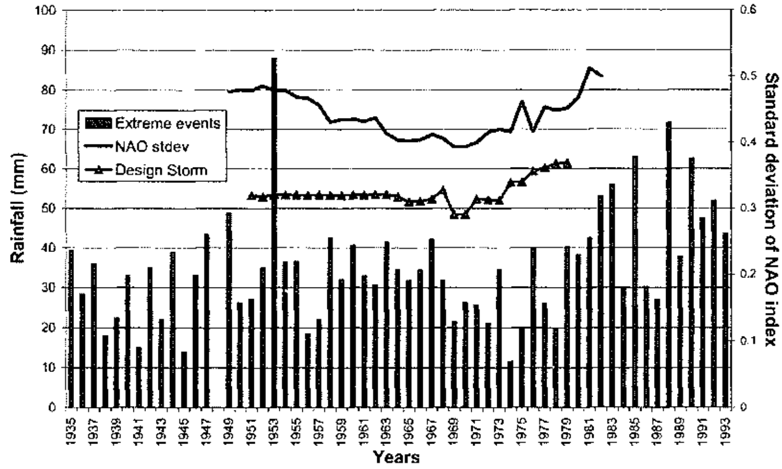

Fig. 3 Standard deviation of NAO index (30-year moving window), annual extreme rainfalls (3 h duration) observed at Firenze and design storms time series (3 h duration, 15-year return period). NAO index and design storms are centred on the 15th year specified by the abscissa.

It is apparent that most of the highest rainfall extremes occurred during high NAO variability periods.

HYDRAULIC DESIGN OF AN URBAN DRAINAGE NETWORK

In order to find the consequences of a change in the design storm as evidenced herein, a hypothetical urban drainage network has been designed. The layout of the network is shown in Fig. 4; it is composed of 122 pipes each serving a sub-basin of extension $A_i = 5$ ha. The length of individual pipes is 300 m in the lateral branches and 500 m in the main line that is represented by the horizontal line in Fig. 4. The slope of all the network is constant and equal to 0.2%. The runoff coefficient has been assumed constant and equal to 0.5. The network has been designed by using the so called "Italian method" that is largely used in Italy; an improved version of the model described by Milano *et al.* (1996) has been used. A program called VIMUDD (Varied

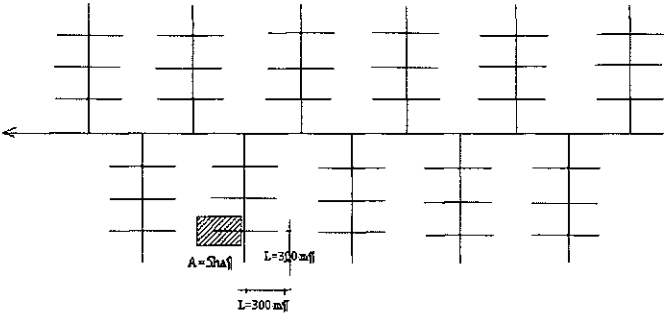

Fig. 4 The urban drainage network.

Italian Method for Urban Drainage Design) has been developed and used for the calculations.

Hourly maximum data from the station of Firenze have been used. The elaboration by means of the GEV distribution and the calculation of the design storm with a return period of 30 years is reported in Fig. 5 in which are represented the rainfall depth for both the cases of progressive and movable window. In the movable window case, a return period of 30 years has been chosen (valuable in hydraulic design of urban networks) and the design data start from the year 1965.

Analysis was carried out in the case of design storms obtained for both progressive windows "pw" (all the years up to the considered one are used in the time series to compute the design storm assigned to the last year considered) and movable windows "mw" (only the last 30 years of the series are used to compute the design rainfall assigned to the last year considered each time).

The rainfall depth–duration curves have been obtained relative to some particular years (i.e. for the years 1950, 1965, 1980 and 1993 for the case of progressive window and 1965, 1980 and 1993 for the case of moving window).

Rainfall depths for a duration less than 1 h are obtained by means of those of 1 h multiplied by known ratios valid for the considered location (e.g. $h_{30'}/h_{1h} = 0.856$). The results of the calculations are reported in Fig. 6. Figure 6(a) shows the ratio R_q (ratio between the value of the discharge relative to a specific pipe in one year and the discharge for the same pipe calculated relatively to a year chosen as reference) with respect to the total area A_t drained by the considered pipe of the network. Figure 6(b) represents the same graphs in terms of the ratio R_d between the calculated diameters of the pipes.

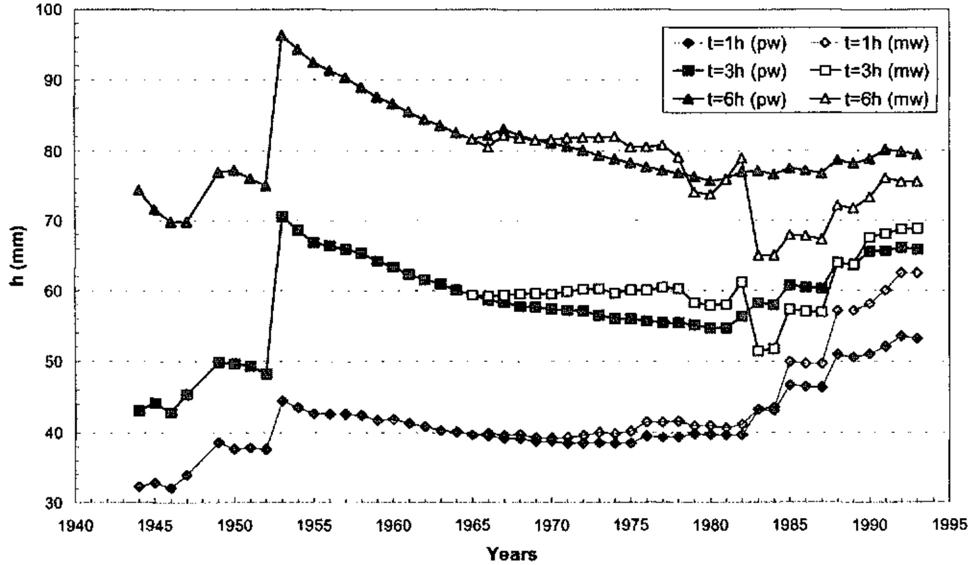

Fig. 5 Design storm for rainfall duration of 1, 3 and 6 h and 30 years of return period for the case of both moving ("mw") and progressive ("pw") time windows for the Firenze gauge (Ximenian Observatory).

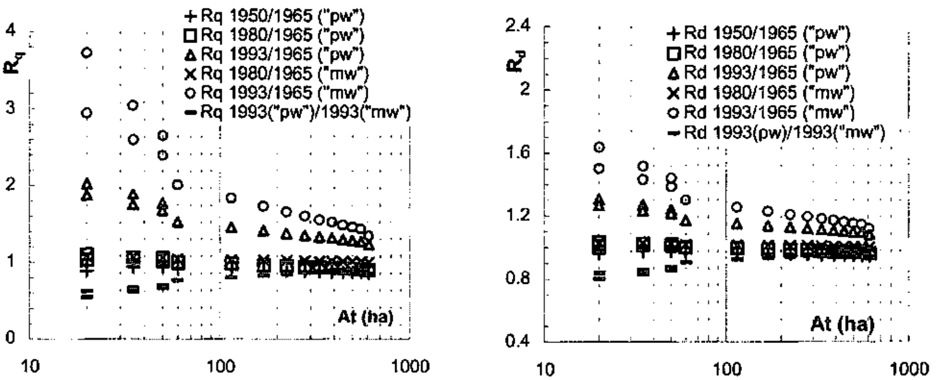

Fig. 6 Ratios R_q and R_d calculated for the years reported in the legend for the urban network of Fig. 4 as a function of the total area A_t drained by each pipe. Data are relative to design storm obtained with progressive window "pw" and moving window "mw".

Looking at the situation of the year 1993 in respect to 1965 (reference year) one can see an increase in the discharge up to four times for pipes that drain little areas and an increase of about 50% in the peak flow for pipes that drain larger areas. there are minor differences in the diameters of the pipes but always in the order of 15% for the bigger areas.

CONCLUSION

The uncertainties in the evaluation of design storms in Tuscany, Italy, were analysed with the aim to evaluate the intrinsic statistical errors and to identify significant atmospheric physical mechanisms underlying the time variation of the estimates.

The Generalized Extreme Value (GEV) distribution has been employed to derive the absolute values of the design storms and the associated statistical uncertainties.

The repeated computation of the design storms in time has allowed the analysis of the variability of the estimates during the recent past. The generally increasing trends contrast with the results of a popular test for trend applied to the extreme rainfall series, which suggests the peculiar statistical behaviour of the most intense rainfall events.

The analysis of the large-scale climatic features with regard to the magnitude of the annual extreme rainfall was aimed at checking the hypothesis that increasing atmospheric variability leads to increasing extreme rainfalls. The atmospheric circulation was tentatively expressed by the North Atlantic Oscillation (NAO) index: its standard deviation during a 30-year moving time window was compared with the magnitude of the extreme rainfalls, showing an overall effect of atmospheric variability on extreme events.

The time change of the estimated design storms was shown to have a large impact on peak flow and the design of channels and pipes in a typical urban drainage network.

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