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Forest cover influence on flood assessment in Italian catchments

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Abstract

The paper aims at evaluating to what extent forest cover could affect the flood peak frequency and magnitude in Italian catchments. The analysis is restricted to evaluating the component of the runoff coefficient which cannot be captured by the catchment lithology alone. A preliminary data mining is performed on data of 75 catchments distributed from South to Central Italy. Cluster and correlation structure analyses are conducted for distinguishing forest cover effects within sample sets of catchments characterized by hydro-morphological similarities. We propose a method for correcting the bias of the runoff coefficient estimated from the catchment lithology only, by accounting for the effect of forest cover. The bias correction becomes significant for small mountainous catchments, characterised by larger forest cover fraction and lower critical rainfall depth. Consistently with what suggested in previous studies, the bias correction decreases as the rainfall depth and return period increase.

1 Introduction

Forest patterns are subjected to significant changes worldwide, with different trends, depending specifically on local socio-economic and environmental factors. There are some areas of the world where forest cover has been reducing as results of logging and land claim for agriculture or urban infrastructures. Other areas, such as Mediterranean landscapes, forest patterns are experiencing a significant expansion in the last decades, as consequence of the abandonment of the agricultural lands in marginal areas, mostly located in hilly and mountainous areas, providing space for the natural development of forest (Agnoletti, 2002; Mazzoleni et al., 2004).

The effect of forest cover on flood regime has been largely studied (e.g. Sorriso-Valvo et al., 1995; Burch et al., 1996; Robinson, 1989; Robinson et al., 2003; Devito et al., 2005; Cosandey et al., 2005) and it is still a controversial argument (Bosch and Hewlett, 1982; Bruijnzeel, 1990; Cognard-Plancq, 2001). Despite the public perception that

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forests reduce flood hazard, there is a large sector of the scientific community asserting that forest cover, although being relevant within the hydrological cycle and in catchment response to small storms, does not contribute significantly to mitigate floods during extreme rainfall events (e.g. Calder et al., 2007; van Diijk et al., 2008). This opinion is also prompted by influential United Nation Policy documents (e.g. FAO-CIFOR, 2005; Hamilton, 2008), which confine the public perception to a misconception conceived by those who are not directly involved in studying hydrological extreme events, including environmentalists and conservation agencies.

According to recent studies, forest cover could be effective in reducing flood discharge during more frequent and thus less intensive rainstorms (López-Moreno et al., 2006), while it is unlikely able to reduce significantly peak flows generated by rainfall events with return periods larger than 10 yr (Bathurst et al., 2011). Other recent studies pointed out that some contrasting conclusions about the relation between forests and floods is the result of catchment paired studies, which do not account for the effect of forest cover on the non-linear dependency between magnitude and frequency of floods (Alila et al., 2009; Lewis et al., 2010).

Experimental studies show that forest cover reduces the annual catchment discharge as result of increased rainfall interception, increased transpiration during interstorm periods and higher permeability of forest soil (e.g. Bosch and Hewlett, 1982; Calder, 1990; Cornish, 1993; Rowe and Pearce, 1994; Stednick, 1996; Fahey and Jackson, 1997; Bruijnzeel, 2004). These effects are expected to be less relevant during extreme rainfall events, although limited field experiments have been conducted for quantifying the impact of forests on the catchment response to rainfalls with low frequency. Moreover, the effect of forest cover on flood peaks is difficult to be isolated, being the flood discharge influenced by other factors, such as initial catchment conditions, forestry and agricultural activities, road constructions, etc. (Moore and Wondzell, 2005).

Assessing magnitude and frequency of flood peaks is fundamental for planning and design structural and non-structural risk mitigation actions. Flood frequency analysis aims at estimating the probability distributions of flood peaks, enabling one to define the

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design flood for a given return period. Time series of flood peaks, which are employed for a direct assessment of flood frequency and magnitude, are generally available only for a limited number of catchments even in developed countries.

Rational formula is widely applied as an indirect method for assessing flood peaks in ungauged catchments. The annual flood peak, Q_{T}, for a given quantile of the cumulative probability distribution or return period T, can be expressed as

$$Q_{\mathrm{T}} = C \cdot \frac{h_{c,\mathrm{T}}}{t_c} \cdot A \quad (1)$$

where: $h_{c,\mathrm{T}}$ is the annual maximum of rainfall depth with a return period T, in a time interval t_c equal to the catchment concentration time, according to the rainfall intensity-duration curve; C is the runoff coefficient, which combines the effect of surface storages, infiltration losses and catchment flood dampening.

The parameters of the rational formula are often regionalized, by exploiting hydrological similarities among catchments and the scaling properties of flood and rainfall statistics (e.g. Cunanne, 1988; Gupta and Waymire, 1990). Runoff coefficient is generally estimated through empirical regressions of the observed annual peak discharge to rainfall ratios with respect to selected catchment parameters, such as the soil properties, land use and catchment morphology. Soil and land use properties are identified by those features that can be easily distinguished at regional scale. Soil properties are defined by the lithology, which is exploited as a surrogate of the soil permeability, whereas land use is often classified in two categories including forested and non-forested areas.

In this study we evaluate the influence of forest cover fraction on the regional estimate of the flood peak in Italian catchments. Specifically, we investigate to what extent the forest cover can explain the residual variability of runoff coefficient at regional scale, which cannot be captured by the catchment lithology only.

The paper is structured as follows: the following section presents the data source and the study catchments; the third section illustrates the methodology employed to infer the dependency of the runoff coefficient from the forest cover; in the fourth section we

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present a new simplified conceptual model for assessing runoff coefficient accounting for the forest cover.

2 Study catchments

We examine data of 75 catchments in Central and Southern Italy, distributed from Sicily and Tuscany (Fig. 1). For each of these catchments we evaluated the parameters which are widely used for computing the flood peak according to the Italian flood assessment procedure (Birtone et al., 2008; Calenda et al., 1997, 2003; Di Stefano and Ferro, 2007; Preti et al., 1996; Preti, 2004; Rasulo et al., 2009; Regione Toscana, 2007).

At regional scale, the lithological features of the catchments are grouped according to two or three different classes corresponding to different degrees of permeability (e.g. Fiorentino and Iacobellis, 2001): (1) highly permeable lithoid complexes constituted by sediments and rocks with porosity based permeability, rocks with fissure-based permeability, and those having a mixed permeability; (2) lithoid complexes with medium permeability constituted by permeable lithologies which outcrop on a steep surface or lithologies more or less fractured and filled by clayey material; and (3) impermeable lithoid complexes represented by clayey formations. In some regions, runoff coefficient is generally estimated from catchment lithological features only, while land use is neglected (e.g. Calenda et al., 2003).

The spontaneous vegetation and land cover in Central and Southern Italy is quite consistent with climatic features and morphological characteristics of the territory. Arid and semiarid zones are characterized by scarce vegetation, which gradually turns into subhumid Mediterranean undergrowth and pasture land, to finally reach the mountain woods of humid and hyperhumid areas (Fiorentino and Iacobellis, 2001).

In this study, in order to assess the component of the runoff coefficient which might be explained by forest cover, we explore the dependencies among the following parameters, which are employed in the rational method as generally applied in Italy:

- catchment extent (A);
- catchment mean elevation (Z_m) above catchment outlet;
- catchment concentration time (t_c);
- critical rainfall depth (h_c), corresponding to the maximum annual rainfall depth within a time interval equal to (t_c);
- the runoff coefficient estimated from rainfall and runoff data (C_{obs});
- the runoff coefficient (C_{L}) estimated from the catchment lithology only;
- the component of the runoff coefficient not explained by the catchment lithology, $\Delta C = (C_{\mathrm{obs}} - C_{\mathrm{L}})/C_{\mathrm{obs}}$;
- catchment fraction with highly permeable lithoid complexes (S_p);
- forest cover fraction (S_b).

Catchment concentration time is indirectly estimated from catchment morphological properties, according to the *Giandotti* empirical formula, widely employed in Italian flood studies (Benini, 1990; Ferro, 2006):

$$t_c = \frac{4\sqrt{A} + 1.5L}{0.8\sqrt{Z_m}} \tag{2}$$

where A is in km^2 and L is the main river length in km.

The *observed* runoff coefficient is obtained by calibrating the rational formula against the flood peak value $Q_{\mathrm{T,obs}}$ with a reference return period $T = 20$ yr, as directly estimated from discharge data, mostly collected from 1960 and 1990 (e.g. Ferro and Porto, 2006):

$$C_{\mathrm{obs}} = \frac{Q_{\mathrm{T,obs}} \cdot t_c}{h_{c,\mathrm{T}} \cdot A} \tag{3}$$

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The forest cover S_b employed in this study is estimated as the average value from land use maps of the same period analysed for assessing the *observed* runoff coefficient.

Runoff coefficient C_L is derived according to different regional regression models within the examined regions. However, as depicted in Fig. 2, C_L is highly correlated by S_p, which explains almost 80 % of the overall variability of C_L among the examined catchments.

3 Data mining

3.1 Preliminary data analysis

We first explored the dataset to assess the main hydro-morphological features of the catchments which might be relevant for the present study. In particular, the following analyses have been conducted:

- histogram analysis;
- non parametric correlation analysis based on Spearman ranking among the hydro-morphological variables;
- dependence analysis of ΔC from each of the hydro-morphological variables and the forest cover fraction.

Histograms show the large variability of the hydro-morphological features of the examined catchments (see Table 1 and Fig. 3). A large number of catchments have an extent smaller than 1000 km^2 and a surface fraction with high permeability smaller than 20 %.

The analysed hydro-morphological variables exhibit significant cross-correlation (see Table 2), while none of these variables appears significantly correlated with ΔC. As expected, there is a significant positive correlation between A, t_c, and h_c. In fact,

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smaller catchments are characterised by higher slope, smaller concentration time and smaller critical rainfall depth.

We also conducted an exploratory analysis among terns of variables $\Delta C - Y - S_b$ by selecting different hydro-morphological variables Y. In Fig. 4, the contour maps, colored according to a grey-scale, represent the variability of S_b values with respect to the variable ΔC along the x-axis and the hydro-morphological variable Y along the y-axis.

The contour maps show that there is not any general dependence applicable to the entire data set. These configurations indicate the need to explore the dependence between S_b and ΔC within group of basins showing some hydrological similarities.

3.2 Cluster analysis

Catchments are grouped according to a *k-means* cluster analysis following two different procedure: (i) clustering based on individual hydro-morphological variable, in order to assess the role of each parameter in the $S_b - \Delta C$ relation; (ii) clustering including all parameters (hereafter indicated as *HP* case), to explore the effect of the reciprocal interaction among different parameters in the $S_b - \Delta C$ relation. Catchment clusters are indentified by maximizing the mean of the silhouette plot (*Sh*), which is a distance metric based on the squared of the Euclidean distance. *Sh* indicates the distance of each catchment value within a given cluster from the catchment values belonging to other clusters. This distance varies from +1 to −1: +1 indicates that the catchment value is very distant from the other cluster values; 0 indicates that the membership of a given catchment value to the assigned cluster is not clearly distinguished; −1 if the catchment value is assigned to the wrong cluster. Examples of silhouette plots are depicted in Fig. 5.

Table 3 shows the *Sh* for a number of clusters between 2 and 5, for each of the parameter examined and for the *HP* case. The value in bold indicate the *Sh* threshold value above which further clustering does not add much to the catchment classification. We identified 2 clusters for the catchment extent A and three clusters for each of the remaining 5 parameters. When we analysed all parameters (*HP*), we selected 2 clusters.

Tables 4 and 5 show mean and standard deviation of the parameters within each cluster. The differences between clusters have been also verified by a statistical test on the mean value of the hydro-morphological parameters belonging to each cluster, with significance level 0.01. All clusters, except in *HP* case, are significantly different in mean, i.e. the null hypothesis that they belong to the same population can be rejected with a significance level equal to 0.01.

The value range of each parameter represented within each cluster is identified by the quantiles 0.05 and 0.95 of the corresponding sample distributions in each cluster, as illustrated in Tables 6 and 7. These ranges do not overlap when the clusters are identified by analyzing one parameter at a time, except for the clusters identified with the parameter *A* only. When all parameter are considered in the clustering process (*HP*), the distinction of each cluster is more difficult, since value ranges overlap, as we might expect by examining the corresponding mean and *std* values (see Table 5).

3.3 Correlation structure

We calculated the Spearman's rank correlation and the corresponding p-values between $S_b - \Delta C$ for each combination of parameters and for each cluster indentified. Significant correlation occurs for the cluster with the largest number of samples for each fixed parameter. This suggests that for those clusters with a limited number of samples, the correlation might be underestimated. For the *HP* case no significant correlation has been identified.

We also assessed the dependence between ΔC and S_b by linear regression, in order to evaluate the component of the runoff coefficient which could be explained by S_b. The goodness of fit of the linear models are estimated by sum of squared errors (SSE), coefficient of determination (R^2), coefficient of determination adjusted for the number of predictors ($adjR^2$) and root mean square error (RMSE). The regression analysis is applied to three different sets: (i) including all (S_b, ΔC) couples belonging to

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the examined cluster (*LRtot*); (ii) including (S_b, ΔC) couples which values of the corresponding hydro-morphological parameters are below its intra-cluster average (*LRinf*); (ii) including (S_b, ΔC) couples which values of the corresponding hydro-morphological parameters are above its intra-cluster average (*LRsup*). The trend significance is estimated with the Mann-Kendall test. Results are listed in Table 9. Figure 6 shows the computed regression lines for the selected clusters.

The possibility to explain ΔC with S_b is highly variable, particularly in the case all catchments belonging to a cluster are included in the regression analysis (*LRtot*). Higher R^2 can be gathered if only those catchments in the lower range of the corresponding parameter values are included in the regression analysis (*LRinf*). The best fitting is obtained for *LRinf* within *CL-3 fixed*(Z_m), *CL-2 fixed*(h_c) and *CL-3 fixed*(S_p).

The regression lines show that ΔC is always decreasing for increasing forest cover fraction, as expected. The highest linear correlation is observed within *CL-2 fixed*(h_c). It is also interesting to observe that there is a high linear correlation for all three sub-sets of *CL-2 fixed*(h_c), with consistent regression coefficients m and q. Moreover, within *CL-2 fixed*(h_c) it is also possible to observe the highest non-parametric correlation with ΔC (see Table 8).

These results suggest the possibility to explore new models for predicting the runoff coefficient, accounting for the forest cover S_b, at least within catchments classes which can be considered homogeneous with respect to h_c.

4 A new simple conceptual model for runoff coefficient assessment

Predicted values of the runoff coefficients from the catchment lithology (C_L) are generally negatively biased with respect to the observed runoff coefficient C_obs. Moreover, the difference $C_\mathrm{obs} - C_\mathrm{L}$ tends to be higher for smaller catchments, as for example illustrated in Fig. 7, where the difference $C_\mathrm{obs} - C_\mathrm{L}$ is plotted versus the catchment concentration time.

This suggests that there are larger margins for correcting the prediction of the runoff coefficients in smaller basins, which are generally those basins characterized by larger forest cover fractions, as the outlets of smaller catchments are mostly located in mountainous areas.

A significant linear correlation can be found between $C_{obs} - C_L$ and the ratio $S_b/h_{c,T}$ (Fig. 8a) This linear correlation increases if we restrict the analysis to individual clusters, such as *CL-1 fixed* (t_c) (Fig. 8b).

This result suggests the possibility to modify the rational formula as follows:

$$Q_T = C_{mod} \cdot \frac{h_{c,T}}{t_c} \cdot A = \left(C_L - \frac{V_b S_b}{h_{c,T}} \right) \cdot \frac{h_{c,T}}{t_c} \cdot A \quad (4)$$

According to Eq. (5), we adjust the runoff coefficient estimated from the catchment lithology only (C_L) by reducing it by a factor $V_b S_b / h_{c,T}$, representing conceptually an additional abstraction loss of the total rainfall due to the storage capacity of the forested soils, with a specific volume equal to V_b.

By minimizing the squared root difference

$$\sum_i (C_{obs} - C_{mod})^2 = \sum_i \left(C_{obs} \cdot \Delta C + \frac{V_b S_b}{h_c} \right)^2 \quad (5)$$

we obtained an optimal $V_b = 13.9$ mm for the entire data set.

Figure 9 compares the observed (C_{obs}) to the predicted runoff coefficients C_L and C_{mod}. Prediction performances are compared by computing the following statistics:

$$\begin{aligned} \text{ME} &= \frac{\sum_{i=1}^{N} \text{err}_i}{N} \\ \text{MAE} &= \frac{\sum_{i=1}^{N} |\text{err}_i|}{N} \\ \text{RMSE} &= \sqrt{\frac{\sum_{i=1}^{N} (\text{err}_i)^2}{N}} \end{aligned} \quad (6)$$

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where N is the total number of catchment data and err_i represents the deviation between the observed and the predicted runoff coefficients, $\text{err}_i = (C_{\text{obs}} - C_{\text{mod}})$ or $\text{err}_i = (C_{\text{obs}} - C_{\text{L}})$. As illustrated in Table 10, on average there is a slight improvement of the predicted runoff coefficient. However, a significant bias correction is gained with C_{mod} particularly in smaller catchments, which are those characterized by higher forest cover fraction. This aspect is illustrated in Fig. 10, which shows how the bias correction reduces as the catchment concentration time decreases.

Further improvements (regression line in Fig. 9 $C_{\text{mod}} = 0.978\ C_{\text{obs}}\ R^2 = 0.8659$) can be obtained if different V_{bi} values are calibrated for catchment clusters with respect to t_c:

- $V_{\text{b1}} = 15.4$ mm for CL-1 fixed(t_c);
- $V_{\text{b2}} = 9.6$ mm for CL-2 fixed(t_c);
- $V_{\text{b3}} = 4.4$ mm for CL-3 fixed(t_c).

The result that the calibrated V_{bi} values decrease for increasing value range of t_c is consistent with the observation that the effect of forest cover decreases in larger catchments, i.e. in catchments characterized by larger concentration time, where forest cover is more fragmented and the flood response is dominated by other hydrological and hydraulic processes (e.g. Bathurst et al., 2011).

5 Conclusions

The analysis of data from 75 Italian catchments evidenced that the role of forest cover is not negligible when predicting flood peak with rational formula.

We evaluated to what extent the runoff coefficient estimated from the catchment lithology only, can be improved by including the forest cover fraction as predictor. The dependency of the runoff coefficient from the forest cover can be isolated within clusters

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of catchments exhibiting similarities with respect to those hydro-morphological parameters contributing to the prediction of the flood peak within the rational formula. In fact, given the high cross-correlation among forest cover and the other hydro-morphological parameters, the effect of forest cover might be masked or indirectly included in other parameters.

We suggest a new simple conceptual model for estimating catchment runoff coefficient by accounting for the effect of the forest cover. The model conceptualises the effect of the forest cover as an additional storage capacity. As the forest abstraction capacity is scaled by design rainfall depth employed in the rational formula, $h_{c,\mathrm{T}}$, the effect of this storage capacity or the concentration time t_c tends to decrease as the storm frequency decreases.

This study focused the analysis to rainfall and discharge data with a reference return period of twenty years. Further investigations should be devoted to understanding the dependency of the runoff coefficient from the return period and as forest cover effect reduces with increasing return periods. Also, in this study we did not account for the spatial cross correlation between lithology and forest cover, as is possible that forest cover is more frequent within assigned lithological classes. This would be help for better isolating the forest cover fraction on the flood peak. Eventually, it is also interesting to explore weather different values of the forest capacity V_b could be calibrated for different forest formations or for different climatic indices, accordingly to Fiorentino and Iacobellis (2001).

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Table 1. Mean (μ) and standard deviation (*std*) of the hydro-morphological variables for the examined catchments.

	A (km^2)	Z_m (m a.s.l.)	t_c (h)	h_c (mm)	S_p (%)
μ	712	383	9.2	76.5	25.5
std	1129	177	7.2	25.4	29.6

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Table 2. Spearmann rank (r_k) correlation and corresponding *p*-values (p) among the hydro-morphological variables for the examined catchments.

r_k\p	A	Z_m	t_c	h_c	S_p	ΔC
A	1	*0.003*	*0*	*0*	*0.048*	*0.216*
Z_m	0.332	1	*0.230*	*0.435*	*0.113*	*0.076*
t_c	0.968	0.14	1	*0*	*0.068*	*0.115*
h_c	0.731	0.091	0.744	1	*0.410*	*0.430*
S_p	0.228	0.184	0.211	0.096	1	*0.394*
ΔC	0.144	−0.205	0.183	0.092	0.099	1

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Table 3. *Sh* values for different clustering levels. In bold *Sh* threshold value above which further clustering is not acceptable.

	Sh(CL2)	*Sh(CL3)*	*Sh(CL4)*	*Sh(CL5)*
A	**0.906**	0.874	0.79	0.785
Z_m	0.754	**0.756**	0.747	0.729
t_c	0.754	**0.812**	0.71	0.748
h_c	0.747	**0.77**	0.719	0.706
S_p	0.835	**0.838**	0.81	0.795
HP	**0.9**	0.858	0.708	0.569

Table 4. Catchment clustering based on the analysis of single parameters. Statistics of the parameter values in each cluster: mean μ, standard deviation (*std*) and number of samples (*n*).

	$\mu(CL1)$	$std(CL1)$	$n(CL1)$	$\mu(CL2)$	$std(CL2)$	$n(CL2)$	$\mu(CL3)$	$std(CL3)$	$n(CL3)$
A	299.98	322.58	64	3114.4	1161.2	11	–	–	–
Z_m	735.56	67.082	10	256	61.475	42	463.11	57.115	23
t_c	3.858	1.571	40	11.965	2.611	25	23.616	4.173	10
h_c	33.576	5.295	11	66.993	8.784	31	99.767	11.254	33
S_p	87.461	11.176	8	46.441	11.127	21	5.221	7.634	46

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Table 5. Catchment clustering based on the analysis of the entire set of parameters (HP). Statistics of the parameter values in each cluster: mean (μ), standard deviation (*std*) and number of samples (*n*).

	$\mu(CL1)$	$std(CL1)$	$n(CL1)$	$\mu(CL2)$	$std(CL2)$	$n(CL2)$
HP(A)	854.57	1341.2	32	607.25	944.94	43
HP(zm)	322.55	129.15	32	428.79	195.85	43
HP(Tc)	10.103	7.967	32	8.519	6.57	43
HP(hc)	69.775	30.291	32	81.526	19.882	43
HP(Sp)	28.984	27.187	32	22.968	31.333	43

Table 6. Value ranges of the hydro-morphological parameters within each selected cluster.

	CL1		*CL2*		*CL3*	
	Min	Max	Min	Max	Min	Max
A	15.584	980	1921.1	5469.9	–	–
Z_m	637	813	154.77	346.32	375.47	561.72
t_c	1.515	6.47	8.597	16.776	18.65	31.416
h_c	24.848	39.617	52.582	80.232	87.06	123.09
S_p	69.801	99.989	27.731	60.806	0.01	22.491

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Table 7. Value ranges of the hydro-morphological parameters within each selected cluster for the HP case.

		HP(A)	$HP(Z_m)$	$HP(t_c)$	$HP(h_c)$	$HP(S_p)$
CL1	Min	12.1	154.42	1.409	26.607	0.01
	Max	4014.2	548.35	27.699	111.71	93.485
CL2	Min	31.28	196.92	1.872	52.981	0.01
	Max	3078.7	789.45	24.472	112.55	85.436

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Table 8. Spearman's rank correlation S_b-ΔC and corresponding p-values, within each cluster for a given parameter set. In bold those with p-values below 0.05.

Parameter set	*CL1*	*CL2* r_k	*CL3*	*CL1*	*CL2* p	*CL3*
A	**−0.36**	−0.29		**0.003**	0.386	
Z_m	0.078	−0.233	**−0.466**	0.838	0.136	**0.026**
t_c	−0.285	**−0.403**	−0.066	0.074	**0.046**	0.864
h_c	−0.318	**−0.636**	−0.203	0.341	**0.000**	0.255
S_p	0.19	−0.271	**−0.474**	0.664	0.233	**0.000**
HP	−0.052	−0.201		0.774	0.196	

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Table 9. Results of linear regression analysis: slope (m) and intercept (q) of the regression lines; sum of squared errors (SSE); coefficient of determination (R^2), coefficient of determination adjusted for the number of predictors ($adjR^2$) and root mean square error (RMSE).

		m	q	SSE	R^2	$adjR^2$	RMSE	τ
	CL-1 fixed(A)	−0.004	−0.01	13.822	0.065	0.05	0.472	0.002
	CL-3 fixed(Z_m)	−0.007	0.297	4.036	0.198	0.16	0.438	0.018
	CL-2 fixed(t_c)	−0.007	0.218	3.384	0.116	0.078	0.383	0.071
Lrtot	*CL-2 fixed*(h_c)	−0.01	0.342	5.809	**0.291**	0.267	0.447	0
	CL-3 fixed(r)	−0.01	0.312	8.649	**0.223**	0.207	0.428	0
	CL-3 fixed(S_p)	−0.003	−0.035	5.564	0.087	0.066	0.355	0
	CL-1 fixed(A)	−0.003	−0.123	4.136	0.086	0.055	0.371	0.039
	CL-3 fixed(Z_m)	−0.011	0.482	1.682	**0.452**	0.397	0.41	0.013
	CL-2 fixed(t_c)	−0.006	0.224	2.162	0.091	0.015	0.424	0.192
Lrinf	*CL-2 fixed*(h_c)	−0.009	0.326	1.251	**0.496**	0.46	0.298	0.041
	CL-3 fixed(r)	−0.009	0.254	2.006	**0.227**	0.194	0.295	0.025
	CL-3 fixed(S_p)	−0.008	0.325	0.737	**0.557**	0.536	0.187	0.001
	CL-1 fixed(A)	−0.007	0.22	9.288	0.079	0.049	0.556	0.082
	CL-3 fixed(Z_m)	−0.002	0.02	1.885	0.015	−0.093	0.457	0.282
	CL-2 fixed(t_c)	−0.007	0.175	1.124	0.121	0.023	0.353	0.282
Lrsup	*CL-2 fixed*(h_c)	−0.012	0.411	4.454	**0.218**	0.158	0.585	0.027
	CL-3 fixed(r)	−0.01	0.383	6.594	**0.224**	0.188	0.547	0.002
	CL-3 fixed(S_p)	−0.001	−0.173	4.384	0.009	−0.037	0.456	0.101

Table 10. Performance statistics of the predicted runoff coefficients by exploiting: the catchment lithology only (C_L); both the catchment lithology and the forest cover (C_{mod}).

Predicted values	*Bias*	RMSE	ABIAS	$(err_i)_{min}$	$(err_i)_{max}$
C_L	−0.08	0.16	0.13	−0.38	0.20
$C_{mod} = C_L - \frac{V_b S_b}{h_{c,T}}$	0.01	0.10	0.08	−0.25	0.24

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Fig. 1. Italian regions where the outlets of the 75 study catchments are located; from South (dark grey) to North: Sicily (12 catchments) , Campania (12 catchments), Latium (17 catchments), Tuscany (34 catchments).

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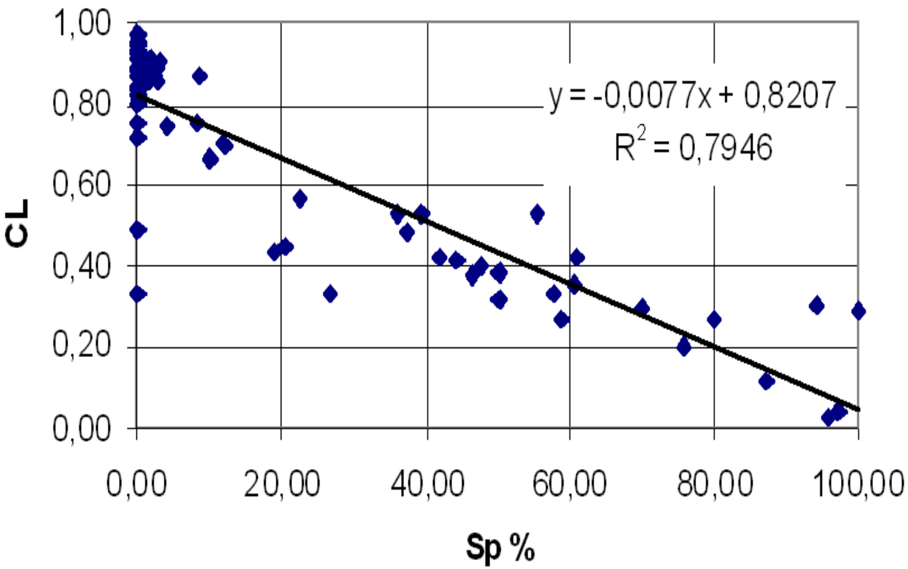

Fig. 2. Relation between C_L and Sp (%).

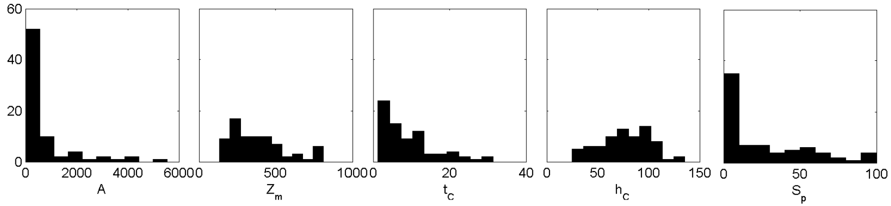

Fig. 3. Histograms of the hydro-morphological parameters: catchment extent (A, km^2); elevation above catchment outlet (Z_m); concentration time (t_c, hours); maximum annual rainfall depth within a time interval equal to t_c and a return period of 20 yr (hc, mm); catchment fraction with highly permeable lithoid complexes (S_p, %).

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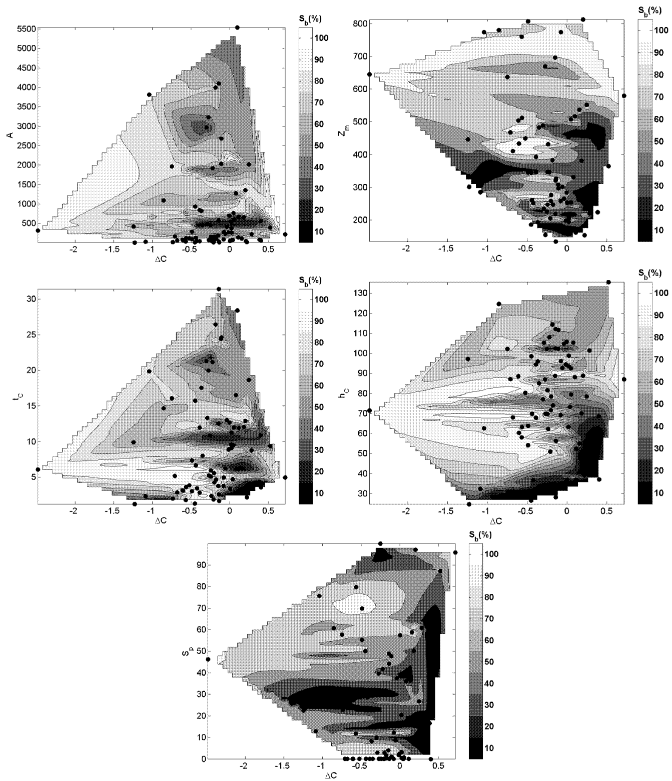

Fig. 4. Contour maps of S_b with respect to ΔC for different hydro-morphological variables. Black dots indicate the observed values.

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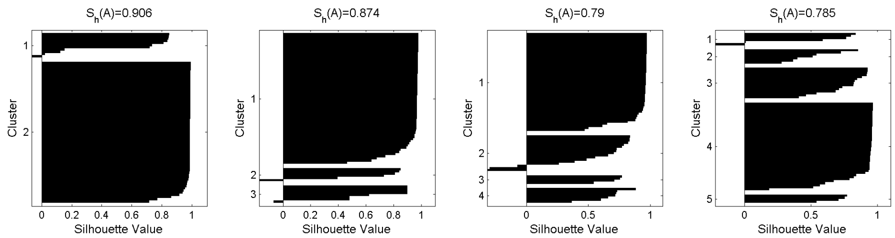

Fig. 5. Example of silhouette plots for cluster analysis.

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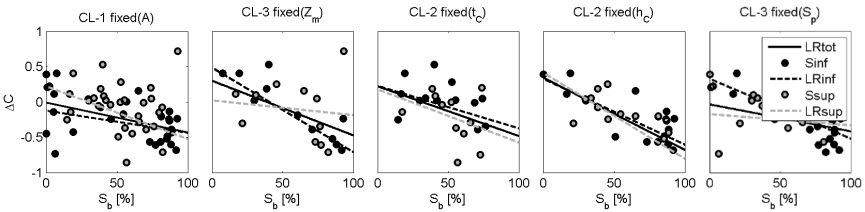

Fig. 6. Regression lines between ΔC and forest cover fraction for selected clusters of the study catchments: (i) including all (Sb, ΔC) couples belonging to the examined cluster (LRtot); (ii) including (Sb, ΔC) couples which values of the corresponding hydro-morphological paramters are below its intra-cluster average (LRinf); ii) including (Sb, ΔC) couples which values of the corresponding hydro-morphological paramters are above its intra-cluster average (LRsup).

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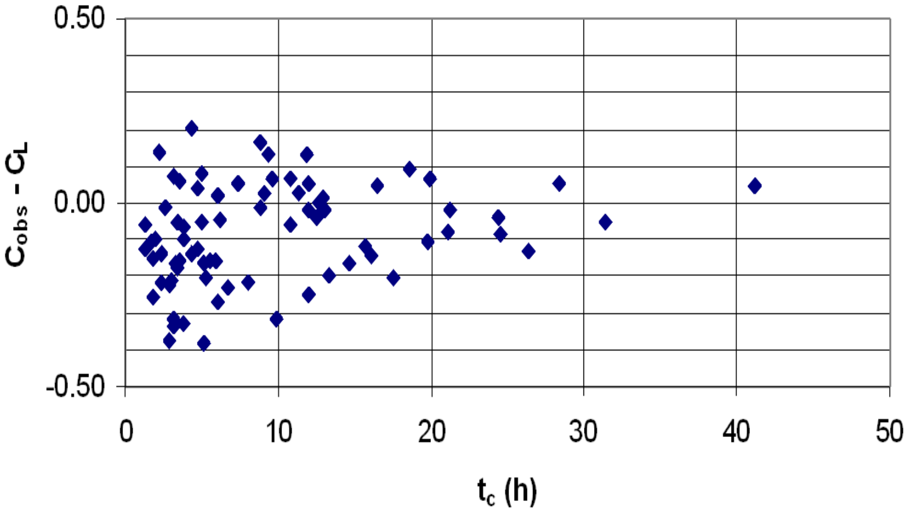

Fig. 7. Differences between C_{obs} and C_L versus the catchment concentration time.

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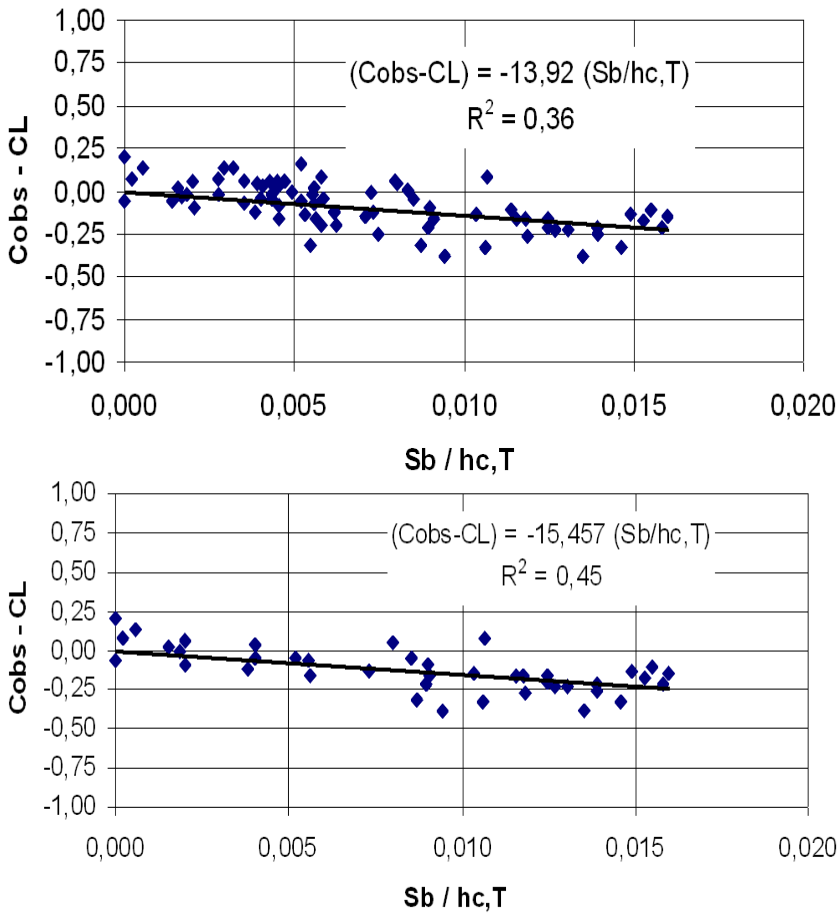

Fig. 8. **(a)** Cobs-CL versus $S_b/h_{c,\mathrm{T}}$ (mm^{-1}) considering all catchments; **(b)** Cobs-CL vs $S_b/h_{c,\mathrm{T}}$ (mm^{-1}) restricted to CL-1 fixed(tc).

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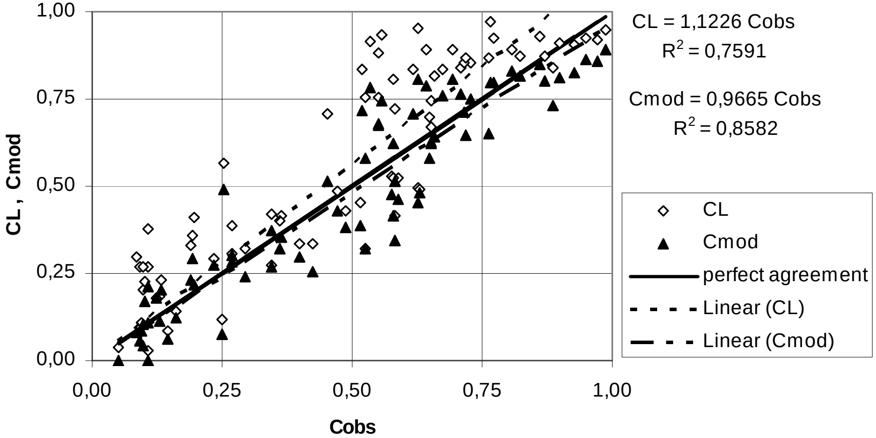

Fig. 9. Comparison between observed and predicted runoff coefficient: open circles, (Cobs, C_L); filled circles, (Cobs, $C_\text{mod} = C_\text{L} - \frac{V_b S_b}{h_{c,\text{T}}}$)

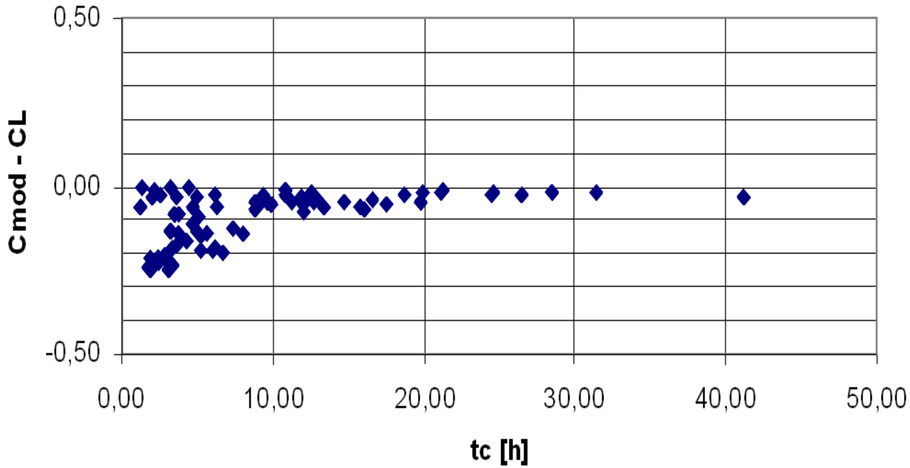

Fig. 10. Differences between C_{mod} and C_L versus the catchment concentration time.