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Impacts of land cover and climate changes on peak floods probability distribution function

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SUMMARY Climate and land cover are the main regulators of discharge formation. We combined here 5 alternative land cover case with 2 different precitation scenarios. Land cover scenarios are: (a) present land cover accordng to CORINE 2006 maps, (b) ICES scenario at 2050, (c) IMAGE scenario at 2050, (d) cementification scenario C1 and (e) cementification scenario C2. The ICES and IMAGE scenarios are based on consideration of economy and population growth, cementification scenarios 1 and 2 are intented as exemplificative what-if scenarios for urbanization of rural areas. Precititation is modelled as (a) the observed one and (b) increasing of 10% the average value. Peak flood probability distributions are analitically for each of the 10 land cover-climate combinations. The case study is the Secchia river basin in Emilia Romagna region. Results show that in absence of changes in the precipitation regime, the peak flood associated to low return period (<25 years) show a higher increase in percentage than those associated to higher return periods. If the land cover changes are combined with an increase of the precipitation, changes in peak flood are almost the double in percentage.

Keywords: Climate change, Land cover change, Peak flood probability

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INTRODUCTION

River discharge is the most visible hydrological response of the territory to climate. Floods are the extreme manifestation of river discharge and they are defined as an increase in the river level (or in the discharge) and they can result in the presence of water over regions that usually are dry (flooded areas). Floods are usually due to (i) snow-melting (ii) heavy (intense) or (iii) prolonged precipitation. Floods driven by snow-melting are a seasonal phenomenon that can be monitored and results in an increase in water level within the river but usually does not cause damages because is a slow phenomenon. Floods driven by precipitation are a more casual phenomenon that occurs when the precipitation rate exceeds the soil infiltration capability and the water in excess reaches in a relative short time the river channel causing an increase in the river level. The soil infiltration capability is a function of soil type, land cover, land use and soil moisture antecedent condition, [9]. Changes in land cover and use contribute in increasing the risk of city flooding. Within this Research Paper, we will focus on the impact of land cover change in the annual maximum peak flood probability distribution. We addressed the problem by deriving the peak flood distribution from the one of precipitation through a lumped model. The methodology applied, uses as inputs the depth-duration curve of annual maximum precipitation and the curve number (function of the land cover) parameters and provides as output the peak flood probability distribution, [6, 11]. Since the precipitation and soil parameters are independent each from the other we modify them separately and together to estimate their impacts on peak flood. The next sections provide (a) an introduction to the lumped model used and its components, mathematical details can be found in [6, 7, 9], (b) a description of the land cover and precipitation scenarios and (c) of the case study area and the data used. Thus the results are presented and discussed.

METHOD AND MODELS

In the next paragraphs we recall the main components of the rainfall-runoff-discharge applied here. The model is made by three component nested each other, first precipitation is described through a depth-duration-frequency curve, then the excess of precipitation is estimated applying a rainfall-runoff model (SCS-CN) and, at the last, the rainfall exceedance is transformed into discharge by applying a rational formula.

Areal precipitation: Depth-Duration-Frequency Curve

The annual maximum areal precipitation over an area for assigned duration and return period can be expressed as the product among (i) depth-duration curve, (ii) growth factor, and (iii) areal reduction factor.

The depth-duration curve provides the average annual maximum rainfall depth, h(d), for given duration d:

$$h_T(d) = a_1 d^{1-\nu} \tag{1}$$

where a_1 is the annual maximum of intensity for 1 hour duration and ν is the climatic exponent.

The growth factor x_T is a function of the return period (T)

$$x_T = \begin{cases} \epsilon_d - \alpha_d \left[\ln\left(-\ln\left(1-\frac{1}{T}\right)\right)\right], & \text{if } k_d = 0 \\ \epsilon_d + \frac{\alpha_d}{k_d}\left[1-\left(-\ln\left(1-\frac{1}{T}\right)\right)\right]^{k_d}, & \text{if } k_d \neq 0 \end{cases} \tag{2}$$

where $\epsilon_d > 0$ is the position parameter, $\alpha_d > 0$

the scale parameter, and $k_d \leq 0$ the shape parameter, if x is described by a GEV distribution. The subscript d indicates that, the parameters of the growth factor are dependent on the duration considered. For scale invariant precipitation data a single set of parameters can be estimated and used. The annual maximum precipitation with assigned duration and occurrence level, $h_T(d)$, is obtained by the multiplication of the annual maximum rainfall depth, h(d), for the growth factor, x_T.

The maximum areal precipitation for given duration and occurrence level is estimated applying a dimensionless areal reduction factor (ARF) function of area, A, and duration d to the $h_T(d)$, [2]. The ARF is defined as

$$ARF(A,d) = \left(1 + \omega \left(\frac{A^z}{d}\right)^b\right)^{-\nu/b} \quad (3)$$

where A is the area in km^2, ω is a normalization factor and b a scaling exponent, for the mathematical derivation of ARF see [5, 7]. The estimate of the ARF parameters requires to aggregate at different spatial and temporal scale the observed data and to identify for each spatio-temporal scale the maximum rainfall. Once the matrix of area, time aggregation and maximum rainfall is available, the ARF parameters can be estimated, [7]. As result the areal rainfall for assigned area, duration and occurrence level, is given by Eq.(4).

$$h_T(A,d) = a_1 d^{1-\nu} x_T(d) ARF(A,d). \quad (4)$$

For the case of our interest, the duration is assumed equal to the concentration time t_c of the basin, i.e. the time for runoff to flow from the most hydraulically remote point of the drainage area to the point under investigation and can be expressed as:

$$t_c = \frac{4\sqrt{A} + 1.5L}{0.8\sqrt{H}} \quad (5)$$

where A is the basin area in km^2, L is the length of the main river channel in km, and H is the average basin height in m, the concentration time is expressed in hours.

Rainfall-Runoff-Discharge: SCS-CN model and the rational formula

The hydrological response is modelled through the SCS-CN method [9] to estimate the effective rainfall and a lumped model to convert rainfall excess (runoff) into peak flood values. According to SCS-CN model the rainfall excess, h^*, is a function of rainfall depth, h,

$$h^* = \begin{cases} 0, & \text{if } h \leq I_a \\ \frac{(h-I_a)^2}{h-I_a+S}, & \text{if } h > I_a. \end{cases} \quad (6)$$

where $S = 254(100/CN - 1)$, in mm, is the maximum soil potential retention, and $I_a = 0.2S$ is the rainfall lost as initial abstraction. CN is the curve number and depends on the soil type, the land use, and the antecedent moisture condition (AMC). Table 1 reports the CN value for each land cover present in the Secchia river basin, CN values were reported in CORINE maps. The CN parameter is also a function of the antecedent soil moisture expressed in terms of the precipitation cumulated in the previous five days, [9], the CN value increases for saturated soils (precipitation occurred in the previous five days) and consequently the soil infiltration capacity reduces, it is usually indicated as CN_{III}, while CN_I refers to the opposite condition. The reference CN value is sometime indicated as CN_{II}. The different behaviour of the soil in saturated/unsaturated condition is relevant when the SCS-CN method is simulated a

flood from its beginning to the end. For the particular case treated here, we refer to the CN_{II} parameter.

The discharge related to h^* is $q^* = \phi \times h^*$ where ϕ is a proportionality coefficient

The cumulative distribution of q^* can be derived by that one of h as

$$F_Q(q^*) = \begin{cases} \exp\left(-\exp\left(\frac{q^* + \sqrt{q^{*2} + 4\phi S q^*} + 2\epsilon_q)}{2\alpha_q}\right)\right), & \text{if } k_q = 0 \\ \exp\left(-\left(1 - \frac{k\left[q^* + \sqrt{q^{*2} + 4\phi S q^*} + 2\epsilon_q\right]}{2\alpha_q}\right)^{\frac{1}{k_q}}\right), & \text{if } k_q \neq 0 \end{cases} \tag{7}$$

where

$$\begin{cases} \alpha_q = \phi \alpha_p \\ \epsilon_q = \phi(\epsilon_p - I_a) \\ k_q = k \end{cases} \tag{8}$$

and

$$\begin{cases} \alpha_p = \alpha a_1 t_c^{1-\nu} ARF \\ \epsilon_p = \epsilon a_1 t_c^{1-\nu} ARF \end{cases} \tag{9}$$

for $q*$ large enough, i.e. if $\sqrt{q^{*2} + 4q^*\phi S} \simeq q^*$, Eq.(7) simplifies as

$$F_Q(q^*) = \begin{cases} \exp\left(-\exp\left(\frac{q^* - \epsilon_q}{\alpha_q}\right)\right), & \text{if } k_q = 0 \\ \exp\left(-\left(1 - \frac{k_q(q^* - \epsilon_q)}{\alpha_q}\right)^{1/k_q}\right), & \text{if } k_q \neq 0. \end{cases} \tag{10}$$

However, analysis carried on rivers in Emilia Romagna region (included Secchia river) show that Eq.(10) overestimates the highest quantile of the annual maximum peak flood, [11]. For this reason, a correction factor based on return period, β, has been introduced:

$$\beta(T) = \begin{cases} \beta_0 + \beta_1 \ln(10), & \text{if } T \leq 10 \\ \beta_0 + \beta_1 \ln(T), & \text{if } T > 10. \end{cases} \tag{11}$$

The use of a correction factor based on the return period is accepted in hydrological literature [4]. The parameters β_0 and β_1 are estimated from the ratio between theoretical and derived quantiles of the peak flood. However the application to different closure sections of rivers in Emilia Romagna shows that β_0 and β_1 can be easily regionalized, this will allow to use the proposed approach to derived peak flood distribution in any closure section. The peak flood discharge for assigned return period is correctly estimates as $q_{T,\beta} = \beta(T) q_T^*$.

CASE STUDY

Secchia river is located in Emilia Romagna, and is one of the main tributaries of the Po river. It is 172 km long and its drainage basin is about 2300 km^2 wide. It originates at Alpe di Succiso (2017 m asl) in the Tuscan-Emilian Apennines and it reaches the Po river close to Mantova, see Fig.1.

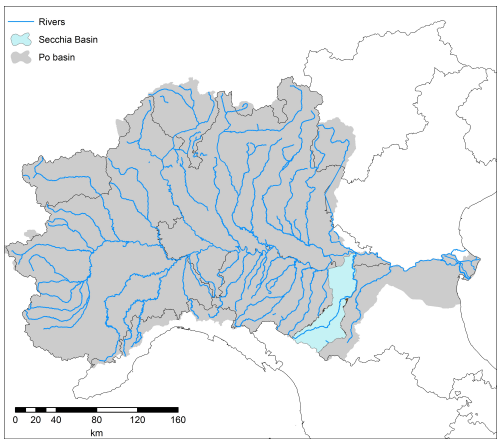


Figure 1:
Location of Secchia river basin (light blue) within Po river basin (grey).

Precipitation. The areal depth duration curve parameters have been estimated from observed maximum annual precipitation at 1,3,6,12,24 hours reported in Hydrological Annals (`http://www.arpa.emr.it/sim/?idrologia/annali\_idrologici`) updated at 2012. Figure 2 provides the areal depth-duration-curve for the different durations (from left to right 1,3,6,12,24 hours), note that data are not scale invariant.

The concentration time of Secchia river basin estimated from Eq.(5) is about 14 hours. We uses as ϵ_d, α_d and k_q those estimated from a duration of 12 hours, thus $\epsilon = 0.86$, $\alpha = 0.25$, $k = 0$ with $a_1 = 32.7$ mm, $\nu = 0.53$, $\omega = 0.01$, $z = 2.78$, $b = 0.17$, $\phi = 7.22$, $\beta_0 = 1.02$ and $\beta_1 = -0.0041$.

CORINE land cover map. From 1985 to 1990, the European Commission implemented the CORINE Programme (Coordination of Information on the Environment) creating a common information system on the state of the European environment at EU level. The coordination of the CORINE databases, including the updates, is done by the European Environment Agency (EEA2007) CORINE project is mostly based on the acquisition of observation from satellites. The first CLC inventory refers to 1990 (CLC1990) and has been updated in 2000 (CLC2000) and more recently in 2006 (CLC2006). Land cover is provided at a scale of 1:100.000, the dimension of the minimum mapping unit is 25 hectares and the minimum width of linear elements is 100 metres. The standard CLC nomenclature includes 44 land cover classes grouped in a three-level hierar-

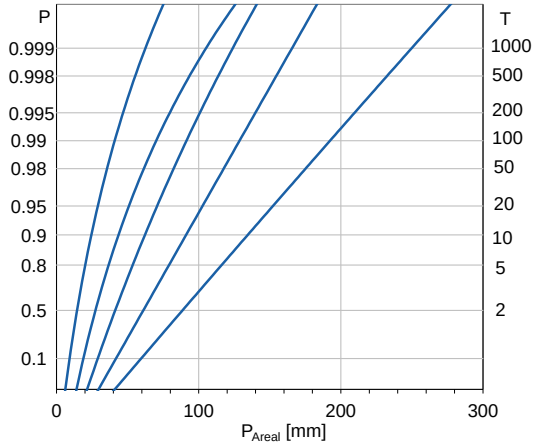
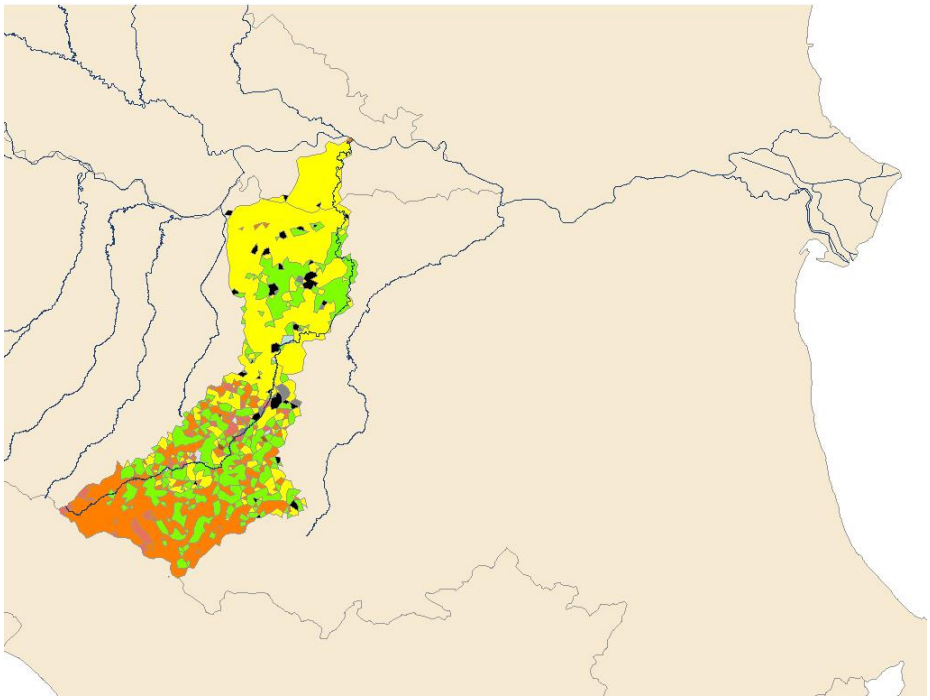


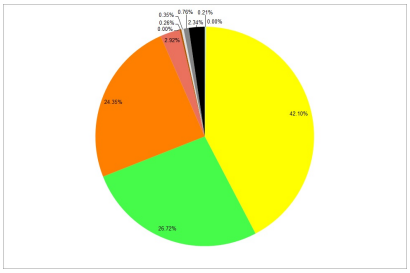
Figure 2:
Depth-duration-curve for the areal annual maximum precipitation over the Secchia river basin for the accumulation periods of 1,3,6,12,24 hours. On the left (right) y-axis is reported the cumulated probability (return period).

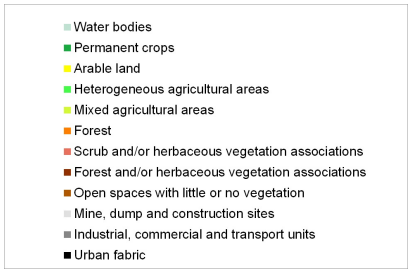
chy, Table 1 uses this nomenclature, [1]. Figure 3 provides the (a) spatial distribution, (b) percentage, and (c) legend of land cover grouped at the level 2 of CORINE classification. For Secchia river basin the CN parameter is about 70 and it an be compute as the average CN value weighted on the percentage of land cover, see Table 1.

Peak flood. Peak flood data updated at 2011 at Ponte Bacchello have been provided by SIMC ARPA Emilia Romagna, the variable ranges between 148 m^3/s and 823 m^3/s with an average value of about 423 m^3/s. Figure 9(a) provides the empirical plotting position of the data compared with the CDF resulting from the application of the above described methodology.



(a)





(b) (c)

Figure 3:
CORINE land cover map within Secchia river basin.

SCENARIOS

The estimated areal precipitation depth-duration-frequency curves are the reference climate scenario to estimate the impact of changes in the land cover on the peak flood distribution while the CORINE map constitute the land cover reference scenario for evaluating the impact of changes in the precipitation regime. In the next paragraphs we present a fictitious climate scenario and four land cover scenario. The combination of climate and land cover scenario allows us to draw conclusion on their separate and joint impacts on peak flood, the reference peak flood distribution is the one obtained from observed precipitation and CORINE map, and is indicated in blue in Figures 9 and 10 while orange lines indicate the CDF obtained from the climate-land use scenario.

Precipitation

To compare the effects of land cover changes to those of a different precipitation regime we create a fictitious precipitation scenario by assuming an increase of 10% in the average value for all the duration, i.e. the a_1 parameter is increased by the 10 %. Figure 4 provides the comparison among observed (blue) and modified (orange) depth-duration-frequency curves for the Secchia river basin and Figure 10(a) compares the peak flood distribution using observed (blue) and modified (orange) precipitation.

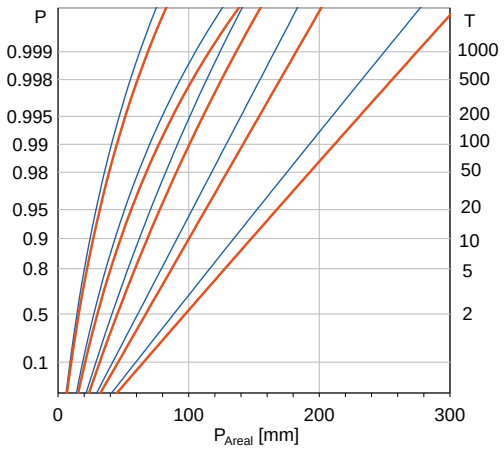


Figure 4:
Depth-duration-curve for the areal annual maximum precipitation over the Secchia river basin for the accumulation periods of 1,3,6,12,24 hours. On the left (right) y-axis is reported the cumulated probability (return period).

Land cover

To assess the role of land cover changes in flood hazard we tested 4 different situations: (i) ICES and (ii) IMAGE scenarios, both projected at 2050, derived by land cover change simulations performed using LUC@CMCC model at 10 km resolution for agriculture, forestry, and pasture activities, while urban/artificial and water/wetland areas were assumed stable and eventual burnt areas were assumed as disappearing under general recovery, and two cementification scenarios (iii) C1 and (iv) C2 both characterised by an increasing of urbanized area reducing the soil infiltration capacity; C1 and C2 scenarios are intended as exemplificative of the consequences of massive urbanizations but are not supported by any consideration on population and/or economical growth processes. Table 1 provides the percentage for each land cover considered. Due to the difference in the spatial scale of CORINE maps and ICES/IMAGE scenario we add some fictitious classes to those of CORINE maps. These mixed classes are indicated with the $*$ in Table 1.

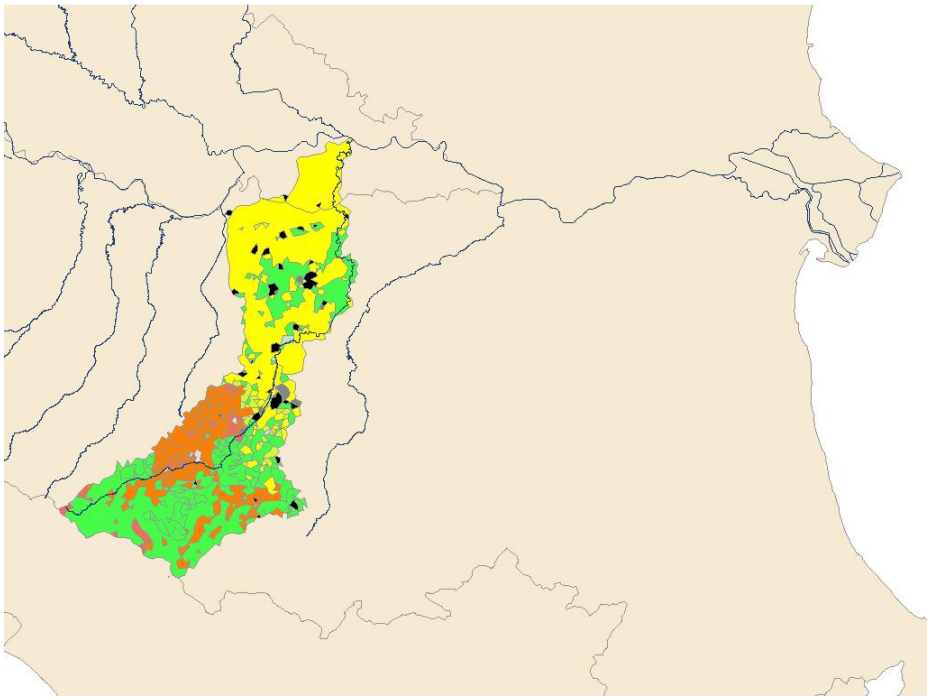
ICES and IMAGE land cover scenarios. The ICES [8] scenario is based on v6 of the Global Trade Analysis Project (GTAP) database [3] which represents the world economy evolution with respect to year 2001. The IMAGE framework [10] projects the amount of area for each land cover on the basis of demography, technology, trade, food and energy consumption. The model gives a multi-country, multi-market representation of the economic system allowing the analysis of distributional implications across sectors and regions, accounting for market adjustments and feedback mechanisms. In both scenarios the territory occupied by agriculture significantly increases and forest reduces, in ICES forests are almost halved while in IMAGE forests are almost null but pastures areas are present, see Tab.1. The CN parameter assumes the value of 72(74) for ICES(IMAGE) scenario.

Cementification land cover scenarios: C1 and C2. Scenarios C1 and C2 are exemplicative of an increasing urbanization of rural areas in the lower part of Secchia river basin: the industrial, commercial and transport areas increases from 1% (CORINE) to 9% (ICES) and 43% (IMAGE) while the agricultural areas reduces from 69% to 60% and 28%. The CN parameter assumes the value of 73(82) for C1(C2) scenario.

Table 1

Curve number associated to each land cover and percentage of area observed and covered in the different scenarios. Classes indicated with ∗ are fictitious and have been introduced to describe combinations of land cover resulting from ICES and IMAGE scenarios.

	Description	CN	CORINE	ICES	IMAGE	C1	C2
Artificial surfaces							
Urban fabric	Discontinuous urban fabric	85	2.3	2.3	2.3	2.3	2.3
Industrial, commercial and transport	Industrial or commercial units	98	0.8	0.8	0.8	9.2	42.5
Mine, dump and construction sites	Mineral extraction sites	79	0.3	0.3	0.3	0.3	0.3
Agricultural areas							
Arable land	Non-irrigated arable land	69	42.1	37.2	38.4	40.9	7.6
	Annual crops associated with permanent crops	69	0.03	0.03	0.03	0.03	0.03
Heterogeneous agricultural areas	Complex cultivation	69	13.3	10.2	11.1	6.1	6.1
	Land principally occupied by agriculture, with significant areas of natural vegetation	80	13.4	28.6	31.1	13.4	13.4
Mixed arable land*	Various*	70	0.0	2.2	2.2	0.0	0.0
Permanent crops	Vineyards/Olive groves Fruit trees and berry plantations*	71	0.0	0.0	1.6	0.0	0.0
Forests and semi-natural areas							
Forests	Broad-leaved forest	66	23.8	3.0	0.2	23.8	23.8
	Coniferous forest	66	0.2	0.1	0.1	0.2	0.2
	Mixed forest	66	0.3	0.3	0.2	0.3	0.3
	Different types of forest*	66	0.0	12.7	3.0	0.0	0.0
Shrub and/or herbaceous vegetation associations	Natural grassland	80	1.3	1.1	0.9	1.3	1.3
	Transitional woodland/shrub	67	1.6	0.9	0.03	1.6	1.6
Open spaces with little or no vegetation	Beaches, dunes and sand plains	79	0.1	0.0	0.0	0.1	0.1
	Sparsely vegetated areas	79	0.2	0.02	0.0	0.2	0.2
Agricultural areas and Forests and semi-natural areas*							
Forest and/or herbaceous vegetation association*	Sparsely vegetated areas/grassland/pastures*	80	0.0	0.0	7.3	0.0	0.0
Water bodies							
Inland waters	Water bodies	86	0.2	0.2	0.2	0.2	0.2



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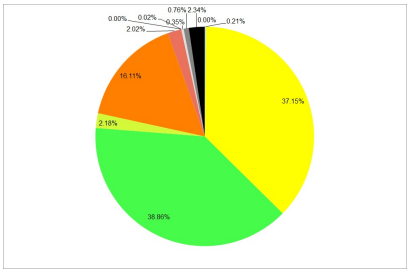
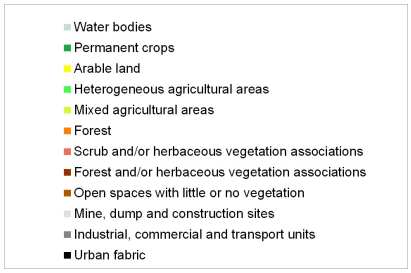
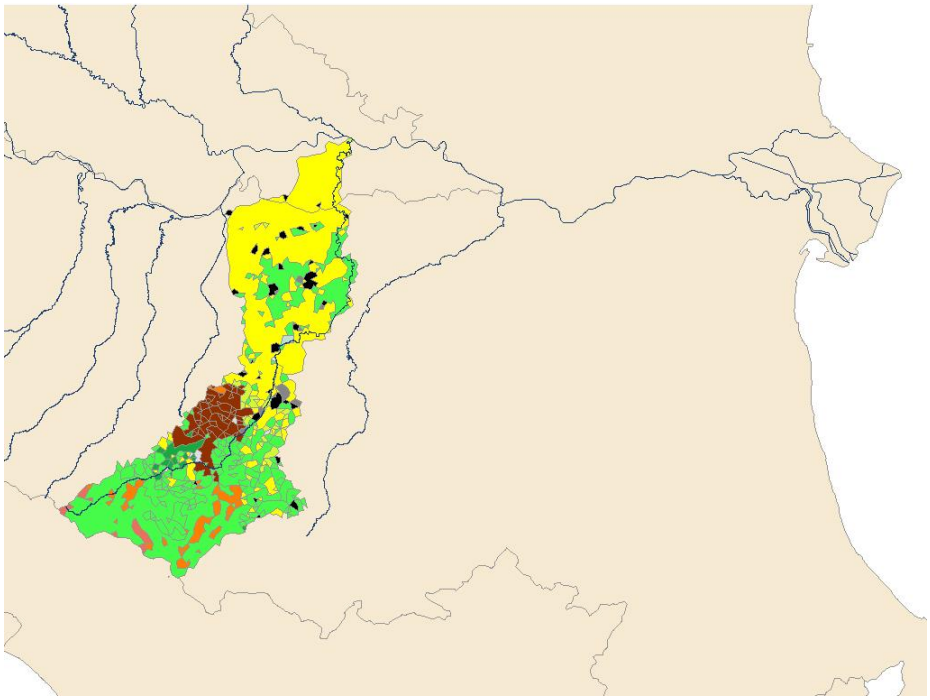




(b) (c)

Figure 5:
ICES land cover map projected at 2050 within Secchia river basin.



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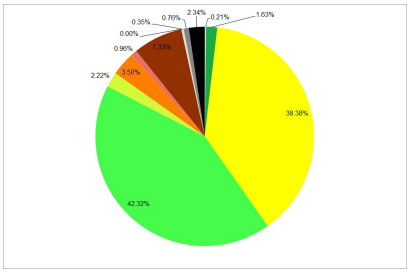
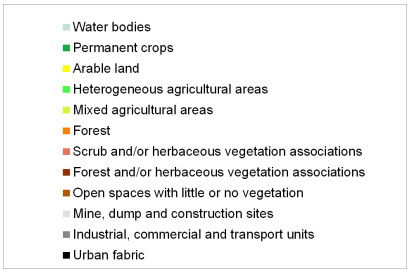
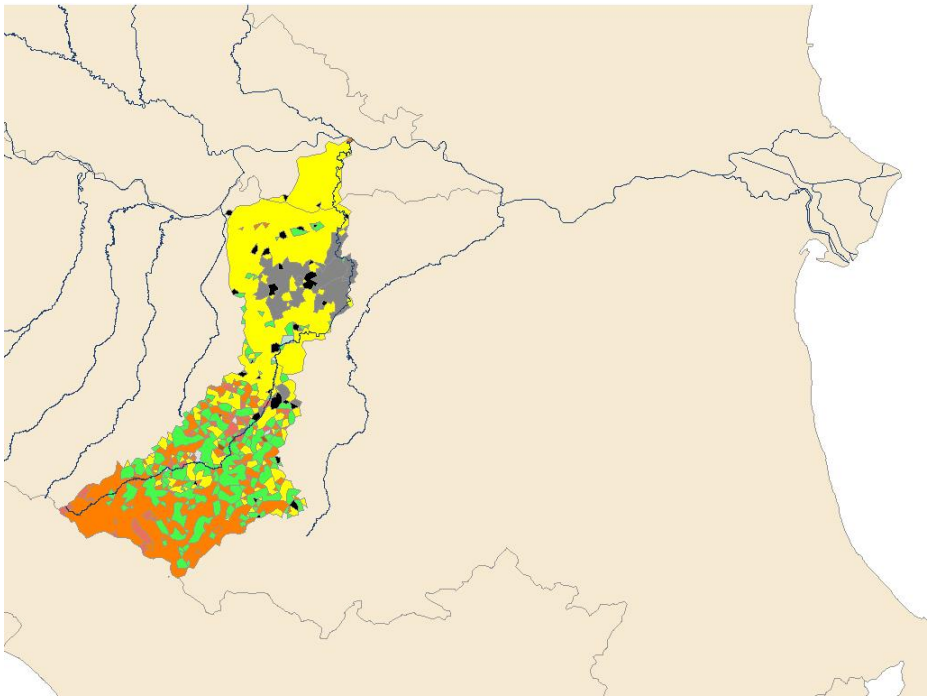


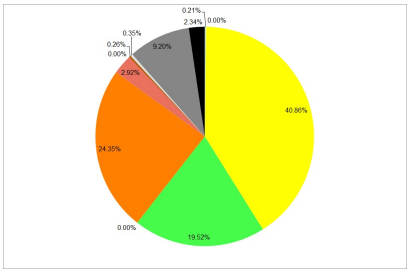


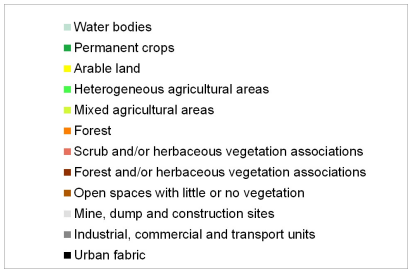
(b) (c)

Figure 6:
IMAGE land cover map projected at 2050 within Secchia river basin.



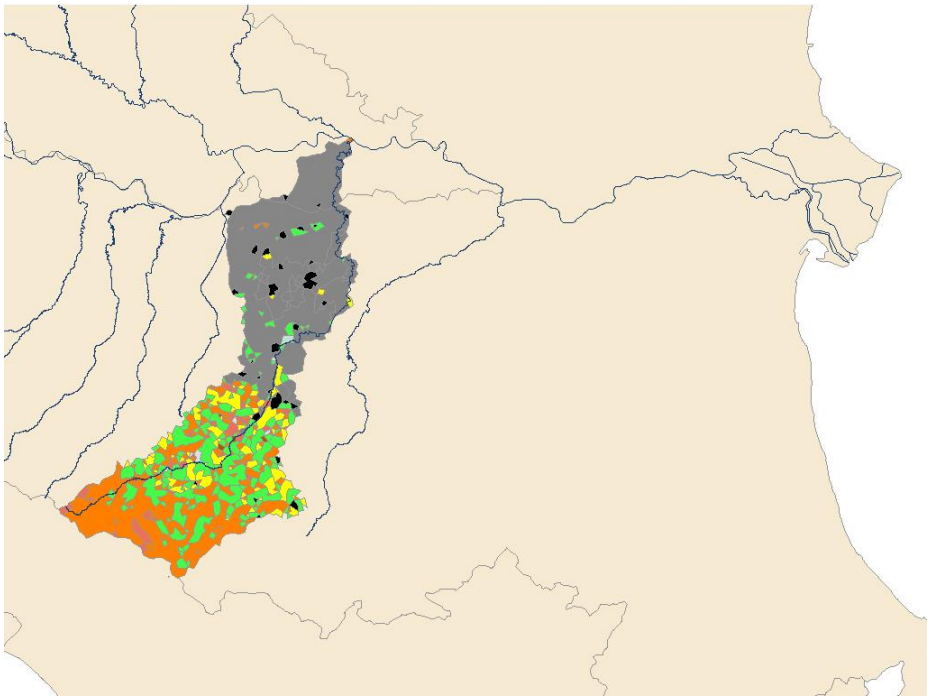
(a)





(b) (c)

Figure 7:
C1 scenario land cover map within Secchia river basin.



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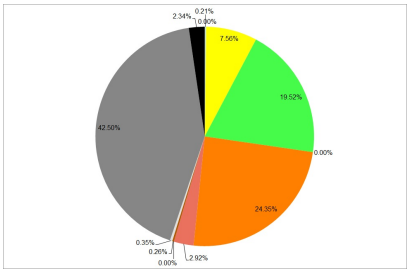
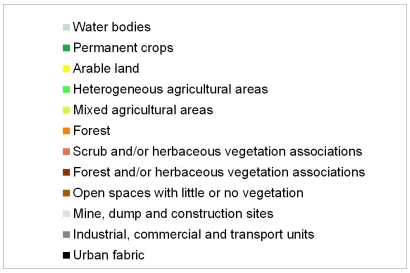


(b)



(c)

Figure 8:
C2 scenario land cover map within Secchia river basin.

Table 2
Peak flood discharge, in m^3/s, for selected return periods, in years, for the different scenarios in absence of changes in the precipitation regime

T	CORINE	ICES	IMAGE	C1	C2
2	345	363	373	367	427
5	495	513	524	517	577
10	594	613	623	616	676
25	719	737	747	741	801
50	811	829	840	833	893
100	902	920	931	924	984
250	1022	1040	1050	1044	1103

Table 3
Peak flood discharge, in m^3/s, for selected return periods, in years, for the different scenarios in presence of changes in the precipitation regime.

T	CORINE	ICES	IMAGE	C1	C2
2	395	410	424	418	479
5	560	575	589	583	645
10	670	685	699	693	754
25	807	821	835	830	891
50	908	923	937	931	993
100	1008	1023	1037	1031	1093
250	1140	1155	1168	1163	1224

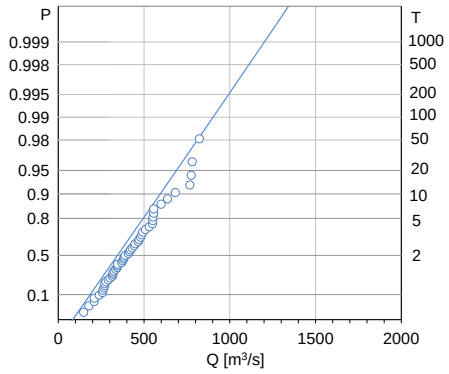
RESULTS

In presence of only land cover changes, the ICES, IMAGE and C1 scenarios do not significantly alter the peak flood distribution as while in scenario C2 a significant increase in the peak flood for assigned return period is detected, compare Figure 9(b)-(d) and Table 2. This result is coherent with the values of CN parameter: in IMAGE, ICES and C1 scenarios, is almost the same of CORINE, while in scenario C2 is significantly higher.

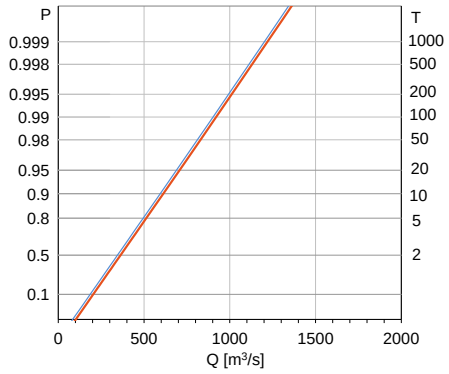
The impact of a changes in the precipitation regime leaving unvaried the land cover is reported in Figure 10(a), while Figures 10(b)-(e) report the impacts of changing both precipitation and land cover scenarios. In the specific case we are considering the changes in land cover and precipitation reinforce each other causing a generalised increase in the peak flood for assigned duration, compare value in Table 3. The most significantly impact is related to scenario C2.

CONCLUSIONS

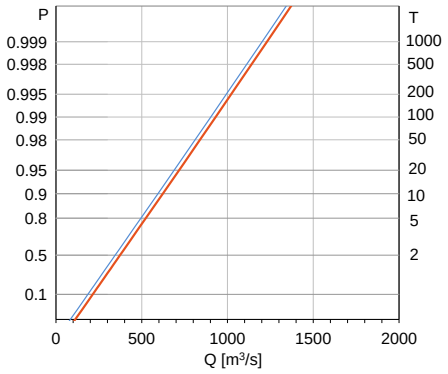
Changes in land use simulated in ICES, IMAGE, C1 and C2 scenarios are sufficient to increase peak flood hazard event in absence of precipitation changes. The increase in peak flood quantiles according to scenarios ICES, IMAGE and C1 will be less than 10%, and between 10% (for a return period of 250 years) and 25% (for a return period of 2 years) for the C2 extreme scenario. The highest increases in percentage are expected for the more frequent peak flood values, thus the most common events will become more severe. The projected increase in precipitation intensity empathized the impacts of land cover changes, under the precipitation scenarios the peak flood with a return period of 2 years will increase of about 15% (no land cover changes), 19% (ICES), 23% (IMAGE), 21% (C1) and 39% (C2) while the 250 years peak flood will vary of about 13% in all land cover scenario with exception of C2 were a +20% change is expected. Results, even if derived from a simplified model, show that land cover has to be taken is a main issue to be discussed and analysed in climate change adaptation policies for the mitigation of flood hazard.



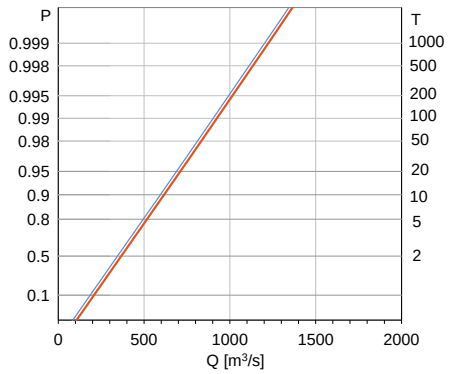
(a) CORINE



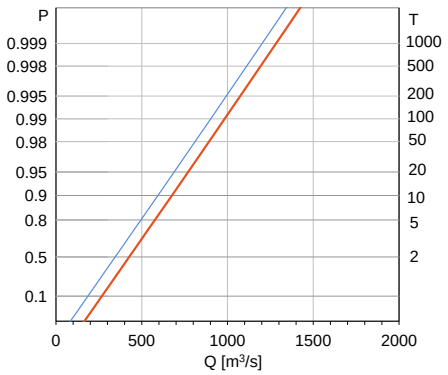
(b) ICES



(c) IMAGE

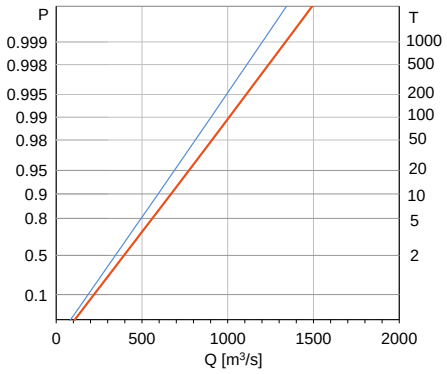


(d) C1

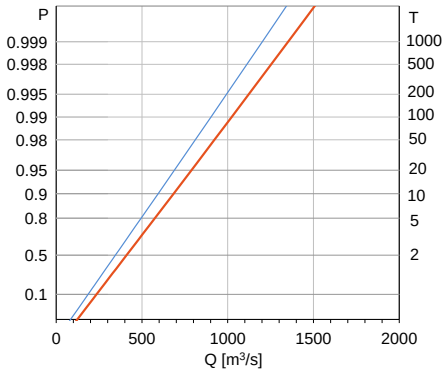


(e) C2

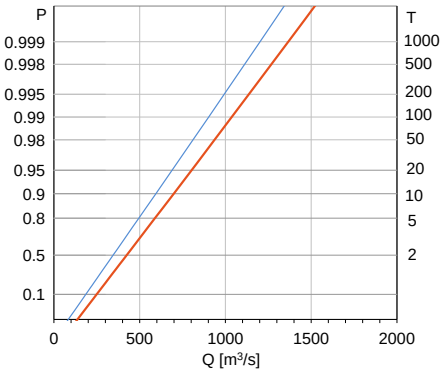
Figure 9:
On the left (right) y-axis is reported the cumulated probability (return period).



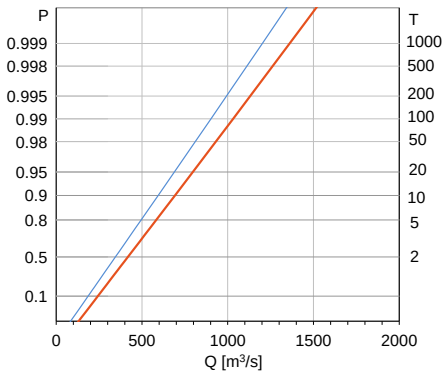
(a) CORINE



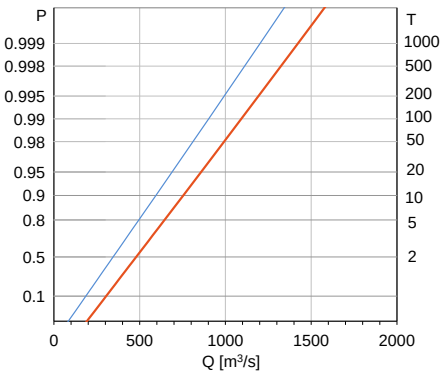
(b) ICES



(c) IMAGE



(d) C1



(e) C2

Figure 10:
On the left (right) y-axis is reported the cumulated probability (return period).

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