Hydrological impact of forest fires and climate change in a Mediterranean basin

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Hydrological impact of forest fires and climate change in a Mediterranean basin

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Abstract Forest fire can modify and accelerate the hydrological response of Mediterranean basins submitted to intense rainfall: during the years following a fire, the effects on the hydrological response may be similar to those produced by the growth of impervious areas. Moreover, climate change and global warming in Mediterranean areas can imply consequences on both flash flood and fire hazards, by amplifying these phenomena. Based on historical events and post-fire experience, a methodology to interpret the impacts of forest fire in terms of rainfall-runoff model parameters has been proposed. It allows to estimate the consequences of forest fire at the watershed scale depending on the considered burned area. In a second stage, the combined effect of forest fire and climate change has been analysed to map the future risk of forest fire and their consequence on flood occurrence. This study has been conducted on the Llobregat river basin (Spain), a catchment of approximately 5,000 km^2 frequently affected by flash floods and forest fires. The results show that forest fire can modify the hydrological response at the watershed scale when the burned area is significant. Moreover, it has been shown that climate change may increase the occurrence of both hazards, and hence, more frequent severe flash floods may appear.

Keywords Forest fire · Climate change · Hydrological impacts · Risk assessment

1 Introduction

Forest fires are one of the major factors affecting the soil conservation of natural areas and increasing the vulnerability to extreme floods in Mediterranean basins. Such fires can be either natural or human. Human-caused fires constitute the greater percentage of forest fires, while

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natural fires constitute the great majority of the total area burned (Wang et al. 2010). In both cases, the destruction of the vegetated layer after an extensive fire may modify the hydrological behaviour of the affected natural catchments. Mediterranean areas, characterized by warm, dry summers and cool, wet winters, are particularly affected by these hazards. Their plant communities mostly composed of different types of pines are highly inflammable. As a consequence, the average annual amount of forest fire throughout the Mediterranean area is close to 50,000 ha (Alexandrian et al. 1999). For example, in the 1980s 15 % of the total forested area in Spain was burned in less than 10 years, and the consequences of the fires in Portugal in 2005 or in Greece in 2007 were catastrophic. It seems that this trend is expected to increase in frequency with predicted climate change (Moreno et al. 2009; Lenihan et al. 2003; Williams et al. 2001). For these reasons, it appears necessary to develop methodologies in order to assess the risk of fire and their hydrological impacts in the future.

Fire-risk evaluation and, in particular, understanding the factors that contribute to making an environment fire prone are essential for Mediterranean vegetation management. During the last decades, several fire-risk indexes have been introduced to map and express the water stress of vegetation and the surface temperature. They represent the first step to averting disastrous and damaging incidents. To this end, fire-risk maps have become widely used in many countries (Bonazountas et al. 2005). These risk maps are typically constructed at coarse resolutions (several km^2) using wildland fuel models or vegetation maps (Keane et al. 2001; Chuvieco et al. 2004; Hessburg et al. 2007). Some of these indicators can be calculated by means of a combined study of different physical, thermochemical, and biological parameters such as calorific values or chemical composition (see Núñez-Regueira et al. 2000 for example). Moreover, satellite remote sensing has also appeared as a powerful tool to compute maps with a spatial and temporal resolution higher than the meteorological ground stations (Jaiswal et al. 2002; Hernandez-Leal et al. 2006). Nevertheless, these indicators are based on numerous variables that can only be measured at the present time, but will be very difficult to predict and evaluate in the future. In consequence, the computation of future risk maps needs to depend only on variables that could be estimated in the future (usually meteorological data).

On the other hand, the impact of forest fire on hydrology has been studied in many studies. Fire reduces protection of the surface due to the loss of vegetation cover and increases the soil hydrophobicity (Soto and Díaz-Fierros 1998; Neary and Ffolliott 2005). As a consequence, during a rainfall event, less rain is intercepted by plants, and more reaches the hill slopes. Many studies have shown that after a fire, the watershed response to rainfall events is governed by many factors interacting with each other, such as fire severity (DeBano 2000; Giovannini and Lucchesi 1997), amount and type of vegetation (Doerr et al. 1998; Imeson et al. 1992), soil texture (Debano 1981), soil moisture (Doerr and Thomas 2000), and time since burning (Debano 1981). In addition, the formation of a water-repellent layer at or near the soil surface will reduce soil infiltration capacity and increase overland flow (Letey 2001).

Nevertheless, in the literature, there are few studies that evaluate the effect of fires on the hydrological response of catchments, particularly on flood generation. The lack of such quantitative hydrological studies reflects the strong difficulty to have good data to compare hydrological behaviour before and after a fire event. Scientific interest in a burned area generally starts only after the fire, and no previous study and pre-fire data are available to compare. Most stream flow change experiments have been conducted on well-gauged small basins (tens of km^2). Several studies carried out in burned catchments (see for instance Scott and Van Wyk 1990; Scott 1997; DeBano 2000) have demonstrated that the watershed response, whatever the studied time step (annual, monthly, daily), increases during the first year following a fire. This modification is then attenuated during the second year to recover the original properties. Runoff ratio and flood peak are modified depending on the basin size. The smaller the basin, the higher the effect of fire on hydrological response. As a consequence, flow peak can increase significantly from 45 (Anderson et al. 1976) to 600 % in large catchment (Nasseri 1988) and to 5,700 % in small catchment.

Even less studies were conducted at the event scale considering discharge fluctuation at short time step (1 h). Comparing the discharge data before and after a fire which destroyed 85 % of the vegetation of a small basin (146 ha), Lavabre et al. (1993) concluded that fire induces reduction in soil retention and potential evapotranspiration, and an increase of annual and monthly runoff. It also led to a 30 % increase in daily runoff mainly concentrated in the high-water days. Concerning flood regime, the shape of the hydrograph was modified with post-fire responses sharper and quicker. In this case, the watershed did not require previous saturation and produced immediately runoff to the drainage network. In detail, the changes in the hydrological properties affect:

- The response time: 60 % decrease in characteristic time of the hydrograph
- The runoff volume: 60 % increase in the runoff ratio
- The peak discharge: 100 % increase in the peak
- The frequency of flood: the previous 10-year return period event is characterized by a 1-year return period after the fire

At an even smaller scale, Rulli et al. (2006) compared the hydrological response of small spots (30 m^2), one recently burned and another burned 6 years before. The results show peak runoff and runoff ratio were generally increased about 3,000–6,000 % (Rosso et al. 2007). As a consequence, the frequency of flood is modified and the 10-year return period flood can increase up to 100 % after the passage of fire (Rulli and Rosso 2007). This has been confirmed by Candela et al. (2005) who studied the effects of forest fire on Flood Frequency Curves (FFC) in a natural catchment. After a fire, FFC exhibited higher peak discharges, showing a reduction in frequency occurrence of the same order.

Based on these considerations, the risk of forest fire and its hydrological impacts have been studied. This paper aims to propose a methodology to assess the risk of forest fire on a Mediterranean basin and its consequence in terms of hydrological behaviour and flood occurrence. Established on past data (both concerning forest fire and hydrology), this method will be applied using future climate scenarios in order to assess the consequences of climate change on forest fire and flood frequencies over the twenty-first century. The methodology will be applied to the Llobregat Basin (Spain 5,000 km^2), which is particularly affected by forest fires and flood events.

This paper is organized as follows: the next section presents the scope of the study in more detail, including a description of the area of study, the historical forest fires, and the hydrometeorological data. Section 3 describes the methodology applied to map the risk of forest fire by using only meteorological data. Section 4 presents the results obtained in the assessment of the hydrological impacts of forest fire by using a distributed hydrological model. Both forest fire mapping and hydrological assessment are combined by using future climate scenarios to study the impacts of climate change and are presented in Sect. 5. Finally, Sect. 6 summarizes the main results and concludes on future improvements.

2 Case study

2.1 Forest fire in Catalonia

Catalonia is located in the northeast of the Iberian Peninsula and covers a surface of approximately 32,000 km^2. Its marked orography is characterized by an increasing altitude from the sea to the inner regions. According to climatic atlas of Catalonia (Ninyerola et al.

2000), the average annual rainfall over the region is about 600 mm, being higher in the Pyrenees (up to 1,200 mm) and lesser in the southwest (around 400 mm). Despite these mountainous areas with cold winters, the majority of Catalonia has a Mediterranean climate with winter precipitation and summer drought.

Approximately 60 % of the territory is covered by scrubland and forests. According to the First Ecological Forest Inventory of Catalonia (Gracia et al. 1997), current forests are in majority occupied by conifers (Pinus sylvestris, Pinus halepensis, Quercus ilex, and Pinus nigra). A recent study conducted in Catalonia (Díaz-Delgado et al. 2004) has shown that the active fire policy has diminished the total number of fires in recent years, but has not been able to decrease the contribution of large fires to the total burned area. In other words, the dramatic increase in the number of large fires in the last decades is due to the increase in summer drought (Moreno et al. 1998, Piñol et al. 1998).

A database of historical forest fires has been compiled in Catalonia from 1986 to 2010 (provided by the Center for Ecological Research and Forestry Applications, CREAF[1]). During this time period, 246 forest fires were listed. Landscape fire scars greater than 0.3 km^2 were mapped by subtracting consecutive images of Landsat MSS (see Salvador et al. 2000 for more details). The large majority of the historical events are quite small: 80 % are characterized by areas under 30 km^2, and more than 90 % by areas under 100 km^2. In this region, the natural fire rotation (number of years in period/(total area burned over period/size of the study area)) reaches an estimated value of 133 years (Díaz-Delgado et al. 2004).

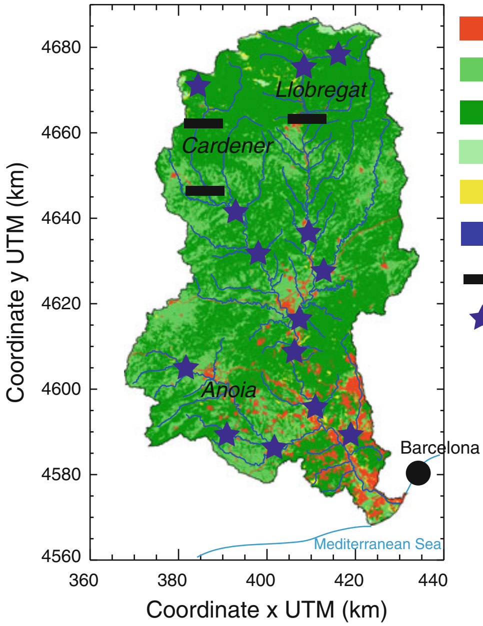
2.2 The Llobregat basin

In order to assess the occurrence and the hydrological impact of forest fires, the Llobregat basin has been chosen for the case study. The Llobregat river source is in the Pyrenees mountains (1,950 m) and flows into the Mediterranean Sea very close to the city of Barcelona (Fig. 1). It is 175 km long and covers a catchment of 5000 km^2, which is mostly inhabited near its outlet. The River Llobregat has two main tributaries, the river Cardener and the river Anoia, and its downstream part is regulated by 3 dams. Its regime is characterized by high water levels in spring, with a maximum in May, and others in autumn, more variable, with a maximum in October–November, which often causes flash floods and floods. The regime decreases in January because of snow retention in the upstream part dominated by high peaks of over 2,000 metres high, while the minimum in August is due to the dry summer. This watershed is mainly covered by rural landscapes: forest, scrublands and crops. The mountainous Northern part of the watershed is covered by dense forest of pines and firs. The central part of the basin, characterized by lower elevations and calcareous soils, is covered by a less dense forest of Aleppo pines and farmland. Finally, the downstream part of the basin is more urbanized, and the vegetation is almost limited to scrubland and crops (see Arozarena Villar et al. 2006 for a detailed description of the land cover).

Because of its high proportion of forest and agricultural land, the Llobregat basin is frequently affected by fires that can have dramatic consequences. Regarding the historical database of forest fires, three significant events occurred with a burned area over 100 km^2: in July 1986 with a total burned area of 158 km^2, in July 1994 and in July 1998 with burned areas of 454 and 163 km^2 respectively.

[1] http://www.creaf.uab.es/.

Fig. 1 The Llobregat basin, the main types of land cover, and the hydrographical network



From a hydrometeorological point of view, the studied watershed is covered by a quite dense measuring instrumentation network. On one hand, daily climatological and hydrological data comprising precipitation, temperature, and discharge have been compiled on the 1980–2010 historical time period. Nineteen temperature sensors and 22 rain gauges covering the whole basin with complete time series have been selected. These punctual data have been interpolated at the watershed scale using a spline method. On the other hand, hourly precipitation and discharge data have also been compiled from the Automatic System of Hydrological Information (SAIH). Note that these data are only available from 1996.

3 Mapping of forest fire risk

3.1 Forest fire characterization using Canadian Drought Code (CDC)

The American Meteorological Society defines drought as "a period of abnormally dry weather sufficiently long enough to cause a serious hydrological imbalance" (AMC 2000). Drought plays an important role in making the conditions favourable for forest fires to occur. Experience over the years has helped to establish a close relationship between cumulative dryness, or drought, and destructive fires (www.wrh.noaa.gov/sew/fire/olm/KEETCH.htm). The occurrence of fires is highly dependent upon the availability of moisture during the growing season, with more severe fires occurring during the drier, warmer years. The Canadian Drought Code (CDC), which is a component of the Canadian Forest Fire Weather Index (FWI) System, is a good indicator of seasonal drought effect at quite large scale, and it is usually used to characterize forest fire (Turner 1972; Van Wagner 1987). The CDC represents a rating of the water content of a deep, compact organic layer in the soil by computing the net effect of daily changes in evapotranspiration

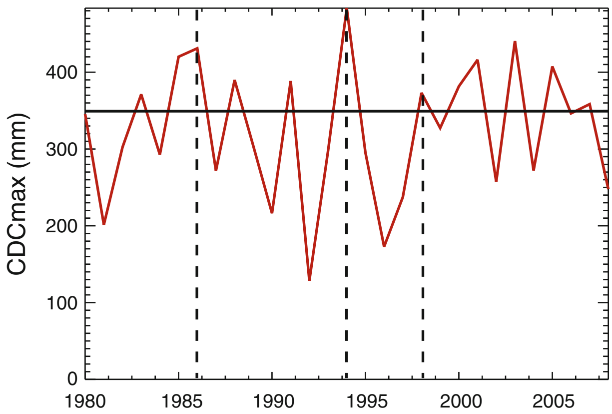


Fig. 2 Maximal annual value of CDC computed on the Llobregat basin during the historical period. The 3 main forest fires are represented by dashed line

and precipitation on cumulative moisture depletion. The CDC index has been used in many studies all over the world (Field et al. 2004, Girardin et al. 2006, Drever et al. 2008). It has also been successfully applied in Spain (Castellnou Ribau et al. 2005, Moreno et al. 2009, Loepfe et al. 2010).

CDC has the great advantage of being easily computed because it depends only on daily temperature and precipitation values, and sunshine duration. CDC calculation is shortly presented below (more details are presented in Girardin et al. (2004)). First, a rainfall phase (RP) is computed to estimate the rainfall contribution to soil moisture:

$$\mathrm{RP} = [800/\exp(\mathrm{CDC}_{d-1}/400)] + 3.937\mathrm{ER} \quad (1)$$

where CDC_{d-1} is the drought value of the previous day and ER the effective rainfall (in mm) calculated from the daily precipitation (when over 2.8 mm) and taking into account canopy interception by empirical relationship.

Second, the potential evapotranspiration (PET, in mm) is estimated as follows:

$$\mathrm{PET} = 0.36T + L \quad (2)$$

where T is the daily temperature (°C) and L a seasonal sunshine duration coefficient adjusted depending on the studied region.

Finally, CDC_d is computed as a combination of RP and evapotranspiration loss:

$$\mathrm{CDC}_d = 400\ln(800/\mathrm{RP}) + 0.5\mathrm{PET} \quad (3)$$

As these climatological data are usually available in future climate scenarios, the computation of future CDC will be possible. For this reason, CDC has been chosen to characterize the risk of forest fire in this study.

In a first step, CDC time series have been reconstructed for the Llobregat basin on the historical period 1980–2010 and compared to the records of historical fire events in order to find a relationship between CDC values and a situation of forest fire risk. As depicted in Fig. 2, two of the most significant forest fires occurred during years for which the highest CDC values were calculated: in 1986 and 1994, the CDC exceeded the value of 400 mm. This confirms that forest fires are reported mostly during drought period, and the CDC is able to identify these periods correctly. In order to select the three fire events, the value of 350 mm has been chosen as reference to characterize a situation of risk. Above this

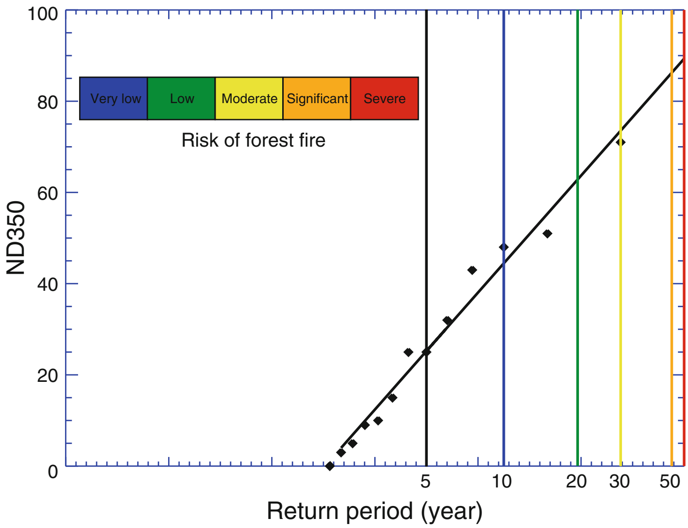


Fig. 3 Gumbel distribution adjusted for ND variable representing the number of days per year that exceed the reference threshold of 350 mm. The return periods related to a certain level of risk are added

threshold, it is considered there is a risk of forest fire occurrence. Note that 12 of the 30 years of the historical period are concerned by such a risk.

On this historical time period, the number of consecutive days per year that exceeded the reference threshold has been computed (called ND350 in the followings). It is an easily computed indicator representative of the state of soil moisture. The higher the number of days, the longer the drought and the more important the risk of fire. A Gumbel statistical distribution of ND350 has been adjusted to represent as well as possible the historical trend and define a scale of risk (see Fig. 3). Regarding the different estimated return periods, 5 levels of risk of fire have been defined:

- Very low: ND350 ∊ [0–50] corresponding to a return period of less than 10 years
- Low: ND350 ∊ [51–65] corresponding to a return period between 10 and 20 years
- Moderate: ND350 ∊ [66–75] corresponding to a return period between 20 and 30 years
- Significant: ND350 ∊ [76–85] corresponding to a return period between 30 and 50 years
- Severe: ND350 > 85 corresponding to a return period higher than 50 years

3.2 Mapping of forest fire characterization

In order to define the risk-prone areas of the Llobregat basin, this methodology has been applied on each sub-basin where a forest fire can occur (those which are mainly covered by forests and agricultural lands). For each sub-basin, the CDC time series have been computed. ND350 has been calculated for each year of the time period, and an average value for the total period has been computed (ND350mean). A level of risk has been incremented as a function of the value of ND350mean regarding the rules defined above. The results are presented in Fig. 4.

The Anoia river basin and the upstream part of the Cardener basin are characterized by the highest level of risk (low). The rest of the basin, the higher and the more urbanized

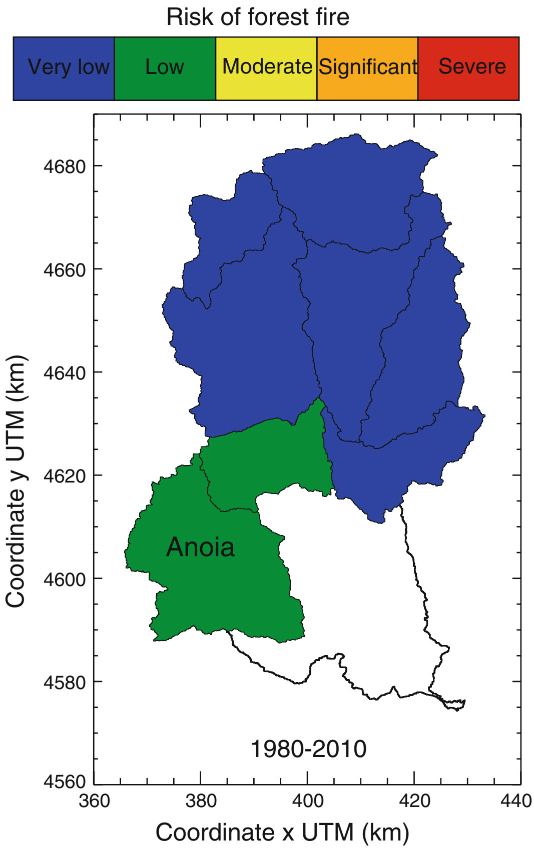


Fig. 4 Risk of forest fire estimated on the historical time period (1980–2008) and based on the ND350mean occurrence

parts of the Llobregat basin, is characterized with a very low level of risk. For this reason, the Anoia sub-basin has been chosen to study the hydrological impact of forest fire. Moreover, this part of the watershed has the advantage of not being regulated, and hence, the resulting consequences of flood are not attenuated. The last significant forest fire occurred in the Anoia basin in 1986, where 80 km^2 were burned. Note that for this year, only daily hydrometeorological data are available.

4 Assessment of the hydrological impacts due to forest fire

A distributed rainfall-runoff model has been used to simulate the discharge in the Anoia river basin at the hourly time step (in accordance with the input data). This model had to be able to take into account the burned area resulting from a forest fire by modifying its parameters.

4.1 Presentation of the rainfall-runoff model

The Anoia basin has been split into hydrological cells of 1 km^2 that are connected to the outlet of the basin following a simplified drainage network based on topography. Each cell is treated as a hydrological unit, where a lumped model is applied.

The lumped model employed here is based on the Soil Conservation Service (SCS) Curve Number (CN) method (Mockus 1957). It assumes that flood flows are essentially composed of surface runoff water or at least fast-responding runoff processes, and depends on a unique soil parameter, CN, representing hydrological soil characteristics. Because of its simplicity and minimal data requirements, the SCS-CN method is widely used in flash flood simulation (see for example Borga et al. 2007; Rozalis et al. 2010; Versini et al. 2010; Marchi et al. 2010). It is based on the water balance equation and a proportionality stating that the ratio of the amount of cumulative infiltration ($F(t)$, in mm) to the amount of potential maximum retention capacity (S, in mm) is equal to the ratio of the amount of total runoff volume ($V(t)$, in mm) to the maximum potential runoff volume, the latter being represented as the total rainfall amount since the beginning of the event $P_{\text{tot}}(t)$, to which the initial abstraction I_a (both in mm) is subtracted. Assuming $F(t) = P_{tot}(t) - I_a - V(t)$, total runoff volume can be computed as:

$$V(t) = \frac{(P_{\text{tot}}(t) - I_a)^2}{P_{\text{tot}}(t) - I_a + S} \tag{4}$$

From this formula, the instantaneous runoff coefficient at time t, $C(t)$, can be deduced. This coefficient has then to be multiplied by the rainfall intensity $P(t)$ to estimate the direct runoff $Q_f(t)$:

$$C(t) = \frac{\partial V(t)}{\partial P_{\text{tot}}(t)} = 1 - \frac{S^2}{(P_{\text{tot}}(t) - I_a + S)^2} \tag{5}$$

Retention capacity S is related to the CN coefficient which is usually estimated from the soil properties and taking a value between 0 and 100:

$$S = \frac{25400}{CN} - 254 \tag{6}$$

An a priori method has been used to estimate distributed CN values over the Anoia basin. Geomorphological data (slope, geology, and land cover) at cell scale have been used to compute the CN according to the recommendations of MOPU (1990). Previous studies based on this method (Corral et al. 2000, 2002) have shown significant differences between effective field capacities and those obtained with this a priori method: simulated discharges have a clear tendency to be overestimated. For this reason, an average curve number correction factor (FCN) has been calibrated to scale the map of CN values.

In many applications of the SCS method, the initial abstraction I_a does not take into account antecedent moisture condition and is deduced from the potential maximum retention S. In this study, I_a is estimated from stream gauge measurements identifying by means of the hydrograph initial rising time. I_a represents the total amount of precipitation from the beginning of the event to the first initial hydrograph rising time (deducing the response time of the watershed).

Since the SCS loss function only considers the direct runoff, a base flow formulation has been added to consider slow hydrological processes $Q_s(t)$. The conceptual function described in Weeks and Boughton (1987) has been chosen. It assumes that there is a constant ratio between the runoff component $Q_f(t)$ and the variation of the slow component between two time steps. Base flow is also recursively estimated from the previous value and depends on a parameter γ (units: time^{-1}).

The total runoff $Q_{\text{tot}}(t) = Q_f(t) + Q_s(t)$ generated at each cell is then routed downstream following the drainage network. A single hyperbolic unit hydrograph is applied in each cell to represent the hillslope flow propagation:

$$H(t) = 2 \times Hp \times \frac{(1/Tp)^{\alpha}}{1 + \left(^{1}/_{Tp}\right)^{2\alpha}} \tag{7}$$

It depends on 2 parameters: the peak intensity (Hp) and the time to peak of the unit hydrograph (Tp). The linear diffusive wave unit hydrograph (Szymkiewicz 2002) is then applied on the river course (from the hillslope cell to the outlet) to represent the propagation of the stream flow. It depends on 2 parameters and is detailed in Versini et al. (2011a, b, c).

To summarize, the adjustment of the model required the calibration of 6 parameters: the curve number correction factor (FCN), the base flow parameter (γ), and four routing parameters (Hp and Tp for the hillslope cell and the 2 parameters for the river cell).

4.2 Model calibration

This rainfall-runoff model has been calibrated using 8 past significant rainfall events that all happened between 1996 and 2008. As the last forest fire affecting the Anoia river basin occurred in 1986, it has been assumed the parameters are not affected by the consequences of forest fire and considered stationary on this time period. The Nash efficiency (Nash 1969) is selected and used as the optimization criterion to evaluate the performance of the model (difference between both observed and simulated discharges):

$$\text{Nash} = 1 - \frac{\sum_{i=1}^{n} (Qobs_i - Qsim_i)^2}{\sum_{i=1}^{n} \left(Qobs_i - \overline{Qobs}\right)^2} \tag{8}$$

where $Qsim_i$ represents the simulated discharges, $Qobs_i$ the observed discharges, the average observed discharge during the storm, and n the number of time steps.

The performance of the model in terms of Nash efficiency varies from one rainfall event to another (average Nash criterion value of 0.43, reaching 0.0 for the worst event to 0.80 for the best one). The simulations' accuracy is acceptable in the light of the results obtained in comparable case studies (ungauged basins or poorly instrumented framework), for which the model calibration was done with a longer historical database (e.g. Borga 2008; Versini et al. 2010). The performance of the model is generally better for the largest rainfall events characterized by intense peak discharge. The hydrological response to smaller events appears to be a little more erratic and is probably linked to the nonlinearity of the rainfall-runoff transformation.

As rainfall-runoff model and fire-risk model are both conceptually based on the soil moisture balance, estimated initial abstraction (I_a) has been compared to the CDC value at the beginning of each event. It appears these variables are not correlated (correlation coefficient equal to −0.5). The 4 events that occurred in summer are all characterized by a significant CDC (higher than 250 mm), while the winter events are characterized by smaller values (lower than 150 mm). I_a are more fluctuating and seem to be related to the event and to the simulation accuracy, regardless of the context of antecedent rainfall. The seasonality is of great importance in this region where intense precipitation generally occurs in summer. This kind of event can produce intense runoff despite low soil moisture. For these reasons, both parameters characterizing initial abstraction in the hydrological model and soil moisture in the fire-risk model can not be easily connected.

The calibration of the rainfall-runoff model has been carried out under a number of limitations (given the scarcity of data, number of rain gauges, etc.) that may have a significant impact on the performance of the model. Despite its limitations, the rainfall-runoff model has been used to simulate discharge on the Anoia river basin.

4.3 Interpretation of the hydrological impacts in terms of rainfall-runoff model parameters

For the hillslope cell, the rainfall-runoff model parameters have to be modified after a fire occurs in order to take into account the changes in the hydrological properties. As described in the introduction, very few works were realized in order to model the impact of forest fire on hydrological behaviour. Based on the study realized on the Rimbaud basin (Lavabre et al. 1993) and the modifications observed in hydrological behaviour, Sempere-Torres (1996) proposed a methodology to modify the parameter of a simplified rainfall-runoff model based on the common SCS-CN. This method has been transferred and applied to the Anoia basin because of its similarity with the Rimbaud basin in terms of (1) The size of the Rimbaud basin is the same order of magnitude as that of the cell (1 km^2), (2) soil occupation with a land essentially covered by scrubland and pine forest, and (3) hydrological consequences after the fire with an increase in runoff noticed during the year following the fire of 1986.

The methodology to modify the parameter of the rainfall-runoff model has been established by Sempere-Torres (1996) by comparing observed discharge during significant rain events before and after the forest fire occurred on the Rimbaud basin. First, the consequence on the routing function was assessed. A FDTF method (First Differenced Transfer Function, see Duband et al. 1993, Rodriguez et al. 1991) was applied to identify a specific unit hydrograph for each period (before and after the fire). A hyperbolic unit hydrograph was then adjusted (as presented in Eq. 4) for each case. Second, a global retention capacity (parameter S of the SCS model) was adjusted for both series of events in order to reproduce the discharge before and after the forest fire.

By comparing the adjusted parameters before and after the forest fire, rules to modify the model parameter were identified. They generate consequences on response time, infiltration coefficients, and peak discharges as follows:

- The parameter governing the infiltration capacity is decreased in order to increase the runoff:

$$S^* = S \times 0.7 \tag{9}$$

- The parameter governing the peak intensity of the unit hydrograph is increased:

$$Hp^* = Hp \times 2 \tag{10}$$

- The parameter governing time to peak of the unit hydrograph is decreased:

$$Tp^* = Tp \times 0.6 \tag{11}$$

Then, the parameter α is adjusted in order to obtain a unit hydrograph (area equal to 1, see Eq. 4).

It has been assumed these consequences in terms of hydrological behaviour noticed on the Rimbaud basin (on both loss and routing functions) can be transferred and applied on the burned hillslope of the studied basin. As detailed in the Introduction, the hydrological consequences of forest fire vary from a basin to another and depend on its size, vegetation, and soil texture. For the smallest scale (as 30 m^2 in Rulli et al. 2006; Rulli and Rosso 2007), peak discharge and runoff ratio can be multiplied by 20 or 40 after a wildfire. In this study, it has been decided to use the parameters estimated on the Rimbaud river which conduct to less impact of forest fire. It can appear as an arbitrary choice that has the advantage to be based on a similar basin in terms of vegetation and size and to not likely overestimate the possible consequences of forest fire.

4.4 Application of the model in a forest fire context

In order to assess the impact of forest fire at the watershed scale, several simulations have been processed taking into account different situations of forest fire. The basin has been progressively burned from upstream to downstream, according to four scenarios. The resulting simulated hydrographs have been computed for these different situations and compared for the 8 rainfall events. Some of the results are presented in Fig. 5. Depending on the burned area and the rainfall event, the following trends have been noticed:

- An average increase in the peak discharge from 5 to 40 %: the peak discharge is the mostly influenced parameter, although increase and decrease in the peak are less influenced by the forest fire.
- An average increase in the runoff ratio from 5 to 30 %: as a consequence of the peak discharge increase, the runoff ratio is significantly modified with less water infiltrated.
- A small decrease in the peak time from 0 to 20 min: The peak time is little influenced by forest fire. Although the parameter governing time to peak of the unit hydrograph

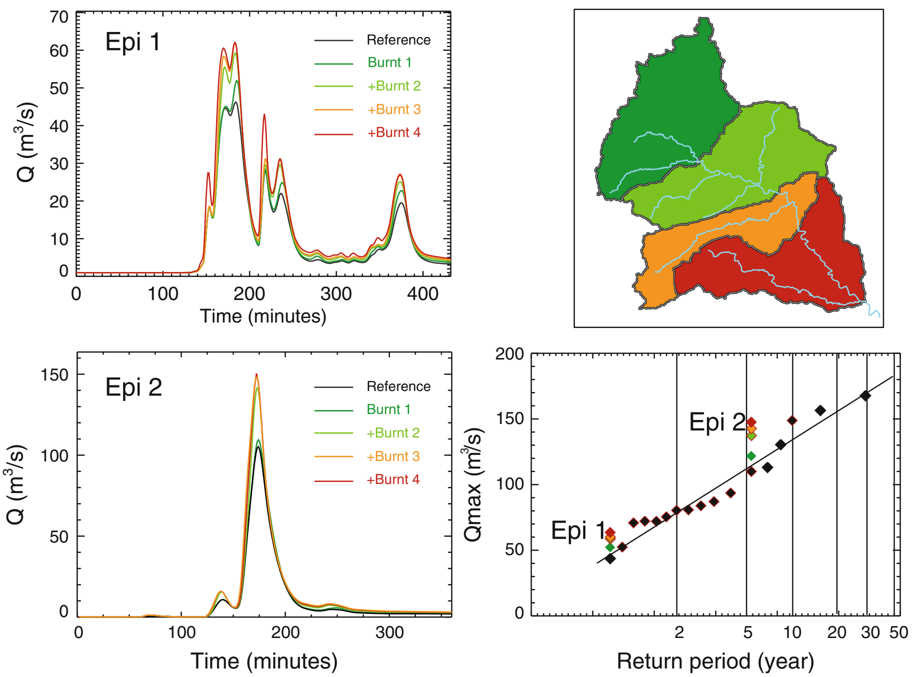


Fig. 5 Simulated hydrographs for different situations of burned areas: first, the *dark green* area is burned, then the *light green* one, then the *orange* one, and finally the *red* one. The corresponding simulated discharges are represented according to the same colour set for two events. In the *bottom right* corner, the Gumbel distribution of the maximum discharge is represented: the modified peak discharges are added for the different scenarios of burned area

has decreased at the hillslope cell by about 30 %, the routing at the basin scale is slightly modified. Routing in the river flow is predominant at the basin scale.

As a consequence, the return period of the peak discharges is also modified. It is particularly true for the most significant event characterized by a peak discharge of 106 m^3/s and a return period of around 5 years (see Fig. 5). This value and the four ones corresponding to the four scenarios of burned areas have been reported by the Gumbel distribution. When the entire basin is burned, the corresponding discharge rises by more than 150 m^3/s, corresponding to a return period comprised between 10 and 20 years.

Severe forest fires can also have major consequences at the basin scale. A significant increase in the peak discharge may lead to greater damages than originally expected for a given flood event. That should be taken into account by water management services in order to adapt their measures and actions to this increased risk of flooding.

5 Impacts of climate change

In order to assess the future impacts of climate change on both forest fire and peak discharge occurrence, future climate scenarios have been used to (i) compute CDC time series and map future risk of forest fire and (ii) simulate peak discharge and draw future statistical distribution of extreme values.

5.1 Future climate scenarios

The Catalonian Meteorological Service (SMC) has provided high-resolution climate data for the 1971–2100 time period with a resolution of 15 km (Barrera-Escoda and Cunillera 2010a, b; Marchi et al. 2010). The MM5 mesoscale model has been nested into ECHAM5-MPI/OM atmosphere–ocean global coupled model in order to generate regionalized scenarios forced by two of the Intergovernmental Panel on Climate Change (IPCC 2000) Special Report on Emission Scenarios (SRES) CO2 emission scenarios (A2 and B1). A2 assumes a high anthropogenic impact on climate, whereas in B1 the impact is assumed to be more moderate (Nakicenovic and Swart 2000). Although the model seems to reproduce correctly the evolution of annual anomalies for Catalonia (Barrera-Escoda and Cunillera 2010a, b, 2011), the daily data have been downscaled using a method of analogues (Versini et al. 2011a, b, c). The objective was to provide climate scenarios adapted to study hydrological impact at small basin scale. In general, satisfactory results were obtained on historical period. They have shown a reliable distribution of the simulated precipitation spatial patterns for annual and semi-annual precipitation compared to observations.

Future seasonal variability of temperature and precipitation computed over the Llobregat basin are represented on Fig. 6 for three different time periods (2011–2040, 2041–2070, and 2071–2100). These 30-year periods have been defined in order to be comparable with the historical period characterized by the same duration. The historical reference has been also drawn in order to evaluate the possible changes. SMC scenarios appear to be pessimistic, and among them, the worst are those based on A2 IPCC scenario. They establish a general decrease in precipitation, especially during wet periods (spring and autumn), and a strong increase in temperature. Whatever the future time period and the IPCC scenario, the average temperature will increase by 2–8 °C during the twenty-first century.

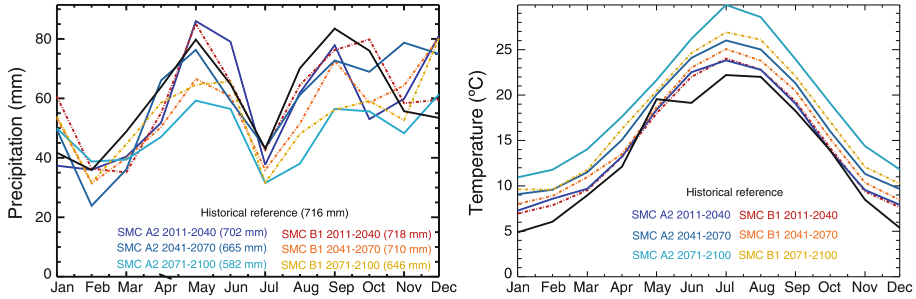


Fig. 6 Seasonal precipitation (*left*) and temperature (*right*) cycle on the future time period for SMC scenarios (2011–2100). The annual accumulation of precipitation is written in parenthesis

5.2 Future risk maps

The future time series of CDC have been computed using these scenarios of future temperature and precipitation provided by the SMC. Applying the methodology to map forest fire risk proposed in Sect. 3, the future levels of risk have been computed for each sub-basin of the Llobregat watershed. The results are illustrated in Fig. 7 for both A2 and B1 scenarios.

During the first time period (2011–2040), the risky areas appear to be similar to those obtained for the historical time period (see Fig. 4). According to SMC scenarios, few changes are noticed in precipitation and temperature estimations during the dry period. The average increase in precipitation during spring compensates the increase in temperature in summer. For the second time period (2041–2070), the slight decrease in precipitation and the increase in temperature cause the intensification of drought periods during summer. This change could be more pronounced for the A2 scenario with significant and moderate fire risk mapped on the downstream sub-basins. Finally, during the last time period (2071–2100), previously estimated trends are intensified. Almost the entire basin is characterized by a severe level of risk for the A2 scenario, whereas it is only the case for the downstream sub-basins according to B1 scenario. This is due to the pessimistic predictions of temperature provided by the SMC with an increase of 4–8 °C.

5.3 Consequences on peak discharge

The consequences of climate change have also been analysed from a hydrological point of view. Future peak discharge distributions have been computed for the different climate scenarios and time period. As hourly climate data are not available for the future time periods, daily precipitation and temperature scenarios have been used as input data to a continuous hydrological model to compute daily time series of discharge. The model chosen, HBV (Bergström 1992), has been previously calibrated on a historical period, providing good results (Versini et al. 2011a, b, c). The hourly peak discharge has then been deduced from the daily peak discharge using the Fuller formula.

Gumbel distributions of extreme values have been calculated for every scenario (A2 and B1) and for every time period (2011–40, 2041–2070, 2071–2100). The results obtained have been compared to the historical distribution and are illustrated in Fig. 8. First, it has to be noticed that future distributions seem not to follow the Gumbel pattern as it was the case for the historical extremes. Average discharges characterized by a return period comprised

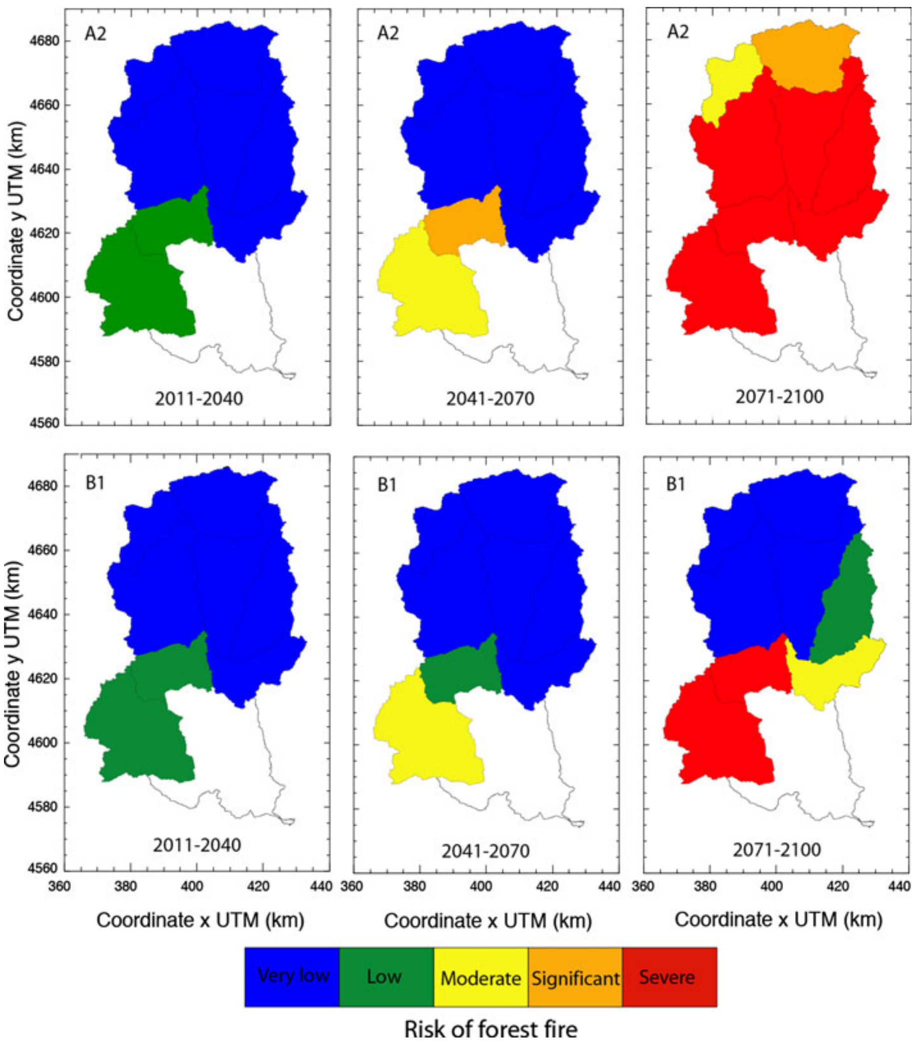


Fig. 7 Future scenarios of risk of forest fire for the Llobregat basin based on SMC climate scenarios A2 (*top*) and B1 (*down*) for three time periods (2011–2040, 2041–2070, and 2071–2100)

between 3 and 10 years are lower than the previous ones. This is certainly due to the decrease in precipitation assumed by the future scenarios. Then, the increase in the distribution curves is stronger and no longer linear. Nevertheless, it appears that the most intense situation should be more frequent in the future depending on the climate scenario or the time period. A2 scenario provides pessimistic perspectives in terms of average temperature and precipitation (see Fig. 6), but the resulting extreme discharges seem not to differ from historical values. Conversely, B1 scenarios show a higher frequency of extreme events—or a higher intensity of these phenomena. It is particularly true for the 30-year return period extremes where Qmax values reach 200 m^3/s and 260 m^3/s for 2041–2070 and 2071–2100 time periods, respectively (the historical reference is 160 m^3/s).

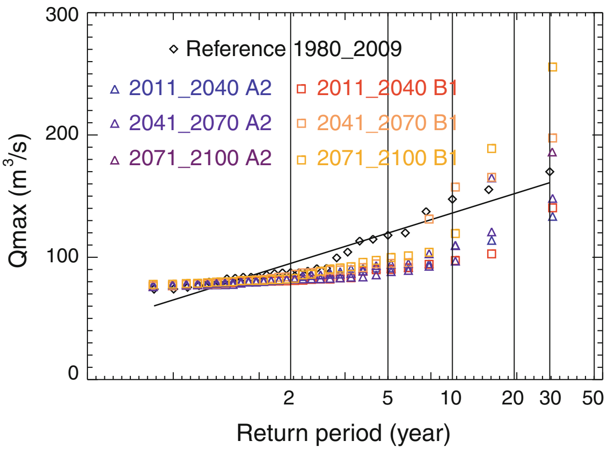


Fig. 8 Gumbel distributions of the maximum peak discharge for the different future climate scenarios and time periods. The historical distribution is also represented as a reference (*black line*)

5.4 Cumulative impact of climate change and forest fire

The expected increase in extreme peak discharge combined with a higher occurrence of forest fire can significantly alter the flood frequency and cause dramatic consequences in the future. For example, the value of 170 m^3/s, simulated for the B1 scenario over the 2041–2070 time period, is approximately characterized by a 12-year return period. Such a value was historically characterized by a 30-year return period. An increase of 20 % in the peak discharge due to the burning of half of the basin can lead to a value of 212 m^3/s currently characterized by a return period higher than 50 years.

6 Conclusions

The risk of forest fire and its impacts on hydrological behaviour have been studied considering historical knowledge and future climate scenarios. A simple method to assess the risk of forest fire and its consequences has been developed and applied to the Llobregat basin.

First, the risk of forest fire has been mapped using the CDC. Based on daily temperature and precipitation, CDC represents a simple estimator of seasonal drought that could be applied using future climate scenarios. CDC time series have been computed over the historical time period and related to the occurrence of past forest fire. The different levels of risk have been defined as the number of days per year exceeding a reference threshold.

Second, using past studies dealing with the hydrological consequences of forest fires on real burned watersheds, impacts of forest fire have been interpreted in terms of rainfall-runoff model parameters. A simple model based on the SCS equation has been chosen to simulate discharge and to take into account the burned areas. The parameters controlling the burned cells have been modified in order to simulate a faster and more intense peak discharge. The modified model has been applied to the Anoia river basin by progressively burning the basin. As expected, the destruction of the vegetation cover and soil alteration by fire have crucial consequences on the hydrological properties: (i) increase in peak discharge of up to 40 %, (ii) increase in runoff ratio of up to 30 %, (iii) low decrease in peak time of up to 20 min. As a consequence, the frequency of floods is also significantly altered.

Finally, the methodology to map the risk of forest fire has been applied by using future climate scenarios in order to assess future risk of fire due to the climate change. It shows a gradual increase in risk during the twenty-first century. Moreover, statistical distributions of peak discharge have been computed with climate scenarios. They have shown an increase in intensity for the most extreme events. The most pessimistic scenario coupled with the entire burning of the basin could imply the doubling of the discharge initially characterized by a 30-year return period.

The results presented illustrate the interest of such a study for forest fire and flood risk assessment. However, there are a number of implicit hypotheses and limitations that are worth discussing:

1. The application of the rainfall-runoff model with modified parameters should be validated by comparing its results after a fire with real observations. In this study, we assumed the hydrological impact on the Rimbaud basin and its interpretation in terms of model parameters to be valid on the Anoia basin. As it has not been possible for now to validate this assertion—because of the lack of hourly discharge data after a fire event—we have to wait until another fire event occurs in the Anoia basin or a similar basin to assess the model and possibly modify its parametrization. Regarding other studies dedicated to this topic, our assumptions can appear as a low hypothesis that should underestimate the impact of forest fire on the hydrological response.
2. The statistical distributions of future peak discharge have to be taken with care. They result from a modelling chain including climate model (MM5), hydrological model (HBV), and empirical formula (Fuller), being each linked in the chain affected by uncertainty. We have assumed the satisfactory results obtained for the historical period allow transferring and applying these models in the future (stationarity hypothesis). The different sources of uncertainty should be estimated in the future to achieve more formal conclusions. However, the results obtained in terms of peak discharge distribution seem consistent with those obtained in similar studies (Lehner et al. 2006; Dankers and Feyen 2008).
3. Land-use change is one of the most conspicuous changes in cultural landscapes in many regions of the world. In addition to climate change, land-use change is expected to have a strong impact on the water budget of river catchments (DeFries and Eshleman 2004). In this study, land-cover change has not been considered. Since the upper part of the basin contains very limited urban surfaces and limited land capable of urbanization, the future evolution in that zone could mainly concern shifts between forest, pasture, and agricultural land. So, we have assumed that urbanization will not be extended in the studied basins and that the vegetation (forest pines and shrubby maquis) will remain the same in the future. This assumption could be discussed in the future since several land-use scenarios exist: EURURALIS (Eickhout and Prins 2008), PLUREL (Nilsson et al. 2008), PRELUDE (EEA 2007). It is then possible to identify and evaluate the potential impacts produced by climate and land-use changes at the watershed scale (see Cabello et al. 2011).

Despite these limitations, this study could represent a first step to assess forest fire and flood risk in the future, as they have major consequences in terms of risk management. Indeed, Mediterranean regions are subject to violent flash floods that could be intensified in the future due to forest fire and/or climate change. These factors should be taken into account in future flood warning systems and flood policy. Based on the work carried out in this study, the IMPRINTS project (http://imprints-fp7.eu/) aims to develop a rule-based system that should be able to assign future consequences of climate change and propose adaptive measures to take into account possible increases in peak discharge.

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