

Wildfire impact on Boreal hydrology: empirical study of the Västmanland fire 2014 (Sweden)

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Abstract. Land cover changes at watershed scale constitute key issues in general hydrology. Wildfires are one of the drivers of the changes in vegetation, which might affect hydrological fluxes and the water balance. The Västmanland fire in central Sweden burned 14 000 hectares and removed the Boreal forest in this area during the summer 2014. Here, we have studied the change in flow signatures during 3 years after the wildfire. In the empirical experiment we used a paired catchment methodology to compare 2 catchments highly affected by the wildfire with 2 unaffected catchments nearby, of similar character and climate to avoid the impact of natural variability in the analysis of wildfire impact. The average size of the catchments is 20 km² and a total of 23 catchment characteristics of flow and physiography were defined, trying to isolate each of the hydrological processes affected by the wildfire. We used both *in situ* flow measurements and remote sensing information (e.g. yearly volume at the outlet of the subbasins, fraction of vegetation or fraction of snow). The results show a three main changes in the hydrological behaviour of the burnt areas: variation in duration and timing of snow season and the main spring streamflow peak associated to the melting, change in consecutive flow conditions and variations in flashiness from rainfall-events. This is related to an earlier and quicker snowmelt due to the increased solar radiation reaching this snowpack, the reduction of snow albedo due to charred forest remains and the higher exposition to wind of the snowpack and a change in interception and evapotranspiration rates from vegetation after the wildfire, respectively.

1 Introduction

The topic of forest-fire effects to catchment hydrology is important for scientific understanding of hydrological process interactions and societal preparedness to indirect consequences after wildfires. There is a huge literature on hydrologic effects of wildfires (e.g. Moody and Martin, 2001; Onda et al., 2008; Gleason et al., 2013; Gleason and Nolin, 2016; Havel et al., 2018) and paired-catchment approaches have been used before for detecting changes from various pre/post perturbation. Although, to our knowledge, forest-fire effects to catchment hydrology has not yet been explicitly evaluated at the catchment scale using various sources of empirical data. Here, we combine remote sensing and hydrologic data pre-wildfire and post-wildfire to interpret the broad scale impacts of forest wildfire to hydrological parameters, using two experimental and two “control” catchments from a recent large wildfire in Sweden, Northern Europe. The overall aim is to explore what changes on hydrology we can expect from wildfires in Boreal forests.

The studied region was exposed to the largest forest wildfire in Swedish modern history, which took place in Västmanland County, south-central Sweden, in the summer of 2014. The extremely high temperatures during the beginning of the summer, 3.5 °C above the average over this region, and reduced precipitation, 25% offset for a normal July, favoured the development of the fire, which was ignited by a forest vehicle performing subsoiling. The wildfire was active from the 31st of July till the 17th of August affecting a total area of 14000 hectares with different severities depending of the local conditions during the wildfire. Most part of the burnt area was covered by coniferous, needle-leaved evergreen forest characteristic of the southern part of the boreal forest (Bodin and Nohrstedt, 2016; Lidskog and Sjödin, 2016). The burnt area was also composed mainly by shallow rocky outcrops and well-drained mineral soils (Bohlin et al., 2017) which after the wildfire were completely remove or highly decreased in depth (see Figure A1 in the Appendix).

Land cover constitutes one of the crucial components controlling hydrological processes and river flow at basin and regional scales (e.g. Blöschl et al., 2007; Hall et al., 2014) and changes in its distribution have direct impacts in timing and magnitude on different component in energy and water budget (Bronstert et al., 2002; Cassiani et al., 2015; Tianming et al., 2013; Scanlon et al., 2005). Forest wildfires are the most common non-directly planned anthropogenic changes that drastically change the land cover across large areas. Forests work as a natural storage capable of absorbing and retaining rainfall during the wet season and releasing it slowly during the coming dry season (Calder, 2005; Qazi et al., 2017). Therefore, the most clear hydrological effects of a radical removal of vegetation will be related with the modification of the forest storage capacity and its interactions with the system. An increase in the total volume of effective precipitation (Madduma, 1974; Crockford and Richardson, 2000; Jeffery et al., 2014) is the most direct consequence. Additional modification include the partition between soil and vegetation evaporation fluxes (Gerrits et al., 2010; Wang-Erlandsson et al., 2014) and soil moisture dynamics (Liancourt et al., 2012; van der Ent et al., 2014; Boer-Euser Tanja et al., 2016). Increasing soil evaporation can result in drier top soil with a subsoil that is wetter because the marked reduction in canopy transpiration (Silva et al., 2006). The variation in water runoff volumes and consequently riverflow are the last and more palpable consequences regarding hydrology. Higher runoff coefficients are expected after a big wildfire, which may also increase the erosion capacity (Cerdeira and Robichaud, 2009) and the consequent problem related with water quality due to an increasing number of suspended sediments (Löfgren et al., 2009; Smith et al., 2011). When the forest is located in snow dominated areas, such as the boreal forest, wildfires can also affect snow dynamics. Several studies have demonstrated that changes in forest structures due to wildfires alter accumulation and melt (Faria et al., 2000; Micheletty et al., 2014; Gleason et al., 2013; Gleason and Nolin, 2016). In burnt forests, snowpack is more exposed to solar radiation and snow albedo is lower due to darkening of the surface from burned forest debris (Burles and Boon, 2011; Gleason et al., 2013; Gleason and Nolin, 2016).

All these impacts are extremely conditioned by scale (Blöschl and Sivapalan, 1995). Most of the mentioned hydrological changes can be clearly observed at plot-scales (Beeson et al., 2001; Brown et al., 2005; Woods and Balfour, 2008; Ebel et al., 2012; Stoof et al., 2012; Harpold et al., 2014). However their direct extension at large scales, e.g. catchment-scale, can imply an overestimation of the changes; forest wildfire effects are smoothed, mixed, diluted or filtered at large scales (Cammaraat, 2002; Bracken and Croke, 2007). In this study we linked information from stream flow gauges with remote

sensing products to quantify the areal impact of the catchments studied. Remote sensing products constitute an excellent tool to monitor land cover changes at medium-large scales, facilitating extra information to the traditional discharge measurements in gauge station that allows linking hydrologic effects with measurable land cover changes (Hall and Riggs, 2016; Dozier, 1989).

5 Although the hydrological effects of wildfire are well documented in low and mid latitudes, where warm and dry conditions favour wildfire occurrence (Hulbert, 1969; Lavabre et al., 1993; Moody and Martin, 2001; Onda et al., 2008; Micheletty et al., 2014), there is lack of studies about its effects in cold regions. The wetter condition, periodical snow coverage, and the vegetation characteristics of boreal forests make wildfire a phenomenon less recurrent in the northern latitude (Moritz et al., 2014; Andela et al., 2017). However, current global warming may impact hydrological regime with changes in precipitation, 10 evaporation and snow (Arheimer and Lindström, 2015). Scholze et al. (2006) show circumpolar boreal regions as highland venerable, with high risk of boreal forest losses and with an increasing wildfire frequency, especially in eastern Canada. This increase in wildfire frequency is not yet shown in Swedish boreal forest; nevertheless, the destructive Västmanland forest wildfire, could be possible future effect of the consequences of a drastically/extreme change in climate can cause to the land system.

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In this context, the objectives of this study are: (1) to assess the changes in land cover that the wildfire produced in system, and (2) to understand the hydrological effects that these land cover shifts introduced in the wildfire affected areas. For that, different indicators were defined to exclude natural variability, detect land-cover shifts and identify the eventual changes in flow signatures before and after the wildfire. A paired catchment methodology (Brown et al., 2005), commonly used to study 20 changes in the hydrological system after vegetation shifts, was used. Four small gauged catchments were examined; two affected by the wildfire with different intensities and two non-affected, respectively.

2 Study site and available data

This study was carried out in four small gauged catchments, in which two were affected by the wildfire (catchments A and 30 B, in red and orange respectively in Figure 1); and two non-affected catchments situated very close to the burnt area, with the same type of climate and original land cover (C and D, marked with blue in Figure 1).

In the paired catchment methods applied, the non-affected areas work as reference sites to validate that the impact that we discovered from the wildfire was not caused by natural climate variability of the system. All 4 studied catchments represent similar size, altitudes, slope and vegetation (Table 1).

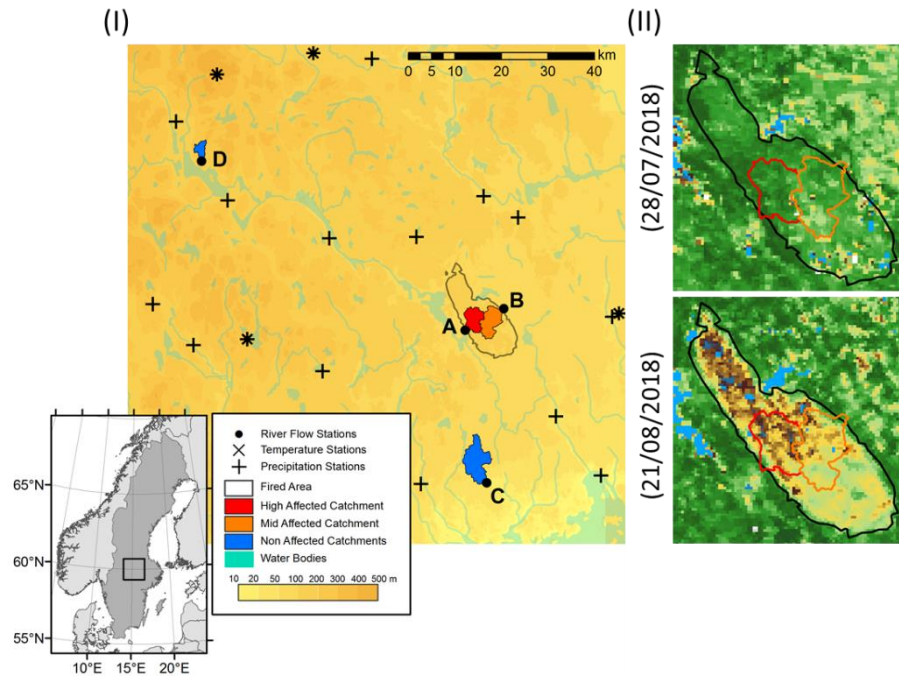


Figure 1 (I) Location of the Västmanland fire (black line) and the 4 small catchments analysed (in red, subbasin A, highly affected by the wildfire; in orange subbasin B, mid affected by the wildfire; in blue, subbasins C and D, reference site unaffected by the wildfire) **(II)** Fractional Vegetation Cover, before (20/07/2018) and after (21/08/2018) the wildfire.

Table 1 Description of the catchments selected for the study: topographic and land cover descriptors and availability of discharge measurements in their outlets

Gauge Station Name	Gauge Station ID	Catchment area (km ²)	Mean elevation (m a.s.l)	Mean Slope* (%)	Forest area (%)	Monitored timeserie of daily water discharge
Vallsjöbäcken	A	17.7	105	6.0	0.94	1979-01-01 – 2001-01-08 2014-11-12 – 2017-09-30
Gärsjöbäcken	B	22.5	109	3.2	0.80	2014-09-10 – 2016-10-05
Svenbybäcken	C	36.5	56	2.3	0.71	1980-08-31 – 2017-09-30
Finntorget	D	7.0	259	8.6	0.86	1979-09-04 – 2017-09-30

(*Calculated using the digital elevation model (DEM) GSD Terrain elevation databank (50x50m) from Lantmäteriet (cadastral and land registration Swedish authority); and defined as the average value of slope in each DEM cell within the catchment)

Three main sources of information were used in the study. First, Earth Observations (EO) products to evaluate the changes in land cover. The MODIS/Terra (MOD13Q1) and the MODIS/Aqua (MYD13Q1) Vegetation Indexes (VI) version 006 were employed to evaluate the changes in vegetation before and after the wildfire (Didan, 2015a, 2015b). These two products have spatial and temporal resolutions of 250 m and 16 days, respectively (Table 2). However, the combinations of both products, which have a time overlap, permits increase the temporal resolution from 16 to 8 days. Among the two VI available, Normalized Difference Vegetation Index (NDVI; Tucker, 1979) is used in this study.

Table 2 Summary of Earth Observation (EO) products used in the study. Spatiotemporal resolution, available dates and the number of scenes/dates analysed (the wildfire was located between two of the MODIS tiles with sometimes did not have the same availability, for this reason the table makes a difference between them)

Land Cover	Product/version	Spatial Res. (m)	Temp. Res. (days)	Available period	Number dates analysed (tile name)
Vegetation	MOD13Q1/006	250	16	2002-01-01 – 2017-09-14	364 (h18v03) - 358 (h18v02)
	MYD13Q1/006	250	16	2002-07-04 – 2017-06-18	334 (h18v03) - 350 (h18v02)
Snow	MOD10A2/006	500	8	2000-02-18 – 2017-09-30	805 (h18v03) - 807 (h18v02)

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- MODIS Vegetation EO products (Table 2) are used to assess the wildfire severity over the whole burnt area and specifically in each of the two experimental catchments. Fractional Vegetation Cover (FVeg) before (28/07/2018) and after (21/08/2018) the wildfire has been derived from NDVI following Gutman and Ignatov (1998). The wildfire severity differs between the two selected catchments (Figure 1.II; Table 3.) This fact allows including the wildfire severity as another aspect to consider in this study.
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- Table 3. Severity of the wildfire in the whole affected area and in each of the two selected burnt catchments.**

	Before Wildfire	After Wildfire	Change (%)	Severity
Burnt area	0.712	0.353	50	-
Catchment A	0.776	0.123	84	HIGH
Catchment B	0.678	0.284	58	MID

To assess the variability on the snow distribution, the MODIS/Terra Snow Cover (MOD10A2) version 006 is used (Hall and Riggs, 2016). This product provided eight-day maximum snow extent observation at 500 m resolution generated from Normalized Difference Snow Index (NDSI; Dozier, 1989; Table 2).

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- Second, discharge measurements at gauges station located in the outlet of the selected catchments were used. Gauge stations A, C and D (Figure 1 and Table 1) were measuring flow before the wildfire and are part of the national monitoring network of stream flow run by the Swedish Meteorological and Hydrological Institute (SMHI) across the country. These stations measure the water level every 15 minutes, a discharge value is then computed using a site-specific rating curve for each station and a daily average is calculated for river flow. Gauge station B was installed after the wildfire by the Swedish University of Agricultural Sciences (SLU) using a Doppler, which measures changes in pressure of the water vs a reference on land, which is then transformed into stream flow from a site-specific rating curve. Gaps in flow discharge time series, (periods 2002-2014 and 2000-2014 for gauging station A and B, respectively) were filled with flow discharges calculated by S-HYPE, national multi-basin model system for Sweden (Lindström et al., 2010; Strömqvist et al., 2012). The model performance for the study sites was evaluated for each of the defined flow signatures (see Appendix material Table A1); concluding that only significant changes between model and observations appear for the signature the annual number of reversal (Rev).
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Third, meteorological data were achieved from the national database PTHBV at SMHI, which is a 5 km gridded product of daily precipitation and temperature. It is based on observed data from some 700 meteorological stations across the country of Sweden (450.000 km²) which has been processed using optimal interpolation (i.e. kriging) with variables such as wind direction, altitude, slope, radiation, land cover to produce the grid (Johansson, 2002). The meteorological stations used by the gridded product and nearby the selected catchments, 18 station for precipitation and 4 for temperature, are shown in Figure 1 I.

3 Methodology

Hydrological changes in the study sites were analysed using the paired catchment methodology regarding: a) natural climate variability; b) land cover changes in vegetation and snow; and c) characteristic flow signatures during the period before the wildfire (2000-10-01 to 2014-09-30) and after the wildfire (2014-10-01 to 2017-09-30), respectively. The flow signatures were chosen to characterize different shapes of the hydrograph and flow regimes with importance to hydro-ecology based on the suggested metrics by Olden and Poff (2003) and Kuentz et al. (2017). In total, the 23 descriptors (2 for climate, 5 for land cover and 16 for flow signatures) were defined to detect and evaluate changes in each study site (Table 4). Climate and land cover descriptors were aggregated to the area of each one of the selected catchments and flow signatures were computed from measured or modelled time-series (see above Section 2). Climate descriptors were only used to validate that the unaffected reference sites were representing undisturbed conditions for the catchments affected by the wildfire, to make sure that the analysis were not biased by natural variability.

Table 4 Definition of the descriptors used to evaluate the hydrological changes over the wildfire area, regarding: a) climate, b) land cover and c) flow signature

Descriptor		Variable	Units	Description
Climate				
		Prec	mm	total annual/monthly precipitation
		Tem	°C	annual/monthly mean temperature
Land Cover				
Vegetation		FVeg	–	annual/monthly Fractional Vegetation Cover (derive from NDVI following (Gutman and Ignatov, 1998))
Snow	Magnitude	FSC	–	annual/monthly Fractional Snow Cover
	Duration	SnowIni	day of the hydrological year (DOHY)	beginning of the snow season, defined as the first day with more that 10% FSC in the watershed
		SnowEnd	day of the hydrological year (DOHY)	ending of the snow season, defined as the first day with more that 10% FSC in the watershed
		SnowDays	days	duration of the snow season
Flow Signatures				
Magnitude of flow events	Average flow conditions	Skew	–	annual/monthly skewness = mean/median of daily flows
		Qsp	mm	annual/monthly mean specific flow
		CVQ		annual/monthly coef variation = SD/mean daily flow
	Low flow conditions	BFI	–	base flow index: 7-day minimum flow divided by mean annual/monthly flow
		Q5	mm	annual/monthly 5 th percentile of daily specific flow
	High flow conditions	HFD		annual/monthly high flow discharge: 10 th percentile of daily flow divided by median daily flow
		Q95	mm	5 th percentile of daily specific flow
Frequency events of flow	Low flow conditions	LowFr	year ⁻¹	total number of low flow spells (threshold equal to 5% of mean daily flow)
	High flow conditions	HighFr	year ⁻¹	total number of high flow spells (threshold equal to 50% of mean daily flow)
Duration of the flow events	Low flow conditions	LowDurVar	–	coef. of var. in annual mean duration of low flow (threshold 25 th percentile)
	High flow conditions	Mean30dMax	–	mean annual 30-day maximum divided by median flow
Timing of flow events		Const	–	annual constancy of daily flow (Colwell, 1974)
Rate of change in flow events		Rev	–	annual number of reversals (change in the sign in the day-to-day change time series)
		RBFlash	–	annual/monthly Richard – Baker flashiness: sum of absolute values of day-to-day changes in mean daily flow divided by the sum of all daily flows
Catchment response		RunoffCo	–	annual/monthly runoff coefficient: ratio between mean annual/monthly flow divided by mean annual/monthly precipitation
				annual/monthly actual evapotranspiration: mean annual/monthly precipitation minus mean annual/monthly flow
		ActET	mm yr ⁻¹ /month ⁻¹	

Two different analyses were performed to evaluate the changes. First, temporal evolution of the main descriptors (precipitation (Prec) , temperature (Temp), fractional vegetation cover (FVeg), fractional snow cover (FSC) and mean specific flow (Qsp)) was assessed for the pre- and post-wildfire periods. These time-series were analysed by visual inspection and specific metrics for changes in trends, (i.e. average values, beginning and end of the snow/vegetation season).

5 Second, annual and/or monthly values, depending on the descriptor definition, of each descriptor during pre- and post-wildfire period were compared. Mann–Whitney U test or Wilcoxon rank-sum test (Mann and Whitney, 1947) was performed to evaluate if the changes were statistically significant. This test is a non-parametric test used to test whether two samples are likely to derive from the same population. Moreover, Mann–Whitney U test can be applied to samples with different sizes (such as in our case 14 and 3 years for periods before and after the wildfire, respectively) for detecting statistically
10 significant changes between them.

4 Results

Table 5 shows that only 11 of the 23 defined descriptors were exposed to statistically significant changes (high significance (99%), normal significance (95%) and no significance (>95%)) after the wildfire on the annual scale, according to the Mann-Whitney U test. Nevertheless, none of these significant changes are constant throughout the year; instead they are being
15 significant only under specific months and can thus be linked to processes controlling the hydrological fluxes during these events.

**Table 5 Statistical significance of the Mann–Whitney U test for the changes between pre- and post- wildfire in all descriptors defined for each catchment (A to D, Figure 1) on the annual and seasonal scales: 1) High significance (99%) increase (‡) and decrease (=); 2) Normal significance (95%) increase (+) and decrease (−); 3) No significance, (·); 4) Non defined descriptor (blank),
20 due to descriptor definition or values out of season in the case of snow and vegetation.**

	Annual						Seasonal						
	ABCD	Oct ABCD	Nov ABCD	Dec ABCD	Jan ABCD	Feb ABCD	Mar ABCD	Apr ABCD	May ABCD	Jun ABCD	Jul ABCD	Aug ABCD	Sep ABCD
Prec	++++
Temp	++++	++++	++++	‡‡‡‡	‡‡‡‡
Fveg	----	----	----	----	----	----	----	----
FSC	----	----	----
SnowIni	+...
SnowEnd	----
SnowDays	----
Skew	=...	‡‡
Qsp	+...
CVQ	----	‡‡
BFI
Q5	+...
HFD	+...	+...	----
Q95	----	++++
LowFr
HighFr
LowDurVar	----
Mean30Max	----
Const
Rev	...‡
RBFflash	+...	+++	+++	‡‡	+...
RunoffCo	‡+
ActET	----

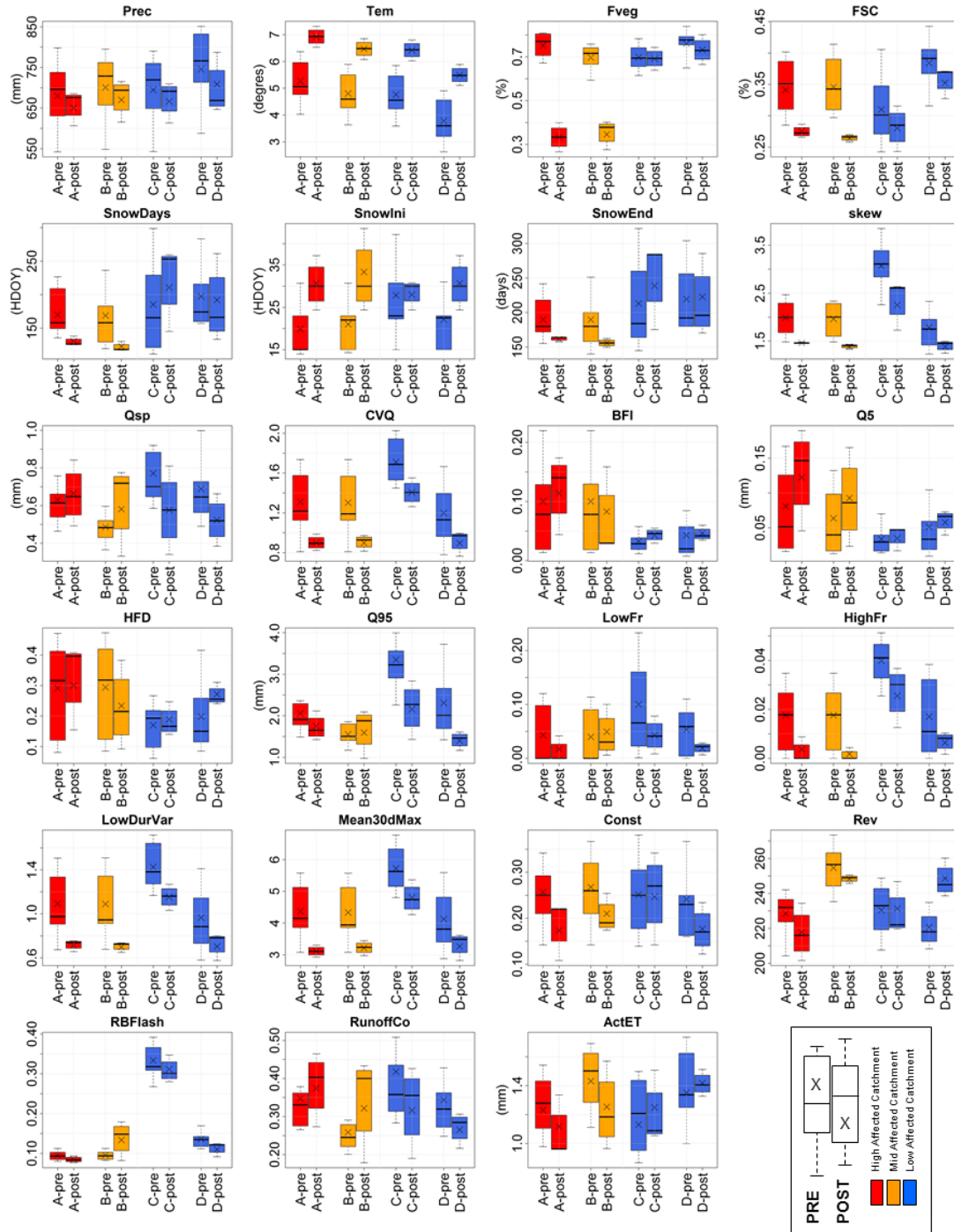


Figure 2. Distribution of annual values of the 23 descriptor for the pre- and post-wildfire period in each of the four selected sites. The box shows 50% of the data, solid line is the median value and x is the mean value of the dataset (in total 17 samples, 14 and 3 respectively in each dataset). Red box represent high affected site; orange box low the medium affected site and blue boxes represents the non-affected catchments.

The climate variables show some variability between the two periods studied, with temperature being higher during the years after the wildfire, mainly due to warmer autumn and winter seasons (Fig. 2). However, the same temperature effect is detected in both affected areas and reference sites. Precipitation, on the other hand, was relatively stable, with only some lower values for the month of September. Again, the changes are similar in all catchments studied, which indicate that any further differences found between the catchments cannot be related to natural variability. The results illustrate the importance of considering climate variability in comparative studies, as this factor controls much of the water cycle dynamics and may confuse the findings when exploring other causes to hydrological change.

When studying time-series from the EO products, land cover showed significant changes for all studied variables between the catchments affected by the wildfire and reference sites on the annual scale. The results clearly show that for vegetation the growing season is from April to September, while the snow season ranges from October to April in this region.

Significant differences between wildfire-affected and reference sites were found only for 5 of the 16 flow-signatures studied. Looking into specific months, however, gave significant differences during specific months in 10 signatures, as described more in detail below (also see the Appendix section, Figure A).

4.1 Shifts in Climate and Land cover

Both temperature and precipitation show similar pattern for the 4 chosen sites after the wildfire (Figure 3) and thus, climate cannot be considered as the dominant driving factor to explain the differences between burnt and reference sites. During the post-wildfire years a clear increase, about 5 °C, in mean daily mean temperature occurred between autumn and early winter (Oct-Jan), while the rest of the months showed the same values as in the pre-wildfire period. This reflects the natural weather fluctuations between years and could be observed in all 4 catchments. The changes in annual cumulative daily precipitation are negligible, only some small significant change can be observed during September.

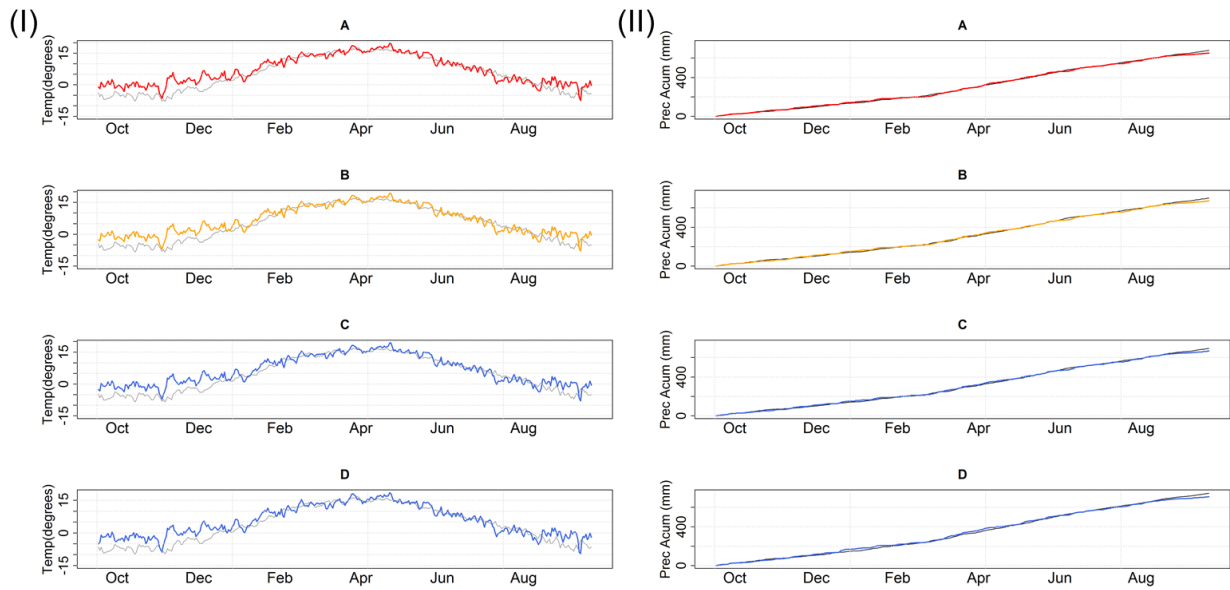


Figure 3 Seasonal evolution of climate variables: (I) mean daily temperature (left panel) and (II) annual cumulative daily precipitation (right panel) for pre-wildfire (grey lines) and post-wildfire (coloured lines) periods in each of the four catchments.

- 5 The drastic change in vegetation during the wildfire and the following vegetation recover was clearly identified by EO products (Figure 4 I). The affected area is not fully recovered after 3 years; however, some vegetation is now growing here again. The satellite product shows that about half of the affected area has recovered some type vegetation with annual mean values of fraction of vegetation cover for the third year after the wildfire of 0.42 (0.75 in the pre-wildfire period) for site A and 0.44 (0.69 in the pre-wildfire period) for site B. Similar recovery rate are observed in both sites for the first year, about
- 10 42% per year, however this rate change during the second year with higher recovery in site A, 15% per year, than in site B, 6% per year. The satellite information used in this study cannot distinguish which kind of vegetation has replaced the original boreal coniferous forest; however, some field campaign show that mosses, small shrubs and isolated pines trees have started to grow in the affected area (Figure A). As expected no changes in vegetation were found in the non-affected reference sites.

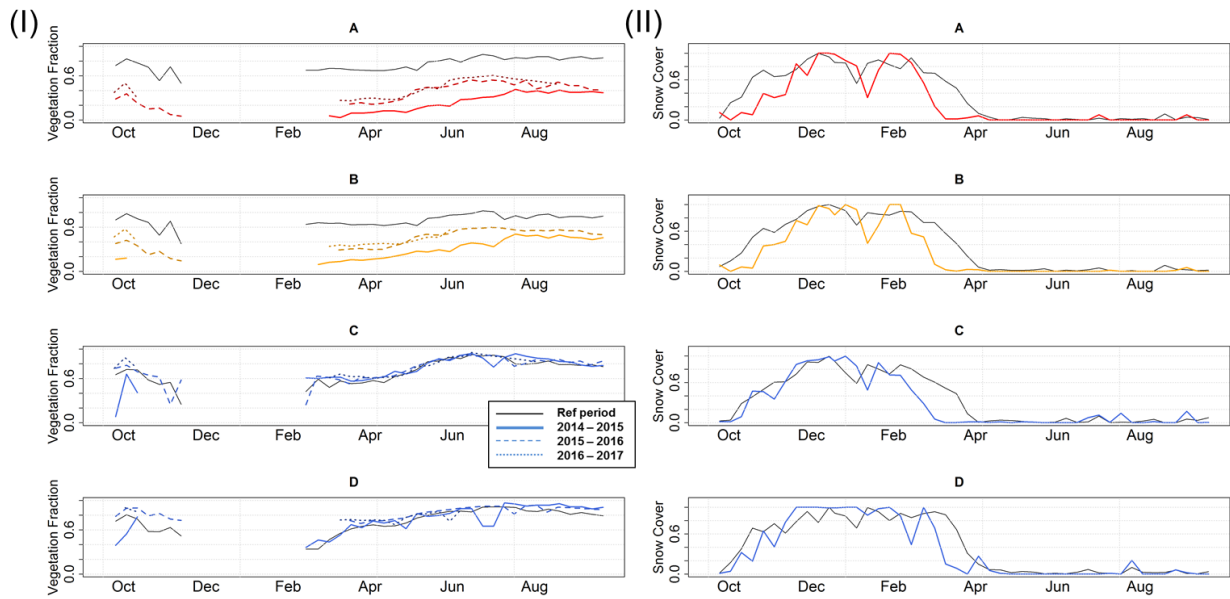


Figure 4. Seasonal evolution of land cover descriptors: (I) daily fractional vegetation area (left panel) and (II) daily fractional snow cover (right panel) for pre-wildfire (grey lines) and post-wildfire (coloured lines) periods in each of the four catchments.

5 Similarly, the catchments affected by the wildfire also show a clear change in snow cover evolution (Figure 4), with a significant reduction of the snow annual mean snow fractional cover. Although the duration of the snow season during the post-wildfire period is shorter in all studied sites, the change is only statistically significant in the areas affected by the wildfire (A and B). This is a consequence of the clear shift in onset and end of the snow accumulation phases, which change 15 and 9 days (in median for A and B respectively) for the beginning of the snow season, and 15 and 21 days for the snow-
 10 season ending. This effect is not seen in the reference site and is thus not caused by higher temperatures but rather by the loss of forest canopy (Figure 2, boxplot 1). The higher exposure to shortwave radiation due to greater openness favour by the loss of forest vegetation hinders the snow accumulation at the onset of the snow period and favours the melting at the end of the snow season. Shortwave radiation is also affected by the rest of charred forest that dirty the snowpack decreasing the albedo.

4.2 Impact on Flow signatures

15 Time-series analysis of stream flow does not show any significant change in water volumes, however, a more variational behaviour, less smooth and more peaked, can be found in mean condition of the river flow after the wildfire in burnt areas (Figure 5 I). Regarding seasonality, the spring peak of streamflow, directly linked to the melting of the snowpack, occurs about one month - 27 days in average for the two sites - earlier than before the wildfire. On the contrary, this change is not seen in the reference sites (Figure 5 II). This change in flow dynamics is probably due to the earlier snowmelt onset observed
 20 after the wildfire in affected sites. In addition a more peaked flow was found during summer after the loss of vegetation. The

lower interception and evapotranspiration due to lack of vegetation canopy, as well as lower capacity to retain water due to loss of soil during the wildfire event, are probably two main factors controlling these higher peak in summer period. Similar results have been reported in several studies world-wide (e.g. Evans et al., (1999) in Australia, Inbar et al., (1998) in Israel and Moody and Martin, (2001) in western USA).

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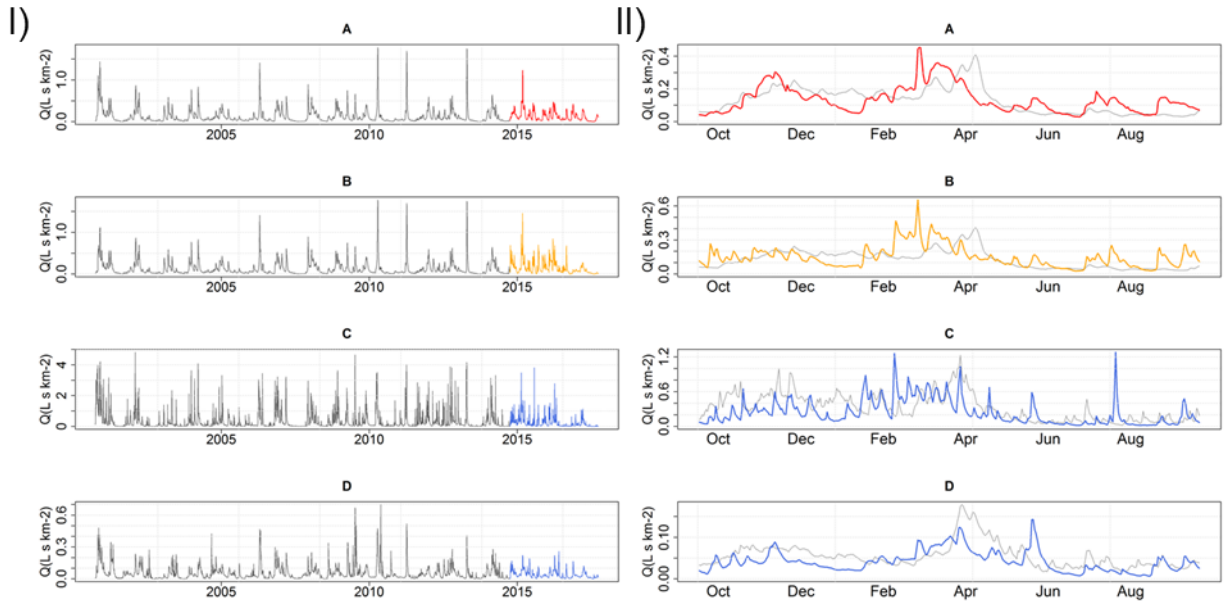


Figure 5 Temporal evolution (left panel) and (II) Seasonal evolution (right panel) of daily flow for pre-wildfire (grey lines) and post-wildfire (coloured lines) periods in each of the four catchments.

10 The boxplots of Figure 2 confirms these time-series analysis (Figure 5 I). Regarding magnitude of the flow events, a statistically significant decrease was found for skewness and the coefficient of variation of the streamflow after the wildfire occurred, in addition to a less influence from climate on high flows. This means that the variation in flow is less extreme after the wildfire, with closer values between mean and median flows and smaller standard deviation. Again, the changes in water storages due to a quicker snow melting, with shorter snow season and maybe more winter mid-melting events, are the main causes of the less pronounced flow peaks. The same causes generate statistically significant differences in flow duration, with shorter duration periods of both low and high flow conditions (Figure 2). Hence, both lower peak flows and lower duration of the peak flows were altered after forest fire occurred.

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For the studied flow signatures that illustrate frequency, timing, rate of change in the event and catchment response, no significant changes were observed between affected areas and the reference sites at annual scale; however, changes in flow signatures on the monthly scale were detected. Especially during September when we had a significant change in precipitation and temperatures between the two periods studied (see section 4.1), which resulted in significant higher mean

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specific flow, base flow, high flow, and runoff, while actual evapotranspiration was much lower. Probably the loss of vegetation and soil affected the storage capacity of the precipitation at these events. Higher flashiness during the summer period (August) was found after the wildfire, which may be due to more water available due to lack of interception and evapotranspiration from the canopy and lower storage capacity from canopy and soil loss during the wildfire event.

5 **5 Discussion**

Three main changes in the hydrological regime could be observed due to the loss of vegetation and tree canopy after the wildfire: variation in duration and timing of snow season and the main spring streamflow peak associated to the melting, change in consecutive flow conditions and variations in flashiness from rainfall-events. These modifications could be attributed to modifications of some hydrological drivers over the burnt catchment - lower interception, higher solar radiation reaching the snowpack, lower infiltration and evapotranspiration - which result in a different magnitude of the water and energy fluxes generated before and after the wildfire (Figure 6).

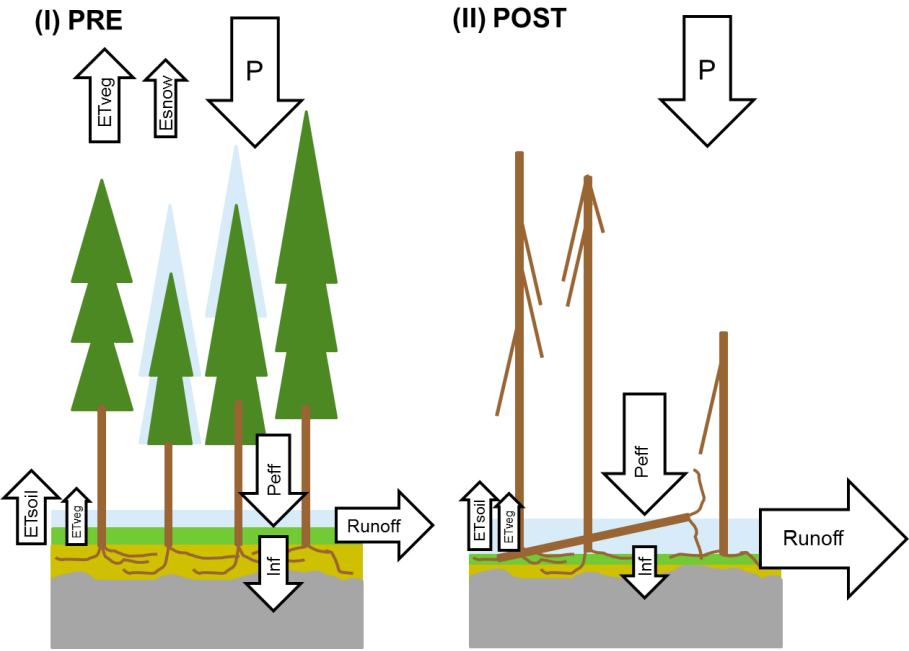


Figure 6. Conceptual Scheme of water bucket and fluxes in the system before and after the wildfire. The size of the arrows means the importance of the flux in the system.

First, regarding changes in snow dynamics, the main finding is a reduction of the duration of snow season. The loss of forest canopy has a direct impact in snow interception, reducing drastically the amount of snow stored by the canopy. The remained dead tree branches, after the wildfire, are able to storage some snow; however, this amount is negligible in comparison with boreal forest canopy interception (Smith et al., 2011), which according to Pomeroy and Schmidt (1993) can reach 60% of the total snowfall and can be traduce in a total sublimation loss component than can reach 30-40% of the total

intercepted snow. Despite a bigger amount of snow getting to the ground, the increased solar radiation reaching this snowpack, the reduction of snow albedo due to charred forest remains and the higher exposition to wind of the snowpack, make that this snow suffers a quicker melting than before the wildfire. In the three years after the wildfire, we observed a mean shorting of 18 days in the snow season for the burnt sites; with average values that range from 30 to 10 days from the first and last year after the wildfire, respectively. This shorting is also found in similar studies during the first snow season after the wildfire over the Sierra Nevada Mountains (California) (Micheletty et al., 2014) and sub-alpine forest in Oregon (Gleason et al., 2013), with a mean reduction of the snow season in 7.5 days and 23 days, respectively. The trend observed in the following years, which points to closer values to the ones observed in the reference sites, is also find in a similar study (Gleason and Nolin, 2016), which mainly attribute this effect to the change in albedo due to the charred forest remains. Gary (1974) and Gleason et al., (2013) affirm that snowmelt rate can be duplicated between burnt and non-burnt sites and attribute these effects to the bigger amount of available energy in the now opened wildfire areas. Finally a major exposition to wind effects after the fire can favour the contribution of the turbulence energy fluxes (Link and Marks, 1999).

Regarding changes in consecutive flow conditions and flashiness from rainfall-events, the wildfire altered the interception, infiltration and evapotranspiration dynamics with clear variations during the summer period, more peaked flow, less evapotranspiration and more runoff, only statistically significant during September. Therefore, the capacity of the soil to store water was completely diminished, altering the runoff and evaporation dynamics. The flashiness is also affected by shifts in interception and evapotranspiration. The forest interception capacity, which in boreal forest can range between 20-30% (Grelle et al., 1999), has completely changed after the wildfire. Regarding evapotranspiration, Grelle et al. (1997) decomposed the evapotranspiration for a nearby experimental site into 65% transpiration and 20% evaporation of the intercepted precipitation in the canopy, and 15% coming from soil evaporation. Therefore, without the canopy, the two main components in the evaporation did not play a role. More water was able to evaporate but the new characteristic of the system were not able to do it, and consequently, the catchment responded quickly to precipitation events. However, this quick response is less significant during winter period when the role of the snowpack storing water delay the runoff effects.

As empirical study, all our findings are dependent on the data availability. Therefore, the results may be affected by discrepancy in duration of time series and the time series gaps We have used tested methodologies to solve this limitations (e.g. Mann-Whitney U test to assess significant changes in samples with different sizes, streamflow reconstruction done by using a hydrological model validated in the area) Nevertheless, there are other intrinsic data uncertainty (e.g. the different instruments used in the flow gauging stations and the common error associated to them, the possible smoothed interpolation of the weather, or the uncertainty in the algorithm used in deriving EO products) that has not been assessed in this study but can also conditions our findings.

6 Conclusions

Wildfires do impact Boreal hydrology, which might be of importance in a future climate as an indirect consequence of climate change. Global warming is most significant in the Arctic region and as a consequence, wildfires may become more frequent and severe in boreal forests in the future. However, it should be noted that overall the detected impact on hydrology from wildfires is rather small compared to other on-going environmental changes (for instance direct effects of climate change or river regulations). Nevertheless, this empirical study we found that:

- The loss of tree canopy has changed the infiltration, interception, evapotranspiration and snow patterns; not only modifying the capacity of soil, vegetation and snow to retain water but also altering the water fluxes between them.
- Hydrological changes on the annual scale were found in relation to snow season duration, shorter and earlier, and its consequent spring flow peak. In addition, statistically significant decreasing changes in the flow skewness and variation coefficient were detected in the affected areas after the wildfire. Only changes in specific summer months were found for shifts in evaporation and runoff.
- The paired catchment methodology was very useful. Comparing nearby reference sites with the ones affected by the wildfire made it possible to separate natural variability from the wildfire impact in the hydrological interpretation of the data. Separating the time series into flow signatures, made it possible to identify changes which were not seen in simple time-series analysis. Finally, the use of EOs helped both to identify the extension of burnt areas and to assess the vegetation recovery after the wildfire. After three years, half of the fractional vegetation cover was recovered. However, the EO product used cannot distinguish which are new vegetation types.

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Appendix

Table A1. Statistical significance of the Mann–Whitney U test for the changes between model and observation for all flow signature descriptors defined in each catchment (A to D, Figure 1) at annual scales: 1) High significance (99%) increase (‡) and decrease (=); 2) Normal significance (95%) increase (+) and decrease (−); 3) No significance, (·)

	YEAR	
	ABCD	
Skew	·	· ·
Qsp	·	· ·
CVQ	·	· ·
BFI	·	· ·
Q5	·	· ·
HFD	·	· ·
Q95	—	· ·
LowFr	·	· ·
HighFr	·	· ·
LowDurVar	·	· ·
Mean30dMax	·	· ·
Const	·	· ·
Rev	‡	‡ ‡
RBFflash	·	· ·
RunoffCo	·	· ·
ActET	·	· ·



Figure A1. Example of the new vegetation appearing after the wildfire

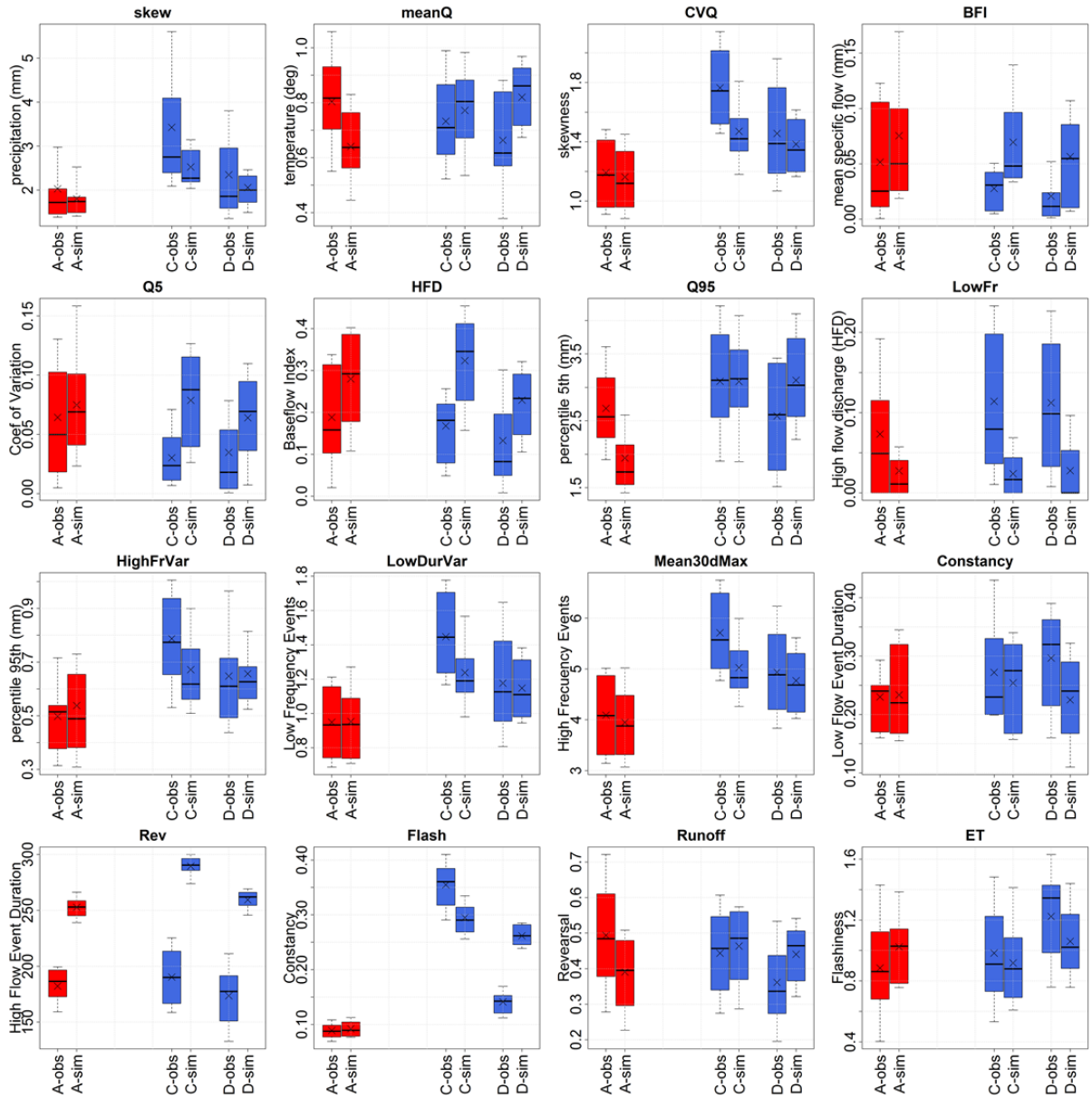


Figure A2 Annual distribution of the 16 flow signatures for observation (Table 2) and simulated (S-HYPE) values in each of the four selected sites. Red box high affected site; orange box mid affected site and blue boxes, non-affected areas.

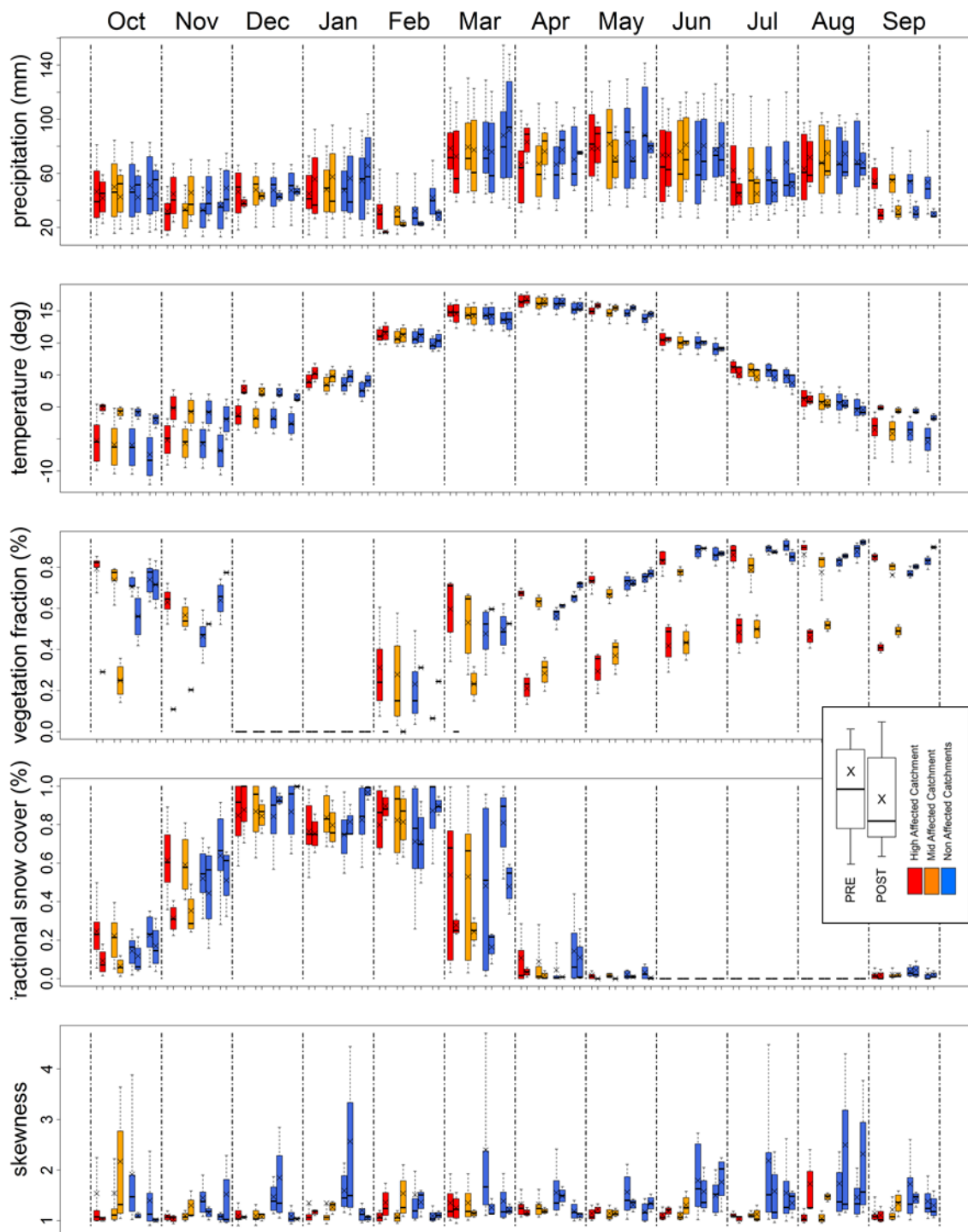


Figure A3 Seasonal distribution of the 13 descriptor defined at monthly scale for the pre- and post-wildfire period in each of the four selected sites. Red box high affected site; orange box mid affected site and blue boxes, non-affected areas.

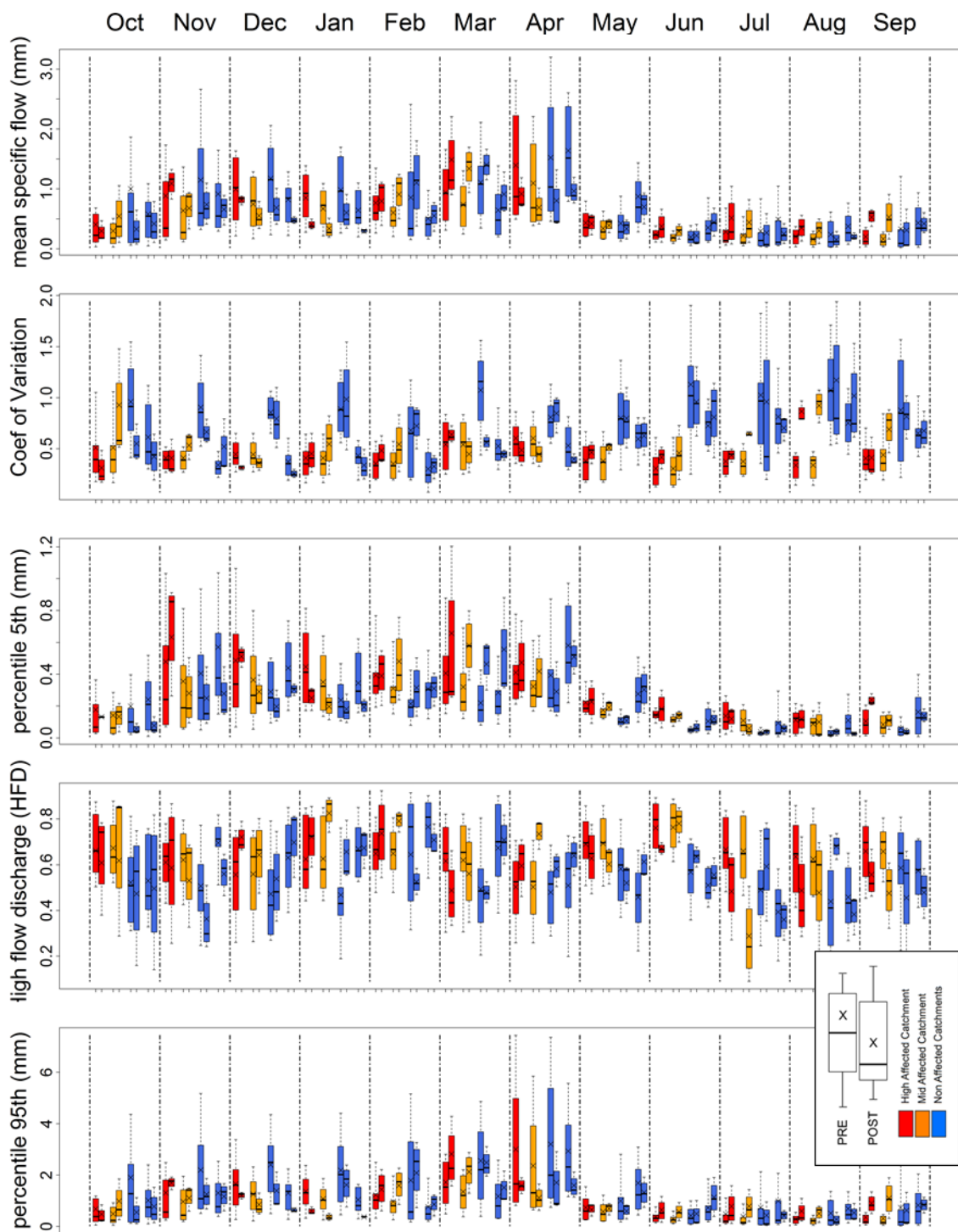


Figure A3 Seasonal distribution of the 13 descriptor defined at monthly scale for the pre- and post- wildfire period in each of the four selected sites. Red box high affected site; orange box mid affected site and blue boxes, non-affected areas (cont)

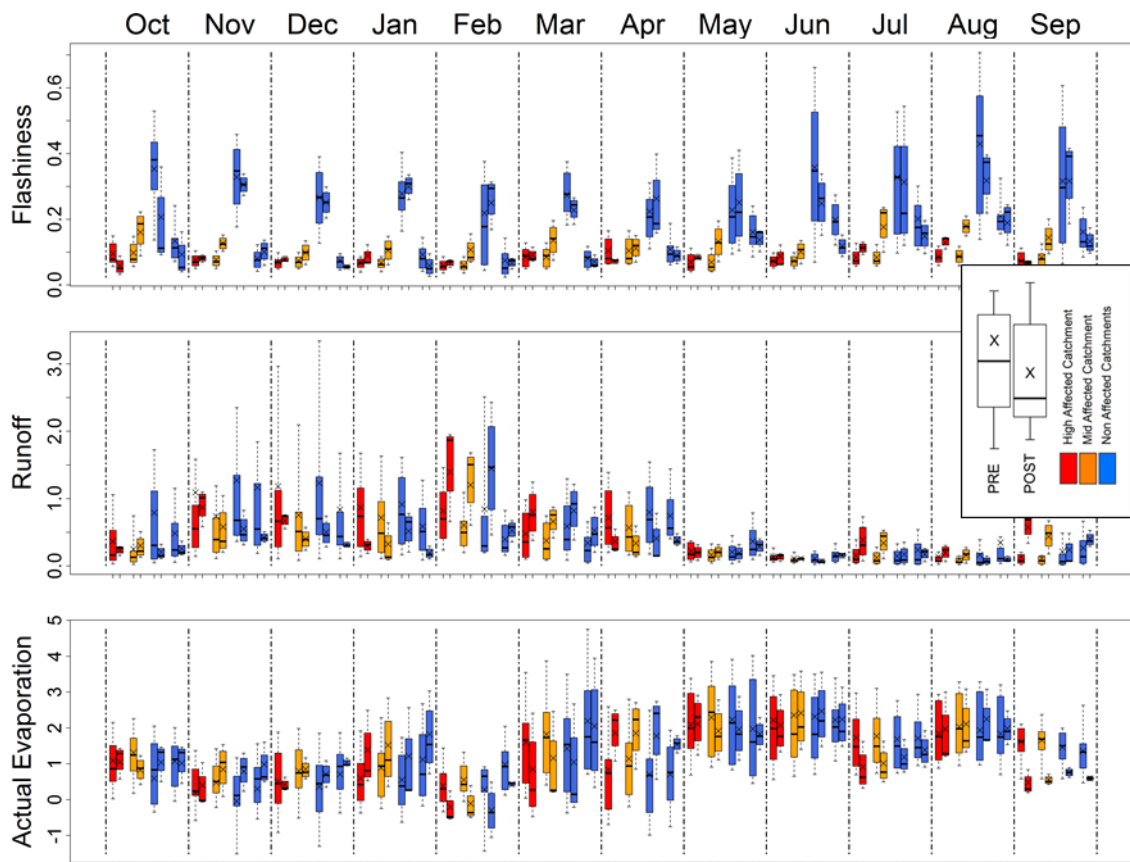


Figure A3 Seasonal distribution of the 13 descriptor defined at monthly scale for the pre- and post-wildfire period in each of the four selected sites. Red box high affected site; orange box mid affected site and blue boxes, non-affected areas (cont)