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Looking at trends in high flows at a local scale: The case study of Wallonia (Belgium)

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ABSTRACT

Study Region: 84 catchments across the Walloon region of Belgium
Study Focus: This study aims at analysing trends in high flows by examining annual maxima (AM), peaks over threshold (POTs) and the number of peaks per year (frequency). Trends were identified using statistical tests (regression analysis, Mann-Kendall and Pettitt tests).
New Hydrological Insights for the Region: Almost 12 % of the sites show a trend in the magnitude of AM and frequency, and 6% show a trend in the magnitude of POTs. Globally, more negative trends have been detected, but the proportion of positive trends is higher in the Scheldt catchment than in the Meuse catchment. The results of nonstationary analysis indicate important changes in the magnitude of the 100-year flood (up to 18 % increase/11 % decrease in 10 years) and the frequency of peak flows (up to 42 % increase/31 % decrease). These changes could therefore impact future flood risk management in Wallonia. However, the time-series are short (30–50 years) and some uncertainty remains. Understanding the mechanisms responsible for the trends is essential to obtain better estimates of future flood flows. A first analysis of potential drivers reveals that changes in precipitation match the trends in high flows, and lower snowfall quantities and higher evapotranspiration rate, caused by the increase in temperature, could have contributed to the decrease in high flows in some regions.

1. Introduction

Over the past two decades, many researchers have studied the changes in hydrological data worldwide: Robson et al. (1998) in the UK, Vogel et al. (2011) and Archfield et al. (2016) in the USA, Giuntoli et al. (2012) in France, Mangini et al. (2018) and Blöschl et al. (2019) in Europe, to cite just a few. In 2008, Milly et al. wrote an article entitled “Stationarity is dead”, explaining that it should no longer be a default assumption in water management. Indeed, the means and extremes of hydroclimatic variables such as precipitation, evapotranspiration and river flow are changing, altered mainly by anthropogenic changes of Earth’s climate. Nevertheless, non-stationarity is not taken into account in most water management studies such as the design of flood storage areas and flood maps.

Despite this general statement from Milly et al., studies looking at high flows usually show more contrasted results. In the USA, for example, more than 60 % of the 345 stream gauges analysed, using mean daily streamflow, did not show any statistically significant trends in either the peak magnitude, frequency, duration, or the volume of frequent flood events over the period 1940–2013 (Archfield et al., 2016). In Europe, Mangini et al. (2018) found statistically significant trends in the magnitude of the annual

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maximum flood peak and the frequency of the peaks for the period 1965–2005 for only 17 % and 21 % of the sites studied (629 gauging stations recording mean daily discharge) respectively, and almost half of those trends were negative.

Notwithstanding the fact that global warming will lead to an increase in the frequency and intensity of heavy precipitation events in many regions is quite certain (IPCC, 2014), there still exists some uncertainty regarding the predictions of extreme river flows, mainly because of the complexity of all the different processes involved. Indeed, river flows are influenced by many climatic and non-climatic factors which interact with each other. For instance, the increase in temperature leads to an increase in rainfall quantity due to the higher water-holding capacity of the air according to the Clausius-Clapeyron relation. On the other hand, it also leads to a decrease in snowfall quantities and an increase in the evapotranspiration rates (Alfieri et al., 2015). Therefore, depending on which flood generating processes dominate in the catchment, responses in high flows will be different (Thober et al., 2018). Besides global warming, there has also been a global change in land use, including deforestation, changes in agricultural practices and urbanisation. This also has an impact on high flows as the type of land use plays an important role in the flood generation processes, for example influencing runoff and infiltration.

Since results of flood change detection and prediction vary from a region to another, mainly due to the range of climate and land use changes, we think studies at local scales are necessary.

Our study focuses on Wallonia (Southeast Belgium) and articulates into three parts: the first part aims at detecting trends in the magnitude and frequency of high flows, then an analysis of the trends is carried out using nonstationary frequency analysis, and in the last part, potential drivers of changes in high flows are discussed.

2. Methodology

2.1. Data

The study region, Wallonia, is located in the southeast of Belgium and covers an area of 16 844 km^2. The altitude increases gradually from the northwest to the southeast, and ranges from 50 m to 694 m. Both temperature and rainfall follow the gradient in the topography: the mean temperature varies between 7.5 °C and 11 °C while the total annual precipitation varies between 700 mm and 1400 mm (SPW - DGO3 - DEMNA - DEE, 2017).

On the Walloon territory, there is an extensive water level monitoring network: almost 300 stations spread over the whole area. This network, however, is quite recent: the first station equipped with monitoring instruments taking hourly measurements was installed in 1967. For our analysis, the stations located on non-navigable watercourses and providing flow data for at least 30 years (up to 2017) were selected, i.e. 84 stations. Amongst the stations selected, 66 are located in the Meuse catchment, covering 70 % of the area of Wallonia, 17 in the Scheldt catchment, representing 20 % of Wallonia, and the last one is in the Moselle catchment which is part of the Rhine river basin district (Fig. 1). The size of the station catchments ranges from 1.4 km^2 to2900 km^2, the median being

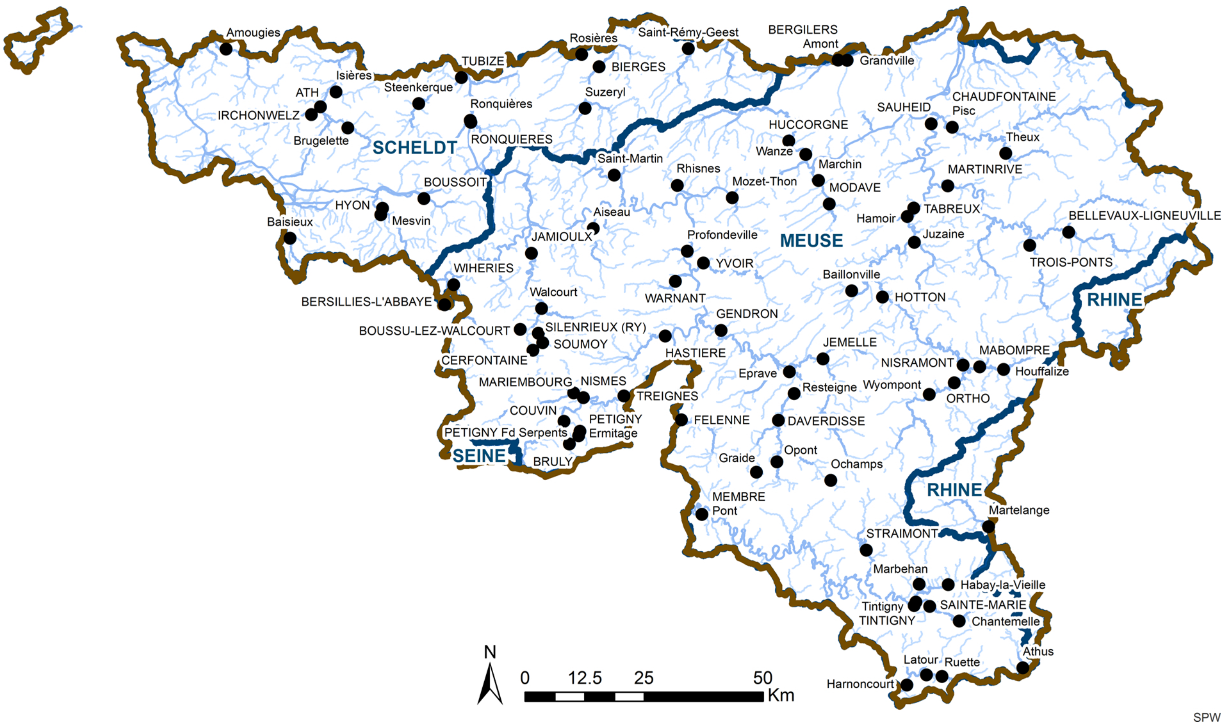

Fig. 1. Map showing the stations analysed and the boundaries of the river basin districts in Wallonia.

143 km^2.

To characterise high flows, annual maxima (AM) and peaks over threshold (POTs) were extracted from the hourly flow data. The number of POTs per year was also used to analyse the frequency of high flows. The water year (October-September) was used to avoid separating the high flow season into two different years.

Unfortunately, data is not continuous and a non-negligible quantity of data is missing for 60 stations. On average, 2.5 years of data are missing, but it varies between a few days and 6 years. To minimise the impact of this missing data, the hydrograph of such stations was visually compared to the hydrograph of a station in the same catchment or in a neighbouring catchment with a similar hydrological regime. The annual maximum of a year with missing data was discarded only when the annual maximum of the comparative station occurred in the period of missing data. Similarly, the number of POTs per year was adjusted taking into account the number of missing peaks in the record. In case of uncertainty, a conservative approach was preferred and the data for that year was deleted from the data set.

2.2. POT extraction

The main advantage of the POTs is that all peaks above a threshold are included: not only the maximum but also the subsequent highest peaks every year which are sometimes higher than the annual maximum of other years. This method is therefore very interesting for short time series as it increases the number of observations analysed. It also allows studying the frequency of high flows using the number of POTs per year.

However, the extraction of POTs is quite complex. The first step is to select a threshold: it must be low enough in order to select enough peaks, but high enough so that the peaks are independent from each other. Setting the threshold to a fixed quantile for all the time series is frequently used as it is a simple and quick rule, but it is inappropriate from a theoretical point of view (Scarrott and MacDonald, 2012). In this study, those arbitrary rules were avoided and a more robust method that takes into account the data characteristics of each station was preferred. The chosen method is the one described by Lang et al. (1999) and Coles (2001). It is based on the adjustment of the Generalised Pareto (GP) distribution to the exceedances over the threshold for successive values of the threshold. The threshold must be sufficiently high to meet the assumptions of the GP law, but low enough to obtain unbiased estimations of the distribution parameters. This is ensured by selecting the threshold based on the analysis of three graphs: the mean residual life plot, the parameter stability plot, and the dispersion index plot. On the mean residual life plot, the lowest threshold from which the mean exceedance above threshold follows a linear trend is selected. The parameter stability plot allows checking if the shape and scale parameters of the GP distribution are constant for all threshold values above the selected threshold. The dispersion index is the ratio between the variance and the mean of a data set. According to the extreme value theory, the number of exceedances in a defined time period (usually one year) follows a Poisson distribution, for which the dispersion index equals 1. The dispersion index value for the selected threshold must therefore be close to 1.

Once the threshold has been chosen, we must ensure that the selected peaks are independent. Again, different approaches exist in the literature, usually based on a minimum number of days between peaks depending on the catchment area, sometimes combined with a condition on the flows between two peaks (Cunnane, 1979; Interagency Advisory Committee on Water Data, 1982; Lang et al., 1999; Li et al., 2016; Mangini et al., 2018; Svensson et al., 2005; Willems, 2009). In this study, the declustering method described by Coles (2001) has been used. It consists in grouping consecutive values exceeding the threshold and keeping the maximum value for each cluster, the clusters being separated from each other by a certain number (r) of values below the threshold. The other values of the clusters are set to the threshold in order not to lose information regarding the frequency of peaks, notably for the flood frequency analysis. However, choosing the value of the parameter r is complex: it must be high enough to ensure the independence of the peaks but not too high to avoid losing valuable data. It is a compromise between bias and variance, for which general guidelines do not exist. The approach taken here was to do a first declustering with r equal to 5 days, assess the dependence of the peaks on the hydrograph, and repeat those two steps with increasing values of r until peaks are independent. The extremal index was also taken into account; it measures the dependence of extremes and is equal to 1 for independent data series (Coles, 2001).

Finally, the minimum number of POTs per year was set to 2 following the studies and advice of Cunnane (1973) and Taesombut et Yevjevich (1978) in order to preserve the added value of the POT approach comparing to AM and, in many cases, ensure a Poisson-distributed number of POTs per year.

2.3. Trend detection

Once the series of AM and POTs had been extracted from the hourly flow data, an exploratory analysis was carried out. This analysis consists of examining the data on graphs in order to identify potential problems or trends in the data. These trends were first quantified using a simple linear regression of the AM and POTs as a function of time; the slope characterising the magnitude of the trend. However, caution must be taken regarding those results as linear regression is sensitive to outliers and give better results when residues follow a normal distribution (Svensson et al., 2005). This exploratory analysis also included tests to verify the assumptions linked to the statistical tests such as normality, lack of autocorrelation and homogeneity (Kundzewicz and Robson, 2004).

Trends were then detected with more confidence using other statistical tests. The Mann-Kendall test is often used for trend detection as it does not require the normality of the data and is therefore suitable for hydrological extremes (Šraj et al., 2016). However, the results are sensitive to the autocorrelation of the data which can lead to an over- or underestimation of the statistical significance of the test. The autocorrelation of the data was therefore tested beforehand, and a modified Mann-Kendall test was used when the data was autocorrelated (Giuntoli et al., 2012). This modified test adjusts the variance used in the Mann-Kendall test taking into account the effective sample size (Hamed and Ramachandra Rao, 1998). Indeed, the data redundancy decreases the effective data set size and thus artificially increases the variance (Serinaldi and Kilsby, 2016). In addition, the Sen's slope was calculated; it is the non-parametric equivalent to the slope of the linear regression and therefore a good indicator of the magnitude of the trend (Mangini et al., 2018). It is actually the median of the slopes of the lines crossing all pairs of points; it is not sensitive to outliers and thus more robust (Sen, 1968). The Pettitt test was also used to detect changing points in the data series. As it is sensitive to the presence of a monotonous trend in the data (Rybski and Neumann, 2011), the test was also done on the residues of the linear regression (i.e. data from which the linear trend was, to a certain extent, removed).

To assess the trend in the number of POTs per year over time, a Poisson regression was carried out. The statistical significance of the trend was calculated using the Chi^2 test on the regression slope, testing if it is significantly different from 0. This method is seen as the most suitable for count series in the absence of overdispersion (Mangini et al., 2018).

The level of statistical significance was set to 5% for all statistical tests.

2.4. Nonstationary frequency analysis

Stationarity is one of the requirements for standard frequency analysis; the statistical properties of the studied variables, their probability distribution in particular, must not change with time (identically distributed variables). If the variables are not stationary, then nonstationary frequency analysis should be used (Coles, 2001). This analysis consists in making the parameters of the probability distribution vary with time. Many authors have studied changes in high flows using this technique: Šraj et al. (2016) on two rivers in Slovenia, Delgado et al. (2010) on the River Mekong in China, and Vogel et al. (2011) on a number of watercourses in the USA, amongst many others.

We used the Generalised Extreme Value (GEV) distribution for the annual maxima and the Point Process (PP) approach for the POTs. The PP approach is also called Poisson-GP as the Generalised Pareto (GP) distribution is fitted to the threshold excesses and the Poisson distribution is fitted to their occurrence. Its main advantage, comparing to the classic GP distribution, is the independence of its parameters from the threshold, which makes the nonstationary frequency analysis easier to carry out (Gilleland and Katz, 2016; Scarrott and MacDonald, 2012).

Both distributions have a location parameter, a scale parameter and a shape parameter. The Poisson-GP has an additional rate parameter which is the mean number of occurrences (number of POTs per year in this study).

Four models were tested for each time series showing a statistically significant trend:

1 The parameters are constant (stationary model).
2 The location parameter is a linear function of the hydrological year y: $\mu(y) = \mu_0 + \mu_1 y$.
3 The location and scale parameters are both linear functions of the hydrological year y: $\mu(y) = \mu_0 + \mu_1 y$ and $\sigma(y) = \sigma_0 + \sigma_1 y$.
4 The location and scale parameters are both linear functions of the hydrological year y and the exponential is used for the scale parameter to ensure it has a positive value for any value of the year: $\mu(y) = \mu_0 + \mu_1 y$ and $\sigma(y) = \exp(\sigma_0 + \sigma_1 y)$.

The shape parameter is usually kept constant as its estimation is much more complex (Coles, 2001). The maximum likelihood method was used for the estimation of the parameters.

Models were compared using the AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) performance indices as well as the likelihood ratio test which allows testing whether adding a variable in the model is statistically significant or not (Gilleland and Katz, 2016). The model with the lowest AIC and BIC and for which the likelihood ratio test was statistically significant when compared to the stationary model was considered the best model.

The chosen nonstationary model was then used to compute specific return period floods. In particular, the 100-year return period flood for the year 2017 was compared to the stationary 100-year return period flood. The flood magnification factor, defined by Vogel et al. (2011) as the ratio between the flow value in 10 years (2027) and the actual flow value (2017), was also calculated. However, caution needs to be taken with such extrapolations as they assume the high flows will follow the same observed trend in the future (Gilleland and Katz, 2016).

For the frequency of high flows, the number of peaks in 2017 calculated using the Poisson regression equation was compared to the mean number of peaks per year under stationary conditions; the magnification factor was also computed.

2.5. Analysis of potential drivers

Flood generating processes depend on many factors that can undergo changes. These changes can be continuous or sudden and can occur once or several times. The potential drivers of trends in high flows are therefore numerous (Merz et al., 2012):

– climatic changes: changes in rainfall, snowfall, atmospheric circulation, temperature, evapotranspiration, antecedent soil moisture, etc.
– land use changes: urbanisation, deforestation, changes in types of crops or agricultural management practices, drainage of wetlands and agricultural areas, construction of flood storage areas, etc.
– river modifications: straightening, narrowing, deepening (by dredging for example), construction of dams or changes in their operation, etc.

Table 1
Annual indices used for the different climatic variables.

Climatic variable	Annual index
Precipitation	1-day annual maximum (mm)
	2-day annual maximum (mm)
	3-day annual maximum (mm)
	7-day annual maximum (mm)
Snow	Total annual snowfall quantity (mm)
	Annual maximum of snowpack depth (mm)
Temperature	Annual mean (°C)
	Winter (December-March) mean (°C)
	Winter (December-March) minimum (°C)
Evapotranspiration	Annual total (mm)

Some of these factors were analysed more closely in this study, using the same method as for flows i.e. trends were detected using linear regression, Mann-Kendall and Pettitt tests. Similarly to the nonstationary frequency analysis, the analyses were only carried out on the catchments showing a statistically significant trend in the high flows.

We focused on climatic variables. Precipitation, snow, temperature and evapotranspiration data were obtained for each catchment from 1 January 1961 until 31 December 2017 using the EPICgrid model (Sohier et al., 2009). In this model, snow data is actually derived from precipitation data when temperature falls below 0 °C; snowfall is therefore calculated in mm of precipitation. It also allows the simulation of quantities of melted snow and snow left on the ground at the end of each day, the latter being used in this study as an approximation of snowpack depth. As for the resolution of the data, the model works on a 1-km grid but the original data was on a 5-km grid obtained from kriging meteorological station data. However, this data was not available at an hourly rate. Annual indices were calculated from daily data in order to make the comparison with flow annual maxima. These indices were computed for each catchment, by hydrological year, for the same period as the flow data as well as for the whole data set period (since 1962). Table 1 below shows the different annual indices used for each type of climatic data.

Other factors, such as urbanisation and the installation of sewerage networks, were also analysed qualitatively using satellite images and information from utility companies.

All the statistical analyses in this study were done on *R* version 3.4.3 (R Core Team, 2017) using the following packages: *extRemes* version 2.0–8 (Gilleland and Katz, 2016), *POT* version 1.1–6 (Ribatet and Dutang, 2016), *trend* version 1.1.0 (Pohlert, 2018) and *fume* version 1.0 (Santander Meteorology Group, 2012).

3. Results and discussion

3.1. Trends

Table 2 shows the number of sites where a statistically significant trend was detected and the corresponding percentages over the total number of sites for the analysed variables. Almost 12 % of the stations show a statistically significant trend in the magnitude of AM and/or the number of peaks per year (frequency), but only 6 % show a trend in the magnitude of POTs. In total, there are actually 16 different sites (19 %) which show a statistically significant trend in at least one of the three variables analysed, as statistically significant trends were sometimes detected for different variables at the same site.

We can see there are more negative than positive trends. We also observe that the stations showing a trend in the magnitude are not necessarily the same as the ones showing a trend in the frequency; changes in the magnitude do not imply changes in the frequency or vice versa. Finally, there are more statistically significant trends in the magnitude of AM than in the magnitude of POTs. These three observations are shared with Svensson et al. (2005) who studied 21 stations worldwide with a record of daily mean flow for 44–100 years. They explained the last observation by the fact that lower peaks (below the POT threshold) are selected for AM and the slope of the trend is therefore steeper, which matches our results despite the difference in the length of the time series analysed.

Even though these numbers seem low, they are similar to other European studies. In the study by Mangini et al. (2018) on 629

Table 2
Results of the trend detection analysis: number of sites showing a statistically significant trend (p-level of 0.05) and corresponding percentages over the total number of sites.

	Positive trends	Negative trends	Total
Magnitude of AM	4 (4.8 %)	6 (7.1 %)	10 (11.9 %)
Magnitude of POTs	2 (2.4 %)	3 (3.6 %)	5 (6.0 %)
Frequency (number of POTs/year)	3 (3.6 %)	7 (8.3 %)	10 (11.9 %)
Magnitude of AM, POTs and frequency	1 (1.2 %)	1 (1.2 %)	2 (2.4 %)
Magnitude of AM and POTs only	1 (1.2 %)	1 (1.2 %)	2 (2.4 %)
Magnitude of AM and frequency only	1 (1.2 %)	2 (2.4 %)	3 (3.6 %)
Magnitude of POTs and frequency only	0	0	0

stations recording mean daily flow in Europe for the period 1965–2005, 9.7 % of the sites showed a positive trend in the magnitude of AM and 7.6 % showed a negative trend. For the Continental hydro-climatic region which includes the east of Belgium and France, Germany, the north of Italy, Switzerland, Austria and other Eastern European countries, they found 8.6 % and 6.9 % of positive and negative trends respectively. These numbers are very close to our results for the negative trends (7.1 %) but more positive trends were detected by Mangini et al. (4.8 % in our study). They analysed trends in the magnitude of POTs for several data sets in which the average number of POTs per year differs. As the average number of POTs per year across all the stations in our study is 2.7, we examined their results for 3 POTs per year, and similar conclusions can be drawn: 5.9 % and 3.2 % of the stations in the Continental hydro-climatic region show positive and negative trends respectively, while these percentages in our study are 2.4 % and 3.6 %. They also detected more trends in the frequency of POTs (23.7 %) than in their magnitude (9.1 %); these percentages are, respectively, 11.9 % and 6 % in our study.

The European FloodFreq report on flood frequency analysis in a changing environment includes the results of trend detection studies on extreme precipitation and/or streamflow in 21 countries (Madsen et al., 2013). They concluded that extreme precipitation is generally increasing, but there are no clear indications of a general increase in extreme streamflow at the regional or national scale. However, increases in extreme streamflow were detected for smaller regions. Several studies also report a decrease in extreme flows in regions where snowmelt is the main flood generating process.

The more recent study of Blöschl et al. (2019) on 3738 European gauging stations found regional patterns. In northwestern Europe, 69 % of the stations showed an increasing flood trend when analysing annual maxima based on daily mean or instantaneous discharge for the period 1960 – 2010. Only a few Belgian stations were included in this study, and statistically significant positive trends were found for stations on the Lower Meuse and its tributaries. A station in Germany near the eastern border of Belgium showed a significant negative trend.

When mapping the results (Figs. 2 A, B and C), we observe there is no general trend for the whole Wallonia but local patterns are present, which confirms the importance of studying changes in high flows at a local scale. On these maps, the stations have been colour-coded according to the sign of the Sen's slope and the statistical significance of the trend, the level of significance being 5%.

We can see that, for the annual maxima (Fig. 2 A), the trends in the Scheldt catchment are mainly positive. In the Meuse catchment, except for the Lesse, negative trends dominate and they are mainly located in the south (Semois-Chiers and Moselle catchments) and the east (Ourthe, Amblève and Vesdre catchments). The map for the magnitude of POTs (Fig. 2 B) displays very similar patterns with a lower number of statistically significant trends. As for the frequency (Fig. 2 C), a few stations in the Meuse catchment which show a positive trend or no trend in the magnitude show a negative trend in the number of POTs per year.

Robson et al. already explained in 1998 that the internal variation in the flood records, usually linked to climate fluctuations, makes trend detection very difficult. Statistical detection is possible only for very noticeable trends or for long data sets. Although they used 40- to 50-year periods, they recommend redoing the analyses with more data to confirm the presence or absence of trends. Blöschl et al. (2019) also stated that trends are influenced by the observation period and could therefore be different if a longer period was analysed. This clearly shows the limitation of our data as the length of the records ranges from 30 to 50 years. However, Milly et al. (2015) argue that, even if trends are not statistically significant and some uncertainty exists, climate change effects are increasing in magnitude in such a way that they cannot be ignored in future water management, and in particular in the design of structures that are supposed to last decades.

3.2. Nonstationary frequency analysis

Stationary and nonstationary models described in Section 2.5 were fitted to the time series showing a statistically significant trend. Tables 3 and 4 give a summary of the results of this analysis.

In Table 3, we can see that models 3 and 4 (with both scale and location parameters being time-dependent) perform the best for most stations. The difference between the stationary 100-year return period flood and the 2017 100-year return period flood calculated with the best nonstationary model ranges from 2.6 % to 30.1 %, and the decadal magnification/reduction factor ranges from 0.89 to 1.18 for the magnitude of AM and POTs. This is lower than the magnification factors observed in the USA ranging from 0.45 to 3 (Vogel et al., 2011). This could be explained by the differences in catchment characteristics between Wallonia and the USA, but also by the fact that Vogel et al. used an exponential relationship to describe the evolution of quantiles over time. The difference between the observed mean number of POTs per year and the number of POTs per year in 2017 calculated using the Poisson regression varies between 28.8 % and 87.2 %. As for the decadal magnification/reduction factor, it ranges from 0.69 to 1.42.

For some catchments, although a trend was detected in the time series using the statistical tests, the stationary model was outperforming the nonstationary models. These catchments are therefore not included in Table 3. The nonstationary model could potentially be improved by replacing time as a covariate by other explanatory variables that are more related to the physical processes, such as precipitation and land use changes, or by using other types of relationships to describe the evolution of high flows over time. This highlights the need to better understand the trends in high flows (origin and type) before doing more complex (and especially predictive) analyses. According to Serinaldi et al. (2018), non-stationarity in the population cannot solely be inferred from trend detection tests carried out on observed data. The causes of the detected inhomogeneities need to be understood in order to extrapolate conclusions beyond the period of records and justify the use of nonstationary models. Otherwise, the models would give unrealistic predictions (Serinaldi and Kilsby, 2015).

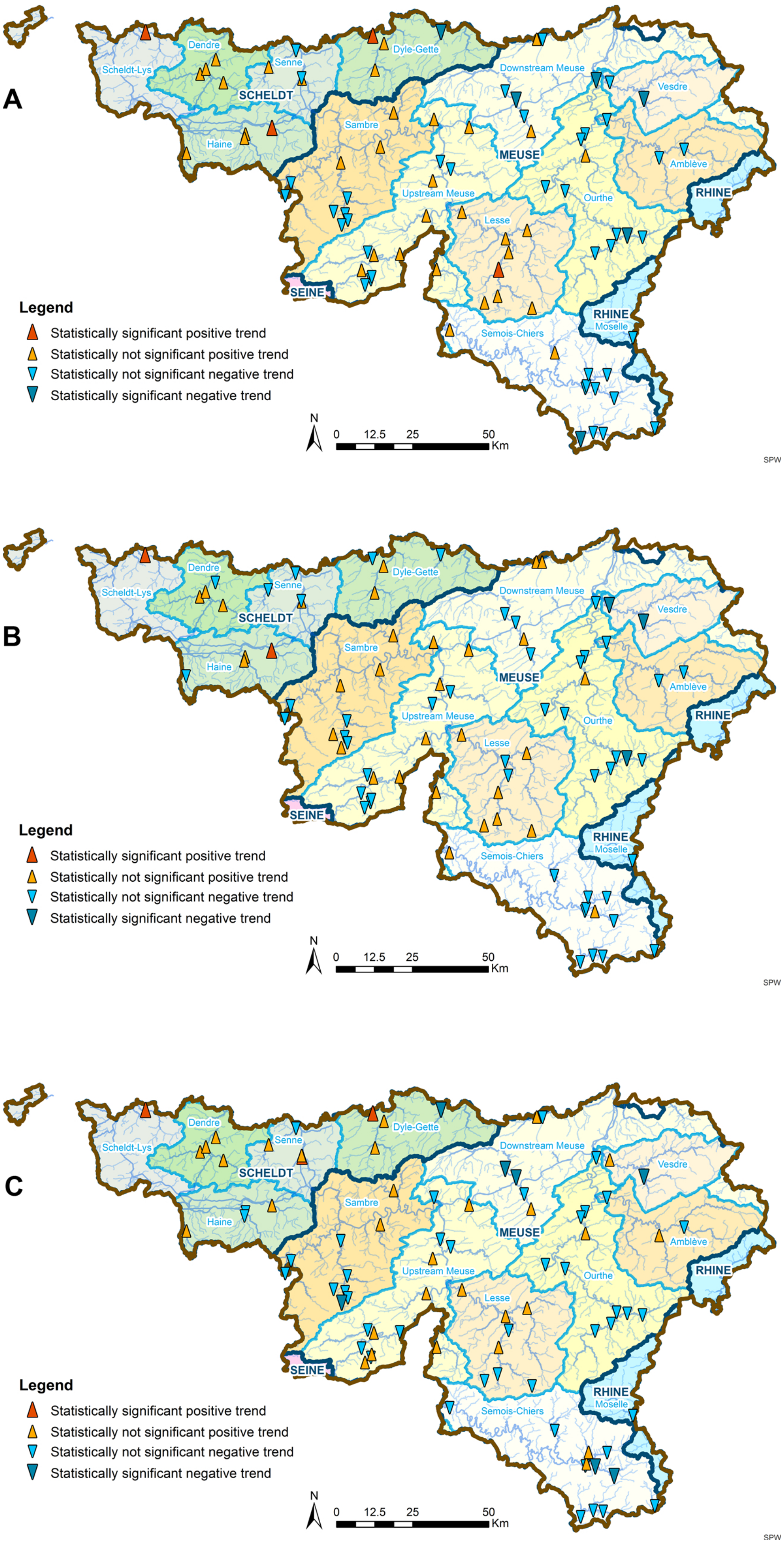

Fig. 2. Maps showing the trends in the magnitude of annual maxima (a), the magnitude of POTs (b) and the number of POTs per year (c). The statistical significance level was set at 5%.

Table 3
Results of the nonstationary frequency analysis on data series showing a statistically significant trend in the magnitude of high flows (AM for all 5 stations, as well as POTs for Amougies and Boussoit). Models 3 and 4 include time-dependent location and scale parameters, the scale parameter being strictly positive for Model 4. The 95 % confidence interval values are presented within brackets for the stationary and nonstationary 100-year return period floods.

Station name	Catchment	Best model	Stationary 100-year return period flood (m^3/s)	2017 nonstationary 100-year return period flood (m^3/s)	Difference between the 100-year return period floods (%)	Decadal magnification/reduction factor
Amougies	Scheldt-Lys	3 for AM	24.9 [21.8 ; 27.4]	27.9 [23.8 ; 31.3]	11.9	1.10
		3 for POTs	24.8 [22.2 ; 26.6]	27.0 [23.3 ; 29.2]	9.2	1.09
Rosières	Dyle-Gette	3 for AM	13.8 [9.7 ; 20.6]	18.0 [12.3 ; 28.2]	30.1	1.18
Boussoit	Haine	3 for AM	32.0 [25.5 ; 39.6]	35.7 [26.4 ; 42.6]	11.6	1.11
		3 for POTs	30.5 [25.6 ; 35.0]	32.3 [25.3 ; 36.4]	6.0	1.09
Wanze	Downstream Meuse	4 for AM	46.0 [31.2 ; 70.4]	44.8 [23.6 ; 169.0]	−2.6	0.96
Harnoncourt	Semois-Chiers	4 for AM	45.9 [39.7 ; 50.8]	33.4 [28.0 ; 42.8]	−27.1	0.89

Table 4
Results of the nonstationary analysis on data series showing a statistically significant trend in the frequency of high flows. Standard deviations for the observed mean number of POTs per year and 95 % confidence intervals for the estimations using the Poisson regression are presented within brackets.

Station name	Catchment	Observed mean number of POTs per year	2017 number of POTs per year using Poisson regression	Difference between the numbers of POTs per year (%)	Decadal magnification/ reduction factor
Amougies	Scheldt-Lys	2.49 (2.14)	3.88 [2.78 ; 5.41]	55.8	1.27
Rosières	Dyle-Gette	2.55 (2.39)	4.77 [3.49 ; 6.54]	87.2	1.42
Ronquières	Senne	2.69 (1.94)	3.75 [2.70 ; 5.21]	39.3	1.19
Saint-Rémy-Geest	Dyle-Gette	2.70 (2.01)	1.41 [0.90 ; 2.20]	−47.7	0.73
Huccorgne	Downstream Meuse	3.18 (1.77)	2.26 [1.60 ; 3.20]	−28.8	0.86
Wanze	Downstream Meuse	2.84 (2.14)	1.32 [0.84 ; 2.07]	−53.6	0.69
Theux	Vesdre	2.54 (1.59)	1.68 [1.09 ; 2.60]	−33.9	0.81
Cerfontaine	Sambre	2.78 (1.62)	1.68 [1.09 ; 2.60]	−39.5	0.77
Chantemelle	Semois-Chiers	3.35 (1.79)	2.16 [1.50 ; 3.10]	−35.6	0.80
Sainte-Marie	Semois-Chiers	2.07 (1.37)	1.22 [0.76 ; 1.97]	−41.1	0.78

3.3. Potential drivers

First, precipitation was analysed: negative trends in at least one of the indices (1-, 2-,3- and 7-day annual maxima) were found for five catchments in the east of the region, and positive trends were found on the River Lesse and at two sites in the Scheldt catchment. These trends match the increase or decrease observed in high flows at those sites. However, when looking at the whole period for which the rainfall data is available (1962–2017), only one station in the Scheldt catchment and one in the Meuse catchment still show statistically significant positive trends, and there are no negative trends. This confirms that trends depend on the observation period (Blöschl et al., 2019). One possible explanation could be that these negative trends are more recent and therefore weaker when taking into account more historical data; they would get stronger in the future. Another hypothesis is that precipitation is linked to atmospheric circulations such as the North Atlantic Oscillation and therefore has a multidecadal oscillatory behaviour, as suggested by Willems (2013). Looking at the results for each index, we notice it is actually the 1-day annual maximum that increases while the maxima of cumulative precipitation decrease, with only one station showing a statistically significant negative trend in the 7-day annual maxima. Blöschl et al. (2019) also analysed trends in the 7-day annual maxima between 1960 and 2010 in Europe, but found increasing trends for all regions except Southern Europe. This demonstrates again the importance of also studying those phenomena at a local scale. However, these increases in precipitation resulted in increasing high flows only in northwestern Europe where winter storms cause winter floods. The increase in high flows on the River Lesse (Meuse catchment), for which 95 % of the AM and 80 % of the POTs occur in the winter, is hence most likely due to the increase in precipitation, the statistically significant trend in the 1-day annual maxima being relevant for the hydrological characteristic of this catchment. In smaller catchments, it is the local, short and high intensity convective storms that need to be taken into account rather than long synoptic storms. This shows the importance of considering the hydrological processes to fully analyse the trends in high flows.

As for snowfall, a study using a model reconstructing the hydroclimatic conditions favourable to winter floods in the Ourthe catchment (one of the main tributaries of the River Meuse) found a decreasing trend in the number of days favourable to floods for the period 1959–2010. This is mainly due to a decrease in the snow accumulation and a shortening of the snow season (Wyard et al., 2017). Our analyses confirm those results and show that this is actually not restricted to the Ourthe catchment as negative trends in snowfall were actually observed at nearly all the 16 study sites for the period 1962–2017 (-54 % on average over 50 years, with a standard deviation of 12 %, calculated using the linear regression equations from the trend detection analysis (snowfall as a function of time) for the years 1967 and 2017). However, from a hydrological point of view, snowfall is mainly relevant for the Meuse catchment.

This decrease in snowfall is most likely due to the general increase in temperature also found for all study sites (+1.5 °C on average for the mean temperature over 50 years, with a standard deviation of 0.3 °C, calculated using the linear regression equations from the trend detection analysis). Annual mean and minimum winter (December-March) temperatures show an increase of 1.8 °C and 3.3 °C respectively (standard deviations of 0.2 °C and 0.6 °C) on average over 50 years, and were actually correlated to the snowfall.

Another important factor in the generation of floods in northwestern Europe is the antecedent soil moisture, which is influenced by evapotranspiration (Kundzewicz, 2012). A positive trend in the total annual evapotranspiration, linked to the increase in temperature, was observed at 11 of the sites for the period 1962–2017. The sites in the east, for which a negative trend in the precipitation was detected, did not show any trends in evapotranspiration. An increase in evapotranspiration leads to lower soil moisture, which in turn leads to lower flows. Decreasing trends in high flows were indeed observed at 6 of those sites. For the other 5 sites, other factors having opposite effects on soil moisture, including the increase in precipitation, must have influenced the evolution of high flows. This shows the complexity of the hydrological processes and their interactions, and thus the importance of analysing them in more detail and together to fully understand the causes of changes in high flows.

For the other factors, less data is available. However, land use changes such as urbanisation are visible on satellite images. Fig. 3 shows an example of an area in the Rosières catchment near Brussels, where an increase in high flows was observed. It can be seen

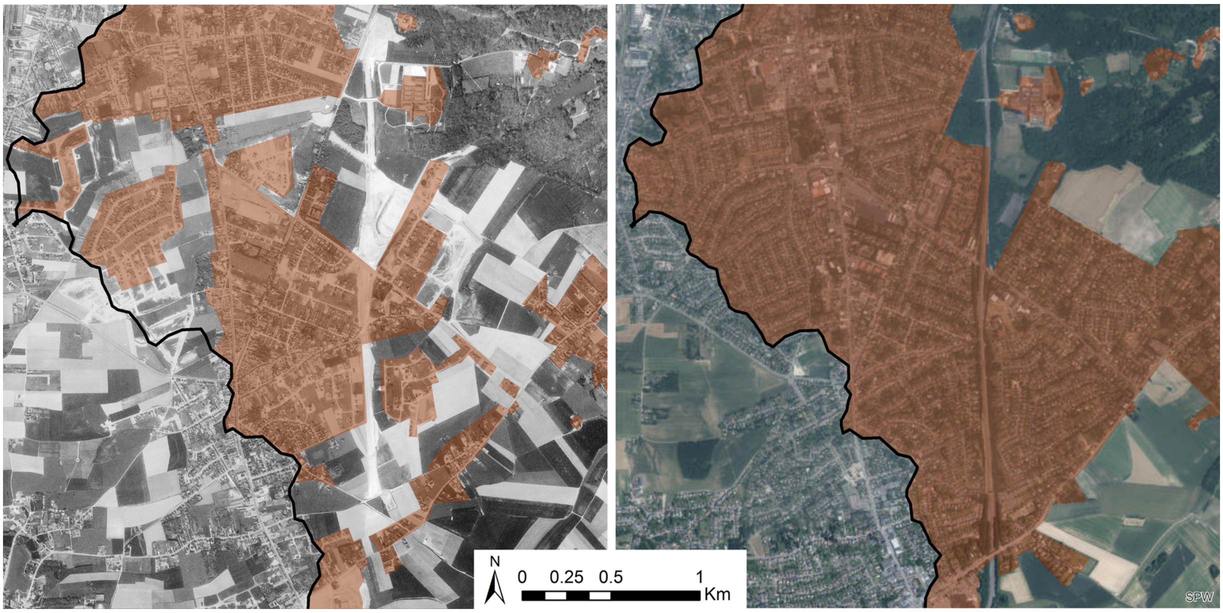

Fig. 3. Example of the increase in built-up areas (approximate extent in brown) in the Rosières catchment between 1971 (left) and 2017 (right). A statistically significant positive trend in high flows was observed for this catchment.

that many agricultural fields were converted to built-up areas between 1971 and 2017. According to the Walloon Government, the surface of built-up areas in Wallonia in 2015 was 30 % higher than in 1985, the highest increasing rate being in the 1990s (19.7 km^2/year on average between 1990 and 2000) (SPW - DGO3 - DEMNA - DEE, 2017).

One factor that is not often mentioned but could have an impact on the measured flow at a gauging station is the installation of the sewerage network since it changes the drainage of some catchments. Sewage and rainwater, which used to be discharged directly into the river, are now collected and transported to the sewage treatment works which is sometimes located downstream of the gauging station. This is the case for Saint-Rémy-Geest for instance and it could partly explain the decrease in high flows at that station, in particular since 2004 when the sewage treatment works became operational.

This analysis gives some insights in the factors that could potentially be responsible for the trends in high flows but did not quantify the relationships between the evolution of each factor or their combinations and the evolution of high flows. One way to do this would be through the use of physically-based deterministic or stochastic models. These allow simulating flow from climatic data and are parameterised according to catchment characteristics. As regional patterns have been observed in the trends, flood change attribution could also be performed by region, as it has been done by Viglione et al. (2016). The framework proposed by these authors uses fingerprints of the drivers, varying with catchment area, which allows quantifying their relative contribution. However, this goes beyond the scope of the study and is left as a suggestion for further work.

4. Conclusions

Changes have been detected in the magnitude as well as in the frequency of high flows over the study period (30–50 years depending on the site): 19 % of the sites analysed in Wallonia (16 out of 84 sites) show either a positive or a negative trend. Some regional patterns have also been observed: the positive trends are mainly located in the Scheldt and Lesse catchments while trends in the east and south of the region are mostly negative. These opposite results for different regions confirm the need for local-scale studies.

Our study has also shown that the magnitude of high flows in Wallonia could increase by up to 18 % or decrease by up to 11 % in 10 years depending on the catchment, while their frequency could increase by up to 42 % or decrease by up to 31 %. These figures give us a first idea of the impact the observed changes in high flows could have on their management in the future. However, a more detailed trend attribution analysis needs to be undertaken. This analysis would increase our understanding of the changes in high flows and their relationships with the changes in the climate, the catchment and/or the river itself, which is needed to calculate more precise estimates of the percentages of change. Indeed, it is all the flood generating processes that can be impacted by various continuous or sudden changes which can occur once or several times. Changes in the climatic variables have been demonstrated in this study: increase or decrease in the precipitation, depending on the site but in the same direction as the changes in flows, general increase in the temperature leading to a decrease in snowfall as well as an increase in the evapotranspiration in some parts of the region. This already shows the complexity of flood attribution, with climate factors having opposite effects (precipitation and evapotranspiration) both increasing at the same sites, but the influence of land use and other catchment changes also need to be included. However, we also observed that trends can change depending on the length of the record period considered, probably because of internal variations in the data or simply because those trends are more recent. This also adds some uncertainty and complexity to the process.

The use of physically-based deterministic or stochastic models is recommended for further work as it would help identify the main factors responsible for the trends. These factors could then be added as covariates in the nonstationary models to improve their accuracy. Once the causes are well understood and modelled, future scenarios of change can also be simulated.

In short, despite the relatively short length of the flow series analysed in this study, changes in high flows, observed elsewhere in Europe and in the world, have also been seen in Wallonia. This study has also highlighted the complexity of determining the causes of those changes, due to the numerous and interacting factors intervening in the flood generating process. However, as changes in high flows could have non negligible consequences on flood management (design of flood protection infrastructures, flood maps), it is essential to further analyse the trends.

CRediT authorship contribution statement

Maud Grandry: Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft, Visualization. **Sébastien Gailliez:** Conceptualization, Validation. **Yves Brostaux:** Methodology, Validation, Writing - review & editing. **Aurore Degré:** Conceptualization, Methodology, Validation, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: https://doi.org/10.1016/j.ejrh.2020.100729.

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