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Regional assessment of the multi-decadal changes in braided riverscapes following large floods (Example of 12 reaches in South East of France)

B. Belletti[1,*], **S. Dufour**[2], **and H. Piégay**[1]

[1]University of Lyon, CNRS UMR 5600, Site, ENS, Lyon, France
[2]University of Rennes 2, CNRS UMR 6554 LETG Rennes COSTEL, France
[*]presently at: Department of Earth Sciences, Univ. of Florence, Via Santa Marta 3, 50139 Florence, Italy

Correspondence to: B. Belletti (barbara.belletti@unifi.it)

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Abstract. The district of the France Rhône basin is characterised by several braided reaches, preserved from the widespread disappearing occurred in the 20th century. Even if the overall pattern is evolving through a general river narrowing, some reaches have shown to be still active and have widened. The preliminary results suggest that differences in width pattern could be related to several factors, such as high magnitude and low frequency floods, and geographical position in the catchment which influences bedload delivery conditions and vegetation recruitment related to climate. From an initial set of 53 braided reaches, we selected 12 sites, distributed into four main hydro-geographical regions. Reaches were selected to be representative of the overall study area. We analysed the braiding width pattern and the vegetation pattern dynamic among five observation periods dating from the 1950s to the 2000s. We hypothesised that a comparative analysis of a detailed temporal trajectory (i.e. five dates) of a set of rivers within several hydro-geographical contexts would allow us to better distinguish the relative role of floods (in terms of magnitude and duration) and other controlling factors acting at the regional scale. We showed that active channel width is controlled mainly by Q_{10} flood and secondarily by bedload availability whereas island pattern is in large part independent of flood series characters. Moreover a clear regional differentiation, constant over time, in terms of riverscape response is observed, mainly opposing south-western and south-eastern reaches. This opposition depends on several concurring factors, i.e. the flood characters, the river activity, the human influence and the climate. Finally, these findings allowed us to highlight those sectors in which the braided pattern could disappear, and those sectors in which the braided pattern is still active, because critical processes responsible of channel dynamic are still present.

1 Introduction

Gravel-bed braided rivers are dynamic systems in which mainly flow, vegetation and sediment regime interact to form the rich mosaic of physical habitat characteristics of such fluvial landscapes. Braided rivers have been affected over the last century by several human activities, which induced a widespread change of the braiding through less dynamic pattern, and this worldwide (Tockner et al., 2006). Major causes of decreases in European braided rivers can be attributed, for example, to gravel mining in Italy (e.g. Surian et al., 2009; Comiti et al., 2011), to a combination of river channelization and gravel mining in the Polish Carpathian rivers (e.g. Zawiejska and Wyżga, 2010), and to channelization and embankment in the French Alps (e.g. Piégay et al., 2009).

The role of flow and sediment regimes on braided river evolution has recently been the object of several studies. In particular, the role of floods on long and mid-term braided river patterns has already been demonstrated; these studies generally focus on a single river (e.g. Zanoni et al., 2008; Comiti et al., 2011; Toone et al., 2012), on a small river subset (e.g. Surian et al., 2009) or on observations at smaller temporal scales (e.g. Hicks et al., 2008; Bertoldi et al., 2009; Welber et al., 2012).

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Concerning the Alpine system, numerous studies have shown a generalised reduction in the braided pattern (narrowing and island development) since the 19th century with an acceleration since the 1950s (e.g. Surian et al., 2009, for eastern Italian Alps), but with some exceptions (e.g. the Durance basin in France, the upper Piave and Brenta and the middle Tagliamento in Italy). These exceptions prove that rivers do not all behave in the same manner; indeed, there seems to exist a sort of geographical response by braided river reaches to mid-term evolution patterns, as observed by Belletti et al. (2013b), in a set of 53 braided reaches in the French Rhône basin between two observation dates (the 1950s and the 2000s). They showed that: (i) the regional distribution of the mid-term dynamic of braided river reaches is related to the history of human settlements and to the intrinsic river activity, which is ruled by sediment regime (longitudinal continuity; Liébault et al., 2012); (ii) for some reaches, braided width evolution seems to be related to low-frequency high-magnitude floods (Q_{10}); (iii) rivers can adjust considerably after floods, more than what has been previously supposed (Piégay et al., 2009); (iv) vegetation also shapes the braiding pattern (island versus bar-braided, sensu Gurnell et al., 2001; see also Tal and Paola, 2010) and its development is not homogenous over the study area and is also influenced by local climate conditions.

Following these findings, the objective of the present study is to better assess the role of floods on braided riverscape patterns, from repeated observations (e.g. a set of comparable sub-periods, ideally 2 with and 2 without critical floods) within a 50 year period. It seems Q_{10} floods play a significant role in term of riverscape organisation (Belletti et al., 2013b) and approaching the problem with a sequence of observations over a few decades would help to validate this hypothesis. Because riverscape patterns are also controlled by the geographical settings (channel energy, sediment availability and vegetation dynamics, controlled by climate conditions and water availability during the growing period), the multi-date analysis will be applied on a set of 12 reaches selected to cover the different regional settings observed in Belletti et al. (2013b) and to better distinguish the flood effects and the geographical setting effects.

2 Material and methods

2.1 Study area

We selected 12 reaches situated in the district of the Rhône basin (S-E of France). Reaches are selected considering a strict condition: having photos of good resolution and quality and according to sequence of periods with and without floods. These reaches are representative of the large subset (53 reaches) in Belletti et al. (2013b) by including 2 to 4 reaches for each of the four main hydro-geographical regions, belonging to five sub-basins of the Rhône catchment (Fig. 1): four reaches are located in the North Alpine hydro-geographical region (N; upper Rhône basin); three reaches are located in the south-west of the study area, in the Rhône river corridor (W; lower Rhône basin); three reaches are located in the south-east of the study area (E; piedmont zone of the Durance basin); the Bans (Durance basin) and the Tinée (Var basin), are situated in the high mountain zone (HM). Figure 1b displays geographical characters of studied reaches organised into the four hydro-geographical regions.

2.2 Data description

This study is based on remote sensing analysis of orthophotos (BDOrtho) and aerial photos (coloured and black and white), property of the French National Geographical Institute (IGN). We also used vector data from the BDCarthage (IGN) and the "*Reseau Valcon*" (Pont and Rogers, 2004), to get general reach and catchment information (i.e. slope, altitude and catchment size), as well as hydrological data series from the national server of the "*Banque Hydro*" (http://www.hydro.eaufrance.fr, software HydroII).

For each reach, we selected five dates for observation according to aerial archived photos availability and flood dates, between the 1950s and the 2000s (about 52 years on average), obtaining four observation periods per site, spaced at about 13 years on average. Table 1 summarises the characteristics of the photos.

2.2.1 Variables characterising flood series

From the selected hydrological stations, for each site we recorded all floods (return period: 2, 5, 10, 20, 50 and Q>50 years) since 1946 when available, and at least since the date of the first observation, according to data series availability. For some reaches data series were incomplete; to complete the dataset, we used other stations situated upstream or downstream on the main stem (the Tinée since 1991), or on a different river in the same hydro-geographical area (the Bans before 1978 and the Eygues after 1996). Selected stations cover hydrological data series for 47 years on average.

At each site and for each observation, we then calculated the number of months since the last flood for all the return periods (Q_2, Q_5, Q_{10}, Q_{20}, Q_{50} and $>Q_{50}$). Each time we considered only floods occurring over the observed period; each Q_X flood is therefore considered once. When more than one flood occurred in the same year, of the same or different magnitude, we took into account only the most recent flood (i.e. month) or the highest in magnitude, as being characteristic of the year. The effect of multiple floods is in part given by the number of days at which the Q_2 discharge is exceeded, calculated for each period (i.e. between two photos), and showing if a period has been morphogenetically active or not.

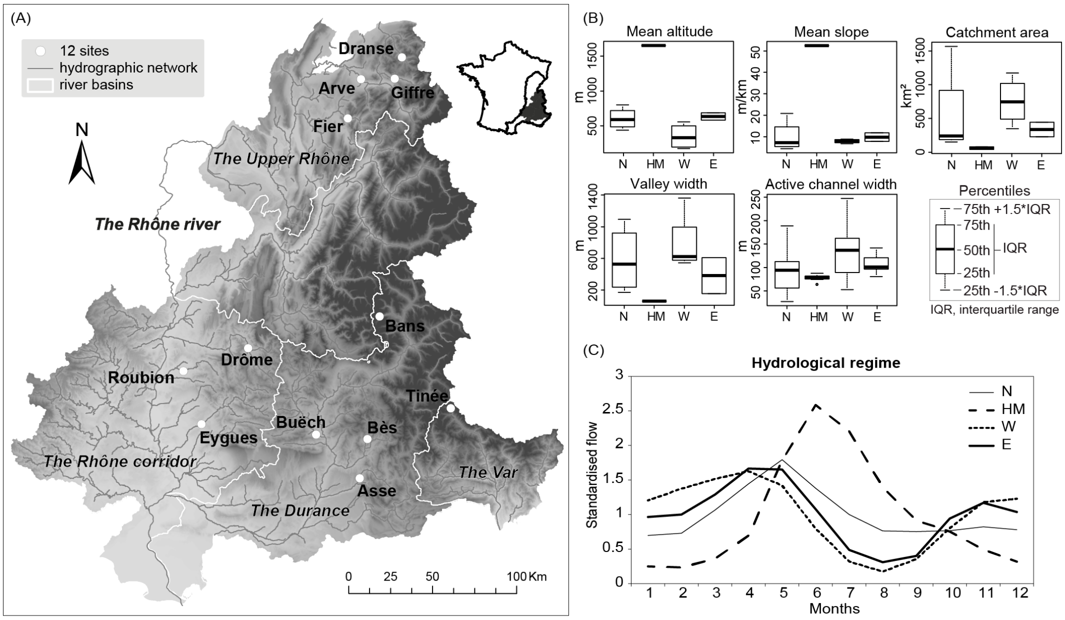

Fig. 1. Study area **(A)**, general characteristics of studied reaches **(B)** and hydrological regimes **(C)**. In **(C)** a monthly index is calculated as the ratio between the mean monthly flow and the mean annual flow, calculated for the set of stations. Reach characteristics are displayed in hydro-geographical groups: N = northern reaches (four reaches; the upper-Rhône); HM = high mountain reaches (two reaches; the upper Durance and the upper Var basins); W = south-western reaches (three reaches; the Rhône corridor); E = south-eastern reaches (three reaches; the Durance basin).

Table 1. Summary of photo scales and years of survey for each of the studied reaches.

Site	Year	Scale	Year	Scale	Year	Scale	Year	Scale	Year	Resolution
Arve	1956	1:25000	1961	1:25000	1973	1:15000	1984	1:15000	2004	50 cm
Dranse	1952	1:25000	1974	1:21000	1984	1:15000	1993	1:20000	2004	50 cm
Fier	1948	1:30000	1968	1:25000	1984	1:15000	1990	1:30000	2004	50 cm
Giffre	1952	1:25000	1974	1:22000	1984	1:18000	1993	1:24000	2004	50 cm
Tinée	1956	1:25000	1978	1:30000	1983	1:17000	1995	1:20000	2004	50 cm
Bans	1952	1:25000	1980	1:30000	1988	1:30000	1993	1:20000	2003	50 cm
Drôme	1956	1:25000	1970	1:30000	1991	1:18000	1996	1:25000	2006	50 cm
Eygues	1947	1:25000	1972	1:15000	1988	1:30000	1996	1:25000	2006	50 cm
Roubion	1946	1:20000	1972	1:15000	1991	1:18000	1996	1:26000	2006	50 cm
Buëch	1956	1:25000	1971	1:15000	1981	1:15000	1993	1:20000	2003	50 cm
Asse	1953	1:25000	1974	1:17000	1993	1:20000	2000	1:25000	2004	50 cm
Bès	1956	1:25000	1974	1:17000	1982	1:17000	1995	1:20000	2004	50 cm

2.2.2 Landscape metrics

The pre-processing of 1950s and 2000s photos, as well as data (polygons) extraction are described in detail in Belletti et al. (2013b), and can be summarised as follow:

- The 1950s and 2000s photos have been pre-treated (image masking and histograms stretching) and then processed on eCognition Definiens® to extract polygons, by adopting a semi-automated, object-oriented approach (i.e. characterising the objects by their radiometric value, shape, texture and context). Results are close to those obtained from photo-interpretation (Wong et al., 2003; Wiederker et al., 2009; Belletti et al., 2013a).
- For the most recent images (the 2000s), has been adopted an expert classification method of extracted polygons, based on an initial photo-interpretation of 6 images. The 1950s images have been entirely classified by photo-interpretation.

Concerning additional observations (between the 1950s and the 2000s), photos have been digitised at a resolution of 800 dpi and then referenced on ArcGis9.2. We defined control points close to the river corridor zone, to avoid distortions due to relief; the RMS (root mean square) error is therefore lower than 10 pixels for each of the points. Because feature extraction was performed by the same operator, we assumed that the amount of total error during photo-interpretation was low in comparison to observed channel changes, as also demonstrated by Toone et al. (2012).

The identified landscape units (features) are: active channel (AC, water and sediments with no vegetation, Toone et al., 2012), vegetated islands (IS, pioneer and mature vegetation included) and pioneer margins (PM, i.e. the pioneer vegetation on the margins which is visually distinct from the riparian forest vegetation, in terms of patch colour and vegetation density) (Fig. 2; Table 2).

Between each pair of observations, we also built the mosaic of the landscape turnover (overlay) and obtained, for each reach, four mosaics composed of the following areas: eroded areas (EA = changed into AC), vegetated areas (VA = changed into IS and/or PM), stable areas (SA = unchanged AC, IS, PM), lost areas (LA = no longer in natural fluvial corridor). We focused then on island vegetation and defined, between each pair of observations, the area corresponding to: new islands (NIs), stable islands (SIs), and eroded islands (EIs) (Fig. 2; Table 2).

For each reach we calculated (Table 2):

- The active channel width variation (ACvar, in percentage) for each pair of observations; we normalised it by the number of years between two consecutive observations (e.g. the percentage of AC variation between Arve 1956 and Arve 1961 rated by five years).

- The island characteristics: according to the results of Belletti et al. (2013b), we plotted the relationship between island density (i.e. the number of island in the total active channel, which is the area occupied by AC and IS; Toone et al., 2012) and island proportion (the surface area of islands in the total active channel) for each site at each date. This allowed us to calculate the residuals of that relationship (REis), intended as a proxy of the spatial island pattern, accounting both for their surface and their number in the total active channel area. At the extremes, multiple island-braided pattern correspond to very high positive residuals where island proportion is lower than 20 %, and island density is high; very high negative residuals mean a large island-braided pattern, where island density is low and island proportion is high; low residuals correspond, in general, to bar-braided patterns or weak island-braided patterns (low island density and proportion).

- The pioneer margin characters: we calculated the surface variation (%) of PM for each pair of observations, normalised by the number of years. PM could be interesting to see if sites adopt different vegetation development strategies (pioneer patches development from the riparian margin versus in-channel island development), and in consequence of control factors (i.e. flood, sediment load, geography, climate).

- The landscape evolution: we obtained the ratio between the total VA and the total EA for each pair of observations, rated by the number of years. That gives an idea of the overall landscape turnover of a reach, in terms of the dynamics of river construction (vegetalisation) and erosion (devegetalisation and floodplain erosion): values higher than 1 mean that vegetated areas prevail; values lower than 1 mean that eroded areas prevail. We also calculated the proportion of NIs compared to SIs for each pair of observations, rated by the number of years. This specifically indicates the development of new vegetated islands and reach ageing; values lower than 1 mean that the proportion of stable island surface prevails.

2.2.3 Sediment availability

According to previous studies on the same geographical area (Piégay et al., 2009; Belletti et al., 2013a; Liébault et al., 2012), we considered W* (the normalised AC width; $m/km^{0.3}$) as a proxy of the bedload availability, where AC width is rated by the catchment size (CA, $km^{0.3}$). Indeed it has been shown that the AC width, as the mean annual or the dominant discharges, increases downstream with the catchment size; it is interpreted as a result of width adjustment to sediment availability which is proportional to catchment size. An active channel is more or less wide for a given catchment size according to differences in bedload availability (unsupplied-limited versus supplied-limited). For each reach we calculated the mean normalised active channel width (i.e. the mean of the single AC widths, rated by the CA, $km^{0.3}$) and rated it by the total number of years (then called "meanW*/year").

2.3 The data analysis

The data analysis is carried out through different approaches and scales.

1. We analysed the overall braided riverscape dynamic (AC and island pattern) according to the hydrological history by testing all return period floods (Q_X) and the number of days, for a given period, at which the water discharge was higher than Q_2 flood discharge (n. days Q>Q_2); we also analysed the response of reaches according to their bedload availability (meanW*/year). We calculated simple Spearman's correlations between extracted landscape variables (ACvar, REis, PMvar, VA/EA, NIs/SIs; see Table 2 for definition) and control factors (the number of months since the last Q_X flood; the n. days Q>Q_2; the meanW*/year), to statistically measure the dependence between pairs of variables.

Table 2. List of acronyms employed in the text.

Acronym	Variable name
Landscape units	
AC	Active channel (water and sediments)
IS	Islands
PM	Pioneer margins
Landscape turnover features	
EA	Eroded areas between two observations
VA	Vegetated areas between two observations
SA	Stable areas between two observations
LA	Lost areas between two observations
NIs	New islands between two observations
SIs	Stable islands between two observations
EIs	Eroded islands between two observations
Landscape variables	
ACvar	Active channel width variation per year (in %)
REis	Island residuals (between island density and surface proportion)
PMvar	Pioneer margin surface variation per year (in %)
VA/EA	The ratio between vegetated and eroded areas between two observations, rated by the number of years
NIs/SIs	The ratio between new and stable islands between two observations, rated by the number of years

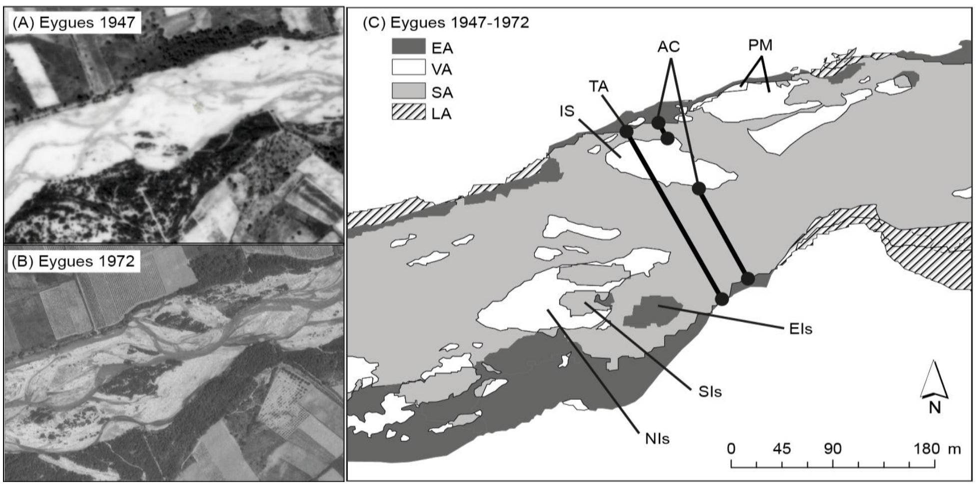

Fig. 2. Schema on landscape units and turnover features. Extract from the Eygues river reach between 1947 and 1972: **(A)** The Eygues in 1947; **(B)** The Eygues in 1972; **(C)** Sketch of landscape units and landscape turnover features: EA = eroded area over the period; VA = vegetated area over the period; SA = stable area over the period; LA = lost area over the period within the natural corridor; AC = active channel width (i.e. water channels and gravel bars); IS = island; TA = total active channel (i.e. AC+IS); PM = pioneer margins; NIs = new island; SIs = stable island; EIs = eroded island.

2. We then built a hierarchical cluster analysis of landscape parameters based on an initial Principal Component Analysis (FactoMineR package on R software) to analyse the riverscape characters of each reach and to highlight regional braided riverscape types in relation to the flood series and the index of sediment availability. The PCA is a factorial method which allows synthesising a set of quantitative and inter-correlated variables, into a lower number of new variables, called principal components. This analysis is then used to highlight the trajectory of each reach in terms of braided riverscape evolution over the observed periods.

3 Results

3.1 Characteristics of the flood series for each of the studied braided reaches

Figure 3 shows the overall number of floods with their return periods occurring at each reach and for each period of observation. The most flooding period was the second one (between the 70s and 80s), when almost all reaches experienced a Q_{10} flood and several Q_{20} occurred. The least flooding period was the third period (between the 80s and 90s). The Dranse and the Fier reaches (northern reaches) recorded the greatest number of floods, where Q_2 prevails; the lowest number of floods was reached on the Giffre river (northern reach) and then by the Drôme and Eygues reaches (southwest).

Consistent with observations about flood frequency, the years between the 70s and 80s, and then between the 90s and 2000s, were the most morphogenetically active years recorded (Table 3). On the other hand, the first period was the least morphogenetically active (to note that it includes, for most of the reaches, almost 20 years instead of 10). Even if no critical flood occurred during the third period (Fig. 3), it was characterized by fairly numerous and frequent floods for most of the reaches and particularly for the Asse and the Bes reaches (south-eastern reaches).

3.2 The general braided riverscape dynamic and its relationship with control factors

Almost all landscape metrics relate significantly with the 10-year return period flood (p value <0.05; Table 4). The variation of the AC width is negatively related to time since the last Q_{10} flood (p value = 0.02; Table 4): the AC is wider where a recent Q_{10} flood has occurred. No significant relationship is observed between island residuals and controlling factors (Table 4). The relative area of pioneer margins is positively but weakly related to Q_{10} (p value = 0.09; Table 4) and to floods having return periods greater than 50 years (p value = 0.03; Table 4). Concerning the landscape turnover, both the ratio of vegetated to eroded areas and the ratio of new to stable island surfaces are positively related to the time since the last Q_{10} (p value = 0.03 for both; Table 4), meaning that development of vegetation prevails during periods without floods. The ratio between vegetated and eroded areas for each period is also positively related to Q_5 (p value = 0.04; Table 4). The ratio of new to stable islands is the only parameter which relates positively, but weakly, to the number of days during which the water flow exceed that of the Q_2 flood (p value = 0.09; Table 4). It also relates negatively to the meanW*/year (p value = 0.03; Table 4).

3.3 Braided riverscape types and control factors

We performed the PCA based on the following riverscape metrics: AC width variation (%, rated by the number of years), island residuals (REis), the ratio between vegetated and eroded areas (VA/EA), and the ratio between new and stable island areas (NIs/SIs) (Fig. 4a–b). We included four observations per reach corresponding to each of the four periods. We excluded pioneer margins because their surface variation is in part implicitly included in the VA/EA ratio (rho = 0.3, p value = 0.07) and they did not contribute significantly to the analysis.

The first two axis of the PCA explain 78 % of the variance between reaches (Fig. 4a):

- the first component corresponds mainly to AC width variation (rho = 0.9, p value <0.0001);
- the second component corresponds mainly to island residuals (rho = 0.9, p values <0.0001).

The NIs/SIs ratio together with the ratio of vegetated to eroded areas (VA/EA) are also significantly and negatively related to the first axis (respectively: rho = −0.74, p value <0.0001; rho = −0.81, p value <0.0001), and more weakly to the second component (respectively: rho = 0.33, p value 0.02; rho = −0.35, p value = 0.01). Finally, the second component shows an opposition between south-western and south-eastern reaches (respectively positive and negative values) (Fig. 4b–c).

Figure 5a shows the results of the hierarchical clustering based on the two main components of the PCA. The riverscape types have then been plotted in boxplots for some relevant hydrological variables extracted from Table 4 (i.e. Q_5, Q_{10}, n. days Q>Q_2; meanW*/year) (Fig. 5b). We identified five braided riverscape types, which show specific behaviours (Fig. 5a and b):

- The first and the second type are composed of widened reaches, which experienced a large flood recently. Accordingly, eroded surfaces prevail over vegetated ones (VA/EA) for both types. Conversely, these types are opposing in terms of island residuals and NIs/SIs proportion (lower for type 1), as well as in terms of pioneer margins development (a relatively wide range of PM surface variation in the first type and low development of PM in the second one).
- The third type concerns stable or fairly narrowed reaches, even if they experienced a large flood recently (Q_5 and a Q_{10}); the island residuals represent low values; it does not develop new island proportion compared to stable ones, however vegetated areas prevail over eroded areas; the variation of the pioneer margin is fairly positive.
- The reaches of types 4 and 5 are both narrowed reaches, and did not recorded a large flood (i.e. Q_{10}) at least during the last 4 years; indeed, in both cases vegetated areas significantly prevail over eroded ones. Conversely, they are opposing in terms of island residuals (the lowest values for type 4 and the highest for

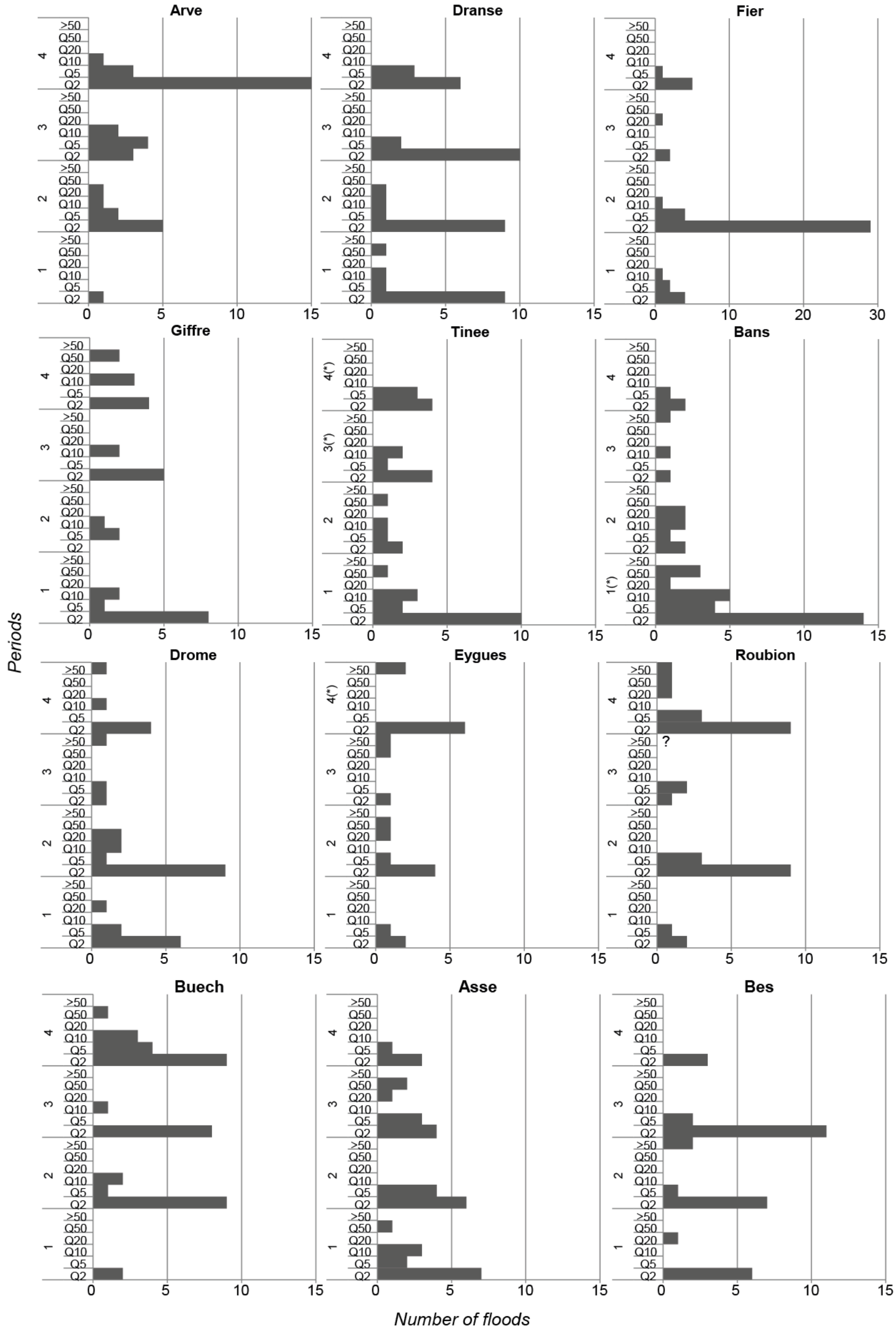

Fig. 3. The number of floods (all return periods) occurring at each period (1 to 4) for all selected reaches. Period 1 = 1950/60–1970; Period 2 = 1970–1980; Period 3 = 1980–1990; Period 4 = 1990–2000). Data for periods (*) are taken on other stations situated upstream or downstream on the main stem (the Tinee since 1991) or on a different river in the same hydro-geographical area (the Bans before 1978 and the Eygues after 1996). For the Roubion, "?" corresponds to the large flood occurring in 1994 when no data series were recorded.

Table 3. The number of days, for each period and site, during which water flow exceeded Q_2 discharge (n. days). The number of years and days per year for each period are also shown. Period 1 = 1950/60–1970; Period 2 = 1970–1980; Period 3 = 1980–1990; Period 3 = 1990–2000.

	Period 1			Period 2			Period 3			Period 4		
	n. days	n. years	days/year	n. days	n years	days/year	n. days	n. years	days/year	n. days	n. years	days/year
Arve	1	5	0.2	9	12	0.7	11	11	1.0	23	20	1.1
Dranse	15	22	0.7	13	10	1.3	11	9	1.2	13	11	1.2
Fier	5	20	0.2	27	16	1.7	5	6	0.8	7	14	0.5
Giffre	13	22	0.6	4	10	0.4	6	9	0.7	12	11	1.1
Tinee	30	22	1.4	10	5	2.0	7*	12	0.6	12*	9	1.3
Bans	144*	28	5.1	86	8	10.7	14	5	2.8	5	10	0.5
Drome	13	14	0.9	16	21	0.8	5	5	1.0	10	10	1.0
Eygues	2	25	0.1	7	16	0.4	25*	8	3.1	73*	10	7.3
Roubion	5	26	0.2	15	19	0.8	5	5	1.0	24	10	2.4
Buech	4	15	0.3	15	10	1.5	8	12	0.7	24	10	2.4
Asse	17	21	0.8	8	19	0.4	16	7	2.3	4	4	1.0
Bes	10	18	0.6	9	8	1.1	13	13	1.3	2	9	0.2

Asterisks (*) indicate that data are taken on other stations situated upstream or downstream on the main stem (the Tinee since 1991) or on a different river in the same hydro-geographical area (the Bans before 1978 and the Eygues after 1996)

Table 4. The values of Spearman's correlation rho (ρ) between the landscape metrics and control factors: the number of months since the last flood, for all studied return periods (Q_2 to $Q_{>50}$), the number of days at which the water flow was higher than the Q_2 discharge (n. days Q>Q_2) and the sediment availability (meanW*/year). Landscape variable acronyms are listed in Table 2. All landscape variables, excepted REis, are related with the number of months since the last Q_{10} flood.

	Q_2	Q_5	Q_{10}	Q_{20}	Q_{50}	$Q_{>50}$	n. days Q>Q_2	meanW*/year
ACvar	0.09	−0.22	**(**) −0.48**	−0.02	−0.20	−0.22	−0.03	0.07
REis	0.13	0.09	0.09	−0.03	−0.01	−0.07	0.18	−0.16
PMvar	−0.13	0.06	**(*) 0.36**	−0.35	−0.15	**(**) 0.80**	0.14	−0.03
VA/EA	−0.08	**(**) 0.35**	**(**) 0.46**	0.43	0.11	0.45	0.10	0.19
NIs/SIs	−0.03	0.06	**(**) 0.44**	0.27	0.04	0.28	**(*) 0.24**	**(**) −0.31**

In bold statistically significant correlations: (**) means the p value <0.05; (*) means the p value <0.1

type 5), and in terms of new island surfaces (the greatest values for the type 5); the PM proportion variation represents positive values for type 4 whereas stable and around zero for type 5.

In terms of sediment regime, types 1 and 4 concern reaches with higher values of meanW*/year compared to others. Braided riverscape types do not seem to significantly differ in terms of time period with water flow higher than Q_2.

As expected, only the first component is negatively and significantly related to Q_{10} (rho $= -0.55$, p value $= 0.006$). The second component is negatively related to meanW*/year (rho $= -0.3$, p value $= 0.04$).

3.4 Braided river types and temporal trajectory

To analyse the temporal trajectory of braided reaches, we plotted them separately on the factorial map, showing the riverscape type to which each reach belongs for each of the observed periods (Fig. 6). We observed that in term of riverscape pattern, the first component is linked to the width pattern: reaches move from wide and poorly or sparsely vegetated reaches after a Q_{10} flood (type 1 or 2), to narrower and more (dense or widespread) vegetated reaches after long periods without Q_{10} floods (type 4 or 5). This is clear for reaches such as the Buëch and the Bes (reach1 and reach3 vs. reach2 and reach4), the Arve (AR1 to AR3), the Asse (AS1 to AS2) and, to a lesser extent also for reaches as the Tinée (except TN2), the Bans (except BN1) and the third observation for the Drôme and the Roubion.

In terms of riverscape patterns, the second component is linked to the vegetation encroachment, during both flooding and no flood periods: it opposes type 1 (e.g. BC2, BC4, BS2, BS4, AS3) from type 2 (e.g. DR4, RB3, RB4, EG3), for reaches which experienced a large flood, and type 4 (e.g. BC1, BC3, BS1, BS3) from type 5, after a period without floods (e.g. DR1, DR2, RB2, AS1). This second component clearly highlights the geographical context of study reaches (Fig. 4b–c) which seems in part ruled by the sediment availability, opposing low W* to high W* values (respectively: positive values, types 2 and 5; negative values, types 1 and 4) (Fig. 5b).

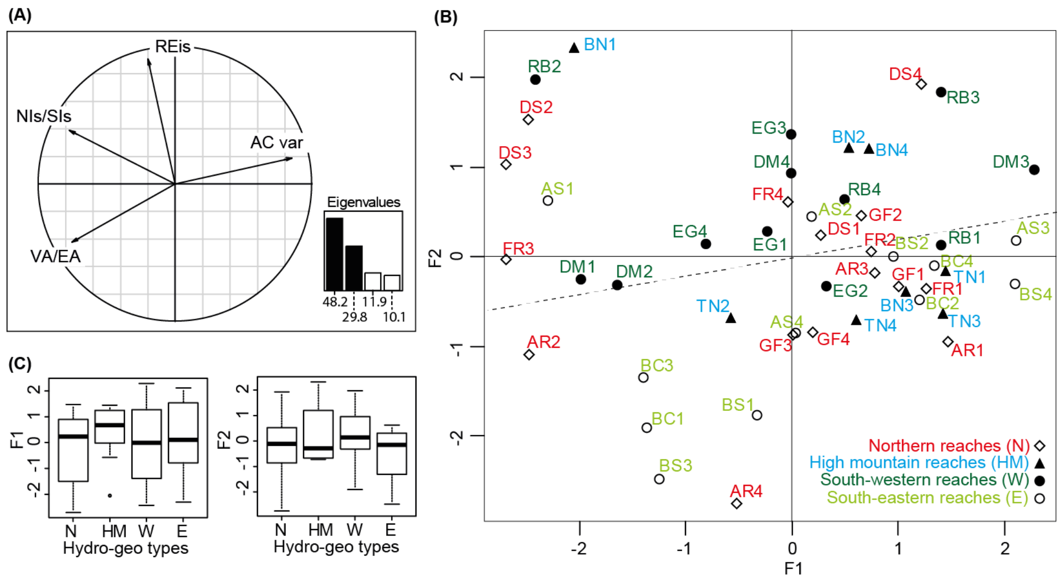

Fig. 4. Results of the Principal Component Analysis performed on the landscape variables, to simplify the large dataset. Landscape variable acronyms are listed in Table 2. **(A)** The correlation circle and the histogram with eigenvalues show, respectively, how landscape variables are related with the two first components of the PCA, and the variance between reaches explained by each component of the PCA (78 % is the cumulative variance explained by the first two components). The first component is related with ACvar (rho $=0.9$, p value <0.0001), the NIs/SIs (rho $= -0.74$, p value <0.0001) and the VA/EA (rho $= -0.81$, p value <0.0001); the second component is related with REis (rho $=0.9$, p values <0.0001) and with the NIs/SIs (rho $=0.33$, p value 0.02) and the VA/EA (rho $=-0.35$, p value $=0.01$). **(B)** The first factorial map displays how each reach is positioned in regard to the first two components; each item is a reach at a given observation date (i.e. reach1, reach2, reach3 and reach4). Reaches have been plotted following hydro-geographical regions. The dotted line is perpendicular to island residual vector, and divides positive from negative residuals. **(C)** The variability of the first two component coordinates, obtained for each reach, among hydro-geographical types (N, northern reaches; HM, high mountain reaches; W, south-western reaches; E, south-eastern reaches).

Such analysis allows demonstrating temporal trajectory of braided riverscapes is both linked to flood series and geographical context. We clearly observed specific temporal patterns according to regions.

For the northern region, early observations of the Fier and Giffre reaches (i.e. reach 1 and reach 2) belong to types 1 and 2, meaning they had larger and widened active channels at the beginning of the study period. The Arve reach was almost bar braided at the beginning of the study period, but developed, in the end, the lowest values of the island residuals (AR4): it means that fewer, large islands establish in the TA. The Dranse reach narrows and develops several new islands at the second and third observations (DS2-3, type 5) independently from the flood history, to change again during the last period during which it widens a little (DS4); that period has been characterized by minor flood events but of high duration (Table 3; Fig. 3).

Amongst the high mountain reaches, the Tinée reach remains quite stable in terms of width and braided riverscape evolution, following in general the flood pattern, except for the second observation during which it narrows a little, developing vegetated areas (TN2), even if a Q_{50} occurred in 1982, during a period characterised by many days during which water flow exceeded Q_2 discharge (Fig. 3; Table 3). The first observation of the Bans shows that it was a multiple island braided reach during the late 70s, even if several large floods occurred before (BN1, type 5; Fig. 3).

In the south-western region, after the very large floods occurred during the third period (for the Roubion, it corresponds to the lack of hydrological data in 1994; Fig. 3), the Drôme and the Roubion remain quite stable in terms of width pattern for the last observation (type 2) even if they again experienced large floods in the 2000s (Fig. 3). For the first two observations, these reaches show different braided riverscapes: the Drôme reach corresponded to type 5 (high island residuals and quite high new island proportion); the Roubion was a truly braided reach at the end of the first period (RB1; type 1), even if was not a particularly flooding period. It then changed to type 5 at the second observation (RB2), during a period characterized by several low magnitude floods (only Q_2 and Q_5) (Table 3; Fig. 3). The Eygues reach remains quite stable in terms of width pattern compared to other two reaches (type 3), but changes significantly in terms of proportion of vegetated areas and island residuals (i.e. type 3 to 2, and back to 3 again); it does not widen after floods which occurred in 1994 and 1995, recording mainly

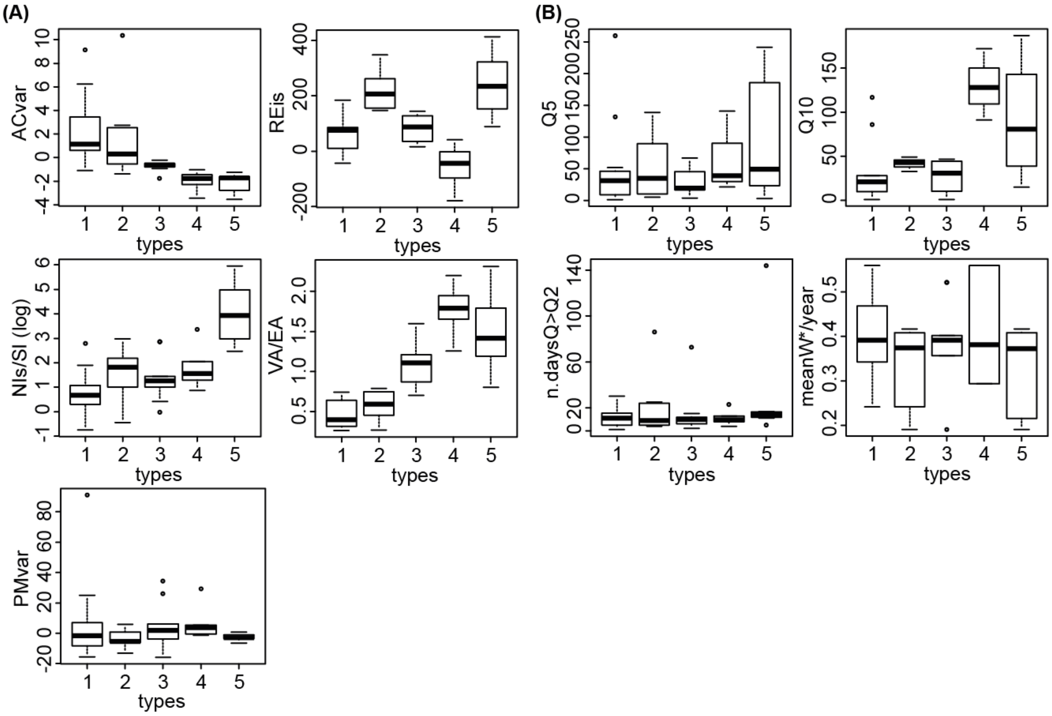

Fig. 5. (A) The characteristics of the five clusters resulted from the hierarchical classification analysis performed on the landscape variables (based on the two first component of the PCA in Fig. 4). Landscape variables acronyms are listed in Table 2. **(B)** The hydrological and morphological characteristics of clusters: Q_5 = number of months since the last Q_5; Q_{10} = number of months since the last Q_{10}; n. days Q>Q_2 = number of days at which water flow exceeded Q_2 discharge; meanW*/year = sediment regime.

an increase of island residuals (EG3, type 2), as well as after the large floods occurred at the end of the study period (it narrows a little; Fig. 3; type 3).

The south-eastern reaches show two distinct behaviours: (i) The Buëch and the Bes range between types 1 and 4 showing a cyclic pattern which follows the flood events. At the first observations (BC1 and BS1), they presented the greatest amount of vegetated areas, with larger islands and higher proportion of pioneer margins (type 4). (ii) The Asse reach shows several patterns: it changes from type 5 (AS1) to type 1 (AS3), (passing through type 2 for the AS2) after a couple of Q_{50} and a Q_{20} (Fig. 3), to finally narrows a little and decreases island residuals, during a period without significant floods (AS4, type 3). At the beginning of the study period, the AS1 showed a clear multiple-island braided pattern (positive residuals and high NIs/SIs values).

4 Discussion

The objective of this study was to demonstrate that the temporal trajectory of braided riverscape pattern is controlled by flood magnitude and duration and this relationship varies regionally because of different sediment availability and vegetation ability to recruit and growth.

Three main braided riverscape behaviours have been finally highlighted:

1. Some reaches (i.e. south-eastern reaches) adjust laterally in relation to flood events showing a cyclic trajectory (i.e. first component of PCA in Fig. 4b and Fig. 6);

2. The behaviour of the overall braided riverscape over time seems to be also structured by the geographical context (i.e. axis F2: south-west versus south-east).

3. Additionally, some other reaches do not show any cyclic behaviour, even if they change their braided riverscape pattern over time (e.g. northern reaches except the Arve, and the Eygues). That means that also other factors than the two ones indicated above play a role.

4.1 The role of floods on braided riverscape patterns: general trends and specific behaviours

4.1.1 The width dynamic

The results of this study confirm in part previous study-cases observed in the same area allowing to consider such results can be generalised at the alpine scale: we observe a general river reach narrowing but also the existence of other patterns, mainly in the southern part of the study area (Belletti

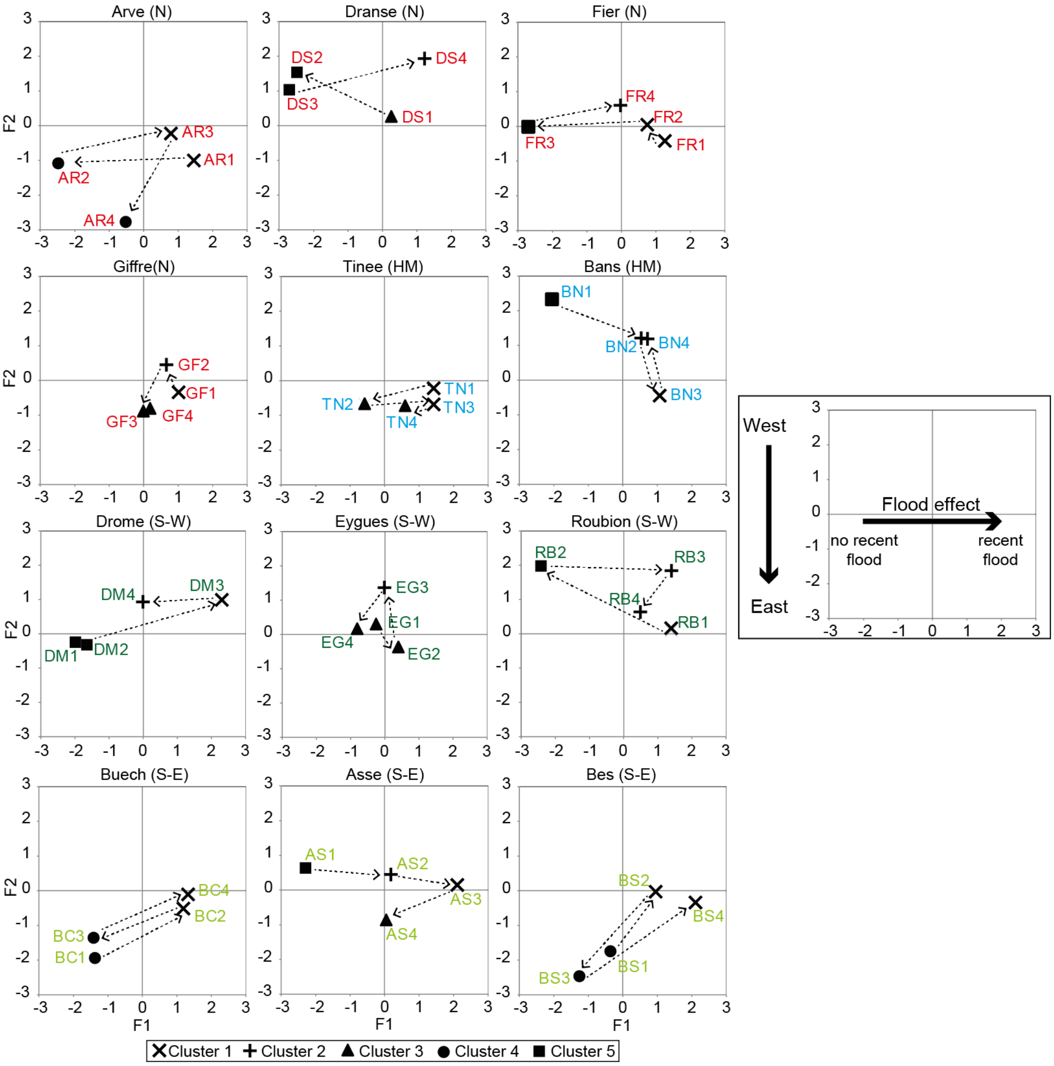

Fig. 6. Temporal trajectory of each reach on the first factorial map. The figure is derived from the first factorial map of Fig. 4b, displaying how each reach is positioned in regard to the first two components and across time; each item is a reach at a given observation date (i.e. reach1, reach2, reach3 and reach4; the chronology of observations goes from 1 to 4). The cluster to which a reach belongs at a given observation date is also indicated, showing how reaches evolve in terms of landscape pattern (see Fig. 5 for cluster characteristics). The physical interpretation of the reach evolution in terms of floods and geographical context is displayed on the right.

et al., 2013b; Liébault et al., 2012). Moreover, the number of months since the last 10-year return period flood significantly determines the braided reach width pattern (Table 4; Figs. 4, 5 and 6; axis F1 of the PCA), as previously observed by other authors (Gurnell et al., 2000; Piégay et al., 2000; Bertoldi et al., 2009, 2010; Surian et al., 2009). This means that, morphologically speaking, Q_{10} flood is much more critical than the $Q_{1.5}$ flood (i.e. the bankfull flow) for such rivers for which the geometry is both controlled by flow hydraulics, sediment transport and vegetation, allowing to discuss the theory of dominant flood as being the morphogenic driver. It also shows that 10 years is a timescale that is quiet consistent to expect a significant narrowing, showing the importance of vegetation dynamics in the active channel width control rather than the flow conditions.

Then, we highlighted that some reaches do not respond systematically to each Q_{10} flood (Fig. 6): if south-eastern reaches widen after each large flood and narrow during periods with no floods (e.g. type 1 versus type 4 for the Buëch and Bes reaches), western reaches behave differently. They narrowed during the 1980s even if floods occurred, certainly in consequence of the sediment mining activities which had been carried on since the 1950s and particularly during the 70s, promoting channel straightening and local bedload starvation and preventing lateral movement of the channel during large floods (e.g. DR2, EG2; e.g. Landon and Piégay, 1994;

Landon et al., 1998; Liébault and Piégay, 2002). After this period they widened, in response to 1990s floods, because the effect of previous river mining, in terms of local sediment starvation, started to decrease. More recent floods, occurring in the 2000s, had no geomorphic effect on south-western reaches, when they remained quite stable or even narrowed (i.e. Eygues). This could be related to the fact that the second period of high magnitude floods happened only few years after the large events of the mid-90s, and reaches have not had enough time to recover (e.g. Wohl, 2007). Northern reaches, more impacted by human activities (e.g. Peiry et al., 1994; Piégay et al., 2009), are in general less sensitive to flood events in term of lateral rejuvenation, mainly after the second half of the 70s (Figs. 3 and 6). High mountain reaches changed less in terms of river geometry in response to floods, because floods in this area are less intense compared to other areas, and floodplains are constrained laterally (e.g. the Tinée reach aggraded of 7.52 m in one century because it reached its maximum width; Liébault et al., 2012). The recent channel widening observed on the southern braided reaches, has also been shown in some Italian braided rivers (e.g. Surian and Rinaldi, 2003; Surian 2006; Surian et al., 2009; Comiti et al., 2011). These authors attributed this recent pattern to a river channel recovery from river mining, which has ceased since the end of 70s. Liébault et al. (2012) made similar conclusions for braided reaches in the French Alps, where in-channel mining had certainly been the major cause of channel degradation, especially in downstream reaches. Liébault et al. (2012) observed that the greatest recovery is occurring where reaches are still in connection longitudinally with their sediment sources (i.e. active torrents upstream), and laterally with their banks. Widening can therefore be linked to a period of significantly high floods and available bedload sediment delivery, allowing aggradation and lateral reactivity. Even if it is not highlighted at the overall scale, in some case flood duration also seems play a role; an example is represented by the Dranse reach (DS4): it widens after minor flood event characterised by high flow duration and it shows local channel aggradation, meaning continuity in sediment delivery (Liébault et al., 2012).

4.1.2 The riverscape dynamics

The braided riverscape dynamics observed for the 12 selected reaches of the Rhône basin is significantly determined by the width pattern, which is mainly a function of the effect of flood history, combined with the human context which influenced the sediment delivery (48 % of the variability explained by the first component of the PCA; Table 4; Fig. 4).

During high flood periods, the AC widens and the proportion of eroded areas on vegetated ones prevails and few new islands develop (low VA/EA; low and/or negative NIs/SIs; types 1 and 2; Table 4; Figs. 4 and 5a). High floods can also involve an island density increase, meaning that the riverine landscape is fragmented or that new surfaces are shaped for rapid island development (e.g. during the third period for the Eygues and Roubion reaches, synchronously to their AC widening, type 2). Similar observations, in terms of flood effects on islands, have been made by Comiti et al. (2011) for the Piave river (Italy), showing a time lag between the increase in island number and its size after flood events.

During periods without critical floods, the AC narrows due to vegetation encroachment. But, while some reaches show a significant increase in new island surface and island density (positive values of the second component; type 5), others develop island surfaces and pioneer margins (negative values of the second component, REis decrease; type 4). The latter is the case of the first and the third periods of the Bes and the Buëch reaches, as well as the Arve (but for the Arve it is accompanied by a greater channel narrowing). These reaches show a cyclic behavior from a bar-braided pattern to a large island pattern according to the hydrological context.

Additionally, it seems that for some reaches the flood duration before the observation also affects in part the response of the reach to floods in terms of relative island surface area and density (REis). For example, for northern reaches (Arve excluded), the REis seems to increase particularly after floods of high magnitude which occurred in the 1980s (e.g. the DS2, the GF2 and the FR3). These floods did not follow a high flood but a high flood duration period (Q_2 and Q_5), in which REis already had increased but only slightly, changing progressively into a multiple-island braided pattern (before 1980 for the Dranse and the Giffre and between 1980 and 1990 for the Fier; Table 3). Long periods of low magnitude floods probably prevent the vegetation establishment and the island coalescence, then promoting riverscape fragmentation when a large flood occurs (REis increase). Finally, the increase of REis combines in general with the overall increase in new island surface (NIs/SIs ratio; axis 2 of the PCA; types 2 and 5; Fig. 5a), and which also seems in part favoured by long periods of low magnitude floods (Table 4). So, long periods of low magnitude flood events may promote the dispersion of vegetation propagules (which is high at high flow frequencies; Bornette et al., 2008), increasing the success of vegetation recruitment, and mainly in low energy systems (NIs/SIs negatively related with meanW*/year).

4.2 The role of the geographical context

As showed above, flood magnitude, and in part flood duration, contribute to determine the braided width and the overall riverscape patterns of the 12 studied reaches of the Rhône basin.

However both during flooding and no flood periods we observed that the overall riverscape pattern differed between some reaches (i.e. respectively type 1 vs. 2 and type 4 vs. 5). The overall braided riverscape pattern cannot be explained only by flood history.

Indeed, depending on the geographic zone, and mainly during periods of no flooding, we observed that:

– The islands develop by attaching to each other, as with the Buëch and Bes reaches in the south-east;

– In the south-west islands develop higher island density (high REis).

We also showed that new island proportion (Table 4; Fig. 5) and in part island residuals (Fig. 5) are also determined by a lower sediment delivery, where low and high delivery seem to correspond respectively to positive and negative values of the second component of the PCA (F2 versus meanW*/year, p value $= 0.04$). This is in part consistent with the distinction between south-western and south-eastern reaches observed by Belletti et al. (2013b) (types 2, 3 and 5 versus types 1 and 4 respectively; Figs. 5 and 6). The opposition is quite constant over time, and mainly observable in terms of island residuals (positive values for south-western reaches and negative for south-eastern ones), as well as in terms of new island development (mainly during no flooding periods) (Figs. 4, 5, and 6). Islands find more favourable conditions to their development in the western areas during both low and high flood periods. A few hypotheses can be proposed for explaining such regional differences: (i) a lower sediment delivery (linked to slope afforestation, less intense rainfall and greater sediment mining), minimising lateral activity with scouring and renewal during low flow events and allowing vegetation to stabilise even after large floods; (ii) a more humid climate, as hypothesised by Belletti et al. (2013b), allowing for a more efficient vegetation recruitment and growth, and explaining higher REis and new island surface development (types 2 and 5). Comiti et al. (2011) also observed a similar riverscape behaviour, in terms of island surface growth, on the Piave river during intense river mining between the 70s and 90s, even while several near-Q_{10} floods occurred (i.e. lower sediment load). To the contrary, eastern reaches behave with a more bar-braided pattern during the entire period of observation; the higher sediment regime as well as the Mediterranean climate prevent vegetation recruitment on dry bars and prevent new island stabilisation and development (types 1 and 4; Fig. 5). During periods without floods, vegetation here mainly develops in terms of island growth (i.e. island coalescence; negative values of REis) and encroachment from the river margins (i.e. positive PM proportion variation for type 4).

So flood magnitude and duration also combine with the geographical setting (i.e. the river activity and the human influence but also the climate and the vegetation pattern) and it is therefore difficult to highlight their relative contribution.

4.3 Cyclic and non-cyclic temporal trajectories

For some reaches, the changes in braided riverscape pattern depend clearly on where the reach is in its trajectory of evolution. For example, we showed that south-western reaches changed little in terms of pattern during the last period of high magnitude floods, because it happened few years after a period already characterised by high magnitude floods (type 2). Therefore a flood occurring close after a first one in a short time period is not enough to cause significant morphological changes in a reach.

As showed before, the magnitude of riverscape changes is almost the same over the study area and through time (Fig. 6), but this is not true for all reaches. In some areas, significant landscape changes occurred because of very important sediment starvation, due to gravel extraction and spontaneous afforestation which stabilised hillslopes and active channels, and prevented sediment delivery from upstream to downstream (Liebault and Piegay, 2002). In such context, mainly observed on the northern reaches, the braided rivers follow a complex non cyclic evolution and their future pattern could not be braided anymore. In the southern areas, the evolution is much more cyclic showing critical processes are still existing to maintain the braided activity.

5 Conclusions

The analysis of 12 selected braided reach evolution in S-E of France, between 1950 and 2000, validates the hypothesis of an existing relationship between Q_{10} flood events and riverscape evolution but this relationship is complex geographically and temporally. Narrowed northern reaches with human-disturbed sediment delivery do not respond, or weakly, to large floods in terms of riverscape; the occurrence of large floods favours island colonisation (i.e. density), which then develop in size during periods of no flooding. In the south-west, reaches were sensitive to floods after mining had ceased (in the 90s), but further floods occurring soon after a first flood series had no geomorphic effect; the island vegetation found favourable conditions to develop in terms of climate and sediment regime, the recruitment being maximised and the scouring minimised. In the south-east, reaches respond to all major floods and show a cyclic pattern through time. Their island pattern seems to be significantly related to flood pattern, because climate and higher bedload activity normally do not favour island stabilisation; vegetation seems to develop mainly in size and through encroachment from river margins during periods of no flooding. Riverscapes follow a complex trajectory controlled mainly by Q_{10} floods, sediment availability and vegetation dynamics. Human can amplify at different time sediment availability through mining or other pressures which explain specific temporal patterns.

A holistic perspective is then powerful to provide managers a general insight at a regional scale allowing gaining time when providing diagnosis at more local scales. W* can be a good indicator of braided activity but vegetation recruitment may influence it and its use is then only accurate in a given bioclimatic context. It is now needed to better distinguish what it is linked to vegetation and to bedload delivery in the braided channel evolution which is not possible with this dataset as the two factors are co-occurring in space. Moreover, W* is very dependent on the observation date relative to the last critical flood and its local variability must be also assessed in time.

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