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## Twenty-five years of FLAG activity: Concepts, foci, trends in research

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1 Twenty-five years of FLAG activity: concepts, foci, trends in research

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18

## 19 1. Introduction

20 The present special issue arises from the 2018 biennial meeting of the Fluvial Archives Group  
21 (FLAG) that took place in Liège (Belgium) between the 2<sup>nd</sup> and 7<sup>th</sup> September 2018. It  
22 consisted of a two-day conference and a three-day excursion in the Meuse catchment. The  
23 special issue includes twelve papers that largely reflect the FLAG foci (Briant et al., 2018b).  
24 The present paper, introducing this special issue, first provides a synthesis of the foci that  
25 characterize FLAG special issues since its inception in 1996. This allows the most 'important

26 terms' of FLAG research to be not only underlined, but also to be discussed and placed in  
27 their conceptual framework. Finally, the content of the special issue is presented.

28

29 2. A review of FLAG foci over the last two decades

30 2.1. Methods

31 The present report completes the analysis of the geographical distribution of the study areas  
32 and the participants presenting during FLAG meetings, that was exposed in the twentieth  
33 anniversary issue (Cordier et al., 2017). As a reminder, this analysis indicates that ~75% of  
34 the study areas are located in Europe, with a significant predominance of the Mediterranean  
35 countries (Iberian Peninsula and Italy = 25% of the total study areas), Germany (~15%) and  
36 the Netherlands (~12%). The other research areas (Eastern Europe, UK, France and Belgium)  
37 each represent ~5-10% of the total. The rest of the world focuses on Asia (China, India),  
38 Oceania (Australia, New Zealand), Africa (Tunisia, Sudan), and America (United States).  
39 This distribution is largely explained by the history of FLAG (which developed as an English  
40 and then a European alliance of researchers) and by the European location of the meetings,  
41 which led to a highlighting of the research carried out by local scientists. In that way, the  
42 present special issue is not an exception, as it includes papers from various places in Europe  
43 but also from China and South America.

44 The present analysis is based on 130 research papers published between 2000 and 2020 in 14  
45 FLAG-labelled special issues (derived from ten FLAG meetings, two INQUA sessions, one  
46 EGU session, and the twentieth anniversary issue) and provides an overview of trends in  
47 FLAG research. The method used for this synthesis is primarily based on the keywords  
48 proposed by the authors. However, this list of keywords had to be enriched: first, several  
49 special issues were published in journals that do not require specific keywords (or ask for a  
50 restricted number of keywords); second, it was necessary to ensure a better homogeneity in

51 the selection of the important terms – actually two papers focusing on similar topics but  
52 written by different authors may be characterized by different keywords, thus concealing their  
53 similarities. To avoid this, the papers were read carefully to extract complementary keywords,  
54 leading to a list of ‘important terms’ for each of them.

55 We acknowledge that this procedure is also not fully objective as the extraction process may  
56 be guided by the ‘important terms’ found in the other papers. However, it allowed the  
57 recognition of trends that obviously contribute to describe precisely the FLAG activity. Other  
58 biases must also be mentioned: the list of ‘important terms’ may actually be influenced by the  
59 topic of the special issue (e.g., the 2008 and 2012 special issues in Geomorphology,  
60 respectively entitled ‘Human and climatic impacts on fluvial and hillslope morphology’ and  
61 ‘Techniques for analyzing late Cenozoic river terrace sequences’), or by the location of the  
62 FLAG meeting (the 2010 special issue in Proceedings of Geologists’ Association arises from  
63 the 2008 conference in Hungary, an area that is rather characterized by tectonic stability or  
64 subsidence rather than uplift, leading to an increasing representation of papers dedicated to  
65 floodplains). These biases, however, also do not likely influence the general pattern, which is  
66 shown below.

67 The ‘important terms’ are divided into four sections respectively dedicated to objects of study  
68 (the what), topics (the why), approaches and methods (the how), and timescales (the when).  
69 For each section, the statistical repartition of ‘important terms’ is primarily considered as a  
70 whole (i.e., without consideration of the year the publication took place) to expose the  
71 highlights of FLAG research, but trends may also be discussed, reflecting the evolution of  
72 research over the last decades.

73

## 74 2.2. The what: FLAG objects of study

### 75 2.2.1. The fluvial terrace: predominance in the FLAG research and attempt to (re)define

76 The analysis of the 118 papers underlines the focus of fluvial (or river) terraces in the FLAG  
77 research: it is the most important geomorphological object of investigation in ~60% of the  
78 publications, far more than all the others. Fluvial terraces are one of the best examples of  
79 geomorphological heritage in fluvial systems, and they are preserved worldwide (Bridgland  
80 and Westaway, 2008). As shown below, fluvial terraces may also be used to decipher many  
81 research issues at various timescales, from the geological periods (Late Cenozoic) to the  
82 Holocene (Ghilardi et al., 2015). Following this, their place in the core of the FLAG  
83 investigations is thus everything but surprising. A similar observation can be made for the  
84 associated important terms “uplift” and “incision”, which appear in 12 and 11 publications  
85 (~10%), respectively.

86 Surprisingly, little attention has been paid to the definition of fluvial terraces in the FLAG  
87 community (in contrast with process-based geomorphologists; see review in Pazzaglia, 2013),  
88 leading to uncertainty in the meaning that it should receive. This ambiguity is clearly reflected  
89 in the accumulation of adjectives added to the term ‘terrace’. The term ‘fluvial terrace’  
90 emerged in the late nineteenth century (Gilbert, 1877; Lesley, 1878). It was defined as an  
91 ancient floodplain preserved above the present-day floodplain. This definition should,  
92 however, be clarified, especially because the terminology associated with fluvial terraces  
93 varies. As shown in university textbooks, geomorphologists typically discriminate between  
94 stepped (or encased) terraces and nested or aggradational terraces (Burbank and Anderson,  
95 2001), the distinction between the two being based on the importance of vertical incision and  
96 also on whether significant aggradation has occurred. The concept of stepped terraces can  
97 hardly be questioned, in contrast with the concept of nested terraces: the *nesting of alluvial*  
98 *formations* is undeniable, especially in the valley floors. Incidentally, it may have a significant  
99 morphological imprint (Arnaud-Fassetta, 2007) and be used in the context of flood risk  
100 management (Ballais et al., 2011). The concept of a *nested terrace* is, however, more

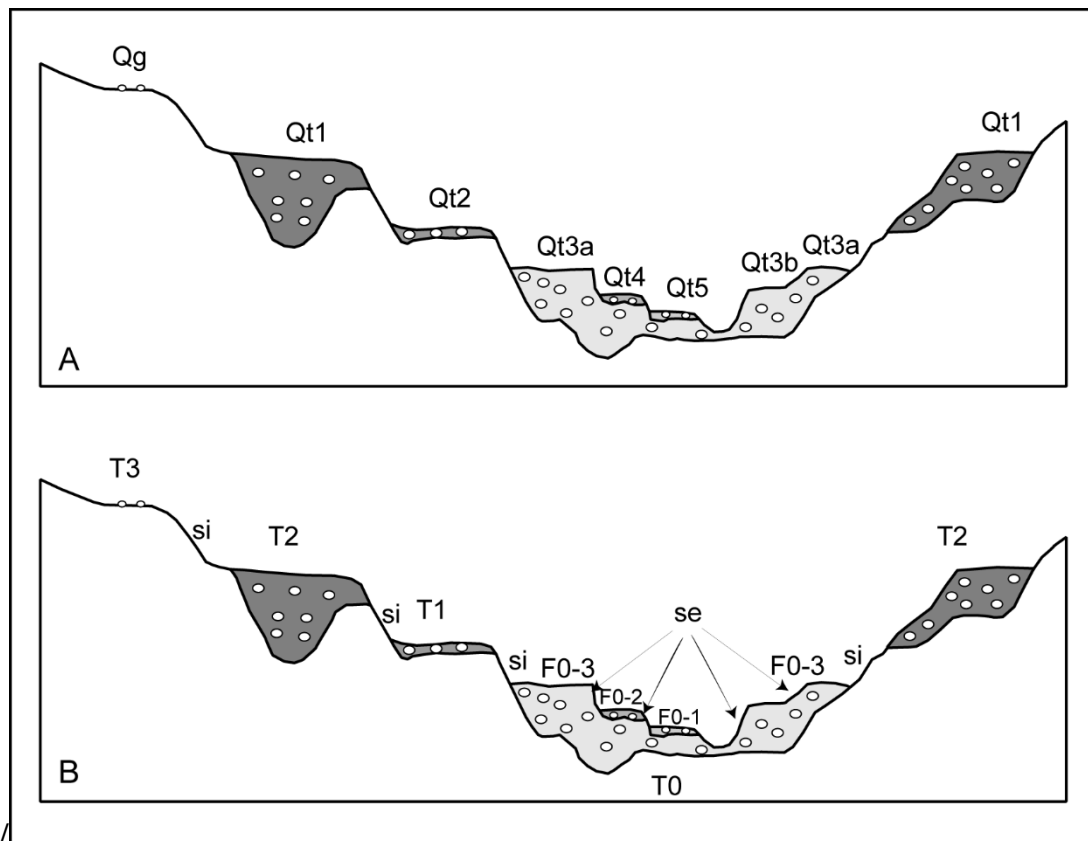
101 questionable: indeed, it typically only applies to the valley floor sedimentary complex, as the  
102 poor preservation in the terraces of the staircase often prevents their recognition. However,  
103 the genesis of this complex cannot differ fundamentally and systematically from the previous  
104 evolution of the river. It is therefore obvious that the term *nested terraces* can only have  
105 descriptive value, associated, for example, with the delimitation of the floodplain and valid  
106 for a relatively short period of time (a few thousand years or less). A similar criticism can be  
107 given to the terms cut- and fill- terraces, commonly used in the English literature (Leopold et  
108 al, 1964). The term degradational terrace (Burbank and Anderson, 2001) is also confusing  
109 because it is applied to both stepped terraces and to a cut-terrace, although the genesis of these  
110 two forms is different. The terms strath terrace (Gilbert, 1877; Bucher, 1932), bedrock strath  
111 terrace (Finnegan and Dietrich, 2011) or bedrock terrace (Reusser et al., 2004) do not seem  
112 more precise as it sometimes relates to the bedrock, and sometimes to the terrace formed  
113 following the cutting of the bedrock, making it the direct equivalent of a stepped terrace  
114 (Lewin and Gibbard, 2010; Pazzaglia, 2013). The term strath terrace also has a  
115 morphosedimentary connotation (terrace associated with thin deposits, these deposits being  
116 only a direct reflection of river dynamics of the river, without accumulative effect; Gibbard  
117 and Lewin, 2009). However, this assumption does not take into account the fact that the  
118 observed sediments can be only the remnant of well-developed fluvial terraces. It also leads to  
119 a problem when the stepped terraces are relatively thick (i.e., thickness comparable to the  
120 valley floor sediments), as is the case in many valleys: some authors may then talk about thick  
121 strath terraces (A. Mather, oral communication, September 2014), showing how imprecise  
122 this term is.

123 To help remove this ambiguity in the language, the following definition can be proposed: a  
124 fluvial terrace includes all fluvial sediments and the associated morphologies (top surface,  
125 bedrock, potentially erosional slopes) set up between two phases of bedrock incision. This

126 definition is similar to that proposed by Pazzaglia (2013), but not necessarily applied (Fig. 1).  
127 It considers the sedimentary complex exposed in the present-day valley floor not only as a  
128 juxtaposition of surfaces and slopes (Macklin et al., 2013), but as a set of fluvial formations  
129 distinguished on a solid basis (facies, age). It is also important to note that this definition is  
130 based on a clear distinction between incision and (vertical) erosion – even if both terms are  
131 associated with erosion, i.e., a collection of physical process leading to river deepening. The  
132 term incision, often used to emphasize the vertical component of river erosion, is here  
133 reserved to a vertical erosion affecting not only previously deposited sediments but also  
134 bedrock (Bull, 1991). This leads to the formation (morphologically speaking) of a fluvial  
135 terrace and is the prelude to the establishment of a new alluvial plain. The term (vertical)  
136 erosion refers to a simple removal of already deposited sediments, with a limited vertical  
137 component: the bedrock is not affected – or at least not significantly. The incision resulting  
138 from a deepening of river channel, in association, for example, with a transition from braiding  
139 to meandering is hence the result of significant vertical erosion. This distinction between the  
140 two terms is too rare in the literature where the term incision often means any form of erosion  
141 associated with a vertical component (Gibbard and Lewin, 2009; Vandenberghe, 2015).

142

143



144

145 Figure 1. Diagram showing the different types of fluvial terraces (adapted from Pazzaglia,  
 146 2013). A: Terminology of Pazzaglia. Qg corresponds to residual sediments present in  
 147 interfluvial position, Qt to different levels of fluvial terraces. These are numbered from oldest  
 148 to newest, according to the International Lithostratigraphic agreement. Note, however, the  
 149 difficulty induced by this approach, because the oldest fluvial terraces are generally less well  
 150 preserved and difficult to correlate. We also highlight the lack of distinction between the slope  
 151 shaped in rock formations (e.g., between Qt2 and Qt3a) and those formed in previous deposits  
 152 (e.g., between Qt3a and Qt4). B: The same pattern with the terminology proposed in this  
 153 paper. T0: valley floor complex, T1 to T3: fluvial terraces, si: slope formed by river incision  
 154 into rock formations, se: erosional slope formed in former fluvial deposits. The numbering is  
 155 from the valley bottom, the most recent fluvial terraces being generally better preserved. The  
 156 valley floor complex (T0) includes three alluvial formations. Their remains should later form  
 157 a single terrace, particularly because the inset terraces may be subsequently eroded by lateral



158 erosion. Moreover, we highlight the contrast between the relative thin fluvial terraces (e.g.,  
159 Qt2) and the great thickness of alluvial valley bottom: this contrast suggests a formation very  
160 specific for the valley floor complex, which is rarely seen in the alluvial sequences, and  
161 difficult to accept in terms of processes leading to terrace formation.

162

### 163 2.2.2. A range of objects of study

164 The previous section highlighted the key place devoted to fluvial terrace studies within the  
165 FLAG community. Other study topics are less frequently represented. Floodplains, for  
166 example, which complement the terrace staircases to form modern landscapes, are only the  
167 core of 13 publications, the majority of them being related to stable and subsiding areas where  
168 fluvial terraces have not been formed (e.g., Portugal lowlands, the Netherlands, Hungary or  
169 Russia). These areas are often characterized by the preservation of palaeochannels, which are  
170 also regularly (but not systematically) associated as important terms (eight references).  
171 Finally, it is worth noting that 10 publications refer to changes in river course (including both  
172 captures and avulsions).

173 Alluvial fans area a term regularly appearing in publications, with nine references, including a  
174 review paper in 2017 (Mather et al., 2017). Finally, three publications refer to the relation  
175 between lakes and rivers.

176 It is important to point out the fact that keywords (and more largely ‘important terms’) mainly  
177 focus on landforms, keeping in mind that in many studies (and for many authors) these  
178 landforms are associated with sediments. The scant presence of important terms as “fluvial  
179 deposits” hence largely underestimated the place devoted to the sediments, as is confirmed by  
180 the synthesis of approaches used in FLAG research (see Section 2.4). The study of fluvial  
181 sediments may be coupled with other deposits, such as aeolian (five references) or volcanic  
182 sediments (three references) or tufa (two references).

183

### 184 2.3. The why: the FLAG topics

185 The topics for which these objects are investigated clearly relate to their formation and how  
186 they allow the unravelling of landscape history. The concept of forcing is here prevalent and  
187 four distinct drivers should be mentioned. Unsurprisingly, the first one is climate forcing,  
188 which is debated in ~60% of the analysed publications and regularly appear over the two  
189 decades of FLAG activity. Tectonic forcing is the core of 36 publications (including five  
190 focusing on Holocene neotectonics). Note that most of these publications took place in the  
191 first decade of FLAG (1996-2008), followed by a slight recession in the subsequent period.  
192 Despite this decrease, tectonics remains a key feature in FLAG research, as demonstrated by  
193 the recent publication of a review paper (Demoulin et al., 2017).

194 Anthropogenic forcing also plays a significant role in FLAG activity, with 24 papers  
195 published during the entire period. About half of these publications, however, originate from  
196 two special issues published in 2008, which explicitly provided a large place to human  
197 influence as shown by their respective titles: “Fluvial architecture and dynamics in rising  
198 mountain chains and related basins - tectonic and climatic influences and human impacts” and  
199 “Human and climatic impacts on fluvial and hillslope morphology”. Beyond the  
200 anthropogenic forcing, the relations between human societies and rivers are also addressed  
201 through archaeological and geoarchaeological investigations in fluvial contexts, which  
202 represent the core of 14 publications. Despite this relatively low proportion, it shows both the  
203 importance of geoarchaeological research in a fluvial context (see research performed within  
204 the Working Group of Geoarchaeology of the International Association of Geomorphology),  
205 and the ability of FLAG to attract researchers interested in various scientific fields. A similar  
206 observation also is also valid for research dedicated to palaeontology (10 publications), fluvial  
207 archives being a key feature for the recognition of fossils and their use to reconstruct past

208 environments. Finally, eustatic sea-level change forcing is only an ‘important term’ in nine  
209 publications. This result may first be explained both by the low proportion of research  
210 performed in coastal areas. Second, the role of eustatic forcing on landscape evolution in  
211 coastal areas has been recognized for many decades as limited: the recognition of the key role  
212 played by climate, and the research on base-level (Schumm, 1993), underline that eustatic  
213 sea-level change forcing is largely conditioned by the morphology of coastal areas (Bridgland  
214 and Allen, 1996; Blum and Törnqvist, 2000) and may only affect the downstream part of  
215 fluvial systems (Morzadec-Kerfourn and Hallegouët, 1977; Lefebvre et al., 1994; Schulte et  
216 al., 2008; Viveen et al., 2012; see also discussion in Bridgland and Westaway, 2012).

217 To conclude this section dedicated to FLAG topics, it is important to underline the links  
218 between FLAG and geomorphological research. This link can here be evidenced by the  
219 regular use of keywords as (fluvial) geomorphology, surface processes, erosion, thresholds,  
220 sediment yield, etc. These items are scarcely mentioned, but their regular presence clearly  
221 demonstrates that the research performed in the FLAG community is related to the general  
222 research in geomorphology.

223 The following section demonstrates in a similar way how FLAG activity can both be  
224 influenced and influence methodological improvements.

225

#### 226 2.4. The how: a multi-proxy approach

227 This section aims to present the methods and approaches developed by the FLAG researchers  
228 to the reconstruction of past fluvial environments. The use of ‘important terms’ rather than  
229 keywords here is meaningful, as many authors rightly choose to use their study areas, topics  
230 and timescales as keywords rather than their methods. Two ‘important terms’ should here be  
231 highlighted, field and geochronology. Both are present in half of the analysed publications.

232 Field work is not spontaneously underlined by authors. It, however, often occupies a  
233 significant place in papers, as evidenced by the numerous descriptions of sections, or by the  
234 realization of geomorphological maps (mapping appears as an ‘important term’ in ~16  
235 publications). This reference to field work seems important to underline the place of the  
236 ‘naturalist’ approach in FLAG research. This approach is even more important bearing in  
237 mind that rivers and valley floors have been largely artificialized and fluvial deposits  
238 exploited for building purposes, leading in many areas to a significant loss in both fluvial  
239 landforms and sediments. FLAG research hence provides useful information on river history  
240 that may not be available in the near future.

241 FLAG researchers, however, do not only act as ‘naturalists’. They commonly use a multi-  
242 proxy approach. This is first seen in the fact that modelling plays a significant role in FLAG  
243 research, with 16 papers largely dedicated to this topic with the aim to find a consistency  
244 between field data and models and to test formation hypotheses (Veldkamp et al., 2017).  
245 Despite significant improvements over the last decades allowing researchers to obtain models  
246 that match with field data, such a consistency remains challenging, particularly in separating  
247 the internal and external controls. This desire to find synergies between the field- and model-  
248 oriented scientific communities (observers/modelers) led to the emergence of the  
249 FACSIMILE (Field And Computer SIMulation In Landscape Evolution) research group in  
250 2014. This group includes several researchers involved in FLAG activity (Briant et al.,  
251 2018a).

252 Second, the field in FLAG research should also be considered not only as a place for  
253 observation, but also as a basis for further investigations, which are predominantly achieved  
254 in laboratories. This is especially the case for geochronological investigations, which (as  
255 mentioned above) represent an ‘important word’ in about half of the references (including a  
256 review paper in 2017; Rixhon et al., 2017). Most of them were published after 2003,

257 following the improvements that characterized numerical dating methods at that time. A more  
258 detailed analysis shows the predominance of two methods, radiocarbon (19 publications) and  
259 luminescence dating (18 publications, starting in 2004, which is a few years after the  
260 development of the Single Aliquot Regenerative procedure by Murray and Wintle (2000,  
261 2003), that largely improved the reliability and accuracy of the method). Despite being less  
262 commonly used (six publications or less), several other dating methods must be cited:  
263 Electron Spin Resonance ESR, U series, Ar/Ar and K/Ar, cosmogenic nuclides, and  
264 dendrochronology. The key place devoted to geochronology underlines how important the  
265 interactions between fluvial systems and dating methods are. On the one hand, improvements  
266 in numerical dating drastically changed the way to study fluvial systems: fluvial archives  
267 could actually be placed in their palaeoenvironmental context, leading to major improvement  
268 in the understanding of forcing on fluvial evolution. The increasing number of numerical ages  
269 obtained with increasing resolution also raised new issues on how fluvial systems could react  
270 to short events such as rapid climate change or human influence.

271 On the other hand, the challenges in research on fluvial archives (and more generally in  
272 palaeoenvironments and geomorphology) likely encouraged geochronologists to improve  
273 their procedures to increase the time ranges of the methods as well as their reliability and  
274 accuracy – leading to high resolution reconstructions. This positive feedback is supported not  
275 only by the tight collaboration between fluvial morphologists and dating specialists, but also  
276 by the fact that a number of researchers are both geochronologists and experts in fluvial  
277 archives.

278 Despite its predominance, geochronology is not the only laboratory method used in FLAG  
279 studies. Sedimentological investigations (including, for example, grain size analysis, loss on  
280 ignition, carbonate content, magnetic susceptibility, heavy minerals, petrography, etc.) play a  
281 predominant role in ~30 papers, most of them being published between 1997 and 2010. The

282 decrease in the last decade should, however, not be interpreted as a decline of  
283 sedimentological methods. It suggests instead that the latter have become so common that  
284 they can be routinely performed, and so are only briefly mentioned in publications.  
285 Additionally, it should be pointed out that the nature of sedimentological investigations over  
286 the last decades significantly changed with the emergence of methods (magnetic  
287 susceptibility, loss on ignition, etc.) and improvements characterizing the existing methods  
288 (e.g., statistical treatment of grain size analysis; see for example Dietze and Dietze, 2019).

289 Another method that is regularly used and associated with sedimentology is biostratigraphy:  
290 palynological and micro-flora investigations are present in 16 publications (most of them  
291 before 2012), in which they allow deciphering environmental changes affecting fluvial  
292 systems. It is also useful here to recognize the 10 publications focusing on palaeontology (see  
293 Section 2.3): the latter is actually both a topic (understanding the history of past hominids in  
294 their environments) and a method enabling researchers to propose relative chronologies and to  
295 highlight paleoenvironmental evidences.

296 Two other methods may finally be mentioned: Remote sensing (including study of aerial  
297 photographs) appears in 12 publications, where they are either used to study recent dynamics  
298 (see Section 2.5) or to build topographic maps that can in turn be used to identify fluvial  
299 landforms. Surprisingly, geophysics is only present in three papers despite its role in  
300 recognizing the geometry and sedimentology of fluvial sediments that has long been proven  
301 useful (Schrott and Sass, 2008). This relative lack of interest is likely to be explained by the  
302 need for FLAG researchers to be able to observe and sample their fluvial archives.

303

## 304 2.5. The when: from the geological (Cenozoic) times to the Late Holocene

305 As regularly underlined in special issue introduction papers (e.g., Cordier et al., 2012), the  
306 FLAG activity primarily aims to cover a wide time range, from the end of the Pliocene (a few

307 millions years) to recent historical periods (a few centuries). This, of course, does not prevent  
308 focusing on longer (e.g., Cenozoic) or shorter (e.g., a few years/decades) periods, as fluvial  
309 archives could also have formed at these time scales. Similarly, it is worth noting that many  
310 studies led to reconstructions that span the traditional stratigraphical or climatic  
311 boundaries/transitions, with these researchers aiming to highlight a continuum in fluvial  
312 system evolution. That said, clear trends may be recognized when considering the timescales  
313 over which the FLAG publications focus; these timescales are related to major steps in the  
314 formation of present-day fluvial landscapes. First, 37 publications cover a “Late-Tertiary-  
315 Quaternary” timescale, which corresponds in many areas to the formation of the valleys, with  
316 alternation between periods of depositional and erosional (incision). Most of the papers are  
317 limited to Quaternary archives and only eight papers focus on older terraces (four extending  
318 until the Miocene and four starting with the Pliocene). The paucity of studies beyond the  
319 Quaternary is caused by the low preservation of the oldest fluvial archives in many areas and  
320 by an insufficient precision of the geochronology, despite the availability of several methods  
321 (such as ESR, K/Ar, Ar/Ar or  $^{26}\text{Al}/^{10}\text{Be}$  burial dating). This clearly contrasts with shorter  
322 timescales. The Holocene and the Late Pleistocene are the focus in 25 and 22 publications,  
323 respectively (including six publications covering both periods). The relative success of these  
324 timescales reflects both the fact that they are associated with several main topics of FLAG  
325 research (climate forcing, anthropogenic influence, etc.) and the fact that many methods, and  
326 in particular a wide range of numerical dating tools, can be more or less routinely applied to  
327 sediments that are more commonly preserved than the older ones in many fluvial systems.

328 Other periods are less represented. They correspond to short timescales (recent centuries, in  
329 particular from the Little Ice Age to present) for 14 publications, half of them appearing in a  
330 special issue (‘Human and climatic impacts on fluvial and hillslope morphology’) explicitly  
331 focusing on relatively recent times. Finally, 10 publications are devoted to Middle Pleistocene

332 fluvial archives, often related to a focus on palaeontology (mammal remains and palaeolithic  
333 artefacts found preserved within fluvial sediments).

334

## 335 2.6. Discussion: what's new in FLAG research

336 Recognition of trends in objects, topics, methods and timescales clearly demonstrates that the  
337 research performed within FLAG is simultaneously characterized by consistency and change.

338 The longevity of 'important terms' first shows that FLAG has found for many years its place  
339 within the research dedicated to fluvial geomorphology and palaeoenvironments. It hence

340 represents a bridge connecting Earth and human sciences, as well as geology and biology. The

341 apparent stability of FLAG research topics also conceals the emergence of new study areas:

342 although several rivers such as, for example, the Thames (e.g., Bridgland, 2006), the Somme

343 (e.g., Antoine et al., 2007, 2015) or the Rhine (e.g., Boenigk and Frechen, 2006) have been

344 investigated for a long time, FLAG research also focuses on many other fluvial systems,

345 including smaller rivers. For example, the present special issue includes contributions

346 focusing on small rivers from Belgium, the Netherlands, Germany, Poland and dry river

347 systems in Peru. The wider geographical distribution of study areas played an important role

348 as it allows drawing comparisons between fluvial systems. In turn, such a comparison makes

349 it possible to question local versus regional forcing. The twentieth anniversary special issue

350 published in 2017 provides examples of how these comparisons enrich research on fluvial

351 archives for a wide range of topics, especially including those on tectonic or climate forcing.

352 Such an enlargement and improvement in research was obviously supported by

353 methodological improvements. In particular, developments in numerical dating allowed the

354 establishment of more robust chronostratigraphical frameworks for fluvial archives, which in

355 turn facilitated the emergence of new research issues (Rixhon et al., 2017). For example, the

356 recognition of terrace staircases in fluvial valleys, which was a key issue at the beginning of



357 FLAG activity, is now a “preliminary” basis that is necessary to unravel more complex issues  
358 (such as the respective role of external, internal or anthropogenic forcing). It is also worth  
359 noting that FLAG activities, in addition to investigations conducted in the framework of  
360 geoarchaeological or palaeoenvironmental research, have contributed over recent decades to  
361 push for a higher chronological resolution and an extension of time ranges available for dating  
362 methods. In a similar way, FLAG research also made it possible to change paradigms, for  
363 example when considering prehistorical artefacts: In the earlier times archaeological remains  
364 were key features to date and correlate fluvial archives, while the latter can regularly be used  
365 to replace traces of human occupation in their stratigraphical framework now, thus allowing a  
366 better understanding of how past humans evolved in relation to environmental changes.

367 To summarize, FLAG research is characterized by its capacity both to use and to stimulate  
368 improvements in methodological and fundamental research. A main issue for the future is the  
369 development of applied research. Several perspectives should be mentioned, such as the  
370 restoration of rivers (see Peeters et al. and Eschbach et al., this issue) or the valorization of  
371 fluvial landforms as part of geodiversity. The first becomes largely applied in European and  
372 North American rivers for more than a decade, and a key issue associated with restoration  
373 projects is the type of river and fluvial landforms that managers wish to create. This, of  
374 course, can only be defined if the history of fluvial systems is well understood. Geodiversity,  
375 now, is another topic that plays an increasing role especially in geomorphological research,  
376 with the aim to preserve and upgrade landforms and their associated sediment. This need is  
377 particularly crucial in fluvial systems because of the destruction of many archives by  
378 urbanization, quarrying etc., while there is, in turn, a social need for people to rediscover  
379 rivers close to their homes. The role of FLAG is here obvious when considering both our role  
380 of ‘archivists’ and the knowledge accumulated in many rivers worldwide. Field excursions  
381 performed in the framework of a FLAG Meeting underline the initial results of programs of

382 valorization (creation of information panels, geomorphological hiking- and cycling tracks,  
383 etc.) that need to be encouraged and developed. You say what's new?

384

### 385 3. Presentation of the special issue

386 The twelve papers included in this special issue reflect the diversity of FLAG research that is  
387 exposed in the present paper. They focus on various timescales, areas, methods and topics.  
388 Four papers focus on Pleistocene fluvial evolution, four others on the Late Pleistocene and  
389 Holocene, and the last four on historical changes, which of course implies an increasing  
390 anthropogenic forcing. Three papers focus on areas and sites visited during the field  
391 excursion of the 2018 FLAG Meeting in Belgium (Rixhon et al., this issue) and five on  
392 surrounding areas in Germany and the Netherlands. Other contributions lead to Poland, Italy,  
393 China and Peru.

394 In the first paper by Rixhon et al., cosmogenic burial dating ( $^{26}\text{Al}/^{10}\text{Be}$ ) was applied to clastic  
395 cave deposits trapped in a multi-level karstic system located in the Ourthe valley, the main  
396 Ardennian tributary of the Meuse River in eastern Belgium. They thereby extended the  
397 database on the Plio-Pleistocene incision and denudation history at the northern margin of the  
398 uplifted Ardennes massif. They also showed that complex speleogenetic processes may  
399 considerably complicate the interpretation of the age results, notably because of intra-karstic  
400 reworking and influx (contamination) of young deposits. Despite these difficulties, burial ages  
401 highlight (i) the acceleration by a factor five of the incision rates (from ~30 to ~150 m/Ma)  
402 during the first half of the Middle Pleistocene and (ii) the spatio-temporal variability of  
403 regional river response during the Plio-Quaternary to coupled tectonic and climatic forcings.

404 Lauer et al. focused on the Mid-Pleistocene evolution of the Saale River in Central Germany,  
405 in the key section of Uichteritz (Saxony-Anhalt). This section, located a few kilometres north  
406 of the southernmost extension of Elsterian and Saalian ice-sheets, exposes interfingering

407 fluvial and glaciogenic deposits, the former including Lower Palaeolithic flint artefacts. A  
408 classical multi-proxy approach was used including stratigraphy, sedimentology, geophysics,  
409 micromorphology and luminescence dating. The investigations made it possible to assess the  
410 role of climate on fluvial landscapes evolution between c. 420 and 180 ka, in particular in  
411 relation with the ice sheets. The fluvial sedimentation could be allocated to cold periods, in  
412 particular before or after the presence of ice sheets covering the area. The presence of  
413 artefacts in the fluvial sediments also supports the idea of a first appearance of hominids in  
414 Central Germany during the MIS 11.

415 Kalicki and Kalicki performed a geomorphological study on fluvial deposits and aeolian  
416 cover sands in the Lomas de Lachay located on the western slope of the Andes in Peru. In  
417 addition to geomorphological mapping and grain size analyses, they used  
418 thermoluminescence dating to establish a chronological framework for periods of fluvial  
419 aggradation and erosion. The results show that the deposition of river deposits during the  
420 Upper Pleistocene in the study area is controlled by periods of increased precipitation at  
421 around 57 ka and between 24 ka – 15 ka. The initial appearance of cover sands correlates with  
422 a climatic shift towards more arid conditions during the LGM. The authors put their new  
423 chronological data in context with already existing chronologies from other Peruvian rivers  
424 and deliver a valuable contribution for the connectivity between climatic shifts and the  
425 response of river systems in western South America.

426 The van Buuren et al. paper focuses on a major section located in the Hanjiang River in  
427 central China. This section exposes middle Pleistocene sediments having fluvial deposits in  
428 the lower part and loess in the top. The core of the paper concerns the interpretation of the  
429 fine-grained deposits preserved in the middle part of the sequence, which may be of both  
430 origins. A high-resolution grain size distribution unmixing (end-member modelling) approach  
431 makes it possible to distinguish between fluvial and aeolian sediments.  $^{10}\text{Be}/^{26}\text{Al}$  isochrone

432 burial dating of the basal gravel section is used to correlate the sequence with those preserved  
433 in the Chinese Loess Plateau. The paleo-environmental interpretation and dating are important  
434 not only for the fluvial evolution, but also for the Hominins artefacts.

435 Woolderink et al. conducted a detailed palaeo-geographical reconstruction of the Roer River,  
436 draining the Rhenish shield in northwestern Europe. Their aim was to understand the external  
437 forcing factors leading to the formation of five observed terrace levels since the Weichselian  
438 Late Pleniglacial. By combining state-of-the-art methods such as LIDAR imagery with  
439 radiocarbon dating and pollen analyses, they were able to show the shift of dominating factors  
440 (climate, tectonic, human impact) determining the river morphology and fluvial sedimentary  
441 system. Whereas climate and tectonics were the main controlling mechanisms from the  
442 Pleniglacial to the Middle Holocene, anthropogenic influence caused the formation of the  
443 final terrace level during the Late Holocene.

444 The following paper by Peng et al. focuses on the Ooijen area in the Lower Meuse in the  
445 Netherlands. Based on archaeological evidence and on the study of well-preserved Meuse  
446 levee sediments, it allows a reconstruction of the Holocene palaeoflooding history, using  
447 flood energy indexes based on results of end-member modelling of grain size distributions.  
448 This paleoflooding reconstruction, which is consistent with data obtained in another study  
449 based on floodplain sediments, is combined with archaeological data to assess the  
450 anthropogenic forcing (in particular, land use) on fluvial evolution over the last millenia.  
451 Further, and more generally, it shows that levee deposits can be used as archives of flooding  
452 in addition to the commonly used records such as floodplain deposits and infills of abandoned  
453 channels.

454 Salomon et al. focus on the Tiber delta in Italy to reconstruct its evolution during the  
455 Holocene. Multi-proxy investigations based on cores performed in the delta include  
456 sedimentology, geochronology as well as Palaeoenvironmental Age-Depth Modelling

457 techniques (PADMs), which allows the integration of all useful data to interpret  
458 stratigraphical sequences. This makes it possible to discuss the respective role of sea level  
459 change and fluvial activity in the construction of the delta, by distinguishing transgressive and  
460 progradational sequences. These results are supported by a comparison with theoretical  
461 models of Holocene coastal evolution. A first map of the palaeochannel evolution for the last  
462 6 ka is also proposed, summarizing the new results and the previous research that took place  
463 in the area. It especially underlines that a branch of the Tiber River existed since 4500-4000  
464 ka BP in the central/southern side of the delta.

465 Van Der Meulen et al. focus on a 4500 km<sup>2</sup> area in the Lower Rhine valley and upper Rhine  
466 delta in Germany and the Netherlands. The authors used a 'top-down' approach to reconstruct  
467 past topography from a modern DEM. Various procedures (e.g., recognition of fluvially  
468 active and inactive zones, DEM stripping, reconstruction of topography and bathymetry in the  
469 active zone), were also conducted on a LIDAR DEM of their study area to reconstruct the  
470 early mediaeval topography, i.e. the topography predating the onset of river dike construction  
471 in the area. This allows an assessment of the anthropogenic changes in terms of elevation and  
472 volume for both the inactive and active zones. The authors finally discuss the potential of  
473 their approach to investigate other lowland areas at various spatial and temporal scales.

474 The next study of Houbrechts et al. matches a classical research focus of the FLAG, which is  
475 the study of archaeological data contained within fluvial archives, including the  
476 geoarchaeology of river corridors. It takes advantage of small-sized iron slags contained in  
477 alluvial deposits, which are residues of iron production since the late Middle Ages. In addition  
478 to other uses of slags in fluvial dynamics such as the quantification of long-term bedload  
479 mobility (Houbrechts et al., 2011), these microslags are employed here as a new stratigraphic  
480 marker. Following an explanation of the methodological guidelines supporting their use, the  
481 authors show how they can be combined with topographic surveys, sedimentological analysis

482 and  $^{14}\text{C}$  dating to unravel centennial-scale floodplain evolution in one Ardennian river  
483 catchment, the Lienne (also visited during the FLAG 2018 field trips). This allowed the  
484 reconstruction of the evolution of the floodplain topography along with the determination of  
485 aggradation rates.

486 The next studies by Eschbach et al. and Peeters et al. focus on the use of fluvial archives as  
487 sources of baseline information for river restoration. Eschbach et al. underline the growing  
488 need for efficient and accurate geomorphic surveys related to physical river restoration. In this  
489 respect, the post-restoration monitoring of restored river reaches is crucial and unfortunately  
490 remains too often neglected (Bernhardt et al., 2005). Eschbach et al. propose an innovative  
491 combination of geomorphic and geodetic (i.e., laser-, photo- and tacheometry) methods to  
492 efficiently monitor the recent morphodynamic evolution of a restored anastomosing side-  
493 channel of the Rhine in the direct vicinity of Strasbourg (Upper Rhine). Various indicators are  
494 used to identify spatio-temporal channel adjustments, and guidelines to enhance restoration  
495 efficiency and sustainability are provided as well. In the wake of the European Water  
496 Framework Directive advocating (among others) the recovery of longitudinal continuity in  
497 hydrosystems, the study by Peeters et al. focuses on the key question of bedload transfer in a  
498 highly impacted river in Belgium, the Bocq. In particular, the role of abandoned weirs on  
499 bedload transport is investigated: reservoirs are not entirely filled and have not much evolved  
500 over recent decades. The authors show that, although a grain size dependent trapping of clasts  
501 occurs ( $>D_{50}$ ), bedload is transported out of the reservoirs and selectively passes over the  
502 weir's crest. The main outcomes of this study, pointing out the complex interactions between  
503 abandoned weirs and fluvial morphodynamics, should be taken into account in river  
504 restorations implying weir – or more generally barrier – removal and thereby targeting  
505 longitudinal continuity of bedload transfer.

506 The last paper by Kalicki et al. focuses on several secondary rivers (catchment sizes ranging  
507 between a few tens and a few thousands of square kilometers) surrounding the Holy Cross  
508 Mountains in Poland, where the 2016 FLAG Biennial Meeting took place. Various analyses  
509 including geochronology (radiocarbon and luminescence), sedimentology, micromorphology,  
510 palynology and historical archives made it possible to reconstruct the evolution of these  
511 valleys over the last several centuries. Human pressures could be recognized not only in  
512 fluvial landscapes (building of features such as embankments, anthropogenic channels, etc.)  
513 but also in fluvial sediments (charcoals associated with industry and mining, changes in  
514 geochemistry, etc.). This underlines the key role played by human activity (both in rivers and  
515 catchments) in fluvial evolution in terms of morphological (river pattern) as well as  
516 hydrological (e.g., floods) response.

517

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