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The overlooked human influence in historic and prehistoric floods in the European Alps

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ABSTRACT

Understanding the role of climate and humans in generating mountain slope instability is crucial because such instability influences downstream fluvial activity and is a major threat to societies. Here, we use the sedimentary archive of Lake Allos (southeastern France), a mountain lake in the European Alps, to characterize mountain flood deposits and vegetation dynamics over the past 7000 yr. Our results support the interpretation of a critical threshold in catchment sensitivity to erosion at 1700 calibrated (cal.) yr B.P. (A.D. 250) probably resulting from long-term, uninterrupted impacts of human activity. The frequency and severity of floods increased dramatically after this date. These results demonstrate that underestimation of human impacts over the Holocene may pose a challenge to a clear understanding of past climate changes because paleoflood records are highly likely to have been affected by geomorphic thresholds. Natural reforestation since the end of the 19th century does not appear to be sufficient to induce a flood regime comparable to that which occurred prior to 1700 cal. yr B.P. This poses the question as to whether forest restoration in high-altitude environments is liable to foster a return to a low-erosion regime over the next decades, or whether the overall severity of soil degradation has been such as to preclude a return to previous conditions.

INTRODUCTION

Accelerated erosion processes are a major environmental concern because they result from a combination of factors that include climate, geomorphology, and human pressure, particularly when landscape disturbances occur at watershed scales and cause a shift to a regime with mean levels and variances higher than those prior to disturbances (Sharpe, 1941). In mountain areas, accelerated erosion is expected to exacerbate torrential floods through mobilization of large amounts of sediments during high-intensity rainfalls. The importance of climate as a hydrological driver depends on the sensitivity of the system in question. Springtime rain-on-snow events and heavy summertime convective rains generally drive floods in alpine regions (Parajka et al., 2010). Through their activities, humans may also have had a major role in flood hazards. Vegetation removal can lead to an increase in runoff efficiency, favoring flood generation and increasing erosion (Cosandey et al., 2005). While it is commonly assumed that climate change weakens present and future watershed resilience to global change, it is crucial to investigate how humans have transformed the

geomorphic response of mountain landscapes to floods beyond the millennial time scale.

North-central Europe and its mountain ranges, notably the Alps, is an exceptionally appropriate area to address these issues because the environment in this setting has been affected by humans for millennia (Fyfe et al., 2015). The spread of human settlements in the Alps dates back to the end of the Neolithic and the Bronze Age (Walsh et al., 2014). From these times to the present day, human activities have been seasonal, with uplands dedicated to grazing and dairy production. Based on a case study of Lake Allos (southeastern France; 44°14'N, 6°42'35"E, 2230 m above sea level), a mountain lake in the European Alps (Appendices DR1 and DR2-A in the GSA Data Repository¹), we examined changes in vegetation, land use, and the sedimentology of flood deposits over the past 7000 yr. Lake Allos is a valuable archive

¹GSA Data Repository item 2017100, Appendices DR1 and DR2 (characteristic of the study site), Appendices DR3 and DR4 (analytical procedures), Appendix DR5 (pollen data), Appendices DR6 and DR7 (chronology), Appendix DR8 (statistical tests), and Appendix DR9 (old postcards), is available online at <http://www.geosociety.org/pubs/ft2017.htm> or on request from editing@geosociety.org.

of torrential floods because its stacked bottom sediments comprise detrital layers detected by their distinct sedimentological signature, including a sharp and coarse base overlain by a fining-upward basal unit and capped by a whitish, fine-grained unit. Wilhelm et al. (2015) have further shown that historically documented floods in the main valley downstream of Lake Allos are well detected in the sediment archive. A core, ALO11, was sampled in the deepest part of the lake (Appendices DR2-B and DR2-C), where stream discharge triggers detrital deposition over the subbasin floor (Wilhelm et al., 2012, 2015; Brisset et al., 2014). Flood layers identified from thin overlapping sections were counted at a resolution of 200 μm under a binocular microscope (Appendix DR3) and distinguished according to the diameter of the coarsest particle of the layer (Appendix DR4). A palynological analysis was carried out on the same core (Appendix DR5), and the chronology was derived from 16 AMS ¹⁴C dates and short-lived isotopes (Appendices DR6 and DR7).

DISCREPANCIES BETWEEN FLOOD FREQUENCY AND CLIMATE VARIABILITY

The age-depth model of core ALO11 provides a record of deposition over the past 7000 yr (Appendix DR6) comprising 1721 flood layers. In order to investigate how human-induced geomorphic changes have impacted the flood record, we tested the hypothesis that flood layer frequency and amplitude have significantly changed over this time frame. This has been tested using regime shift detection (Rodionov, 2004). Figure 1A shows that flood layers (FLs) were more frequent after 1700 cal. (calibrated) yr B.P. (from 150 to 545 floods per 1000 yr) than in any previous period over the past 7000 yr ($p < 0.01$ using *t*-test).

From 7000 to 1700 cal. yr B.P., the Lake Allos flood frequency exhibited low variability (Fig. 1A) and shows poor correspondence with other records from the southern Alps. In the

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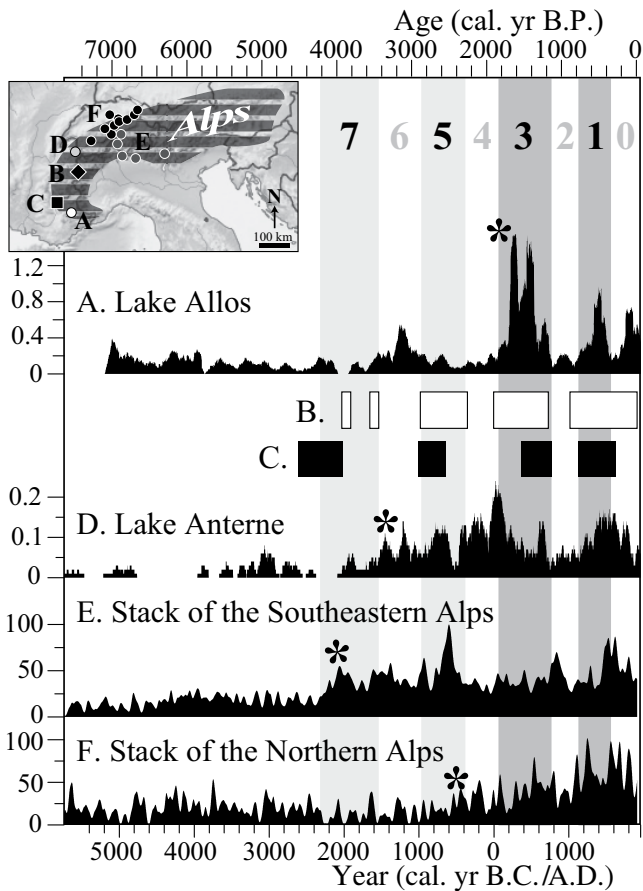


Figure 1. Location map and comparison of lake flood frequency records of European Alps over the past 7000 yr, glacier advances, and slack-water deposition. Phases of humid and cold conditions corresponding to high flood layer (FL) frequency at Lake Allos (southeastern France) are shaded in dark gray; those not corresponding are in light gray. Numbering (0–7) refers to periods discussed in text (black, cold and humid; gray, warm and dry). Asterisks indicate the most significant flood regime shifts ($p < 0.01$, t -tests). A: 100 yr FL moving frequency, Lake Allos (this study). B: Glacier advances (Le Roy et al., 2015). C: Sediment supply of Durance River (southeastern France) (Sivan et al., 2006). D: 100 yr FL moving frequency, Lake Anterne (France) (Giguet-Covex et al., 2012). E, F: Flood activity (%), southeastern and northern Alps, respectively (Wirth et al., 2013). cal.—calibrated.

stacked flood record from five lakes published by Wirth et al. (2013), the flood frequency shifted at 4000 cal. yr B.P. ($p < 0.01$, t -test) (Fig. 1E), while Sivan et al. (2006) showed that periods of alluvial deposition in lower valleys occurred at 4500–3900 cal. yr B.P. and 2500–2900 cal. yr B.P. (periods 7 and 5, Fig. 1C). Since 1700 cal. yr B.P., the flood variability at Lake Allos has appeared to be in agreement with known periods of climatic changes. Higher flood frequency occurred during the Late Antiquity and the Little Ice Age (periods 3 and 1 in Fig. 1), two periods characterized in the Alps by cold and humid conditions (Magny et al., 2002) and glacier advances (Le Roy et al., 2015) (Fig. 1B). Periods of lower flood frequency corresponded to the warmer and drier conditions of the Roman and the Medieval Periods (periods 4 and 2 in Fig. 1).

Discrepancies between these lake records from 7000 to 1700 cal. yr B.P., and agreement since 1700 cal. yr B.P., argue for the fact that climate alone was not the dominant forcing factor of flood variability. Although flood frequency proxies are likely to have been driven by precipitation changes, they are not necessarily a product of climate variability alone over the entire Holocene. This challenges the idea that past floods identified from high-elevation lake records would have been driven exclusively by climate forcing.

EFFECT OF EROSION REGIME SHIFTS ON THE FLOOD RECORD

In order to investigate how geomorphic response impacts the flood layer record, we analyzed the sedimentological characteristics of the FLs, which reflect rainfall intensity and catchment sensitivity to erosion. In general, the size of the coarsest FL particles reflects the maximum river flow velocity reached during a flood (Lapointe et al., 2012), and thickness reflects the abundance of sediment supplied (Schiefer et al., 2011). However, changes in thickness might also reflect changes in catchment erodibility (Giguet-Covex et al., 2012). The increase in FL frequency follows the increase in FL thicknesses, showing the same breaking point at 1700 cal. yr B.P. (Fig. 2). A subdivision of the FLs according to the coarsest particles of each layer (Fig. 2) was carried out in order to investigate the relationship between maximum grain size and thickness (type FL-1, fine silts from 0 to 20 μ m; FL-2, medium silts from 20 to 50 μ m; FL-3, fine sands from 50 to 100 μ m; Appendix DR5). This subdivision shows (Fig. 2) a sudden increase at 1700 cal. yr B.P. of the number of FL-1 layers from a mean of 85 to 395 per 1000 yr. FL-2 and FL-3 have also been more frequent since 1700 cal. BP, but their frequency increase has only been twofold. Using the non-parametric two-sample Mann-Whitney test ($p < 0.01$),

we evaluated the null hypothesis that FL thickness from two periods of different vegetation cover have identical distributions with equal medians, against the alternative that they do not have equal medians. Distributions of FLs are significantly different and FLs are thicker since 1700 cal. yr B.P. (Fig. 2; $p < 0.01$; Appendix DR8). As there is no relationship between bulk density and sediment depth (Appendix DR6), change in FL thickness indicates that whatever the velocity, floods have mobilized systematically more sediment since this date. This is particularly remarkable for FL-3, which has significantly shifted to a higher order of magnitude (from a median thickness of 6–20 mm sediment supply is significantly higher during high-velocity flood events. In addition, FL-1 type events have been more frequent (Fig. 2), indicating that the change in FL frequency at 1700 cal. yr B.P. has been principally caused by an increase in the number of lower-velocity floods. The erosion sensitivity of the source area to rainfall has increased, even for low-intensity ones. These results highlight a modification of the relationship between precipitation intensity and sediment supply. Altogether, the results indicate an increase in catchment erodibility in response to hydro-meteorological processes. The relationship between flood regime and precipitation has shifted to a higher order of magnitude due to local changes in catchment sensitivity.

A HUMAN-INDUCED REGIME SHIFT

Causes of the change in catchment sensitivity have been explored through pollen analysis (Appendix DR5). Two pollen groups are shown in Figure 2, summarizing the abundance in tree cover (arboreal pollen) and domestic livestock grazing (anthropogenic pollen: *Rumex*, *Urtica*, *Mentha*, *Plantago*, *Cerealia*, and *Chenopodiaceae*; Court-Picon et al., 2005). These results bring out four dominant stages in the vegetation dynamics that range from a dense forest from 7000 to 6000 cal. yr B.P. to a progressively more open forest from 6000 to 3500 cal. yr B.P. Since 3500 cal. yr B.P., the impact of human activities has tended to grow, and became intensified from 1700 cal. yr B.P. (attested by the increase in cereals and the *Urtica* pollen curves). Comparison between pollen and FL grain-size patterns suggests that the increase in FL number and thickness has been related to an increase in human-induced vegetation change. But, what is unexpected is the timing of the regime shift, between the Iron Age and the Roman period. These periods are not clearly recognized by the numerous alpine archaeological investigations carried out to date, notwithstanding decades of research. With the exception of some valleys located along transalpine trade routes (Della Casa et al., 2013) where “Romanization” initiated urban growth and new forms of rural land use, high-altitude landscapes were characterized

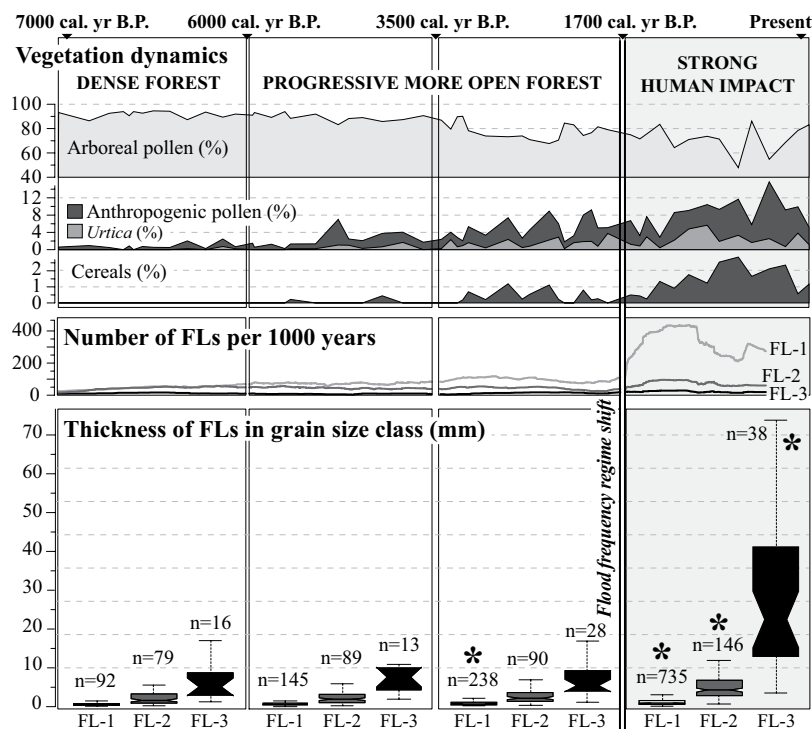


Figure 2. Flood layer (FL) sedimentological characteristics compared to vegetation cover from 7000 cal. yr B.P. to present in Lake Allos, Alps (southeastern France). Arboreal pollen indicates degree of forest openness, and anthropogenic pollen represents agro-pastoralism. FL subdivision is based on coarsest particle size (FL-1, 0–20 μm ; FL-2, 20–50 μm ; FL-3, 50–100 μm). Number of FLs: 1000 yr moving time window. FL thickness distributions are shown by notch-and-whisker box plots (box height is inter-quartile range; thick line is median; notch is median confidence interval, whiskers show 1.5 \times inter-quartile range). Asterisks point out significant change in FL thickness ($p < 0.01$, Mann-Whitney tests). cal.—calibrated.

by a reduction, or, at most, continuity, of pastoral activities (Segard, 2007).

Looking at the situation in more detail, tree cover decline at Lake Allos started before the change in flood regime at 1700 cal. yr B.P. One drawback of pollen is that it may not systematically yield precise information about where changes in vegetation occurred: locally or at the scale of the watershed. However, it is likely that forest clearance and agro-pastoralism led to increased runoff locally, favoring flood generation and exacerbated erosion from 1700 cal. yr B.P.

NON-STATIONARY PALAEOCLIMATIC ARCHIVES

Since 1700 cal. yr B.P., a change in catchment sensitivity has modified the apparent frequency of floods archived in Lake Allos. This type of geomorphic change is liable to distort our perception of long-term climate variability, leading to a misinterpretation of flood frequency and intensity as stationary proxies of precipitation. Similar conclusions were set earlier for climate reconstructions based on paleoecological proxies in many alpine landscapes (Lotter and Birks, 2003). Several alpine paleoflood records show a similar but non-synchronous pattern of late Holocene flood frequency regime shift (Fig. 1)

occurring at 1700 cal. yr B.P. in Lake Allos (Fig. 1A), 3400 cal. yr B.P. in Lake Anterne (France) (Fig. 1D), 4000 cal. yr B.P. for the southeastern Alps (Fig. 1E), and 2500 cal. yr B.P. for the northern Alps (Fig. 1F). Following the example of Lake Allos based on multiproxy analyses, accelerated erosion processes in European Alps are highly likely to have been driven by human activities. As human influence on landscapes has been heterogeneous in time, in intensity, and in quality (Hoffmann et al., 2010), the onset of accelerated erosion has differed among sites.

For the late Holocene, precautions are generally taken to disentangle the respective influence of climate and humans on flood reconstructions (Giguet-Covex et al., 2012). Nonetheless, several studies have directly reconstructed paleoprecipitation variability by assuming that geomorphic settings were unaffected by ancient human practices, and by refuting evidence that human impact has occurred at different points of time in the Alps or that such impact generated multimillennial landscape transformations. Unaffected flood records may rather be found in glaciated or steep catchments unfavorable for human activities during the entire Holocene. Minor human impact may also be invoked for sites located at altitudes higher than that of the Holocene forest extension (Lotter and Birks, 2003). In those

cases, neither vegetation nor soils may have significantly changed. The Lake Allos record demonstrates that catchment sensitivity to rainfall can affect the homogeneity of flood archiving in the sediment record. Underestimation of human impact during the Holocene might, therefore, influence the understanding of climate changes. Non-stationary processes (Milly et al., 2008), especially human-induced geomorphic ones, need to be investigated before using paleofloods as a long-term proxy for flood-risk assessment.

IMPLICATIONS FOR FLOOD-RISK MITIGATION

Changes in vegetation cover have been a decisive driver of the Holocene erosion acceleration at Lake Allos by affecting the flood regime. Prior to 1700 cal. yr B.P., the flood regime was characterized by a low mean level and low variability. In the Alps, forests reached their maximum altitudinal position from 8000 to 6000–4000 cal. yr B.P., depending on the catchment (Brisset et al., 2015). The stable geomorphic conditions were then disrupted following the multimillennial regression of forests in response to intensive human exploitation. Thus, catchment sensitivity to erosion was significantly lower during the Holocene in comparison to the past 1700 yr. Given these results, it could be expected that reforestation of heavily eroded terrain would help to reinstate a lower flood regime as occurred during the mid-Holocene.

Between the 19th and 20th centuries, grazing activities at Lake Allos decreased following rural exodus and forest-protection policies. A comparison of historic photographs of Lake Allos dating from the end of the 19th century to the present (Appendix DR9) shows natural reforestation of the lakeshore. Reforestation and mountain slope management are likely to reduce erosion, as shown for the marly formations of the southern Alps over the past 120 yr (Vallauri et al., 2002), and could contribute to mitigating flood risk. The last decade has been characterized by high flood frequencies (Fig. 2) and by the occurrence of one thick layer (41.2 mm) corresponding to a flood in A.D. 1994 (Etienne et al., 2013). This FL is thicker than all of the FLs deposited from 7000 to 1700 cal. yr B.P., while no significant compaction affects the sediment (bulk density is almost constant; Appendix DR6). Thus, this suggests that the flood regime level and sediment supply are still high. Forest altitudinal expansion does not seem to modify the flood regime at this time scale. Forests have still not yet recolonized the upper parts of the catchment, and the severity of inherited soil degradation might be a lasting obstacle to upslope migration of mature forests. Even though ecological simulations indicate that abandoned overgrazed grasslands could turn into woodlands within 20–50 yr in the southern Alps (Albert et al., 2008), the establishment of mature forests may be conditioned by the requirement of

having developed soils with a sufficient water-holding capacity (Henne et al., 2011). A return to previous conditions (mature forest, developed soils) may require much more time than hitherto assumed. The critical geomorphic threshold that occurred at 1700 cal. yr B.P. might thus be interpreted as a tipping point; a return to the previous state (low flood regime) may not be possible within the time scale of a few human generations (Mori, 2011). A choice in favor of landscape reforestation and possible effects on flood mitigation would also require finding an optimal balance that also maintains mountain landscapes open to the promotion of biological diversity, the preservation of traditional shepherding, and the sustenance of tourism.

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