Synergistic Effects of Climate and Human Activities on Flooding and Soil Erosion: Lac D'Annecy, France

Projected climate change in the western French Alps anticipates increased mean temperatures and precipitation (Gyalistras *et al.*, 1998). This leads to a number of general questions about hydrological mechanisms in the densely populated sub-alpine landscape. How are soil erosion and flooding related to different combinations of land use and climate? Can land use be managed effectively in order to reduce the worst flooding effects? To what extent do past and present interactions between climate and human activities condition future impacts? These questions are at the heart of an ongoing research programme at Lac d'Annecy, eastern France designed to further our understanding of the synergies between climate and human activities through analyses of documentary and sedimentary archives.

Lac d'Annecy, Haute Savoie, France (Lat. 45°48'N; Long. 60 8'E; altitude 460 m) consists of two linked lake basins (Petit and Grand Lac) with a surface area of 26.5 km^2 draining a mountainous limestone catchment (251 km^2) that reaches an altitude of 2350 m. Early studies (Dearing 1979: Higgitt 1985; Higgitt *et al.*, 1991) of the Petit Lac lake sediments found substantial evidence for links between agricultural expansion and sedimentary evidence for enhanced flooding and soil erosion. Later, Thorndycraft *et al.* (1998) identified four sedimentary flood layers attributable to summer/autumn storms dating from the late 17th to early 19th centuries. The present study continues the use of geochemical, organic, physical and magnetic properties of lake and floodplain sediment sequences as proxy records of erosion and flooding over the past 5000 years, with documentary and palynological information providing the main evidence for land use and climate drivers of the hydrological system. However, the wealth of records from documentary sources and instrumental measurements has provided the opportunity to modify conventional paleomethodologies in three main ways. First, we have put great efforts into establishing independent records of forcings and hydrological responses from as many sources as possible (eg. Benedetti-Crouzet, 1972; Benedetti-Crouzet and Meybeck, 1971; French Ministry of the Environment SEMA). Sediment proxies for flooding and erosion are calibrated against modern discharge records, monthly sediment trap data and modern sediment source signatures for the whole catchment. Documentary and monitored records have been compiled from a very wide range of sources, and exhaustively evaluated in terms of accuracy and comparability. Debris flows and inactive gully systems have also been used as geomorphic evidence for past slope instability. Second, we have tried to consider the nature of hydrological change over a very wide range of time intervals and time-resolutions. A long lake sediment sequence allows environmental reconstruction over the past 5000 years with individual sediment increments equivalent to ~3–50 years. About 15 short cores allow spatial reconstruction of sedimentation patterns and hence estimates of sediment yield over the past 100–200 years at a time resolution of ~<1–10 years. Fine visible stratigraphy and analyses of thin sections in selected cores give historical information about discrete events and annual-seasonal changes. Third, we have used meteorological records, extending back to the late 19th century, and regional documentary climate indices back to the 16th century to develop simple climate-driven flood models and crop growth models. The former may be tested against 25 years of river discharge data, the documented record of major flood events at Annecy dating from 1570 and the lake sediment proxy record of flooding. Comparisons between reconstructed records of processes, land management, environmental conditions and modelled processes and conditions should help to discriminate between erosion/flood regimes that were driven by seasonal meteorological events, by specific combinations of land use and climate, or in response to major landscape disturbance. The ability to set each time period in the context of its history also allows us to examine the extent to which different regimes are, or were, conditioned by previous environmental changes.

Modern Calibrations

Establishing calibrations between flood events, suspended sediment sources and sediment deposition at the lake bed during the period of monitoring is the key to interpreting the long lake sediment records. River discharge records 1975–1998 show that 65% of maximum annual floods occur in the period November–March, often linked to snowmelt, while June–August are characteristically months with low flow, except during short duration and high intensity storms. Documentary records since 1570 show a similar pattern with 57% of floods recorded in the months November-May. This pattern is seen in the properties of sediment trapped at water depths of 20 and 46 m in the Grand Lac (May 1998–Oct. 1999) where seasonal differences in sediment magnetic characteristics are related to seasonal storms, river discharge and sediment delivery processes operating in different zones of the catchment. In particular, the total flux of detrital magnetisable minerals (χLF) rises by more than tenfold between September and Feb–Apr before declining rapidly in May (Fig. 1a). Comparing the full range of magnetic properties of the trapped sediment with the spatial patterns of soil magnetism in the Petit Lac catchment (Dearing *et al.* 2000) indicates some seasonal shift in sediment source. Topsoil from lowland and mid-altitude zones appears to make a greater contribution to the sediment load in late autumn following agricultural operations, while thin montane soils and river channel sources contribute most of the load in spring during snowmelt. High resolution analyses of millimetre thin sections from a zone of homogenous lake sediment dated to the early 19th century also show the same characteristic winter peak in susceptibility supported by evidence for seasonal fluctuations in absolute pollen. A preliminary comparison of near-inflow lake sediment susceptibility and smoothed records of daily river discharge since 1975 show a reasonable correlation (Fig. 1b), suggesting that the detrital-bound ferrimagnetic concentrations may be used as a first order proxy of annual discharge. Interestingly, the link to precipitation is weaker, suggesting that modern discharge is strongly affected by seasonal changes in land use, groundwater storage and antecedent conditions. Other sediment properties appear to represent proxies for discrete discharge events linked to particular combinations of land use and storm types, supporting an earlier contention that high magnitude summer flood events are preserved in the lake sediments (Thorndycraft *et al.* 1998).

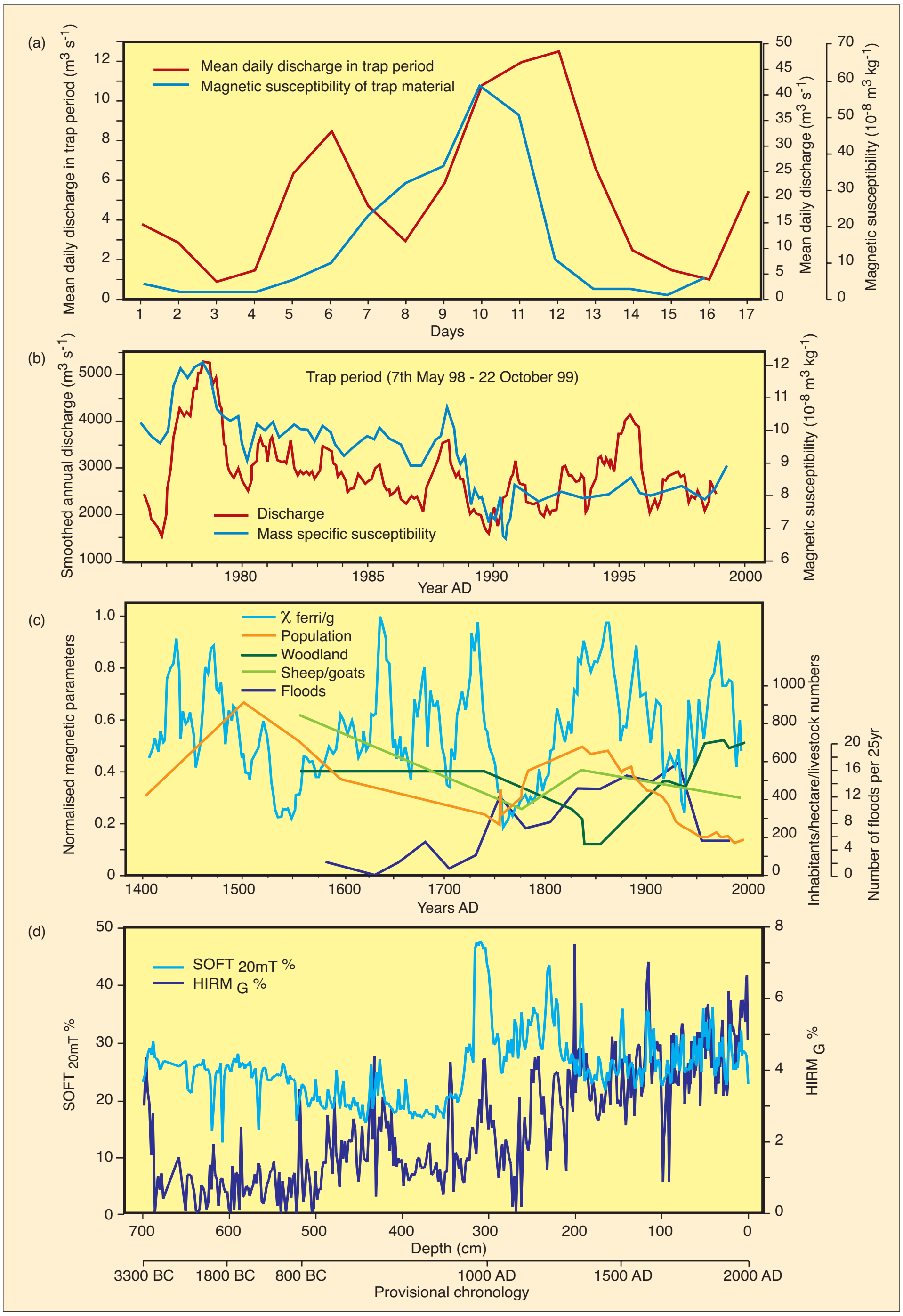

Figure 1: a) Magnetic susceptibility values of trapped sediment and monthly river discharge data May 1998–October 1999. b) Magnetic susceptibility values of lake sediment and smoothed annual river discharge 1975-1999. c) Lake sediment flood proxy record (χferri) AD 1400–2000; historically recorded changes at Montmin for human and livestock populations, and woodland cover; recorded flood frequency in catchment. d) Long term trajectories of erosion over the past ~5000 years using the magnetic parameters SOFT$_{20mT}$ % and HIRM$_G$ % as proxies for lowland surface soil and upland montane soil/unweathered substrates respectively.

The Past 600 Years

Since AD 1400, documentary records show that the catchment has witnessed fluctuations in both land use and climate, and in the intensity and frequency of flooding. Matching the documentary records and sediment data is presently based on an assumed mean sedimentation rate in the long master core of 4 mm/yr, a figure derived from ^{210}Pb, ^{137}Cs, ^{14}C and pollen markers. A direct and positive link between the timing of peak values in a magnetic proxy (Fig. 1c) for annual discharge and the documentary flood frequency (back to AD 1600) is well within the errors for the sediment ages, and appear to be most strongly linked to negative anomalies in Pfister's (1992) precipitation index for the Swiss lowlands and shifts to greater continentality of the climate. A more rigorous hydrological model driven by meteorological data will be used to test these relationships further and to establish the mechanisms by which flooding has been directly linked to climate, but we can already make some tentative conclusions about the role of the agricultural communities. Since AD 1600 the human population in the high valley commune of Montmin has fallen from a peak at AD 1475–1561 to a low at AD 1750 before reaching the most recent maximum at AD 1800–1875. The rise during the period AD 1750–1850 is matched by decreases in the area under pasture and woodland, an increase in the area under cultivation, increases in the numbers of bovine and ovine animals, and is a period of increasing flood frequency (Fig. 1c). The pollen evidence for landscape 'openness' (NAP/AP) also follows the curves for the magnetic discharge proxies (χferri and χferri %). In contrast, a magnetic proxy (SOFT$_{20mT}$%) for summer floods (containing high proportions of lowland surface soil) shows high values ~AD1600 and ~1750 that do not appear to be strongly related to land use and cover. Taking the different records of land use and flooding together, there is strong evidence that annual discharge and erosion throughout the historical period may have been at least partially driven by the degree of vegetation cover determined by agricultural activities, while summer flooding may have been linked to specific timings and locations of individual storms. Preliminary assessments of the socio-agricultural economy for Montmin since AD 1561 based on crop yields, manuring levels and grazing pressures indicates an ill-sustained system where agriculture was potentially marginalised by both climatic and population forces. However a curve for modelled crop

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degree growing days for Montmin shows no significant climatic restrictions on summer crop yields since AD 1525. The weight of evidence gained so far suggests that fluctuations in the subsistence population and agricultural fortunes were determined by non-climatic factors, including outward migration and disease. There is the strong possibility that the most recent rise in human population during the late 18th century was coincidental with the timing of the shift towards more continental climatic conditions. The more open landscape at that time caused the natural climate-controlled processes of flooding to become accentuated in terms of higher magnitude and more frequent flood events that continued into the early 20th century even while the upland agricultural community declined.

The Record Back to 5000 BP

Sparse accounts of settlement before AD 1400, and pollen evidence, suggest that the structure of the present vegetation-agricultural landscape has its roots in Cistercian clearances around 1000 cal. yr. BP. Although the human impact on flooding and erosion probably started earlier, in Roman times, the long lake sediment records (Fig. 1d) show that high magnitude-low frequency flooding, which transported lowland and mid-altitude surface soil (Dearing *et al.* 2000; Noel *et al.*, 2000), reached a maximum at this time. Other evidence for major soil destabilisation comes from charcoal fragments dated to 960 cal. yr. BP found deep within a colluvial soil section in the Montmin valley, and from the Eau Morte floodplain stratigraphy where >2 m of silty overbank sediment has been deposited since ~2000 BP. Prior to 2000 BP, the evidence from floodplain sections and lake sediments is for a hydrological regime typical of stable wooded slopes, delivering clay-sized material from the montane zone except in extremely high energy events. Following the dramatic erosional response to forest clearance at ~1000 cal. yr. BP, the magnetic signatures for low-mid altitude surface soil and montane soil show divergent trends (Dearing *et al.* 2000) with the latter gradually increasing up to the present day (Fig. 1d). This may simply reflect the enhanced storage of surface soil in the floodplain after 2000–1000 BP. Alternatively, it may imply that while the lowland and mid-altitude soil-vegetation systems showed some sense of stabilisation over subsequent centuries, the montane zone progressively deteriorated. We may certainly hypothesise that early deterioration of the montane zone cultivation may have conditioned and, in the present situation, amplified the later hydrological responses to the agricultural changes documented since AD 1500.

Thus the findings are beginning to show that soil-vegetation-hydrological systems in diverse altitudinal zones, within the same catchment, appear to have significantly different degrees of resilience to climate and human activities. Some hydrological responses are clearly direct, broadly linear and exhibit negligible time-lags; other less obvious forcing-response relationships probably involve long term and threshold-dependent nonlinear change. Synergistic interactions between climate, human activities and hydrology in the Annecy catchment are therefore complex and require the present methodological framework in which all relevant spatial and temporal scales are included and integrated.

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For full references please consult *www.pages-igbp.org/products/newsletters/ref2003.html*

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The Murrumbidgee River Catchment, Australia

European settlement in Australia, the USA, and New Zealand had dramatic impacts on the fluvial system, many of which are still working their way through river catchments. These trends, punctuated by episodic floods, produce a complex set of changes that have been documented in the SE Australian catchment of the Murrumbidgee River.

The history of the sedimentary system since 1820 AD, when European settlers arrived, has been reconstructed from a sediment budget for a 130km^2 subcatchment (Jerrabomberra Ck), from analysis of cores taken from Burrinjuck Reservoir (13,000km^2), from flood deposits in the mouth of Tuggeranong Ck (~5,000km^2), from documented large floods that have caused major channel changes and therefore sediment transport, and from major lateral migrations and sediment transport in the downstream river at Mundowey and Narranderra (~80,000km^2).

The Figure opposite shows a trend in sediment yield from Jerrabomberra Creek generated by the growth of gullies the yield from which dominates the budget. Declining yield since 1890 AD occurred as gullies stabilized, a trend reflected in Burrinjuck Reservoir. While erosion of subsoils, via gullies and channels, dominates the sediment transport, periods of high topsoil erosion (estimated from the tracers ^{210}Pb excess and ^{137}Cs) were produced by high runoff and floods.

Records of nutrient deposition and algal response in Burrinjuck Reservoir are also available, and are being compiled with the sediment records.

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