Earth-Science Reviews 135 (2014) 17–37

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Flood stratigraphies in lake sediments: A review

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ARTICLE INFO

Article history:
Received 30 September 2013
Accepted 31 March 2014
Available online 13 April 2014

Keywords:
Lake sediments
Palaeoflood
Geochemistry
Particle size
Limnology
Extreme events

ABSTRACT

Records of the frequency and magnitude of floods are needed on centennial or millennial timescales to place increases in their occurrence and intensity into a longer-term context than is available from gauged river-flow and historical records. Recent research has highlighted the potential for lake sediment sequences to act as a relatively untapped archive of high-magnitude floods over these longer timescales. Abyssal lake sediments can record past floods in the form of coarser-grained laminations that reflect the capacity for river flows with greater hydrodynamic energy to transport larger particles into the lake. This paper presents a framework for investigating flood stratigraphies in lakes by reviewing the conditioning mechanisms in the lake and catchment, outlining the key analytical techniques used to recover flood records and highlighting the importance of appropriate field site and methodology selection. The processes of sediment movement from watershed to lake bed are complex, meaning relationships between measureable sedimentary characteristics and associated river discharge are not always clear. Stratigraphical palaeoflood records are all affected to some degree by catchment conditioning, fluvial connectivity, sequencing of high flows, delta dynamics as well as within-lake processes including river plume dispersal, sediment focussing, re-suspension and trapping efficiency. With regard to analytical techniques, the potential for direct (e.g., laser granulometry) and indirect (e.g., geochemical elemental ratios) measurements of particle size to reflect variations in river discharge is confirmed. We recommend care when interpreting fine-resolution geochemical data acquired via micro-scale X-ray fluorescence (μXRF) core scanning due to variable down-core water and organic matter content altering X-ray attenuation. We also recommend accounting for changes in sediment supply through time as new or differing sources of sediment release may affect the hydrodynamic relationship between particle size and/or geochemistry with stream power. Where these processes are considered and suitable dating control is obtained, discrete historical floods can be identified and characterised using palaeolimnological evidence. We outline a protocol for selecting suitable lakes and coring sites that integrates environmental setting, sediment transfer processes and depositional mechanisms to act as a rapid reference for future research into lacustrine palaeoflood records. We also present an interpretational protocol illustrating the analytical techniques available to palaeoflood researchers. To demonstrate their utility, we review five case studies of palaeoflood reconstructions from lakes in geographically varied regions; these show how lakes of different sizes and geomorphological contexts can produce comprehensive palaeoflood records. These were achieved by consistently applying site-validated direct and proxy grain-size measurements; well-established chronologies; validation of the proxy-process interpretation; and calibration of the palaeoflood record against instrumental or historical records.

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http://dx.doi.org/10.1016/j.earscirev.2014.03.011
0012-8252/

1. Introduction

1.1. Rationale behind lake palaeoflood research

Researchers (e.g., Milly et al., 2002; Gorman and Schneider, 2009) have suggested that the frequency and intensity of extreme flood events may be increasing due to the high sensitivity of the hydrological cycle to a warming climate (Knox, 2000), triggering an intensification of the water cycle (Huntington, 2006). Recent modelling by Hirabayashi et al. (2013) projects a current 100-year return period flood is likely to occur every 10–50 years in the 21st century. However, the complexity inherent in the climate–flood relationship, coupled with the infrequent and short-lived nature of extreme floods, means few data are available for evaluating long-term trends in their frequency and magnitude (IPCC, 2012). Acquiring long-duration datasets of historical floods that extend beyond available instrumental records is clearly an important step in attributing trends in flood frequency and magnitude to climate change and addressing future flood risk. Conventional flood histories derived from instrumental data rarely span sufficiently long timescales to capture the most extreme events (Brázdil et al., 1999; Macdonald, 2012) nor do they enable climatic (non-)stationarity or the attribution of the intensification of precipitation events by global warming to be assessed (Min et al., 2011). Various sources are routinely accessed in order to acquire information on historical floods on timescales extending beyond the instrumental record, including documentary records (e.g., Benito et al., 2004) and sedimentary records extracted from river flood-plains and slackwater deposits (e.g., Baker, 1987).

Lakes act as efficient repositories for clastic material eroded from catchment slopes and floodplains and subsequently transported through the fluvial system (Mackereth, 1966; Oldfield, 2005). If the hydrodynamic relationship between river discharge and entrainment potential of specific particle sizes is reflected in the materials received by the lake basin and incorporated into the sediment record, high-magnitude flows should appear as distinct laminations of coarse material. As a result, a growing number of palaeolimnologists are searching for lake sediment sequences from which records of past floods can be uncovered (e.g., Noren et al., 2002; Czymzik et al., 2013; Gilli et al., 2013; Wilhelm et al., 2013; Wirth et al., 2013a,b; Schlolaut et al., 2014). Lake sediment records can contribute valuable data on flood frequency and, potentially, single-event magnitude over several millennia (Noren et al., 2002). Improvements in the mechanics of coring technology (e.g., UWITEC-Niederreiter (Schultze and Niederreiter, 1990); Mingram et al., 2006) and resolution of analytical methods (e.g., micro-scale X-ray fluorescence (μXRF); Croudace et al., 2006) have aided the extraction of palaeoflood records from lakes in Africa (Baltzer, 1991; Reinwarth et al., 2013), Asia (Ito et al., 2009; Nahm et al., 2010; Li et al., 2013; Schlolaut et al., 2014), Europe (Arnaud et al., 2002; Bøe et al., 2006; Wilhelm et al., 2012; Wirth et al., 2013a), New Zealand (Orpin et al., 2010; Page et al., 2010), North America (Brown et al., 2000; Noren et al., 2002; Osleger et al., 2009) and South America (Chapron et al., 2007; Kastner et al., 2010).

A comprehensive review of the acquisition of flood frequency and magnitude data from lake sediments, the proxies available and the challenges that may hinder robust interpretation is thus timely. Here we outline the flow processes and physical controls on river plume dispersal both to and within a lake, assess how process-controls map to the lake stratigraphical record and evaluate the proxies employed by palaeolimnologists to identify palaeoflood deposits. This paper presents a conceptual model that assesses the catchment-to-lake water and sediment flow pathways and their relative importance for the successful extraction of palaeoflood sequences. It also develops a decision tree outlining the analytical procedures available for identifying and interpreting these data and presents five case studies where these protocols have been applied to reconstruct palaeofloods at widely distributed lakes with different characteristics.

1.2. Non-lacustrine sources of flood data

Gauged river flow data are widely available for the last 30–40 years in Australia and most European countries (Benito et al., 2004), a comprehensive hydrometric network (>3000 gauging stations) has existed in Canada since 1975 A.D. (Pyrce, 2004), and the United States Geological Survey (USGS) has operated an effective, centralised stream gauging programme since 1970 A.D. (Benson and Carter, 1973). In countries where an expansive network of hydrometric stations has existed for longer time periods, such as Switzerland (national hydrological service established in 1863 A.D., more than 30 stations established in the 19th century, more than 70 in operation since 1930 A.D.), more detailed assessments of trends in flood frequency can be undertaken (e.g., Schmocker-Fackel and Naef, 2010a). Elaborate monitoring networks enable good understanding of changes in hydrological regimes at hourly to annual timescales. Nevertheless, obtaining data for the short-duration, high-magnitude flow events is logistically challenging or, as a worst case scenario, monitoring stations can be damaged or destroyed by a flood. For example, the November 2009 extreme floods on the River Cocker in Cumbria, northwest UK, caused significant damage to the gauging station at Camerton on the River Derwent (National River Flow Archive Station #75002; http://www.ceh.ac.uk/data/nrfa/. Last accessed 27/08/2013). This suggests that the 200-year return period calculated for the flood (Everard, 2010) is likely to be an underestimate as the hydrological capacity of the gauging station was exceeded (Miller et al., 2013a,b).

Historical data can be used to improve estimations of flood frequency and magnitude (NERC, 1975; Hooke and Kain, 1982; Bayliss and Reed, 2001; Schmocker-Fackel and Naef, 2010b) and have been acquired from sources including epigraphical markings of peak flow stages on infrastructure adjacent to a river (Macdonald, 2007), paintings or photographs and written documents such as diaries or newspapers (Brázdil et al., 2006). Documentary evidence often expresses an extreme event in terms of its impacts on society, which can be used as a reference for peak flow level, or to assess the recurrence intervals of such events (Benito et al., 2004). Many flood histories extending back several centuries have been compiled using documentary sources in Europe; Brázdil et al. (2006) used historical records to identify a 20th century trend towards lower flood frequency due to regional warming reducing the number of winter floods and Wetter et al. (2011) showed that six catastrophic events (Q (discharge) > 6000 $m^3 s^{-1}$) occurred in the pre-instrumental period that exceeded all more recent events since 1877 A.D. In the UK, Macdonald and Black (2010) demonstrated that more robust flood frequency estimates were obtained for the River Ouse when data from historical sources were integrated with conventional gauged techniques, while Prieto and García Herrera (2009) reviewed the value of documentary sources for reconstructing climate in South America since its colonisation by the Spanish.

Sedimentological techniques have been employed to decipher imprints of past flood events in incised floodplains or canyons, a research field termed 'palaeoflood hydrology' (Baker, 1987). One promising strand involves reconstructing floods recorded in slackwater deposits in floodplain settings. Under high flows, coarse-grained sediments are entrained and deposited in depressions along the floodplain that are separated from the river channel under normal flow conditions, and thus are positions of high sediment preservation potential (Baker, 2008). As a result, the highest magnitude floods are captured as discrete layers in cut-off meanders or in bedrock canyons. Granulometric analyses of these sediment sequences have generated centennial-scale records of meteorologically-generated floods (Werritty et al., 2006) and ice-jam-generated floods (Wolfe et al., 2006). Increasingly high-resolution core scanning techniques (e.g., ITRAX; Croudace et al., 2006) have enabled channel fill sequences to be analysed in greater detail, with selected elemental ratios being utilised as indirect proxies of grain-size (e.g., Zr/Rb ratio in Welsh palaeochannels; Jones et al., 2012).

Discrete landforms produced during high-flows, such as alluvial fans or upland boulder berms, can be dated using radiocarbon (^{14}C) and lichenometry, and these chronologies can produce fragmentary records of palaeofloods (e.g., Foulds et al., 2013). Their precision and utility are limited by the available dating control and the validity of its application (Chiverrell et al., 2009, 2011) but case studies in the UK (e.g., Macklin et al., 1992; Macklin and Rumsby, 2007) and Greece (e.g., Maas and Macklin, 2002) in part overcome these challenges.

Reconstructing peak discharges of jökulhlaups and 'superfloods' (potentially exceeding millions of cubic metres per second; Baker, 2002) through geomorphic investigations (Jarrett and England, 2002) and hydraulic numerical modelling (Carling et al., 2010) has also been a focus of palaeoflood research, due to their capacity to abruptly modify vast landscapes. Examples of such Pleistocene megafloods include Glacial Lake Missoula in north-western USA (Baker, 1973), around the Altai Mountains, Siberia (Herget, 2005), and Glacial Lake Agassiz, constrained by the Laurentian ice sheet (Teller, 2004).

2. Flow processes and depositional mechanisms

2.1. Coupling of lakes with drainage basins

In the case of lakes, palaeoflood studies attempt to explicitly link low-frequency, high-magnitude flows to discrete sedimentary units recorded within long lake sediment profiles sampled by various coring equipment. Interpreting the sedimentary characteristics that represent a single historical flood requires confidence that the material accumulating at the lake bottom reflects the hydrogeomorphic processes taking place in the catchment at this event-specific temporal scale.

Catchment hydrological and sedimentological regimes appear to operate in a cascading manner, where material delivered to a lake as suspended sediment reflects the interplay between sources, transmission, storage and sediment sinks across the slope, gully, floodplain and fluviodeltaic systems (Fryirs, 2012). Both anthropogenic and natural factors can influence system connectivity within a drainage basin (Chiverrell, 2006; Foster et al., 2008), for example by altering soil formation and its susceptibility to erosion (Giguet-Covex et al., 2011). Floodplain sediment stores may subsequently introduce time-lags within the sediment conveyor (Fryirs et al., 2007; Chiverrell et al., 2010). The degree to which a river channel is well- or poorly-connected through time will also influence the nature of material moving downstream (Harvey, 1992; Hooke, 2003). For example, fluvial systems in which only exceptionally high flows generate a sediment pulse are classified as *unconnected* compared to those where sediment is readily transported by low-magnitude floods in more efficient, *connected* channels (Hooke, 2003). Changes in connectivity can potentially modify the geomorphic signal transmitted along the sediment conveyor to the lake, altering the hydrodynamic relationship between lacustrine sedimentation and river discharge through time. The implications for discerning flood magnitude from discrete sedimentary units is that changes in sediment supply through time may result in flood events of equivalent magnitude depositing sedimentary units exhibiting different thicknesses, particle size distributions or geochemical composition. In this context, event sequencing can also be important. Where two floods of equivalent magnitude occur in close succession, the first may exhaust fluvial sediment stores, leaving the subsequent event deprived of material to transport. In summary, for lakes, river systems are best described as sources of sediment where the supply regime is inherently non-stationary.

Integrating multiple palaeoenvironmental proxies offers the most comprehensive approach to gaining a better understanding of changes in fluvial connectivity, soil erodibility and sediment supply as well as identifying shifts in the climate–vegetation–soil relationship (e.g., Koinig et al., 2003). For example, pollen and plant macrofossil records will reflect changes in vegetation cover, which may alter sediment supply and provenance during phases of intensive agriculture (Dearing and Jones, 2003). Environmental magnetic measurements can be an effective sediment-source tracer, highlighting phases of greater topsoil delivery to a lake in response to the expansion of agriculture (e.g., Chiverrell et al., 2008; Shen et al., 2008). Inorganic and organic geochemical measurements also provide insights into catchment soil development and weathering and erosional processes (Giguet-Covex et al., 2011) that may influence sediment supply through time. Without a robust understanding of changes in catchment conditioning through time, quantitative relationships identified between flow stage and sedimentary evidence of palaeofloods may be misinterpreted.

2.2. Sediment deposition in lakes

2.2.1. Mechanics of sediment deposition

Sediment plumes entering lakes are subjected to a number of physical and chemical processes that determine the nature and rate of deposition across the lake bed. Sediments extracted from a lake bed are typically composed of clastic (i.e., terrestrially-derived) material as well as autochthonous biogenic compounds that can include silicates, carbonate and organic matter (Lowe and Walker, 1997).

Palaeoflood records are most effectively extracted from sediment sequences where sufficient river-borne material is delivered during a flood to overprint the near-continuous autogenic (internal) or allogenic (external) sedimentation pattern at the lake bed with a distinctive detrital lamination. Distinguishing the different sedimentary components lain on the lake bed is therefore an important first step but a non-trivial task. Lakes often exhibit a heterogeneous sediment matrix consisting of fine-grained allochthonous clay and silt, siliceous material (e.g., diatoms) and variable organic matter content, composed of detrital plant material (leaves, wood, seeds) and humic substances as well as autogenic planktonic and benthic microbes (Håkanson and Jansson, 1983; Lowe and Walker, 1997). Sediment sequences in lakes that experience climatic conditions conducive to intensive photosynthetic activity, or where considerable Ca-rich bedrock is found in the catchment (including some upland lakes in the European Alps where palaeoflood studies have been undertaken; e.g., Lake Iso; Lauterbach et al., 2012), are more strongly influenced by the precipitation of carbonate while other lakes display annually laminated (varved) sediment sequences (e.g., Czymzik et al., 2013). Palaeoflood records have been extracted from each of these lake settings, although site-specific hydrogeomorphic processes, sediment provenance and within-lake depositional mechanisms must be considered. Broadly, catchments with considerable erodible soil cover and limited interruption of the sediment conveyor in the form of large deltas or extensive floodplains will receive greater allochthonous input (Dearing, 1997) and are therefore better suited to palaeoflood reconstruction (e.g., Foster et al., 2008; Parris et al., 2010).

2.2.2. Sediment dispersal and mixing pathways within lakes

Sediment load is a function of the relative production of autochthonous particles and the delivery of allochthonous material, a relationship that can change significantly through a lake's lifetime (Håkanson and Jansson, 1983). The pattern of sediment accumulation across a lake will be systematically altered based on the distance from the inflow acting as the dominant sediment source while basin morphology may result in selective deposition across the lake bed (Dearing, 1997). Sediment focusing at certain zones of small basins, reviewed extensively by Hilton (1985), poses a challenge when correlating thicknesses of individual palaeoflood units across multiple sediment cores from a single lake. Schiefer (2006) noted a non-linear decrease in sediment accumulation rates in Green Lake, British Columbia (a glacially-scoured upland lake ~2 km^2 in area) of 2 g/cm^2/yr at a delta proximal site declining to <0.1 g/cm^2/yr at more distal locations; results of a similar magnitude were found in Lake Geneva (Loizeau et al., 2012). Thus, assessing the degree of spatial heterogeneity in sediment accumulation through stratigraphical correlation between multiple cores across a lake is crucial where high-resolution data are sought (Dearing, 1997).

The expression outlined by Stokes (1851) describing the frictional force exerted on a spherical particle of a certain diameter in a viscous fluid (Eq. (1)), known as hydraulic equivalence (Rubey, 1933), is the primary control on the rate of fallout from suspension of a sediment particle.

$$V = {}^{g \cdot \Delta_m \cdot D_m{}^2}\Big/_{18\eta} \qquad (1)$$

where g = gravity, Δ_m = submerged density (mineral density δ_m − fluid density δ_f), D_m = diameter of the particle and η = fluid dynamic viscosity (in freshwater, $\delta_f = 1$ g/cm^3 and $\eta = 0.01$ g/cm/s) (Garzanti et al., 2008). Eq. (1) is applicable when laminar flow conditions exist (i.e., Reynolds Number (Re) < 0.5; Håkanson and Jansson, 1983). In turbulent flows with higher Re values (>0.5), settling velocities approach being independent of the drag coefficient (C_d) and Stokes' Law may be invalid. Several attempts to derive empirical equations applicable to turbulent flow exist (e.g., Cheng, 1997; Jiménez and Madsen, 2003). Flows that maintain turbulent momentum are capable of moving considerable distances across a lake bed while transporting high suspended sediment concentrations. These turbidity currents may take the form of high-density hyperpycnal flows, which are considered further in Section 2.2.4.

While settling velocity is primarily a function of particle size and fluid density and viscosity, differing mineral composition or particle shape can also affect settling velocity. In particular, where fluid density remains constant, particles composed of denser minerals (e.g., magnetite) will be deposited at an equivalent velocity to larger particles predominantly made up of common, less dense minerals such as quartz, feldspars or calcite (referred to as a *size shift*; Garzanti et al., 2008). Furthermore, the influence of turbulence and viscosity on settling velocity varies between grains of silt, sand or gravel (Garzanti et al., 2008). In the case of lakes (where gravel deposition is less likely), size shifts can be easily predicted for silt particles, but calculating correct settling velocities for sand which account for size shifts is much more challenging (e.g., Gibbs et al., 1971; Cheng, 1997) as a result of circular interplay between particle size, the drag coefficient of the water column and the mineral composition of the sand fraction. In addition, particles settling in natural settings are rarely spherical, leading Komar and Reimers (1978) to incorporate the Corey Shape Factor (CSF; quartz = 0.7, mica = 0.1 according to empirical estimates; Komar et al., 1984) into Eq. (1).

Mechanisms that generate turbulent flow within the water column, such as wind-induced waves and currents or thermal stratification (the warming of surface waters during summer while cold water remains at depth year-round), drive mixing between adjacent layers (Imboden and Wüest, 1995). These turbulent flows can result in settling velocities deviating from those predicted by Stokes' Law for quiescent fluids (Håkanson and Jansson, 1983).

Wind speed and fetch are the dominant forcings on the size and power of wind-generated waves and currents, respectively, in a lake. Particles at the lake bed may become re-suspended when shear-generated turbulence (controlled by wind speed and water depth) exceeds a frictional threshold (Fig. 1) that depends on the density, size and cohesion of grains (Imboden and Wüest, 1995). Sediment remobilization during periods of high wind-speeds can potentially create hiatuses in the sedimentary sequence or scour prior event deposits. Applying a multi-core extraction protocol across a lake can enable the degree of re-suspension across a basin to be assessed (Dearing, 1997).

Lakes with long wind fetch are also more susceptible to slumping along lake margins, which can generate extensive turbidity currents and leave sedimentological imprints that will complicate the stratigraphical sequence of 'background' and flood-derived sedimentation (Talbot and Allen, 1996). The turbulent effects of waves in small, deep lakes should be minimal, and thus represent a preferred study site characteristic. These effects should be considered, however, where shallow lakes are selected as field sites. Where data on local wind speed spanning long time periods are available, empirical equations have been developed describing the relationship between orbital velocity driven by wave action and fetch and their ability to entrain

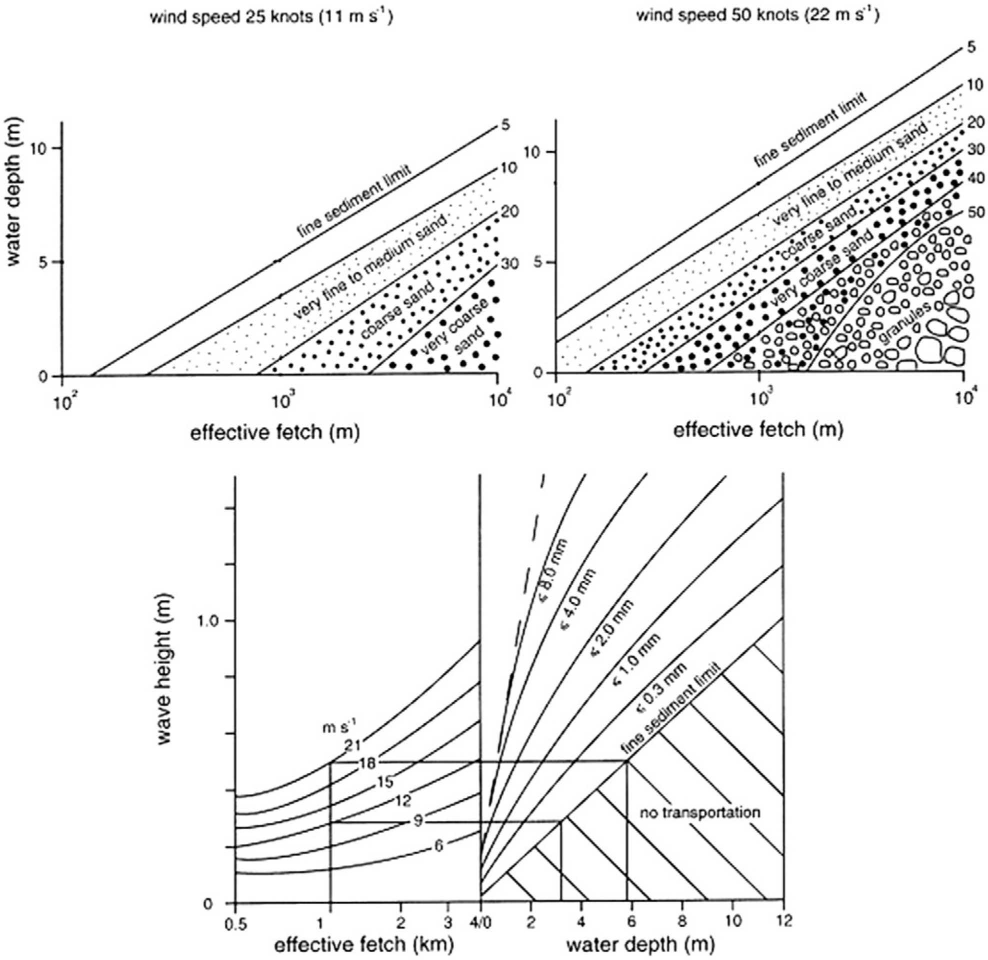


Fig. 1. The relationship between effective fetch, water depth, wind speed and sedimentation thresholds in small lakes for different particle size fractions.
Merged diagram modified from Dearing (1997), upper plate originally published by Johnson (1980) and lower diagram by Norrman (1964). Used with permission of Springer.

sediment, although these relationships are highly complex (Håkanson and Jansson, 1983). If wave motion has been calculated (see Håkanson and Jansson, 1983), Eq. (2) relates its power to move particles smaller than 500 μm (Komar and Miller, 1975), which are typical of suspended sediments likely to reach a lake basin:

$$\rho \cdot {u_m}^2(\Delta_m) \cdot g \cdot d = C \cdot \sqrt{1_n}/d \tag{2}$$

where u_m = horizontal wave velocity (m), d = grain diameter (mm), C = empirical constant reported to be 0.13 (Sternberg and Larsen, 1975), and 1_n = horizontal displacement.

Turbulent flow driven by wind or surface heating is normally confined to the layer above the thermocline in well-stratified lakes. However, wind energy or a density differential between water masses can trigger the vertical or horizontal movement of the thermocline, creating interval waves (seiches) that can affect the entire waterbody (Larsen and Macdonald, 1993; Talbot and Allen, 1996), even in large lakes (e.g., Lake Geneva; Lemmin et al., 2005). Importantly, the propagation of seiche waves across a lake applies shear stresses at the lake bed potentially capable of sediment re-mobilisation (Lemmin et al., 2005). While the frequency, magnitude and effect on basal sediments of these interval waves are highly complex and depend on the stratification of the water column and basin morphology (Larsen and Macdonald, 1993), their effects have been shown to be a prominent feature in the stratigraphical record (Pomar et al., 2012).

The time available for suspended particles to be subjected to these diffusion mechanisms provides an additional control on spatial accumulation patterns. Residence time of water in lakes measures the average time taken for a single water parcel to leave a waterbody from a specified location (Monsen et al., 2002), and a change in this parameter of the hydrological budget, due to climatic change, land cover perturbation or lake-level change (Dearing, 1997) can alter the nature of deposited sediments. For example, fine suspended grains may be removed from lakes with short residence times via the outflow prior to deposition at the lake bed, imparting a negative skew (an excess of coarse grains in the sediment) on the particle size distribution.

Fish foraging at the lake bottom as well as the burrowing of microbes and macrofauna can also result in substantial post-depositional disturbance within the upper, biologically-active zone of profundal lake sediments (Davis, 1974; Håkanson and Jansson, 1983). Bioturbation poses a particular challenge for identifying distinctive laminations (Krantzberg, 1985) and calculating sediment ages using radionuclide techniques by flattening down-core ^{210}Pb concentration profiles and masking ^{137}Cs or ^{241}Am peaks (Appleby, 2001). The extent of lake-bottom benthic activity appears to be spatially variable (White and Miller, 2008) and extracting multiple cores across a lake basin can enable regions of more intensive bioturbation to be identified (e.g., Schiefer, 2006).

2.2.3. Controls on river plume flow patterns

River plumes entering lakes diffuse across the basin as hypopycnal (over-), inter- or hyperpycnal (under-) flows, controlled by the relative densities of the incoming plume and the water column (Fig. 2). Interplay between the concentration of suspended sediment in the incoming plume and the stratification of the lake (due to thermal or density

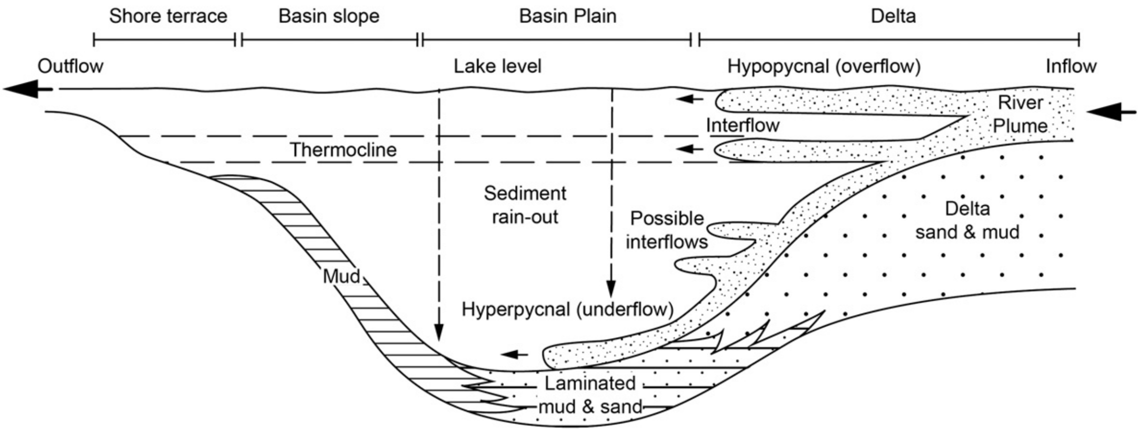


Fig. 2. Processes of sediment dispersal and associated deposits within a lake basin dominated by clastic sedimentation. Lake dimensions and sediment thicknesses are not to scale. Re-drawn from Sturm and Matter (1978).

differentials) thus plays an important role in determining the dispersal of sediment (Talbot and Allen, 1996). Within-lake physical mechanisms (described in Section 2.2.2) subsequently control the movement of suspended particles.

Annual temperature variability of lake surface waters is primarily driven by insolation patterns and, on shorter timescales, by local weather conditions (particularly wind-driven mixing), and is an important control on lake stratification (Hostetler, 1995). At depth, intra-annual temperature variability is normally much less pronounced, thus surface waters (epilimnion) are typically warmer and less dense than deep water (hypolimnion) (Boehrer and Schultze, 2008). The boundary that forms between these layers, most commonly during summer months, is called the thermocline (Fig. 2). Lakes that display thermal stratification may generate interflows at the thermocline as fluvial discharge is often denser than the epilimnion but less dense than the bottom, unmixed hypolimnion (Sturm and Matter, 1978). Cooling of the epilimnion during autumn and winter often causes the water column to turn-over, degrading the thermocline. The potential for mixing is strongly influenced by lake basin morphology (Gorham and Boyce, 1989).

While the seasonality of floods can be explored where annually laminated sequences exist (e.g., Czymzik et al., 2010; Swierczynski et al., 2012), the nature of annual stratification can produce highly variable depositional features (Håkanson and Jansson, 1983) and may complicate the preservation of palaeoflood signatures. For example, if lake stratification breaks down during winter, high-density river flows are more likely to trigger an underflow than during summer, when plumes are more likely to disperse above the thermocline. Weakly or unstratified lakes can thus be advantageous for recording flood stratigraphies, as the hydrodynamic relationship between particle size and river discharge is less likely to be modified by internal processes in the water column.

In the largest lakes, the Coriolis effect will divert incoming river plumes in an anti-clockwise direction from the delta in the northern hemisphere (Håkanson and Jansson, 1983), which could alter the relationship between detrital layer thickness and distance from the delta if cores are extracted counter to the plume direction.

2.2.4. Importance of hyperpycnal flows

Energetic, sediment-laden underflow plumes, first noted by Forel (1885), have been identified as an important process in delivering sediment to submarine deltaic settings on the continental shelf (Mulder et al., 2003; Best et al., 2005; Migeon et al., 2012). These hyperpycnal flows have also been identified in man-made reservoirs (Cesare et al., 2001) and temperate lakes (e.g., Lake Tahoe; Osleger et al., 2009). Hyperpycnal plumes often form when the suspended sediment concentration of the river exceeds the density of the lake water and down the delta, spreading across the basin floor (Mulder et al., 2003). As a result, sedimentary signatures of high-magnitude discharge events have been attributed to hyperpycnal flows because as they are capable of rapidly delivering significant volumes of sediment to the lake bottom.

Hyperpycnal flows can be observed visually (e.g., Mulder et al., 2003) or their potential to form in each lake can be calculated empirically based on suspended sediment load and river discharge measurements (Mulder et al., 2003). Following the calculations of Mulder and Syvitski (1995), the probability of individual rivers to generate hyperpycnal flows can be estimated by comparing mean suspended sediment concentration to the critical concentration of 42 kg/m^3.

Deciphering the triggering mechanism for a sediment-laden hyperpycnal flow at some sites can prove challenging. While such flows have been noted in larger lakes with sediment-laden tributaries (e.g., the Rhone delta at Lake Geneva; Lambert and Giovanoli, 1988), thermally-driven density underflows are often observed in alpine or arctic lakes, where in-flowing rivers deliver water supplied from snow and ice melt that is considerably colder than the ambient lake water (Mulder et al., 2003). Alternatively, the sliding or slumping of large and unstable river deltas (Lambert and Giovanoli, 1988) or subaqueous landslides triggered by seismic activity (e.g., St-Onge et al., 2004, 2012) are capable of generating turbidity currents that traverse across the lake bottom.

In lakes where incoming river water under normal flow conditions is low density and thus disperses near or above the thermocline, the exceptional suspended sediment load experienced during a phase of heightened river discharge (i.e., a flood) may be capable of generating a hyperpycnal underflow (Mulder et al., 2003; Migeon et al., 2012). Thus, if the formation of such hyperpycnal flows can be ascribed solely to high flows, the resulting sediment deposit will represent a palaeoflood signature (Brown et al., 2000).

2.2.5. Role of deltas

Delta morphology can strongly influence the dynamics of river plumes (Talbot and Allen, 1996) but interplay between river discharge, lake morphology and deltaic sedimentation means that delta form is in turn sculpted by incoming river flow, particularly where hyperpycnal flows occur during high discharge events (Olariu et al., 2012).

Many freshwater lakes display steeply-graded, coarse-grained deltas exhibiting classic Gilbert-style morphologies (Gilbert, 1885; Fig. 3), and sediment-laden hyperpycnal flows tend to move down steep deltas. Modelling work by Olariu et al. (2012) of the Red River delta flowing into Lake Texoma, southern USA, shows the direction of delta progradation and steepness of the foreset slope can significantly deflect the flowpath of descending hyperpycnal plumes (~80° from the inflow direction under low flow and steep slope angle, ~8% under highest flow and low slope angle). Lateral shifts in delta morphology may result in sediment being delivered to different areas of the lake through time

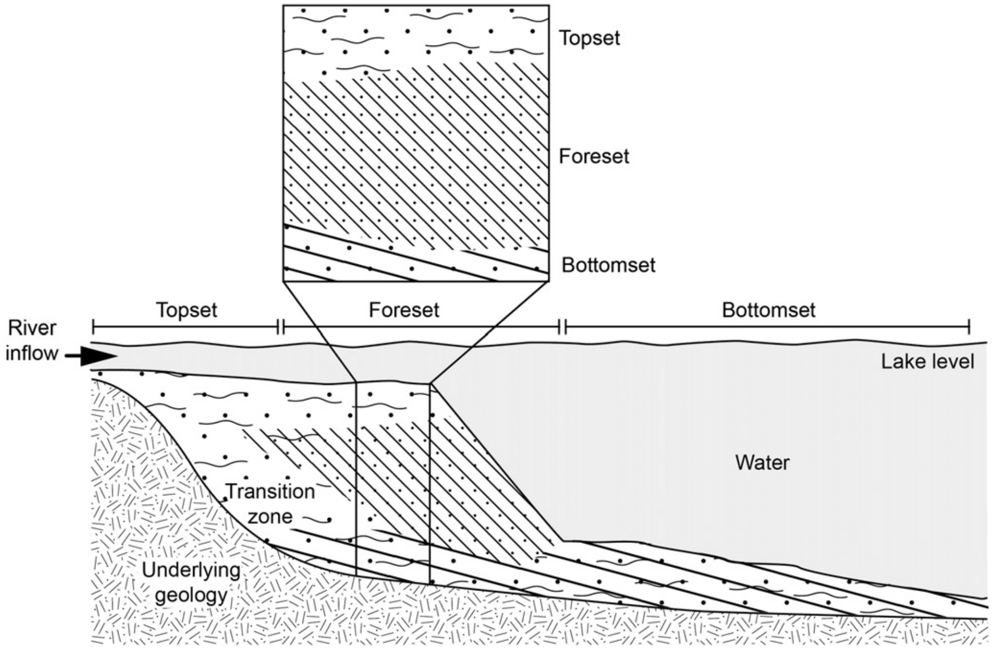


Fig. 3. Conceptual model of the stratigraphy of a coarse-grained Gilbert-style lake delta. Modified from Friedman and Sanders (1978).

(Sastre et al., 2010) while the formation and evolution of multiple, branching channels on top of a river delta will generate highly distributive sediment deposition across the basin (Olariu and Bhattacharya, 2006). Delta morphology is strongly affected by the particle sizes delivered as bedload and suspended load, which in turn can alter sediment dispersal of subsequent events (Orton and Reading, 1993). Lake geometry is also important: in narrow basins or where sublacustrine channels are present, the confined flow may focus sediment deposition or erosion along a particular path (Girardclos et al., 2012), compared to plumes dispersing into broad, circular lakes.

Delta progradation has particularly important implications over longer timescales (centuries or longer) for modifying the thickness and particle size distributions of deposited flood laminations. In lake sediment profiles dominated by river input, flood units are expected to thin and fine away from the delta. However, the zones where thicker and thinner layers are predicted to be deposited may migrate in response to delta progradation, even if flood magnitude remains constant (Fig. 4). This process may render the use of layer thickness as a proxy of stream power problematic and must be considered through the use of multiple (at least three) core locations to characterise the three-dimensional geometry of flood deposits (Jenny et al., 2013). Sites immediately adjacent to the inflow experiencing exceptionally high sediment accumulation rates may be particularly problematic, especially where multiple sublacustrine channels with erosive capabilities are active (Shaw et al., 2013).

2.2.6. Influence of flocculation

Biological factors (e.g., the presence of microorganisms, faecal matter, dissolved and particulate organic matter), the chemical characteristics of the water (e.g., pH, ionic concentration, redox potential) or physical processes (including the turbulence, temperature and suspended sediment concentration of the flow), may trigger fine-silt, clay and organic particles to bind with other entrained grains, due to the electrical charges produced across their comparatively large surface areas and/or through microbial binding (Droppo et al., 1997). This may occur prior to entering the river system (aggregates), or within the fluvial or lacustrine water column (flocculates) (Droppo et al., 1997). Their heterogeneous nature can result in significant changes to particle shape, density and porosity (Droppo, 2001). Most importantly, flocculation can substantially alter the hydrodynamic relationship between particle size and settling velocity,

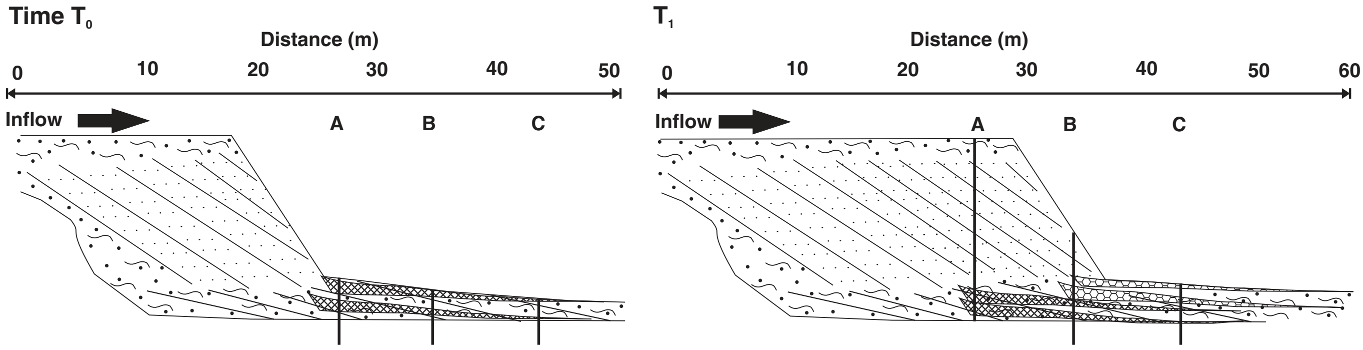


Fig. 4. Schematic illustration of the role lacustrine delta progradation may exert on palaeoflood deposit thickness. At time T_0, recent floods have deposited a series of laminations which thin away from the delta. At time T_1, the delta has prograded substantially into the lake. When floods of similar magnitude to those at T_0 occur at T_1, the flood-related sedimentary units will be absent from core site A and significantly thicker at core sites B and C compared to those lain down at T_0. In essence, a sediment core extracted from site B soon after T_1 will contain multiple flood laminations of variable thickness that in fact reflect floods of equivalent magnitude.

as suspended flocs may settle more rapidly than predicted by Stokes' Law for the individual particles (Håkanson and Jansson, 1983).

The importance of this process in lacustrine settings has been documented by Hodder (2009), who identified macroflocs in the varved Lillooet Lake (British Columbia, Canada; Desloges and Gilbert, 1994) composed of particles two orders of magnitude smaller bound together. Micro- (10 μm–35 μm) and macroflocs (200 μm–280 μm) both make substantial contributions to annual sediment flux in Lillooet Lake.

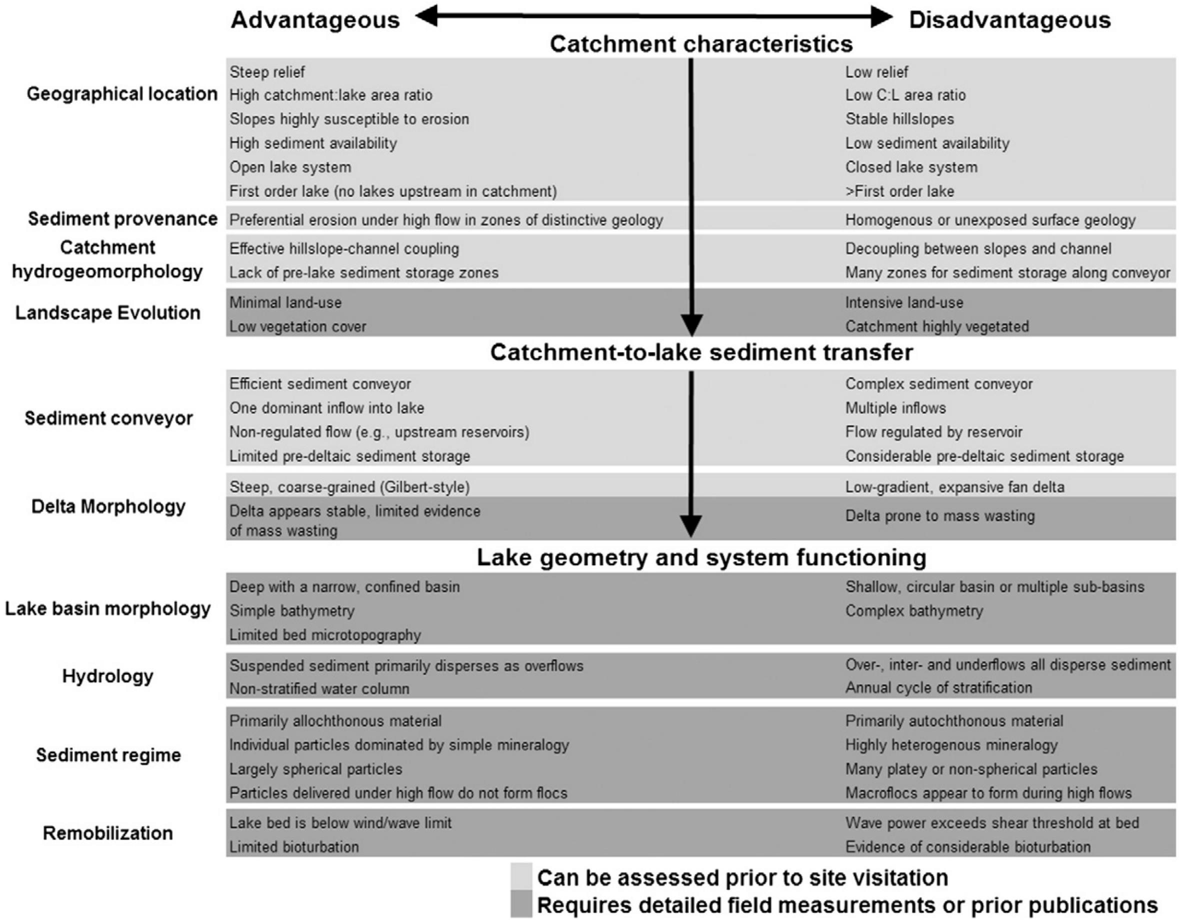
However, detailed exploration of the mechanics of formation, internal floc architecture and rigorous assessment of the degree of flocculation in natural sediments are still on-going (Droppo, 2001) and traditional methods for measuring absolute particle size remain commonplace, but do not fully consider the issue of aggregate size (Haberlah and McTainsh, 2011). Experimental data from a flood-laminated alluvial terrace at Flinders Range, South Australia, in which mixed particle size distributions were decomposed into different end-members, showed that flocs settle out of suspension first during flood events (Haberlah and McTainsh, 2011). Their decomposed distributions showed particle size variability across a flood deposit characterised by a light (sand-dominated) and a dark (silt) band. When considered as mixed distributions, no change in particle size across the bands was observed. This has significant implications when exploring particle size data for evidence of palaeofloods and highlights the value of applying statistical decompositional techniques to particle size datasets (e.g., Weltje and Prins, 2003; Haberlah and Mctainsh, 2011).

However, visual examination under a low-power microscope of sediment trap samples from Brotherswater, a small upland lake in northwest England (discussed further in Section 4.2.1), highlights that dark-brown flocs, predominantly composed of bound fine-silts and organic matter, can be clearly distinguished from discrete sand grains (D. Schillereff, unpublished data). This confirms that the sand fraction settles through the water column and is deposited on the lake floor as individual particles, which differs from the observations of Hodder and Gilbert (2007) who found macroflocs of primary coarse particles bound to microflocs in Lillooet Lake. Absolute measurements of particle size in the laboratory can be acceptable for palaeoflood research in lakes where flood deposits are characterised by primary sand-sized particles within a finer matrix; laboratory tests or a sediment trapping protocol can be used to gauge the extent of this potential issue.

2.3. Conceptual model of palaeoflood analysis

Above, we have discussed the role of environmental setting, the sediment transfer processes and the depositional mechanisms that can regulate how stratigraphical flood signatures are preserved in lake basins. These are integrated here into a conceptual model to act as a rapid reference for researchers exploring the potential for a prospective field site to contain a robust palaeoflood record (Fig. 5). While there will be considerable site-specific variation in terms of local geology, climate, degree of human disturbance or nature of the fluvial system (e.g., Parris et al., 2010), this model outlines a set of considerations to guide field site selection.

Stable and unimpeded sediment transfer from catchment to lake is ideal, while desirable lake characteristics include a deep basin minimising sediment remobilisation, long residence time and weakly- or non-stratified water column, sufficient river-borne material delivered during a flood to overprint the normal sedimentation pattern, and size grading (fining) of particles from inflow-proximal to distal settings.



	Advantageous	Disadvantageous
	Catchment characteristics	
░ **Geographical location**	Steep relief High catchment:lake area ratio Slopes highly susceptible to erosion High sediment availability Open lake system First order lake (no lakes upstream in catchment)	Low relief Low C:L area ratio Stable hillslopes Low sediment availability Closed lake system >First order lake
░ **Sediment provenance**	Preferential erosion under high flow in zones of distinctive geology	Homogenous or unexposed surface geology
░ **Catchment hydrogeomorphology**	Effective hillslope-channel coupling Lack of pre-lake sediment storage zones	Decoupling between slopes and channel Many zones for sediment storage along conveyor
▓ **Landscape Evolution**	Minimal land-use Low vegetation cover	Intensive land-use Catchment highly vegetated
	Catchment-to-lake sediment transfer	
░ **Sediment conveyor**	Efficient sediment conveyor One dominant inflow into lake Non-regulated flow (e.g., upstream reservoirs) Limited pre-deltaic sediment storage	Complex sediment conveyor Multiple inflows Flow regulated by reservoir Considerable pre-deltaic sediment storage
░ **Delta Morphology**	Steep, coarse-grained (Gilbert-style)	Low-gradient, expansive fan delta
▓	Delta appears stable, limited evidence of mass wasting	Delta prone to mass wasting
	Lake geometry and system functioning	
▓ **Lake basin morphology**	Deep with a narrow, confined basin Simple bathymetry Limited bed microtopography	Shallow, circular basin or multiple sub-basins Complex bathymetry
▓ **Hydrology**	Suspended sediment primarily disperses as overflows Non-stratified water column	Over-, inter- and underflows all disperse sediment Annual cycle of stratification
▓ **Sediment regime**	Primarily allochthonous material Individual particles dominated by simple mineralogy Largely spherical particles Particles delivered under high flow do not form flocs	Primarily autochthonous material Highly heterogenous mineralogy Many platey or non-spherical particles Macroflocs appear to form during high flows
▓ **Remobilization**	Lake bed is below wind/wave limit Limited bioturbation	Wave power exceeds shear threshold at bed Evidence of considerable bioturbation

░ Can be assessed prior to site visitation
▓ Requires detailed field measurements or prior publications

Fig. 5. The physical landscape and lake basin characteristics and sediment delivery processes most advantageous or disadvantageous to the archiving of a palaeoflood sequence in lake sediments.

3. Review of analytical methods

A range of methodologies have been used to extract flood data from lake sediments (Brown et al., 2000; Arnaud et al., 2002; Noren et al., 2002; Moreno et al., 2008; Vasskog et al., 2011; Kämpf et al., 2012; Swierczynski et al., 2012; Czymzik et al., 2013; Simonneau et al., 2013; Wilhelm et al., 2013). The focus of the palaeoflood literature has largely been two-fold; either generating millennial-scale records of flood-rich and flood-poor phases for the Holocene and discussing their possible climatological forcings (e.g., Noren et al., 2002; Czymzik et al., 2010; Wilhelm et al., 2012; Czymzik et al., 2013) or adopting an event-scale approach focussing on distinguishing the stratigraphical signature of discrete floods (Thorndycraft et al., 1998; Arnaud et al., 2002) from other mass movement deposits (e.g., Wirth et al., 2011). In practice, many researchers achieve both of these objectives by identifying signatures of detrital layers, counting their frequency and subsequently identifying large-scale climatic or anthropogenic forcings that explain the phases of more frequent high-magnitude floods. Lake sediment records have provided some of the best continental palaeoclimate records using other well-established palaeobiological or stable isotopic techniques (Leng and Marshall, 2004; Oldfield, 2005). However, using the calibre or provenance characteristics of inflow materials for environmental reconstructions presents different methodological challenges. Accounting for the range and variety of depositional mechanisms requires care during field site selection and sample recovery as well as the capability to acquire high-resolution data (Gilli et al., 2013).

By overcoming issues of preservation, post-depositional processes and difficulties in obtaining sufficient analytical resolution, signatures of individual floods can be distinguished from the background sediment matrix. Once identified, confirming that the event laminations are the result of repeated flooding rather than other geophysical events capable of producing similar depositional signatures is critical (Table 1).

3.1. Field procedures

Selecting an appropriate lake and subsequently identifying ideal sites for core extraction should be guided by a thorough knowledge of basin bathymetry. Lakes with broad, flat central basins, and sufficient sediment availability in a catchment well-coupled to a fluvial system capable of transporting material to the lake under high flow conditions are ideal (Section 2.3; Gilli et al., 2013). Identifying safe, secure and easily accessible launch points onto the lake are important to facilitate repeated site visits.

Seismic reflection (Abbott et al., 2000) or multibeam bathymetric surveys of lake basins (Gardner and Mayer, 2000; Miller et al., 2013a,b) that remotely sense the thickness and characteristics of basin sediment fill, can aid selection of coring sites (Debret et al., 2010; Wirth et al., 2011; Lauterbach et al., 2012; Wilhelm et al., 2013). Deposits from other lake proximal sediment sources, in particular delta mass-movement or lake-edge slumping, can often be identified from acoustic reflections and thus avoided (Schnellmann et al., 2002; Girardclos et al., 2007; Lauterbach et al., 2012). These data may also enable subaqueous morphological evidence of palaeoflood deposits to be examined. Channel incision down delta foreset slopes or across the lake bed or the identification of levee formations may indicate past hyperpycnal flows (Talbot and Allen, 1996). Such morphological evidence should encourage further efforts to retrieve long sediment records for palaeoflood analysis.

It is critical that discrete flood laminations are correlated and mapped across multiple cores within lake basins to confirm their origin from river plumes, their three-dimensional geometry (Jenny et al., 2013) and to enable chronological control to be transferred between cores. High-resolution visual analysis of sediment cores (e.g., Czymzik et al., 2013) and proxy measurements (e.g., magnetic susceptibility; Dearing, 1983; µXRF scanning geochemistry) are rapid and effective methods of cross-correlating between cores. Baltzer (1991) traced clastic sediment units across 43 cores extracted from Lake Tanganyika using particle size and X-ray diffraction measurements.

3.2. Stratigraphical analysis

Many proxy techniques have been applied to lake sediment sequences to identify and characterise detrital laminations, including measuring the thickness of visual layers (e.g., Bøe et al., 2006), particle size analysis (e.g., Arnaud et al., 2002), organic and inorganic geochemistry (e.g., Brown et al., 2000; Vasskog et al., 2011), magnetic susceptibility (e.g., Osleger et al., 2009), loss-on-ignition (e.g., Nesje et al., 2001) and density and luminosity measurements (Debret et al., 2010).

3.2.1. Techniques for recording the visual stratigraphy

Logging the visible core stratigraphy prior to sub-sampling has is a valuable technique for deciphering potential event layers that are clearly different from the dominant sediment core material (e.g., Arnaud et al., 2002). High-resolution photography (Cuven et al., 2010), thin-section preparation (Swierczynski et al., 2012; Czymzik et al., 2013), computer tomography (CT) X-ray scans (Støren et al., 2010) and core scanning for a sediment density or reflectance (L^*) signal (Debret et al., 2010; Lauterbach et al., 2012) have been used to characterise and quantify changes in colour, sediment matrix structure and mineralogically-different event layers.

Microfacies analysis of annually laminated sediments from Lake Ammersee (southern Germany) identified three types of detrital layers exhibiting different mineralogical composition and variable grading (Czymzik et al., 2013). Erosional bases across some units are visible and the matrix-supported units are clearly distinguishable by the presence of primary clastic grains held within a calcite matrix. In other instances, thin sections of discrete detrital layers show a basal unit enriched in organic material and thin clay caps, such as at Lago del Desierto, Patagonia (Kastner et al., 2010). CT scanning of sediment cores produces a three-dimensional image from which X-ray attenuation numbers correspond to sediment density at sub-mm scales, enabling extremely thin flood layers to be distinguished from a dark, organic-rich sediment matrix (Støren et al., 2010). Similarly, downcore spectrophotometric measurements (denoted by L^* a^* b^* values, reflecting total reflectance, chromacity along the green to red and blue to yellow visible light axes, respectively) can detect small changes in sediment colour due to greater clastic inputs during floods (Debret et al., 2010).

Table 1
Geophysical processes previously noted as being capable of generating depositional stratigraphical signatures in lake sediment profiles.

Process	Proxy	Reference
Debris flows	Stratigraphy; particle size	Irmler et al. (2006)
Hillslope fires	Geochemistry; loss-on-ignition; pollen; charcoal	Macdonald et al. (1991)
Jökulhlaups	Stratigraphy; particle size; µXRF geochemistry	Lewis et al. (2007), Lewis et al. (2009)
Lake-edge slumping	Stratigraphy; ^{14}C dating	Hilton et al. (1986), Schnellmann et al. (2002)
Seismic activity	Stratigraphy; particle size; ^{210}Pb measurements	Doig (1990), Arnaud et al. (2002)
Snow avalanches	Particle size	Nesje et al. (2007), Vasskog et al. (2011)
Turbidity currents	Stratigraphy; seismic profiles; particle size	Lambert and Giovanoli (1988), Girardclos et al. (2007)
Windstorms or hurricanes	Stratigraphy; particle size	Eden and Page (1998), Noren et al. (2002), Besonen et al. (2008)

3.2.2. Measuring detrital layer thickness

Where detrital laminations exhibit sharp contacts, individual layer thickness can be measured accurately (e.g., Kämpf et al., 2012; Czymzik et al., 2013). Flood-layer thickness theoretically depends on carrying capacity and the duration of the high discharge, but sediment supply also regulates this relationship. Bøe et al. (2006) showed a significant correlation between thickness, higher mean particle size and better sorting for clastic deposits, supporting increased stream power as the dominant delivery mechanism. Matching flood laminations between delta-proximal and distal cores and comparing layer thickness can also provide insight into the depositional mechanism (Czymzik et al., 2013). For example, a unit displaying a thinning trend away from the delta indicates that sediment was delivered in a river plume that decelerated as it dispersed and the volume of material settling out of suspension declined accordingly. Other research has been unable to find a positive correlation between layer thickness and river discharge (e.g., Lapointe et al. (2012) working at East Lake, Canadian Arctic), suggesting that measuring particle size within discrete layers is a more suitable proxy.

Accounting for variable sediment supply through the timescale of deposition, potentially driven by changes in land-use and/or climatic fluctuations, is critical because extreme events of similar magnitude may deposit layers of unequal thickness. Applying statistical techniques that account for temporal changes in background median values can be useful, allowing peaks relative to local background to be assigned as ‘extreme values’ within a time series. For example, Besonen et al. (2008) apply the CLIM-X-DETECT package (Mudelsee, 2006) to a varved lake sediment record from Massachusetts to identify anomalously thick flood deposits triggered by hurricanes over the past millennium.

3.3. Particle size as a palaeoflood proxy

In lake sediment sequences comprising clastic material as the primary component, an imprint of the hydrodynamic relationship between river discharge and the particle size distribution of the suspended sediment should be present. A positive relationship between higher discharge and coarser particles is often observed (e.g., Campbell, 1998; Lenzi and Marchi, 2000) but factors including selective sediment sources, intensity of erosion and local soils and bedrock lithologies may substantially alter this relationship (e.g., Walling and Moorehead, 1989). While some evidence of particle size — stream power decoupling from lake sediments has been published (Cockburn and Lamoureux, 2008), as rivers at low flow generally deliver very little sediment, sediment cores dominated by fine-grained silts and clays most likely reflect sedimentation during slightly elevated flows that commonly occur. Coarse-grained layers punctuating this matrix therefore reflect the highest-energy floods, so particle size analysis identifying the coarsest fraction appears as a valuable palaeoflood proxy (Cockburn and Lamoureux, 2008). This approach has underpinned the development of robust palaeoflood records in Africa (Reinwarth et al., 2013), the European Alps (Arnaud et al., 2002; Wilhelm et al., 2012; Wirth et al., 2013a,b), New Zealand (Eden and Page, 1998; Page et al., 2010), Norway (Bøe et al., 2006; Vasskog et al., 2011) and North America (Osleger et al., 2009; Hofmann and Hendrix, 2010; Parris et al., 2010). In some arctic or pre-alpine lakes capable of depositing annually laminated sediments, particle size measured at annual resolution has been directly correlated with rainfall amounts, including Cape Bounty, arctic Canada (Lapointe et al., 2012) and Rock Lake, British Columbia (Schiefer et al., 2010), enabling more comprehensive hydrogeomorphological interpretations to be drawn.

Measuring particle size at the micro-(sub-mm) and macro-structural (cm) scale has also provided detailed information on depositional processes (Vasskog et al., 2011; Czymzik et al., 2013). For example, graded layers reflecting hyperpycnal flows, finer-grained silt and clay layers settled out of suspension from overflows and matrix-supported layers requiring larger than normal sediment supply were distinguished by Czymzik et al. (2010, 2013) at varved Lake Ammersee, illustrating the ability for process interpretations to be drawn from microstratigraphical particle size measurements. Down-core variation in mean and sorting particle size values (e.g., Blott and Pye, 2001) enabled visually different laminations in Oldvatnet, Norway (Vasskog et al., 2011) to be attributed to different triggering mechanisms, namely river floods, snow avalanches and density currents due to lake-edge slumping.

The graded nature of some lacustrine deposits is a particularly useful sedimentological characteristic for distinguishing flood layers. Thick (many cm), siliciclastic facies in sharp contact with the organic- or carbonate-dominated sediment matrix and often exhibiting normal grading (i.e., classic Bouma (1962) turbidite) have been traditionally attributed to catastrophic events such as glacial outburst floods (jökulhlaups; Lewis et al., 2009) or shelf-edge collapse triggered by earthquakes (Beck, 2009). In many studies, turbidic deposits have been interpreted as reflecting terrestrially-derived material delivered during episodic flood events (Brown et al., 2000; Lauterbach et al., 2012; Czymzik et al., 2013; Gilli et al., 2013; Wirth et al., 2013a). Turbidites can be correlated across a lake basin (Brown et al., 2000) or between multiple lakes (Noren et al., 2002; Glur et al., 2013), confirming their ability to record discrete events.

Some sedimentary units exhibit normal-grading overlying inverse-grading and have been interpreted as reflecting the hydrographs of individual, high-magnitude floods. Mulder and Alexander (2001) developed a classification scheme for the Var turbidite series in the Mediterranean (Mulder et al., 2001, 2003; Migeon et al., 2012) in which this distinctive sedimentation pattern was attributed to the waxing and waning phases of river flow that delivered sufficiently sediment-laden plumes to generate hyperpycnal flows upon entering the waterbody and then rapidly spread across the basin floor (Normark and Piper, 1991). The resulting deposit (“hyperpycnite”) reflects the hydrodynamic conditions of the river, and similar facies have been identified in several lake sediment sequences (Ito et al., 2009; Osleger et al., 2009; Hofmann and Hendrix, 2010; Stewart et al., 2011). The forcing mechanism follows a typical flood hydrograph: river flow velocity will steadily increase following the onset of a flood (i.e., waxing flow), depositing a sedimentary sequence of upwards-coarsening particles, reflecting the progressively coarser particles that can be transported as suspended load as river power increases. The subsequent diminishing discharge (i.e., waning flow) is reflected by an often thicker fining-upwards sequence (Mulder et al., 2003). While these layers are normally mm- or cm-scale, a similar sedimentological structure is observed across a 30 cm thick layer in a sediment core extracted from Lake Puyehue, Chile (Chapron et al., 2007), attributed to a dam-burst megaflood after the 1960 AD earthquake. Stewart et al. (2011) proposed the term ‘inundite’ for lacustrine flood deposits that exhibit this internal structure. Other stratigraphical signatures should be sought, including a basal erosional contact, bedded ripples or rippled, diagonal laminations (Mulder et al., 2003), to confirm such deposits are indeed the result of hyperpycnal flows. Furthermore, the possibility of stacked inverse-to-normal grading units representing a single flood must also be considered, as shown by Saitoh and Masuda (2013) at Lake Shinji, Japan, due to lateral movement of the plunge point of a sediment-rich flood plume across a subaqueous delta.

Assessing particle size distributions alongside stratigraphic data can provide additional information on flood frequency/magnitude and sediment provenance. The degree of sorting, mean or median particle size and the sizes of prominent modes within particle size distributions has enabled deposits corresponding to river floods, shelf edge slumping and snow avalanches to be distinguished (Arnaud et al., 2002; Czymzik et al., 2010; Vasskog et al., 2011). Strong correlations between skewness and mean particle size (Bøe et al., 2006) and sorting and mean particle size (Arnaud et al., 2002) have been used as proxies for fluvial energy. Median (Q50) vs 90th percentile (P90) scatter plots (after Passega, 1964) display points representing low flow sedimentation, river floods and mass wastage events in different quadrants (Wilhelm et al., 2012, 2013).

The tendency for deposited sediments to display mixed grain-size distributions as a result of the range of processes driving sedimentation can make it difficult to infer processes. Employing statistical models to unmix particle size distributions into multiple end-members, each of which represents a differing depositional mechanism, can address this issue (Sun et al., 2002; Parris et al., 2010; Dietze et al., 2012), in conjunction with visual stratigraphical analysis to confirm the reality of each individual end-member. Flood laminations in lake sediment sequences from New England, USA, are clearly represented by the coarse end-member while background material appears as a fine-grained end-member (Parris et al., 2010); standard frequency statistics were unable to effectively make this distinction.

3.4. Indirect particle size measurements

The susceptibility of different minerals to erosion is reflected in the bulk geochemical composition of sediments generated by erosion or weathering, based on the relative proportion of stable and unstable elements (Bloemsma et al., 2012). This relationship can translate into a correlation between particle size and geochemical composition due to the grain-size specific nature of individual minerals. As a result, lake sediment sequences dominated by clastic material may enable certain geochemical signals to be used as a proxy of particle size. Furthermore, high-resolution core scanning devices (e.g., ITRAX; Croudace et al., 2006) enable data at sub-mm scales to be extracted from sediment cores using X-ray fluorescence, potentially revealing sedimentary structures that proxies requiring manual sub-sampling are unable to access.

It is critical that analytical care is taken when interpreting μXRF measurements made on wet sediment because variable down-core water and organic matter contents may prevent precise dry mass elemental concentrations being obtained (Boyle et al., in press-a). The X-ray signal may also contain artefacts due to imperfections of the core surface or the development of a thin water film under the polypropylene cover (Hennekam and de Lange, 2012). In order to acquire more accurate dry mass equivalent geochemical concentrations, Boyle et al. (in press-a,-b) outline two methods to apply in parallel: one applies a simple regression calibration, while the other is a novel technique that estimates water content for the full core from X-ray scatter data collected during the scanning process. We strongly recommend adopting this procedure where water content varies significantly along a wet sediment core. Other researchers have attempted to normalise elements of interest to either another element (e.g., Löwemark et al., 2011) or to back-scatter peaks (e.g., Kylander et al., 2012; Chawchai et al., 2013; Kylander et al., 2013). The potential for Fourier transform infrared spectroscopy (FTIR) to act as a rapid and cost-effective calibration technique alongside XRF scanning was demonstrated by Liu et al. (2013), who analysed inorganic and organic content of sediments from Lake Malawi (Africa) and Lake Qinghi (China).

Site-specific geochemical concentrations and, in some cases, ratios between selected elements, have been used to effectively characterise flood layers. For example, Czymzik et al. (2013) show elevated concentrations of Ti, K and Fe, normalised to back-scatter peaks, across cm-scale flood units at varved Lake Ammersee, where sedimentary rocks in the catchment supply significant volumes of detrital grains. A seasonal record was developed for Lake Mondsee, Austria (Swierczynski et al., 2012), where elevated Ti and Mg concentrations in flood laminations were attributed to high river discharges from the northern siliciclastic-dominated and southern dolomite-rich catchments, respectively. The application of the Ca/Fe ratio as a particle size proxy has been microscopically confirmed via thin-section analysis at Lac Blanc, Belledonne Massif (Wilhelm et al., 2012; Section 4.2.4). Similar assessments using the Zr/Fe ratio at Lac Blanc, Mont Blanc Range (Wilhelm et al., 2013) and K/Ti and Fe/Ti at Cape Bounty in the Canadian High Arctic (Cuven et al., 2010; Section 4.2.3) showed variations in these ratios were effective particle size proxies.

Vasskog et al. (2011; Section 4.2.2) matched the visual stratigraphical record of flood laminations at Oldevatnet, western Norway, to low Rb/Sr values, as Sr is more likely to be eroded from the catchment surface geology. Likewise, Rb is commonly associated with the clay fraction while Zr is often enriched in coarse silts, meaning higher Zr/Rb values should reflect coarser grains (Dypvik and Harris, 2001).

Mineral magnetic measurements have also been used as a particle size proxy, for example at Petit Lac d'Annecy where Foster et al. (2003) showed the χ_{LF} (low field) magnetic susceptibility parameter, measured on sediment trap and lake core samples, correlated positively with discharge-controlled variations in median particle size. An equivalent positive relationship between χ_{LF} and the coarse silt-sand fraction was found at Taihu Lake, China (Li et al., 2013). At Loch of the Lowes (southern Scotland), Foster et al. (2008) attribute the cyclical pattern of the HIRM (hard isothermal remanent magnetisation)/χ_{LF} profile (reflecting the hematite to magnetite ratio) to reflect flood-rich and flood-poor phases. The potential for any single magnetic parameter to be controlled by sediment calibre, source or delivery process (Dearing, 1999) or the presence of bacterial magnetite (e.g., Oldfield and Wu, 2000) can pose interpretational challenges, however.

3.5. Adapting a multi-proxy approach

Combining multiple proxies in a single study can be particularly effective for distinguishing detrital laminations potentially linked to historical floods. High-resolution multi-proxy analysis of the Lake Suigetsu (Japan) sediment sequence (Schlolaut et al., 2014) showed that discrete flood layers are represented by four sub-laminae, each characterised by changes in colour, the presence or absence of grading structure or diatoms and fragments of organic material, distinctive minerology, changes in grain size (assessed via thin section) and variable Ca, K, Si and Ti concentrations (measured via ITRAX core scanner). Thorndycraft et al. (1998) showed coincidental peaks in magnetic and geochemical indicators of clastic material and soil-derived pollen in four recent flood laminations at Lac d'Annecy (SE France), while sediment cores spanning the last 15,000 years from Laguna Pallcacocha (Ecuador) were punctuated by numerous light-grey layers of clastic material characterised by low carbon content, coarse modal grain size and low biogenic silica concentrations, attributed to mobilisation of sediment during El Niño-driven storm events (Rodbell et al., 1999). Groupings of values on scatter plots of multiple proxies can also discriminate between depositional mechanisms (e.g., Støren et al., 2010).

A good knowledge of catchment soil properties and surface geology may enable phases of greater clastic input during a flood to be identified on a site-specific basis (e.g., magnetic susceptibility record reflecting magnetite-rich catchment material; Osleger et al., 2009). Where sedimentation does not record short-term magnetic susceptibility (MS) or loss-on-ignition (LOI) fluctuations, measuring sediment colour and reflectance has proved useful (e.g., Lac Le Bourget (SE France), Debret et al., 2010; Taravilla Lake (NE Spain), Moreno et al., 2008). Furthermore, down-core variability in carbon and nitrogen isotope ratios, reflecting the allogenic or autogenic supply of organic matter (Meyers and Ishiwatari, 1993), can confirm the detrital provenance of flood deposits (Brown et al., 2000; Ito et al., 2009). Concurrent high dry density and low total inorganic and organic C values can also indicate flood layers (Gilli et al., 2003). Combining spectrophotometric and Rock-Eval pyrolysis for discriminating detrital input from autogenic production of organic matter proved successful in two lakes in Gabon (Sebag et al., 2013).

As mentioned in Section 3.2.2, variable sediment supply poses a challenge to deciphering a consistent palaeoflood trend through a core profile. Noren et al. (2002) use singular spectrum analysis to identify sediment deposits from 13 small lakes in New England, USA, that are greater than 1σ from the first principal component of down-core measurements for multiple proxies (visual logging, X-radiography, MS, LOI and particle size). Most detrital layers display significantly high values in two or more proxy techniques, thus providing more confidence in the reconstructed storm record.

3.6. Developing robust chronologies

Establishing a well-constrained chronology is paramount in order to develop a flood history and extract data on event frequency. Palaeolimnologists use a number of chronostratigraphical techniques dependent on the timescales of the research interest and many dating methods and their associated challenges have been recently reviewed by Gilli et al. (2013). The timescales over which different dating tools are most applicable are presented in Fig. 6. The most reliable chronologies are generated by integrating multiple, independent chronological tools and this approach is most successful on historical timescales (spanning, at most, the last few centuries) due to the number of independent techniques that can be employed concurrently.

Lake sediment sequences characterised by annually-deposited laminations (i.e., varves) are of great value to palaeoflood researchers as they offer high-resolution dating constraints (Ojala et al., 2012). Additionally, instantaneous flood deposits create unique layers in the record that may differ substantially from typical varves. As a result, a number of detailed palaeoflood records of annual resolution have been generated (e.g., Czymzik et al., 2010; Stewart et al., 2011; Swierczynski et al., 2012; Czymzik et al., 2013). Where climatic and limnological conditions generate seasonal-specific laminations, seasonally-resolved records of past floods have been obtained (Swierczynski et al., 2012). Lakes often only produce varved sequences under specific conditions and, as depositional mechanisms may not be continuous over long timescales, annually-resolved chronologies must be independently verified using other dating techniques (Ojala et al., 2012).

Radiocarbon dating (^{14}C) is widely employed for dating lake sediment up to approximately 50 kyr BP (Bronk Ramsey et al., 2012) and many palaeoflood reconstructions spanning the Holocene are underpinned by ^{14}C dating (e.g., Lauterbach et al., 2012; Czymzik et al., 2013; Gilli et al., 2013). Radiocarbon dating faces a number of uncertainties (e.g., reservoir effects, 'old carbon', instrument precision; Björck and Wohlfarth, 2001) and identifying temporally precise markers in sediment sequences spanning several millennia is a significant challenge. As a result, such palaeoflood records are generally analysed in terms of flood-rich and flood-poor phases, as opposed to discrete flood events.

Conversely, natural and anthropogenic perturbations to the global carbon cycle during recent centuries (e.g., combustion of fossil fuels, release of nuclear weapons, changes in solar activity) have caused atmospheric ^{14}C concentrations to fluctuate through this time window, meaning calibration of a single radiocarbon date may yield multiple possible age ranges (Hua, 2009). Employing high-precision AMS ^{14}C dating can successfully disentangle recent core chronologies by '*wiggle-matching*' to these variations in atmospheric ^{14}C (e.g., Marshall et al., 2007). This protocol offers substantial value when generating palaeoflood records spanning the past 200 to 300 hundred years, bridging the gap between shorter half-life radioisotopes (i.e., ^{210}Pb) and the conventional ^{14}C timescale. Similarly, nuclear weapons testing in the 1950s–60s released sufficient ^{14}C to significantly increase atmospheric concentrations before declining after the 1963 ban; this trend is recorded as fallout in upper profiles from different sedimentary environments (Garnett and Stevenson, 2004; Hua, 2009).

Measuring the gamma-activity of ^{210}Pb radionuclides is one of the most effective means of dating sediments lain down over the past century (Appleby, 2001). Although ^{210}Pb profiles can be affected by hiatuses in the sedimentary record resulting from periods of rapid sedimentation or instantaneous deposits triggered by seismic activity, mass-wasting or high-magnitude floods, they are usually a critical step when constructing core chronologies (e.g., Arnaud et al., 2002). Importantly, Aalto and Nittrouer (2012) showed a clear response in ^{210}Pb profiles to individual flood events in floodplain sediment sequences. This non-steady-state accumulation means care must be taken when selecting a dating model (Constant Rate of ^{210}Pb Supply [CRS] or Constant Initial Concentration [CIC]; Oldfield et al., 1978). Conversely, periodic spikes in ^{210}Pb concentrations down a lake sediment core, reflecting a response to elevated ^{210}Pb flux during high flows, could act as a palaeoflood indicator, although this would require more time-consuming and costly gamma detector measurements than aiming to calculate down-core sediment ages.

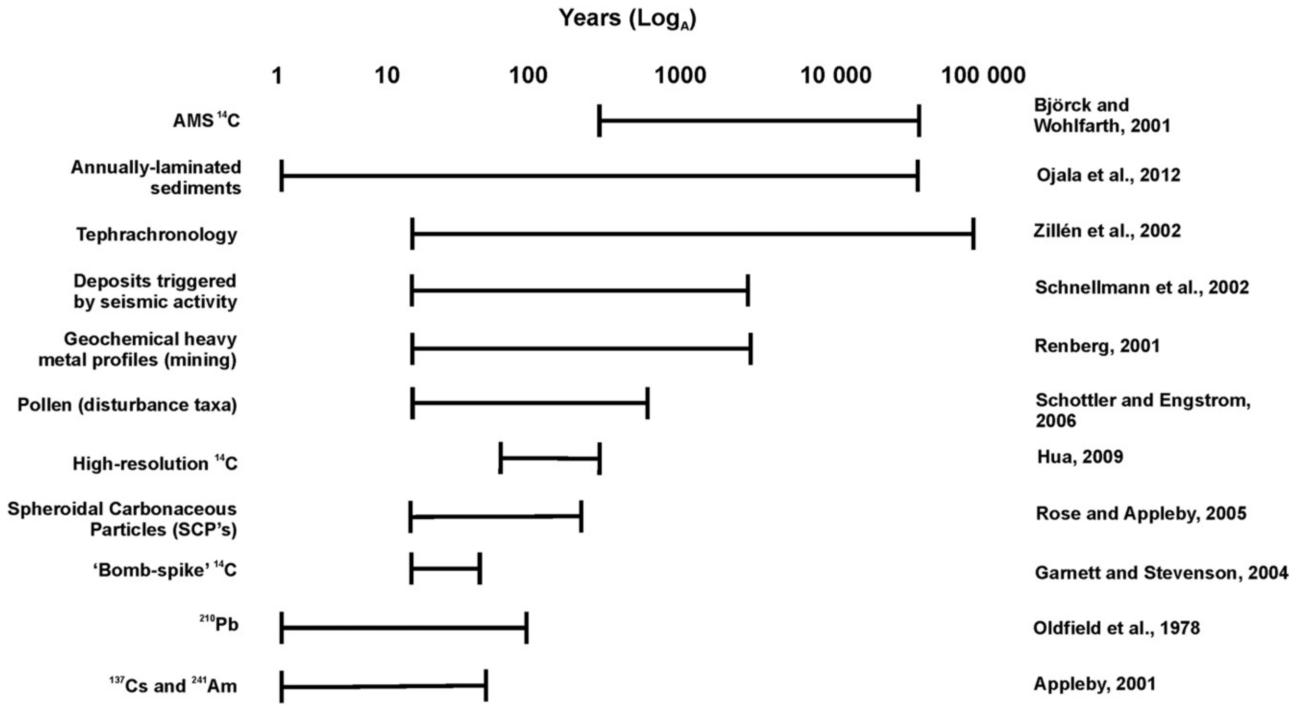


Fig. 6. Timescales at which a range of chronological techniques can be effectively applied and relevant examples from the literature. Log scale on *x*-axis.

Measurements of ^{137}Cs and ^{241}Am activity are often run parallel to ^{210}Pb dating and the identification of two peaks in emission activity, attributed to fallout from atmospheric testing of nuclear weapons in the 1960s and emissions from the Chernobyl accident in 1986, respectively, provides precise chronostratigraphical markers for the late 20th century (Appleby et al., 1991), although artificial radionuclide concentrations are often below detection levels in the southern hemisphere (most nuclear testing took place north of the equator; Humphries et al., 2010). These markers have been used to verify ^{210}Pb profiles at sites where sediment accumulation rates have varied or where there has been downward migration of radionuclides through the sediment profile (Appleby, 2013). At sites where sediment accumulation may be non-uniform, radionuclide flux may be variable or concerns regarding mixing or slumping exist, other independent markers can validate recent radionuclide chronologies. Techniques previously employed include:

(1) Attributing specific pollen-stratigraphical intervals to known phases of local vegetation change, particularly disturbance taxa (Schottler and Engstrom, 2006; Besonen et al., 2008).

(2) Elevated concentrations of industrial metals (e.g., Zn, Pb, Cd, As, Hg) deposited either from atmospheric fallout during industrialization or effluent from mining activity in the watershed (Renberg et al., 2001; Schottler and Engstrom, 2006; Boyle et al., in press-b). Wilhelm et al. (2012) suggest normalising Pb concentrations against Y in order to better differentiate natural- and anthropogenic-derived deposition. Artificial radionuclides (^{137}Cs, ^{60}Co) also serve as a chronological tool for recent decades where anomalously high down-core peaks in their concentrations are temporally correlated with discharges of radioactive substances from nuclear power plants directly into a river upstream of a lake that are known to have occurred at specific times (e.g., Thevenon et al., 2013).

(3) Counting spheroidal carbonaceous particles (SCPs) in the sediment profile, which reflect fossil fuel combustion (Rose and Appleby, 2005). Usefully, SCPs are widely dispersed geographically, are found in many sedimentary environments and display limited post-depositional degradation. Although regional differences are known, SCP measurements are generally useful from the initial rise after 1850 to peak concentrations in the late 20th century (Rose et al., 1999). Down-core behaviour of polychlorinated biphenyls (PCBs), produced from 1927 until a global ban in 1976, can also provide chronostratigraphical markers (Schottler and Engstrom, 2006).

(4) Seismic or volcanic activity can yield additional chronological markers in the form of tephra layers (e.g., Zillén et al., 2002; Turney et al., 2004) or thick, distinctive sedimentary layers which reflect lake-edge slumping trigged by earthquakes (Schnellmann et al., 2002; Wilhelm et al., 2012). Deposited tephras exhibit geochemical signatures unique to individual eruptions, enabling lake sediment chronologies to be refined (Orpin et al., 2010). Chapron et al. (2007) incorporate tephrostratigraphy into their age–depth model for a palaeoflood record at Lake Puyehue (Chile).

The most robust chronologies will often integrate multiple techniques and also consider stratigraphical context from which the samples for dating were extracted in order to better understand the sequencing of events. Such Bayesian approaches to age–depth modelling have been effectively applied on lake sediment sequences (e.g., Chawchai et al., 2013) and slackwater palaeoflood deposits (Thorndycraft et al., 2011), whereby an age–depth model is built that incorporates prior knowledge pertaining to the order of deposition, sediment accumulation rates and depth of sampled intervals within the sediment column when calculating the probability distribution functions for individual points along the core (Bronk Ramsey, 2008). Geoscientific software developed recently facilitates simple application of Bayesian age–depth modelling with Markov Chain Monte Carlo simulations (e.g., Bacon; Blaauw and Andrés Christen, 2011; OxCal, Bronk Ramsey, 2009) to test various plausible age–depth models (e.g., Shen et al., 2008).

The ultimate goal of sediment dating is to generate a well-constrained sequence that overlaps the instrumental river flow measurement period (second half of the 20th century), which may enable quantitative discharge values to be transferred to the palaeoflood record. Fig. 6 highlights a number of techniques which may, in some cases, bridge the temporal gap between the ^{14}C record and the ^{210}Pb record (e.g., heavy metal signatures, pollen taxa, SCPs).

4. Interpretational protocol for flood palaeolimnological research

4.1. Schematic protocol

Researchers have described a number of characteristic sedimentary signatures attributed to historic floods, but local conditions and complex pre-depositional processes present interpretational challenges. We have developed a schematic protocol (Fig. 7) to aid researchers with site and method selection and facilitate more rapid identification of typical flood laminations. Each stage of the model directs readers towards the relevant published material.

4.2. Palaeoflood investigations from lakes: some case studies

To demonstrate the utility and functionality of the protocol for field site selection (Fig. 5) and the interpretational schematic (Fig. 7), and to further explore the mechanics of palaeoflood investigations using lake sediments, we present a series of case studies.

4.2.1. Brotherswater, northwest England

The lake (surface area 0.2 km^2) and catchment (surface area 12 km^2) morphology of Brotherswater (eastern Lake District, Northwest England) appears conducive to the preservation of palaeoflood deposits (D. Schillereff, unpublished), meeting the following key criteria (Fig. 5): steep relief, large catchment area to lake area ratio (72:1), largely deforested slopes with ample sediment supply, a single inflow and limited pre-lake sediment storage. Furthermore, the flat central basin exceeds the depth (maximum 16 m) of potential wind-induced resuspension for the dimensions of this water body, the lake appears weakly thermally stratified and sediment trap data show that coarse sand is delivered as primary particles during phases of high river flow. On 24th March 1968, a severe flood affected much of the eastern Lake District, with a 43-year return period calculated for the River Eden flood levels at Carlisle (Smith and Tobin, 1979). In the Brotherswater sediment sequence (Fig. 8A), two well-defined ^{137}Cs peaks (11–13 cm and 22–23 cm), the result of fallout from the 1986 Chernobyl incident and 1960s atmospheric weapons testing, respectively, bracket a coarser lamination at 14.75–18.75 cm depth that is attributed to this flood. There are no other candidate events in the historical record (Chronology of British Hydrological Events; Black and Law, 2004). The sediment signature of the flood forms a coarsening-upwards followed by fining-upwards grading couplet, seen in the particle size distributions (Fig. 8B). The P90 particle size increases to ~435 μm near the delta and ~280 μm in the lake centre, indicating fluvial delivery as the dominant sediment source. Of the geochemical proxies, the Zr/K ratio (Fig. 8C) mirrors the particle size data most closely, with highest values at 16.25 cm depth (similar to P90) suggesting an association of the ratio with grain size; a similar trend is seen in the Zr/Ti ratio. For other commonly used elemental ratios (e.g., Zr/Rb), this association is less clear or absent. Validating the indicative meaning of the geochemical ratios commonly used as proxies for grain size on a case-by-case basis appears prudent.

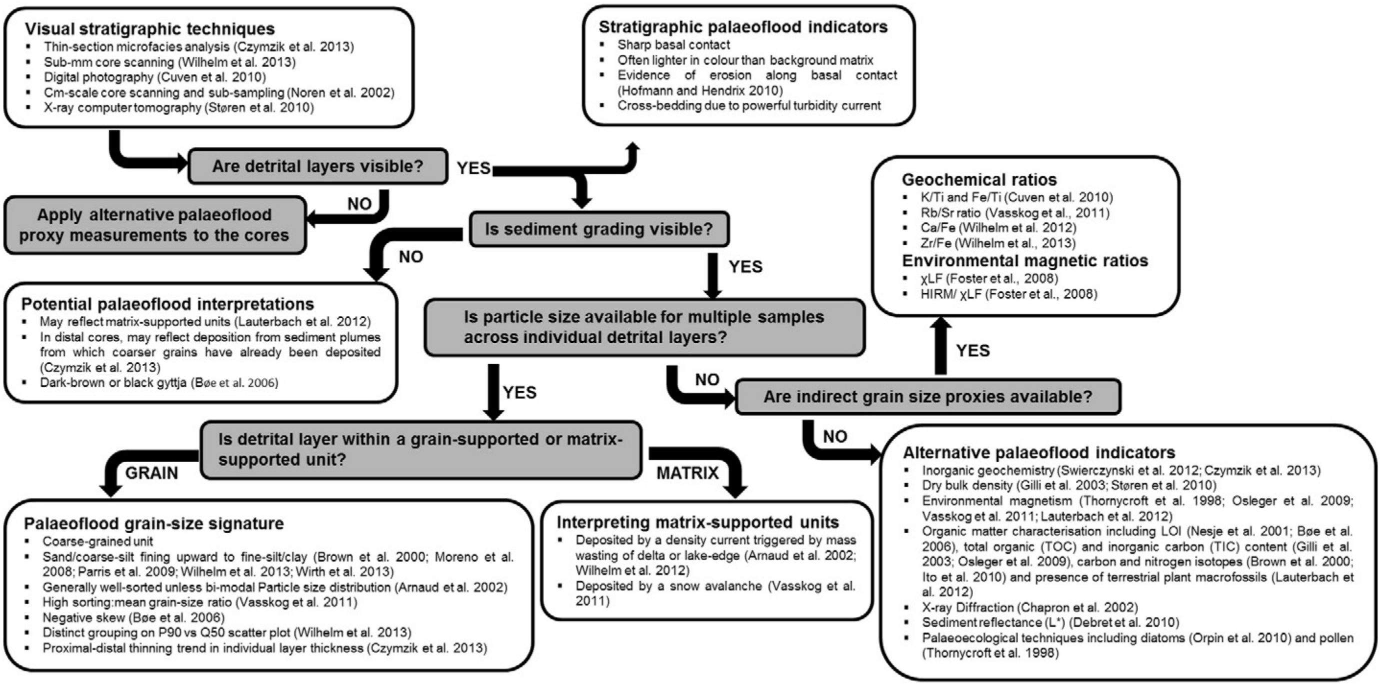


Fig. 7. Schematic methodological pathway for interpreting palaeoflood deposits within lake sediment sequences.

4.2.2. Oldevatnet, western Norway

Working at Oldnevatnet, a large (8 km^2) lake in the Jostedal Mountains in western Norway, Vasskog et al. (2011) established an event-based stratigraphy for the abyssal (~40 m depth) sediments of this long narrow lake. The lake is flanked by mountain slopes rising steeply ~1300 m and fed by glacial outwash from the Jostedal and Myklebust glaciers. At two core locations, background sedimentation is dominated by siliciclastic glacial-outwash materials that are very light in colour, with event layers darker in colour and often displaying higher organic matter content.

Visual stratigraphy and lower Rb/Sr ratio values (measured via ITRAX core scanner) were used to discriminate the darker-coloured event deposits, characterised by a greater supply of chemically-weathered material, from the lighter-coloured, Rb-rich, glacially-derived background sediment because Rb-bearing minerals are generally more resistant to weathering.

The authors recognised that the geomorphic setting provides a context where event layers could be formed by snow avalanches directly entering the lake, by turbidity currents triggered by lake-edge debris flows or by (glacio-) fluvial floods. Thus, the key to developing a flood stratigraphy for Oldnevatnet was material characterisation and process understanding for these three different event types. Vasskog et al. (2011) used grain size analysis applied at one centimetre resolution to identify distinctive sedimentological signatures for each process based on grading across laminations and using the mean particle size compared to sorting ratio. The palaeoflood units have a single mode in the coarse-silt fraction and are better sorted than snow avalanche deposits (material transported during a snow avalanche would be highly heterogeneous), which have a strongly polymodal particle size distribution. The two debris flow units are much coarser (very coarse silt/very fine sand fraction) and better sorted. There remains a resolution mismatch between the particle size analysis (physically limited to 10 mm sub-samples) and the characterisation of the event stratigraphy by ITRAX geochemistry (200 μm) but the consistent match between the visual stratigraphy and Rb/Sr ratio supports their interpretation in this instance.

4.2.3. Cape Bounty East Lake, Canadian Arctic archipelago

Cape Bounty East Lake (Melville Island, western Canadian Arctic archipelago) presents an interesting contrast in the possible temporal resolution of palaeoflood reconstruction, revealing an annually-laminated sediment sequence that has accumulated throughout the last ~2845 years (Cuven et al., 2010, 2011; Lapointe et al., 2012). East Lake is a low altitude (5 m), small (1.5 km^2) and deep (32 m) lake, and has a relatively small non-glacial catchment (11.5 km^2) producing a catchment to lake area ratio of ~8:1. The gains in the temporal resolution of analysis are partially off-set by challenges in independently dating the deeper sediments, with a lack of terrestrial carbon negating the application of radiocarbon dating to validate the varve chronology at depth. The recent (~100 years) varve chronology was validated by comparison with a ^{210}Pb chronology and ^{137}Cs radionuclide markers (Cuven et al., 2011). Eight erosive markers were discernible as interruptions to the varve couplets in the 2845 year sequence, thus the varve chronology is utilised with some confidence (Cuven et al., 2011; Lapointe et al., 2012). Identification of flood laminations in East Lake is enhanced by process monitoring at nearby lakes, including sediment trapping and measurements of fluvial suspended sediment concentrations (Cockburn and Lamoureux, 2008). These data show that intense summer rainfall events are capable of delivering coarser grains, producing hyperpycnal flows and higher sedimentation rates than annual snowmelt pulses. Lapointe et al. (2012) compared the annually-resolved particle size distributions, measured on discrete laminations from 7100 scanning electron microscope images, to 25 years of local precipitation data. They identified a statistically significant positive relationship between the largest annual rainfall events and the 98th percentile (P98) particle size fraction. The P98-rainfall regression model was used to reconstruct rainfall since AD 244 and they found anomalously high rainfall during the 20th century compared to preceding centuries, a finding with significant implications for contemporary climatic changes in the Arctic. Importantly, Lapointe et al. (2012) assessed the relationship between varve thickness and particle size and found a weak correlation, thus advocating linking grain size to single events instead of using layer thickness as a proxy for event magnitude. Detailed examination of geochemical data for the lake

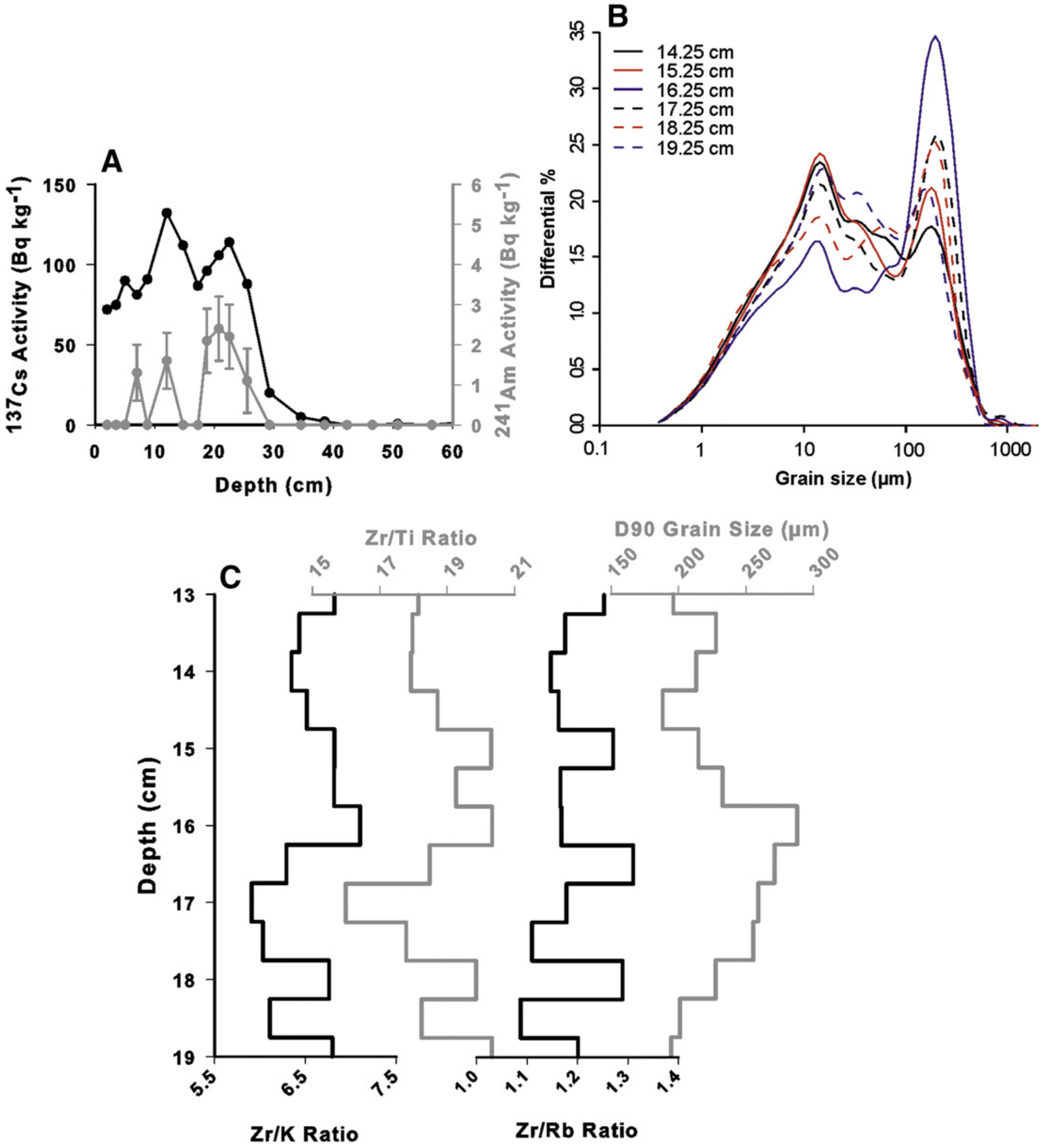


Fig. 8. A) Fallout radionuclide concentrations (^{137}Cs and ^{241}Am) for the uppermost 40 cm of core BW11-2, extracted from Brotherswater, northwest England. The 1963 weapons testing peak falls at 21 ± 1.5 cm and the 1986 Chernobyl peak appears at 11–13 cm. B) Particle size distributions for samples across the interval 14.25–18.75 cm depth in core BW11-2. C) Selected geochemical ratios being tested as particle size proxies for the 1968 flood unit plotted against the P90 profile.

(collected by µXRF; Cuven et al., 2010) pinpointed distinct elemental signatures for each lithozone identified from their microstratigraphical analysis. Lithozones B and C, likely triggered by intensive rainfall, are characterised by high Si and Zr and low K and Fe.

Cuven et al. (2011) subsequently showed that higher Zr/K values correlated with coarser grains delivered under high flow for this system on longer timescales (since ~4000 yr BP). Comparison with subsequent grain-size data (Lapointe et al., 2012) supports this interpretation to a certain extent, although the Zr/K ratio appears to be a better match to the median (Q50) than the P98, especially for the overall trend towards coarser particles since 500 yr BP. Conversely, peaks in Zr/K around 850 yr. BP (Fig. 4, Cuven et al., 2011) lack an equivalent grain size marker (Fig. 4, Lapointe et al., 2012). Variations in catchment sediment sources, storage and fluxes and the arid nature of the Canadian Arctic are possible causes of these differences. This work also demonstrates the value of building a comprehensive body of research at a single lake to more fully understand the hydrological and sedimentological variability and its implications for the sedimentary signatures deposited by floods.

4.2.4. Lac Blanc, western French Alps

Lac Blanc, lying in the Belledonne Massif in the western Alps (SE France), is small (0.1 km^2) with a flat central basin (~20 m depth), a relatively large catchment (3 km^2; catchment to lake area ratio 30:1) and a single dominant glacier-fed inflow with eroded morainic material and glacial flour as the primary sediment sources during summer (the lake is frozen from November to May). Using a multi-proxy approach that integrates µXRF measurements (1 mm resolution) with 5 mm resolution particle size measurements and visual microstratigraphical analysis from thin sections on three cores from different parts of the central basin, Wilhelm et al. (2012) produced a palaeoflood record spanning the past three centuries. They used the Ca/Fe ratio as a proxy of event deposits, citing Cuven et al. (2010), who showed that Fe was associated with finer particles at Cape Bounty East Lake (preceding case study). Transferring geochemical ratios between regions assumes similar sediment sources are active and similar depositional mechanisms are operating and thus is potentially problematic, but, critically, Wilhelm et al. (2012) validated this relationship for the Lac Blanc catchment by showing a strong, positive correlation between median grain size and the Ca/Fe ratio (averaged over 5 mm intervals). Frequency statistics on the particle size data (mean, sorting, Q50 and P99) distinguished three types of sediment deposits. Their 'Facies 2' exhibit fining-upward grading with a thin, light, fine-grained cap, are well-sorted and are positioned on the Q50:P99 scatter plot at points suggesting that phases of higher river discharge are the controlling depositional mechanism. In addition, these deposits can be mapped between three cores across the basin, supporting their flood event origin. An independent chronology was developed using artificial radionuclide markers (^{137}Cs and ^{241}Am), changes in down-core Pb concentrations reflecting atmospheric-derived fallout of known age and the identification of distinctive sedimentary deposits reflecting lake-edge slumping, most likely triggered by four well-dated earthquakes since the 18th century. The authors take the important step of attempting to temporally correlate the palaeoflood layers with fourteen historical events noted in written records from the 19th and 20th centuries and are able to attribute almost all documented floods since 1851 to a corresponding sediment deposit. Uncertainties within the age–depth model before 1851 makes the task of extending the palaeoflood reconstruction more challenging.

4.2.5. Lago Maggiore, Italian–Swiss border

The recent sediments of Lago Maggiore, a large (area 212.5 km^2), deep (177 m mean and 370 m maximum) and low elevation (194 m) montane lake with a relatively large catchment to lake area ratio (31:1) have been used to reconstruct a well-constrained flood history for the last 50 years (Kämpf et al., 2012). Investigations focused on the western shallower basin (~152 m deep), which is proximal to a major inflow, the River Toce, which drains 1551 km^2 to the south of the Alps (maximum elevation 4600 m at Monte Rosa). Glaciers comprise ~1% of the catchment area, and high magnitude river flows driven by heavy precipitation are common from September to November. Sediment trap data (Kulbe et al., 2008) showed that the maximum sedimentation rate during a two-year period occurred as a result of the October/November 2004 flood. The stratigraphy of multiple short (~60 cm) cores was discerned by visual inspection, thin-section microscopic analysis and µXRF, with a robust geochronology secured by ^{210}Pb and ^{137}Cs isotope analysis and biological markers including changes in diatom composition and enhanced nutrient loading during known years. Flood layers 1–12 mm in thickness were discerned from the background sediments as lighter in colour and richer in detrital elements (e.g., Al, Ti and K). Focusing on the uppermost layers, Kämpf et al. (2012) identified 20 detrital layers spanning 1965–2006 and interpreted these as flood laminations, based on their strong basin-wide correlation, increases in detrital elements (Al, Ti and K), fining-upward grain size to 100 µm, and the presence of abundant quartz and feldspars in the basal part of each flood layer. The authors further supported their flood reconstruction by comparison of the sediment record with lake level data, where water levels exceeding a 195.5 m threshold reflect flood events. The authors were able to relate elevated lake levels to 18 of the 20 synchronous event laminations in the sediment record. Two detrital laminations do not correspond with times of elevated lake levels, and conversely four lake level maxima do not appear in the sedimentary record. A similar comparison with recorded (1977–2006) daily river discharges for the outflow (River Toce), with discharges >600 m^3/s assigned as floods, noted 13 out of 15 instances produced an event layer in the lake and five high discharge events left no discernible event lamination in the lake sediment sequence.

A limited relationship was found between layer thickness and the magnitude of river discharge and lake level maxima, with environmental changes in the catchment and lake basin likely degrading the association of sediment transmission with the hydrological regime. Validation of the flood control for laminations in the recent sediments in Lago Maggiore offers the prospect of extending the record back in time, though Kämpf et al. (2012) display caution in this regard given the lack of precise age control and increased minerogenic sediment content for their the deeper record.

4.2.6. Implications for palaeoflood research

These case studies illustrate that lakes of many sizes (surface area of Brotherswater is 0.25 km^2, Lago Maggione is 212.5 km^2) can contain useful palaeoflood records, provided other important physiographical criteria are met. For example, their watersheds tend to be steep, they have one dominant inflow and a single, flat central basin. While sediment sources may differ (e.g., glacially-derived material, eroded soils) and some lakes are frozen for part of the year or experience little background sedimentation under normal or low flow conditions, each lake episodically also receives high detrital sediment flux. This means that sediment transport to the lake under flood conditions should exceed typical autogenic and allogenic sedimentation and thus leave a visible imprint.

Each of the above case studies evaluates in detail the accuracy and precision of the chronological methods used. Multiple and independent techniques have been employed in each case, with short-lived (^{210}Pb, ^{137}Cs) and longer half-life (^{14}C) isotopes most common and integrated with biological (e.g., disturbance pollen taxa), chemical (e.g., mining contamination) and stratigraphical (e.g., earthquake-triggered slump deposits) markers to verify the chronology. Annually-laminated lakes (e.g., East Lake; Cuven et al., 2011; Lapointe et al., 2012) are especially useful for chronological purposes but also because discrete flood deposits exhibit different sedimentological characteristics to the recurring seasonal laminations.

The structure of a flood unit deposited by a known event has been shown at Brotherswater, and this signature can thus be used as an analogue to seek similar deposits deeper in the core. Other case studies used microstratigraphical analyses of thin-sections to show the graded nature of the flood deposits (e.g., Wilhelm et al., 2012) or µXRF measurements showing trends in detrital elements related to phases of sediment delivery during a flood (Cuven et al., 2010). In addition, sediment trap data from Brotherswater, East Lake and Lago Maggiore were used to confirm that elevated river discharges are capable of supplying coarser grains.

Correlating the sediment record with local instrumental data provides tremendous support for palaeoflood reconstructions. Where gauged lake level or river discharge data are available (e.g., Lago Maggiore; Kämpf et al., 2012), discrete flood units that have been accurately dated can be compared on an individual basis to years where an extreme flood was known to occur. Precipitation records may also be useful but it is important to keep in mind that intense rainfall does not always lead to flooding or may be localised. Lapointe et al. (2012) used meteorological data from stations 100 km and 320 km away and found strong positive correlations between grain size and periods of intense precipitation. Regions with highly spatially variable rainfall patterns may require more local meteorological data for any similar trends to emerge. Older flood laminations can be compared to historically documented floods normally over timescales of 100 to 300 years (e.g., Wilhelm et al., 2012).

Clearly, the use of any one proxy is site-specific and palaeoflood signatures must be interpreted in a similar manner; i.e., avoid citing research from another lake that employed a certain proxy to discriminate palaeoflood laminations without demonstrating that down-core variability in that proxy does in fact respond to changes in river discharge at the lake under investigation. For example, the background sediment in many temperate lakes is dark-brown and organic-rich; thus, detrital palaeoflood layers appear lighter in colour. The opposite is the case at Oldevatnet, where the dark layers in fact relate to extreme events (Vasskog et al., 2011). In particular, reliance on geochemical ratios as a proxy for particle size, and its subsequent use as a flood proxy, must be informed by a comprehensive understanding of the catchment geology and sediment provenance and, critically, the relationship should be explicitly demonstrated for contemporary processes and/or in the palaeo record.

5. Conclusions

We have presented a conceptual model and reviewed methodological protocols for using lake sediment sequences as recorders of past floods and thus hope to contribute to a better understanding of flood frequency and magnitude over centennial to millennial timescales. The paper highlights recent advances made by palaeoflood researchers and discusses key challenges for on-going and future research.

(1) While a number of detailed, high-resolution lake sediment palaeoflood records have emerged recently from many regions of the world, pressing concern over future trends in extreme events means there is a need to increase the number and extend the timespans of these records. They potentially provide river managers and decision makers with greater context to assess current flood risk and augment flood rating curves. The presented case studies highlight the value of lake sediment sequences as an archive of past floods and building a palaeoflood database that addresses the global geographical distribution of lakes (all latitudes, lowland and alpine, near urban areas and more remote settings) is a challenge requiring substantial future effort.

(2) We present a framework for selecting appropriate study sites and identifying lakes most predisposed to preserving palaeoflood stratigraphies. The potential for a flood to deposit a distinctive, undisturbed sedimentological unit at the lake bed is a function of catchment processes and within-lake mechanisms. Thus, knowledge of local geology, the efficiency of the sediment conveyor, past inflow or delta migration and progradation, basin morphology and characteristics including water residence time and thermal stratification and the potential for sediment re-suspension are important factors. Understanding changes in catchment conditioning through time is of critical importance, as the sedimentary signature of floods can vary with changes in sediment supply or provenance and, thus, independently of event magnitude.

(3) The dispersal of a sediment-laden river plume across a lake basin is influenced by numerous processes and acquiring sufficient process-based understanding from the sediment record is challenging. Field and laboratory experiments have enabled simplified empirical equations to be developed for many of these processes, such as calculating critical depths for wind-induced sediment resuspension, but the range of variables means they are not globally applicable and that site-specific data should be obtained. Contemporary sediment trap studies characterising current processes of sediment flux and deposition can aid interpretation of the longer sediment record while recovering sedimentary units associated with known floods confers greater confidence to the process interpretation. Extracting multiple cores across a lake provides the three-dimensional sediment geometry of individual flood laminations, ideally following an inflow-proximal-to-distal transect and the repeatability of sediment signatures between core sites and along depositional gradients (e.g., proximal to distal fining of sediments) can also help confirm the palaeoflood interpretation.

(4) Many analytical techniques have been used to discern flood deposits from the background sediment matrix. Visual analysis of the sediment cores can provide important context, with the structure and grading of sedimentary units capable of distinguishing flood layers. Measurements of particle size are critical as they can directly reflect changes in river discharge through time, however more research is needed investigating how floccules in the water column may degrade relationships between particle size and river discharge. Indirect proxies of grain size, particularly ratios between selected geochemical elements increasingly recovered with ease by high-resolution μXRF core scanning are effective but these data must be interpreted with caution as several factors, including variable water and organic matter content, can impede the X-ray signal. The basis for the association of grain size with geochemistry must be proven for specific sites: (1) in a process domain through sediment trapping or (2) for the palaeorecord by correlating geochemical ratios with particle size across individual flood signatures

(5) Developing a well-constrained chronology is challenging but critical for obtaining meaningful data on flood frequency. Integration of multiple chronological markers (e.g., radionuclides, environmental pollution and pollen markers) is preferable and normally most feasible over the past 200 to 300 years. A well-dated, overlapping validation period between the lake sediment sequence and local river flow records can enable the proxy palaeoflood data to be calibrated quantitatively; this should be the ultimate goal of palaeoflood research. Longer-duration palaeoflood records generally have a temporal resolution sufficient to decipher flood-rich and flood-poor phases as opposed to discrete events, although annually- or seasonally-laminated core profiles are especially useful for producing event-scale reconstructions over millennial timescales.

(6) We describe five case studies of palaeoflood reconstructions undertaken at lakes in different geomorphic settings and from geographically widespread regions (England, Norway, Canadian Arctic, French Alps and northern Italy). The selected records were analysed at variable resolutions and span different temporal scales, but illustrate how independent chronological techniques and multiple lines of sedimentological evidence can be integrated to successfully distinguish palaeoflood signatures. Whilst these case studies highlight the feasibility of undertaking palaeoflood research at various locations, we emphasise that each lake meets many of the physical characteristics shown to be most conducive to palaeoflood record preservation.

(7) A key challenge for lake sediment palaeoflood researchers is the extraction of data on flood frequency from these sedimentary records and its incorporation into flood risk assessments. Using these long datasets to refine thresholds of flood magnitude on either a qualitative (e.g., threshold categories) or fully quantitative (e.g., discharge-calibrated particle size metrics) basis will enable the research field to contribute more fully to our understanding of long-term trends in flood frequency and magnitude.

Acknowledgements

DNS would like to thank the School of Environmental Sciences, University of Liverpool for funding this research via a PhD Studentship. DNS is also grateful for additional financial support from the British Society for Geomorphology. Many thanks are also extended to Jan Bloemendal, Jordon Royce and Beverley Todd for assistance with fieldwork and to Suzanne Yee for assistance with producing selected diagrams. We gratefully acknowledge the thoughtful and constructive comments of Stéphanie Girardclos and two anonymous reviewers that significantly improved the final manuscript, as well as valuable guidance from the Editor André Strasser.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.earscirev.2014.03.011. These data include Google map of the most important areas described in this article.

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