Application of sediment studies to the management and planning of water resources in the Sydney region

ANNA K. SIM, WAYNE D. ERSKINE & RUSSELL DRYSDALE

Environmental and Climate Change Research Group, University of Newcastle, Geology Building, University Drive, Callaghan, New South Wales 2308, Australia

anna.sim@uon.edu.au

Abstract Multi-decadal periods of alternating wet and dry periods have been observed in instrumental rainfall and flood records of eastern Australia. These periods are critical for the management of water resources in large cities such as Sydney. High-magnitude rainfall events are the primary source of infill events for Sydney's reservoirs. The occurrence of these rainfall events is linked with multi-decadal periods of high- and low-flood frequency, with an increase in average rainfall of 10–30% in periods of high flood frequency compared to those of low flood frequency. The instrumental record, however, is too brief to capture the full range of this variability. Sediment studies, focusing on changes in sediment deposition over time, have been used to investigate long-term hydrological variability. Discontinuous flood plains in the drowned river valley of the Hawkesbury–Nepean River act as sediment traps, preserving a record of flood events. Sediment cores collected from one of these flood plains have been analysed for particle size distribution, loss-on-ignition, magnetic susceptibility and density. These analyses, in conjunction with a chronology established through radiocarbon and optically stimulated luminescence (OSL) dating, allow a record of sedimentation over the last ~1000 years to be constructed. This provides a proxy flood record, which in turn has been used as a measure of hydrological variability in the region. The reconstructed flood record from the Hawkesbury–Nepean River will be used in long-term climate models, essential for the management and planning of water resources.

Key words multi-decadal hydrological variability; sediment cores; flood frequency; water resources

INTRODUCTION

The planning and management of water resources for Australian cities, including Sydney, has been a major challenge since European settlement. Throughout the 19th and 20th centuries successive weirs and reservoirs were constructed in order to meet increasing water demands of the growing city. Periods of reservoir construction were often preceded by severe drought, where the region's water resources were stretched to the limit. The "federation drought" of 1901–1902, for example, led to complete water famine when levels in Prospect Reservoir, the primary reservoir for Sydney at the time, fell below gravitation levels (MBWSS, 1918). Construction of a series of four reservoirs, known collectively as the Upper Nepean Dams, commenced shortly after this drought. Annual rainfall in the Sydney region has been below average for the last 14 years, with the exception of 1998 (Sydney Catchment Authority, 2009). In response to concerns over decreasing water supply, government initiatives, including restrictions on water usage and augmentation of water supplies through infrastructure (e.g. desalinisation plant) and facilities for increased water recycling, have been introduced (Water for Life, 2006; Sydney Water, 2009).

Multi-decadal periods of relative high and low flood frequency, termed flood-dominated regimes (FDR) and drought-dominated regimes (DDR), respectively, have been observed in the instrumental rainfall and flood records of eastern Australia (Erskine & Warner, 1988, 1999; Sammut & Erskine, 1995). Their occurrence has been linked with the El Niño–Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (IPO; Kiem & Franks, 2004). Kiem & Franks (2003) found that both the magnitude and frequency of ENSO events are modulated by the IPO. There is a significantly increased probability of La Niña events associated with increased rainfall in eastern Australia, and IPO-negative phases occur instead of IPO-positive or neutral phases. Similarly, the probability of an El Niño event, associated with reduced rainfall and droughts in eastern Australia, is increased during an IPO-positive phase compared to IPO-negative or neutral phases (Kiem & Franks, 2004). Accordingly, multi-decadal variability in rainfall increases the probability of occurrence of prolonged drought events during IPO-positive states, and clusters of moderate- to high-rainfall events and associated floods in IPO-negative states. Therefore, hydrological variability has fundamental consequences for water resource management and planning (Kiem *et al.*, 2003; Kiem & Franks, 2004), with the necessity to plan infrastructure to provide water resources throughout prolonged drought during DDRs that are capable of withstanding increased flood risk during FDRs.

Traditional hydrological models typically use instrumental rainfall data to calculate drought risk and associated reservoir volume required to withstand a drought of >6 years (SCA, 2009). The instrumental rainfall records in eastern Australia generally cover a period of 30–50 years, with the oldest records spanning up to 146 years (Erskine & Townley-Jones, 2009). Two DDRs (1901–1946 and 1991–2008) and two FDRs (1856–1900 and 1947–1990) have occurred over the period captured by the instrumental record (Erskine & Warner, 1988, 1999; Sammut & Erskine, 1995; Erskine & Townley-Jones, 2009). With a return period of 15–30 years, the full range of variability of the IPO is not adequately captured by the instrumental record. The use of historical records in flood-frequency analysis has been promoted by many researchers and organisations concerned with hydrology and flood risk management such as the British Institute of Hydrology (Werritty *et al.*, 2006) and Engineers Australia (Franks & Kuczera, 2002). However, historical records in eastern Australia are not significantly longer than the instrumental records. Therefore an alternative method of investigating the flood regime prior to the instrumental record is needed. Applied sediment studies using palaeoflood features preserved in the sediment record provide an alternative method to examine hydrological variability beyond the instrumental record (Ely, 1997).

Applied sediment studies

Sediment can provide a useful tool in understanding the behaviour of hydrological systems through time. Sediment studies with a focus on palaeoflood events have been widely used for risk assessment purposes to investigate the occurrence and magnitude of flood events (Saynor & Erskine, 1993; Sheffer *et al.*, 2003; Benito & Thorndycraft, 2005; Werritty *et al.*, 2006), to extend the flood record within ungauged river systems (Baker *et al.*, 1985), to examine the relationship between flooding and climate systems (Ely, 1997; Grossman, 2001; Huang *et al.*, 2007) and to investigate the occurrence of flood events in relation to climate variability though time (Ely, 1997; Knox, 2000). These applications each have a potentially significant role to play in water resource management.

Palaeoflood hydrology is a multidisciplinary field utilising methods spanning sedimentology, geomorphology, hydrology, ecology, history and statistics (Saint-Laurant, 2004; Benito & Thorndycraft, 2005; Brazdil & Kundzewicz, 2006). Early palaeoflood studies used slackwater deposits in bedrock canyons in arid and semi-arid environments (Kochel & Baker, 1982; Ely & Baker, 1985; Baker, 1987). The range of methods used in palaeoflood studies has rapidly expanded over the last two decades, utilising geomorphological features including overbank deposits (Knox, 1993; Werritty *et al.*, 2006; Huang *et al.*, 2007), boulder berms (Macklin *et al.*, 1992), alluvial fans (Ballantyne & Whittington, 1999) meander cutoffs (Knox, 2000), and flood plain sediment records (Rowan *et al.*, 2001; Winter *et al.*, 2001; Werritty *et al.*, 2006) to investigate the frequency and/or magnitude of palaeoflood events. The specific type of deposit used is therefore dependant on factors such as climate and sedimentary characteristics of the study site, the nature of the river system, and the anticipated application of the palaeoflood data. For example, specific geomorphological criteria are required in order to determine palaeoflood magnitude, such as stable channel margins to calculate channel geometry and presence of palaeo-stage indicators (Kochel & Baker, 1982; O'Connor *et al.*, 1994). However, if flood magnitude is not being calculated sites and deposits that are unsuitable for calculating magnitude may be used (Ely, 1997). Palaeoflood studies concerned with climate and flood events through time can therefore be successfully undertaken in a wider range of environments. Studies concerned with the relationship between climate and flooding hinge on the application of precise and accurate dating (Ely, 1997). This allows not only the number of flood events over a given threshold to be determined, but the timing of those events to also be identified (Ely, 1997).

Palaeoflood records preserved in flood plain sediments in the Sydney region are being utilized in order to provide a proxy record of hydrological variability prior to the instrumental and historical records. The primary aim of this study is to investigate the potential of using flood plain sediments to provide a long-term record of multi-decadal scale hydrological variability through the identification or absence of "flood event clusters" in the sediment record. It is the occurrence of low-frequency high-magnitude rainfall events that lead to major inflows to reservoirs in eastern Australia, and are therefore of great importance for the modelling and long-term planning of regional water resources (Sydney Catchment Authority, 2009). The occurrence of these rainfall events is associated with multi-decadal climate phenomena such as ENSO and the IPO. Therefore, the reconstructed flood record may be used as a proxy for the occurrence of multi-decadal scale climate cycles.

Sediment study in the Hawkesbury–Nepean River

The Hawkesbury–Nepean River system encircles Sydney—the headwaters are located to the south and southwest of the city, the river flows north to exit to the Pacific Ocean to the north of Sydney at Broken Bay (Fig. 1). The majority of Sydney's reservoirs, including the four Upper Nepean Dams and Warragamba dam, are located in the headwaters. The river system is the source of >95% of the water supply for the Sydney region (Water for Life, 2006; Sydney Catchment Authority, 2009). In downstream reaches of the Hawkesbury–Nepean River system the channel is bedrock-controlled with small, disjointed flood plains occurring at the confluence of tributaries with the primary channel. This morphological feature is referred to as a "drowned river valley" and this portion of the Hawkesbury–Nepean River is the location where sediment cores were taken. These small, disjoint flood plains are bound by large (6–12 m high) natural levees that effectively act to dam floodwaters and entrained sediment during moderate to large flood events. Each sample location has relatively small local catchments and the bulk of the sediment within the flood plains is sourced from the greater Hawkesbury–Nepean catchment and deposited during overbank flood events. The flood plain sediment record within provides an archive of the occurrence of flood events in the Hawkesbury–Nepean River system through time. Geology of the study area is denoted in Fig. 1 by the thick grey line. To the north of this line is the Hornsby Plateau and the Cumberland Plain is located to the south. The small, disjoint flood plains located within the "drowned river valley" are shaded (Fig. 1).

METHODS AND PRELIMINARY RESULTS

Sediment cores were collected at three such flood plain lagoon sites and two associated levee sites. Another sediment core was collected from a meander-cutoff lagoon within the alluvial flood plain located upstream of the constriction at the geological boundary between the Cumberland Plain and the Hornsby Plateau (Fig. 1). Preliminary results for one flood plain lagoon site (KW2) are presented here. Prior to sub-sampling, X-ray images were taken of the sediment core, allowing sedimentary units and the level of disturbance through bioturbation to be identified. The core was then sub-sampled at 1-cm increments and analysed for particle size distribution, loss on ignition, magnetic susceptibility and density. Particle size analysis was undertaken using a Malvern Mastersizer laser particle size analyser. Loss on ignition was measured by calculating the mass lost on dried and crushed sediment after combusting at 400, 550 and 1000°C. Magnetic susceptibility and density were analysed using a Geotek core logger. Preliminary results for magnetic susceptibility, density, particle size fractions 2.65 and 190 µm, and loss on ignition at 400, 550 and 1000°C are presented in Fig. 2.

A variety of dating methods were used on sections from core KW2. These include, ^{14}C-AMS dating on charcoal fragments, optically stimulated luminescence (OSL) dating on sand grains from a duplicate core KW3, and $^{240}Pu/^{239}Pu$ ratio to obtain a chronological marker of the nuclear bomb

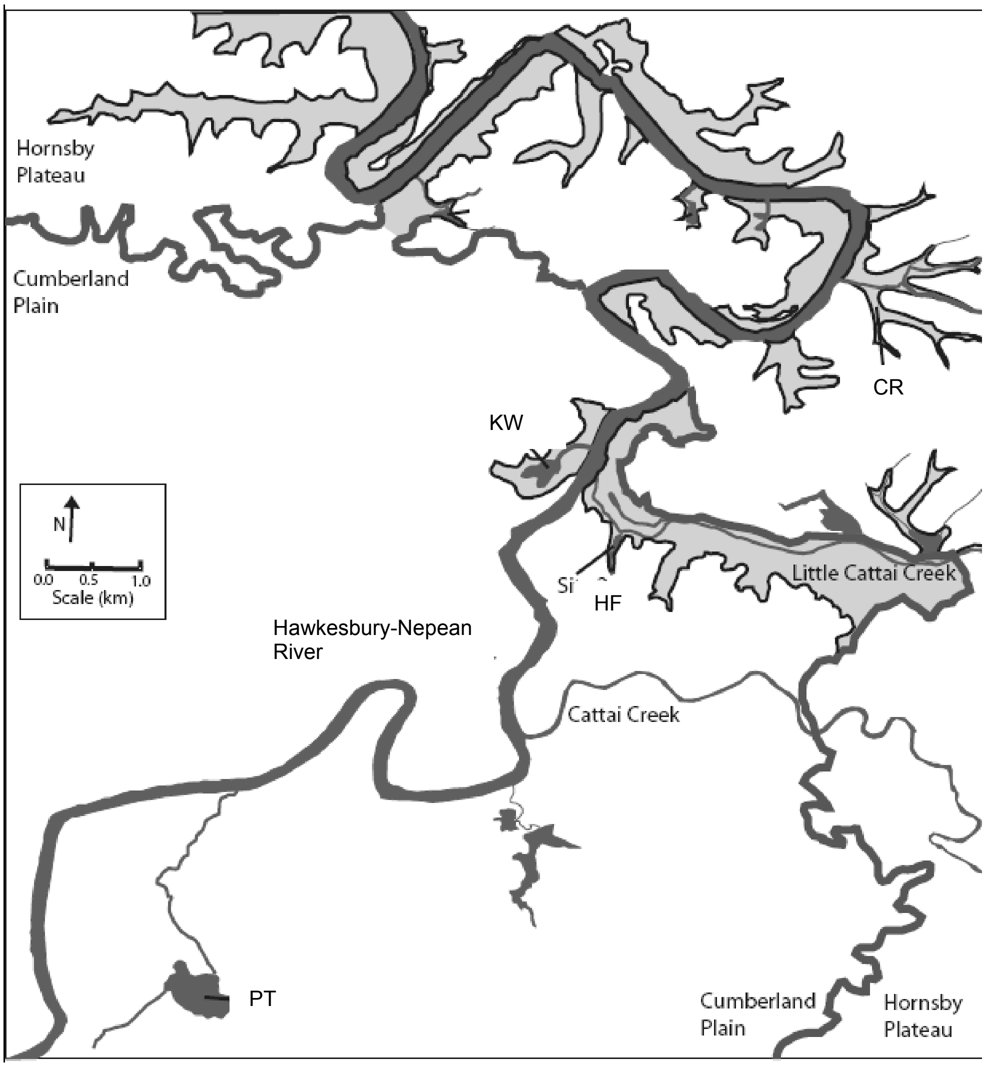

Fig. 1 The location of study sites within the lower Hawkesbury-Nepean River.

pulse from weapons testing in the 1950s and 1960s. Multiple methods of dating were used to overcome the limitations associated with the individual dating methods, thus enabling a more robust chronology to be constructed. At present, two radiocarbon ages have been obtained for core KW2 at depths of 54 and 84 cm (Table 1). Results from OSL and Pu dating were not available at the time of publishing and are therefore not included in this paper. The dates obtained from charcoal fragments provide a maximum age, due to the possibility of reworking (Blong & Gillespie, 1978). Although two dates are not sufficient to make a reliable chronology, a preliminary age/depth relationship constructed from the initial radiocarbon dates suggest an average sedimentation rate of 1 mm $year^{-1}$. Radiocarbon ages provide a maximum age and therefore, the average sedimentation rate is likely to be higher than estimated.

Factor analysis (SPSS PASW 17.0) was used to identify relationships within the particle size data. Five factors with an eigenvalue >1 were identified; however, factors 3–5 did not contribute significantly to the variability. A 2 factor solution was therefore used, with eigenvalues of 35.5 and 13.1 and variable loadings of 28.4 (49%) and 20.2 (35%) for factors 1 and 2, respectively. The factors identified included: particle sizes between 0.2–6.6 μm (clay–silt sized) in factor 1 and 120–300 μm (sand) and 0.06–0.20 μm (ultra-fines) in factor 2. The factor analysis provided each sample depth with a "component score coefficient" value for factors 1 and 2. The component scores were graphed in a scatter plot, and cluster analysis (using JMP8 statistical package) was

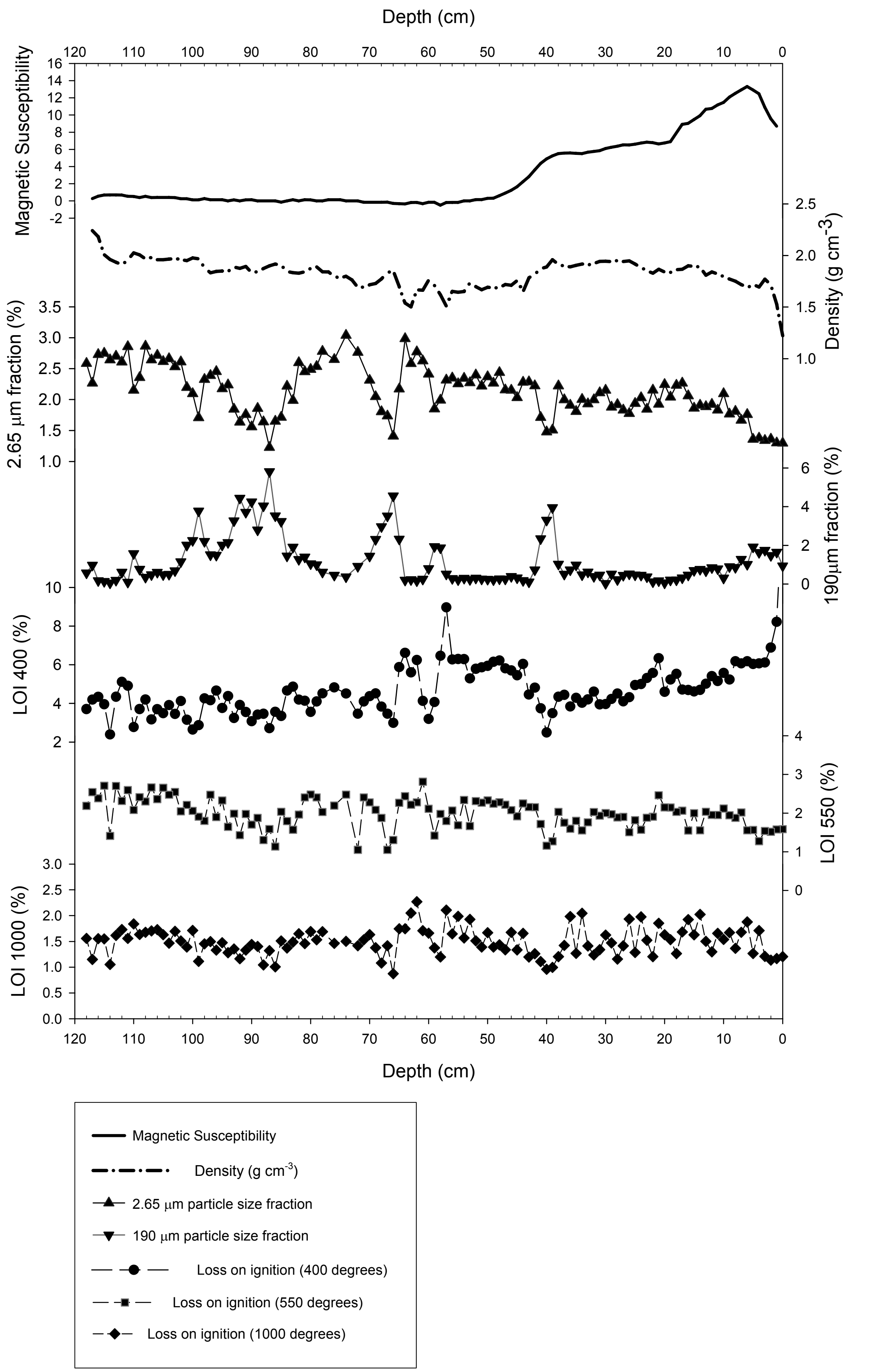

Fig. 2 Preliminary magnetic susceptibility, density, 2.65 µm particle size fraction, 190 µm particle size fraction, results for KW2 and loss of ingnition at 400, 550 and 1000 degrees.

Table 1 Preliminary radiocarbon ages.

Sample ID: Core/depth	ANSTO lab code	Radiocarbon age	Un-modelled calibrated age* range (years C.E.)
KW2/54-55	OZL248	360 ± 50	1460–464
KW2/80-81	OZL265	920 ± 80	998–1262

* radiocarbon age calibrated using SHCal04 (McCormac *et al.*, 2004).

performed to identify groups of particle size distributions within core KW2. Six particle size distribution types (a–f) were identified in the cluster analysis. Particle size distributions characterising each of the clusters are shown in Fig. 3. A core diagram of the clusters identified through factor and cluster analyses was constructed and comparisons made to the visual core description and X-ray images (Fig. 4). It was found that statistical analyses of particle size distribution alone were successful at identifying major units within the sediment core, including some units visible by X-ray imagery that were not visible by eye.

The data show a division in particle size at approx. 60 cm depth, with the top half of the core dominated by clusters a, c and e. Indeed, clusters a and c only occur in the upper 60 cm of the core, whilst cluster e occurs only once below 60 cm depth. The lower half of the core is dominated by clusters b, d and f. The variability of the mean particle size is much greater in the lower half of the core, with a mean diameter of 29 μm and SD of 17 μm compared with a mean of 23 μm and SD of 11 μm in the upper half of the core. This change in particle size distribution may be related to anthropogenic landscape change, a shift in climate state, or a change in nature of the river system. The preliminary chronology suggests that the change occurred at approx. 575 year BP, which pre-dates European arrival in Australia. Further dates are required in order to adequately constrain the age of the change in sedimentation occurring at 60 cm depth.

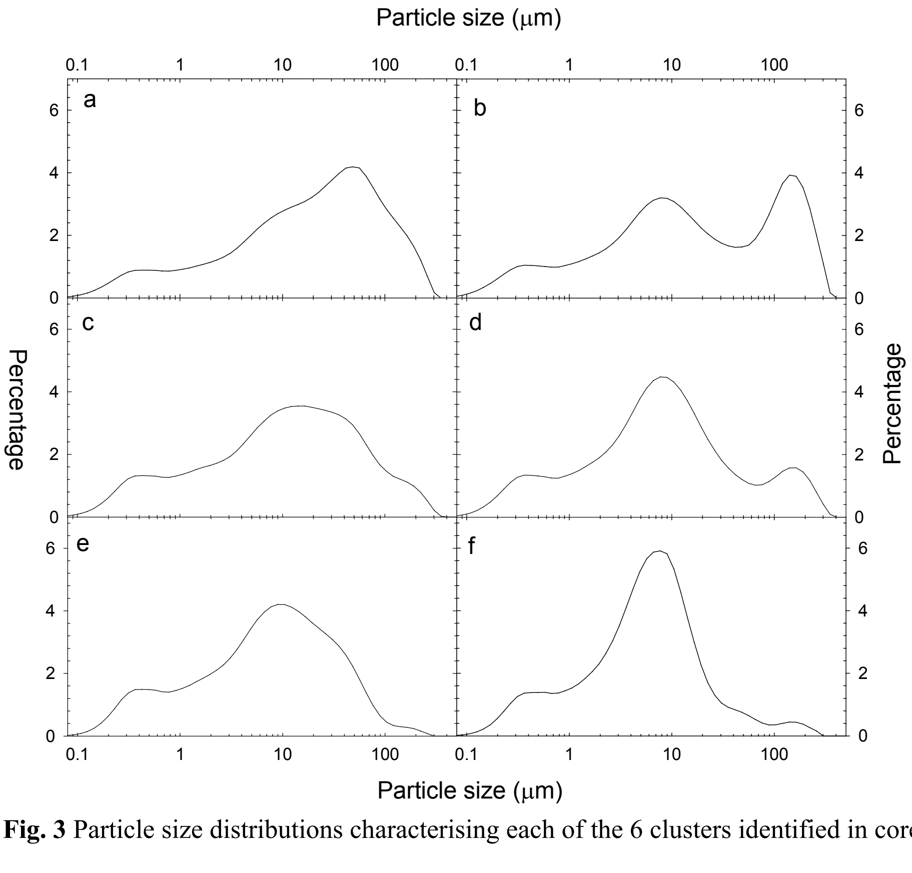

Fig. 3 Particle size distributions characterising each of the 6 clusters identified in core KW2.

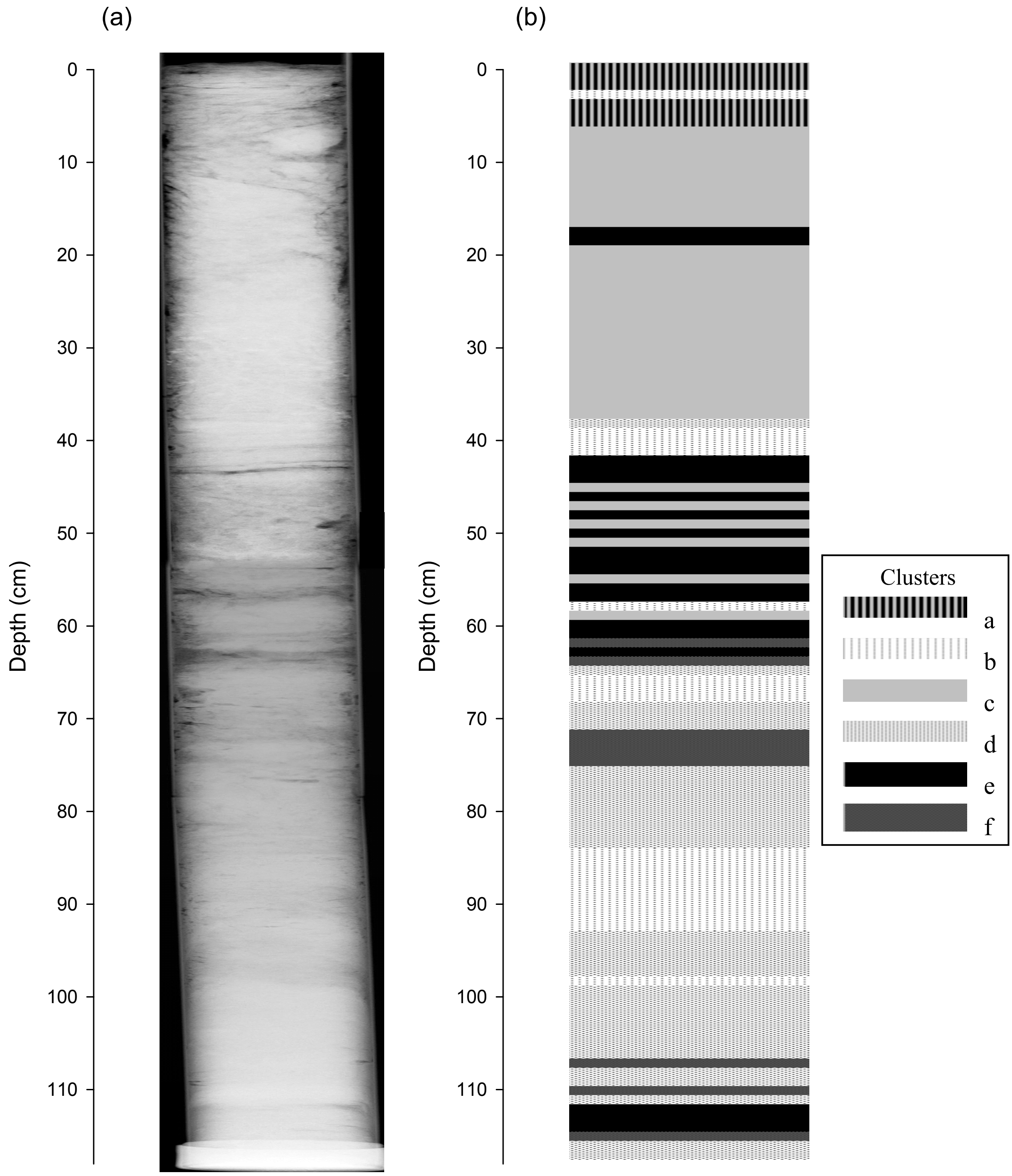

Fig. 4 (a) X-ray image of core KW2; (b) core diagram constructed from clusters identified from particle size distributions.

Cluster a occurred only at the top of the core, at 1–3 cm and 4–7 cm depth. It is likely that this distribution type is a result of disturbance to the site by livestock during recent droughts when the lagoon dried completely and was used for grazing of cattle. The particle size distributions for clusters c and e have a median value of 17 and 10 µm, respectively, but platykurtic distributions suggesting that the sediments are well-mixed. This is reflected in the X-ray image (Fig. 4) and visual observations, where significant bioturbation of sediments can be observed. The particle-size distributions of clusters d and f are very similar; with a median of 8 µm. Cluster d has a smaller peak at 190 µm whereas cluster f does not have a significant peak at this grainsize. It is suggested that cluster d is a mixture of cluster b-type and cluster f-type distributions, or is representative of a lower-energy deposit within packets of sediment deposited during high-flood frequency stages. The particle size distribution of cluster b is the coarsest, with a peak occurring at 190 µm and another at 8 µm. This distribution is likely representative of clusters of moderate-large flood events, leading to the deposition of sand-sized particles in overbank flood events.

Using the occurrence of these particle size distribution clusters within the sediment core, it is possible to infer the effect of hydrological variability on sediment deposition. Alternation between periods of high and low flood frequency is visible in the core, with periods of low flood frequency between 118–108 and 64–42 cm. A period of high flood frequency is evident by the presence of coarser particle size fractions between 107 and 165 cm depth, and another short period of high flood frequency between 41 and 38 cm. From 0 to 37 cm, the particle size distributions differ from deeper sections in the core, with a greater degree of mixing.

CONCLUSIONS

The approach presented here shows great potential for the role of sediment studies in investigating long-term hydrological variability. Physical analyses such as particle size distribution were used to identify patterns and relationships within the sediment core. These patterns are surrogate measures of changes in hydrological regime that lead to changes in the nature of sediment deposition through time. These analyses represent a proxy record of long-term hydrological variability. Such records of hydrological variability beyond the instrumental record are invaluable in the management and planning of water resources. Work is continuing to further develop the method.

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