ISSN 2047-0371

A review of *in situ* measurement techniques for investigating suspended sediment dynamics in lakes

Daniel N. Schillereff[1]
[1] School of Environmental Sciences, University of Liverpool (dns@liv.ac.uk)

ABSTRACT: Lakes can function as important sinks of catchment-derived material, offering a valuable data resource for geomorphologists investigating soil erosion, sediment yields or particulate contamination, for example. The complex internal dynamics of lakes necessitates careful consideration of data collection techniques, however. This contribution outlines the four classes of device used for *in situ* measurements of suspended sediment concentration (SSC) and potentially tracking of river-borne sediment plume dispersal (pressure differential, bulk optic, acoustic backscatter and laser optic) and highlights potential pitfalls and limitations of their use in lacustrine settings. Considerations when designing and installing sediment traps are provided in detail, with a particular focus on appropriate trap dimensions, mooring setup and deployment protocol. The relative merits of employing SSC sensors versus sediment traps are considered and, in general, method selection will be guided by the research question(s). The contribution to process understanding that can be made by comparing *in situ* measurements with lake sediment cores is also highlighted.

KEYWORDS: Limnology, suspended sediment, sediment traps, thermal regime, river plume

Introduction

Lakes represent a critical component of watersheds, acting as effective sinks for particles eroded from catchment slopes and floodplains and subsequently transported through the fluvial system (Mackereth, 1966). As a result, exploring the internal dynamics of lakes, especially the controls on fluxes and fates of catchment-derived particles, may be of interest to geomorphologists investigating catchment erosion rates (Dearing, 1991), sediment yields (Foster *et al.*, 2011), responses to soil-vegetation destabilisation (Foster *et al.*, 2003) or potential hydrometeorological drivers of extreme sediment delivery events (Cockburn and Lamoureux, 2008) or those evaluating risks to aquatic ecosystems from excessive fine particulates (Wood and Armitage, 1997) or trace metal contamination (Douglas and Rippey, 2000).

However, the internal complexity of lakes (see Lerman *et al.*, 1995) means adequately capturing spatial and temporal variability within direct measurements of water and particulates is challenging. This chapter aims to present an overview of *in situ* measurement techniques for some principle physical limnological processes that influence suspended sediment dynamics, including the dispersion of riverine plumes and thermal stratification regimes, as well as reviewing procedures for acquiring high-quality data from sediment traps. The rationale for selecting certain sensors is subsequently considered and, lastly, the value of integrating present-day measurements with sediment cores is emphasised.

Suspended sediment monitoring

Measurement techniques

Traditional methods for monitoring suspended sediment concentrations (SSC) required bottle sampling at discrete intervals; these have been widely superseded by devices capable of near-real time *in situ* measurements (Felix *et al.*, 2013). Instruments developed in fluvial (Gray and Gartner, 2009) or marine (Agrawal and Pottsmith, 2000) settings are also deployable in lakes and tend to be classified based on their underpinning physical principle: pressure differential, bulk optic, acoustic backscatter or laser optic (Figure 1; Wren *et al.*, 2000; Gray and Gartner, 2009; Hubbart *et al.*, 2014). Measuring SSC from a fluvial perspective is covered by Perks (2014) so only brief technical descriptions will be provided here; their respective suitability and methodological limitations when deployed in lakes are emphasised.

i) The pressure differential technique infers SSC from estimations of water density that are based on paired, simultaneous measurements of water pressure from transducers fixed at two known depths and corrected for water temperature (Gray and Gartner, 2009; Lewis and Rasmussen, 1999).

ii) Bulk optic turbidimeters employ either transmissometry (a measure of the visible light fraction reaching a detector from a directly-aligned source) or nephelometry (the optical backscatter of incident light at ≥90° within a chamber). In both cases, the amount of light reaching the detector will reflect the clarity or turbidity of the water. These values are calibrated against empirical measurements that should be performed on a site-specific basis (Wren *et al.*, 2000; Gray and Gartner, 2009).

iii) Acoustic backscatter techniques provide non-intrusive insight into the movement of suspended material within a lake across considerable vertical distances, typically using a Doppler current profiler (Guerrero *et al.*, 2011, 2012). Acoustic backscatter and Doppler shift mathematical principles are described in Kostaschuk *et al.* (2005) and Sassi *et al.* (2012); essentially, high frequency sound pulses emitted sequentially from instrument transducers rebound at strengths that reflect the concentration of suspended particles in the water column (Wren *et al.*, 2000).

iv) Laser optical devices (often labelled 'laser *in situ* scattering and transmissiometry' (LISST); Agrawal and Pottsmith, 2000; Agrawal *et al.*, 2008) are underpinned by laser diffraction theory, whereby the angle of scatter (diffraction) of a laser beam upon hitting a spherical particle is a function of its diameter (Loizeau *et al.*, 1994). Suspended sediment concentrations and the spectrum of particle sizes are calculated from the scattering pattern detected by a ring sensor as a laser beam is emitted into a mass of particles held in suspension (Mikkelsen and Pejrup, 2001).

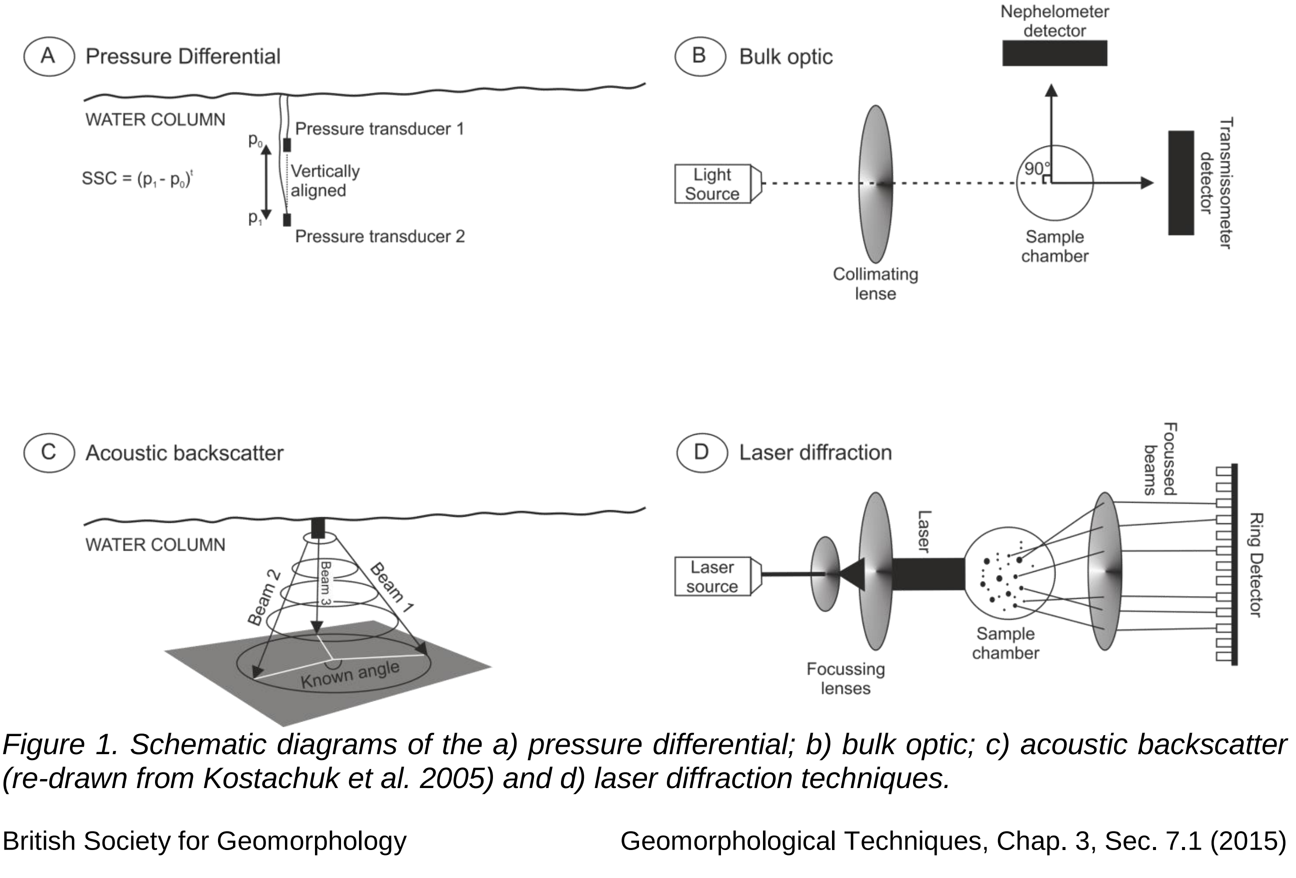

Figure 1. Schematic diagrams of the a) pressure differential; b) bulk optic; c) acoustic backscatter (re-drawn from Kostachuk et al. 2005) and d) laser diffraction techniques.

Suitability and limitations in lakes

Attempting to account for internal movements of suspended material, variable SSC as well as calm or turbulent subsurface flows may prevent certain SSC sensors from operating at maximum capability.

Concurrent temperature measurements at both depths are critical when employing the pressure differential technique (Gray and Gartner, 2009), rendering it potentially unsuitable for thermally stratified lakes. Likewise, tracking the dispersion of a sediment-rich plume as an interflow confined at the thermocline (see Figure 2) will require the precise suspension of both transducers within the plume itself.

The performance of optic instruments can be affected at certain SSC: transmissometers are more sensitive at low SSC, nephelometric sensors in turbid waters (Gray and Gartner, 2009), but both are hampered by exceptionally high particle concentrations (Wren *et al.*, 2000), potentially limiting their effectiveness when measuring infrequent, high-magnitude sediment delivery events.
Optic and acoustic techniques struggle to reconcile accurate SSC readings in the presence of variable particle sizes (Agrawal and Pottsmith, 2000), especially across the silt domain (Ludwig and Hanes, 1990) commonly deposited in lakes. Laser diffraction instruments (LISST-type) are capable of estimating concentrations and size distribution of sediments loads composed of widely distributed particle sizes (Agrawal and Pottsmith, 2000), although a high proportion of particles finer than instrument operating limits (listed in Table 1) may skew SSC values (Andrews *et al.*, 2011).

Catchment geology or the lake-watershed configuration can influence LISST readings. Sediment loads dominated by freshly eroded, angular and/or flaky particles may cause LISSTs to overestimate SSC by 1.5 and 8 fold, respectively (Felix *et al.*, 2013). Similarly in granitic regions where discoid mica particles are a substantial contributor to sediment load, the assumption that particles are spherical when using a LISST-type device may not hold (Agrawal *et al.*, 2008). Highly turbid water (optical transmission $\tau < 0.3$; Felix *et al.*, 2013) may also preclude the use of LISST devices due to excessive lens obscuration (Cockburn and Lamoureux, 2008) or the possibility of multiple scattering (Agrawal and Pottsmith, 2000).

Lamoureux (2005) provides schematics for a LISST-type device deployed on a permanent mooring that contains sensors that detect light emitted from a column of LEDs on the opposite side of the unit. Sediment entering the central tube of the device will systematically impede the emitted light from reaching the adjacent sensors (Lamoureux, 2005). When used in conjunction with a data logger, the sensor can be deployed for multiple months with data acquired at minutely intervals.

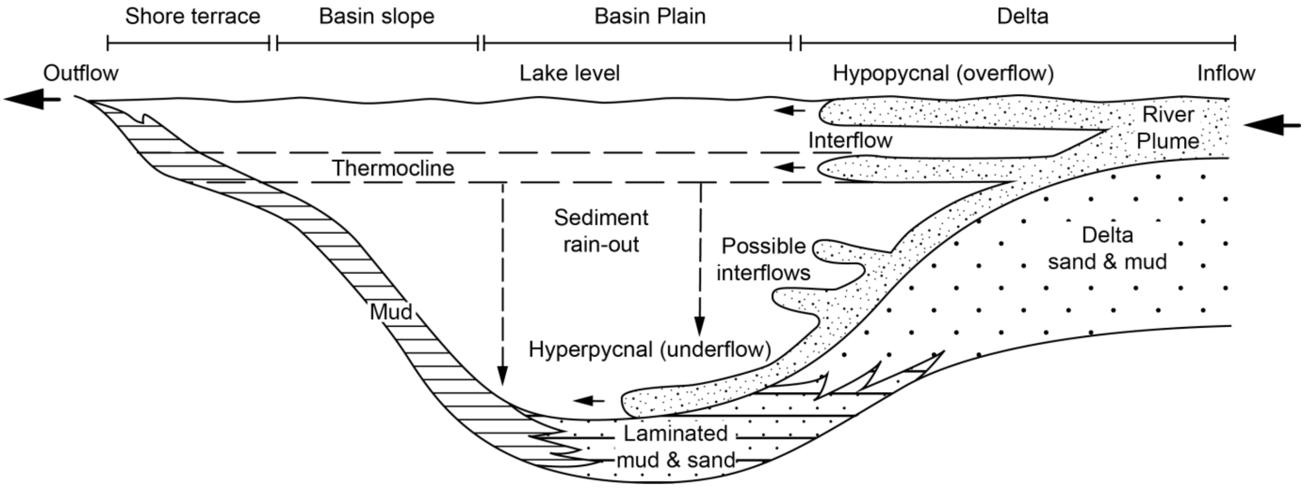

Figure 2: Processes of clastic sediment dispersal within a lake basin. Lake dimensions and sediment thicknesses are not to scale. From Schillereff et al. (2014).

Table 1. Technical details for different suspended sediment concentration sensors discussed in the text.

Operating principle (device name)	**Minimum SSC (mg L^{-1})**	**Maximum SSC (mg L^{-1})**	**Particle size (µm)**	**References**
Pressure differential	10000-20000	-------	-------	Lewis and Rasmussen, 1999 Gray and Gartner, 2009
Nephelometry (Optical Backscatterance Sensor; OBS)	-------	2000[1] 10000[2]	Inaccurate SSC values if <100, ideally 200-400	Ludwig and Hanes, 1990 Gray and Gartner, 2009
Transmissometry	-------	50	-------	Gray and Gartner, 2009
Laser diffraction (Sequoia LISST-100X Type C)	1	800 25 000[3]	2.5 – 500[4] 1.9 – 381[5]	Gray and Gartner, 2009 Felix *et al.*, 2013
Acoustic backscatter (aDCP)	100	10000		Gray and Gartner, 2009

[1] if sediment load is predominantly clay and silt
[2] if sediment load is predominantly sand-sized grains
[3] if optical pathway is narrowed
[4] if predominantly spherical grains are being measured
[5] if random-shaped grains are being measured

Information on both particulate concentration and size distribution can be gathered from acoustic Doppler current profiler (aDCP) measurements, although variable particle sizes pose problems when estimating total SSC from the backscatter profile (Reichel, 1998). Dual or multi-frequency deployments help address this issue (1500 and 500 kHz are common; Kostaschuk *et al.*, 2005). Optimum sensitivity lies in the coarse sand range that is rarely delivered to lakes, whereas fine-grained, cohesive material that dominates lacustrine sediment loads can hamper acoustic backscatter measurements, and higher frequency beams are required to detect silt-sized material (Kostaschuk *et al.*, 2005).

DCP surveys can be a powerful tool for investigating the internal behaviour and short-term pulses of turbulent flows, such as sediment-laden underflow plumes (Figure 2; Best *et al.*, 2005; Kostaschuk *et al.*, 2005). Surveying from both a moored position and along a delta-proximal to distal transect can determine the flow regime of individual flood-generated underflows (Best *et al.*, 2005).

Laboratory testing should be used to develop calibration curves for calculating more accurate SSC values (Gray and Gartner, 2009; Felix *et al.*, 2013). Alternatively, employing multiple techniques in parallel may overcome issues posed by variable sediment load characteristics, but will introduce logistical and financial burdens. A thorough understanding of the lake-catchment system and clear research objectives will also help guide SSC instrument selection.

Sediment traps

Sediment traps have been used extensively in limnological research for a wide range of purposes, and detailed reviews of sediment trap theory and applications have been conducted by Bloesch and Burns (1980), Blomqvist and Håkanson (1981), Håkanson *et al.* (1989) and Bloesch (1996).

Sediment trap design

Sediment traps are simple instruments constructed from cylindrical, funnel or bottle-shaped tubes with a removable vessel attached at the base for capturing sediment (Figure 3). Traps with upward-facing openings installed at water depths of choice intercept the rainout of particles in suspension (Eadie, 1997) that settle vertically at rates determined by their diameters (Stokes, 1851). The often-stronger horizontal forces exerted within lakes (up to ten times the vertical component; Håkanson and Jansson, 1983) diminish as the particle enters the sediment trap opening, enabling it to sink vertically into the capturing vessel.

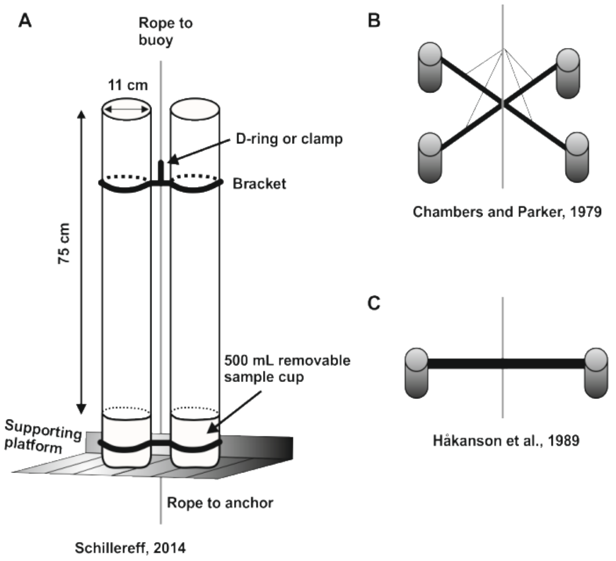

Figure 3. Illustrations of the sediment trap arrays used by a) Schillereff, 2015; b) Chambers and Parker, 1979 and c) Håkanson et al., 1989.

Trap shape determines whether its capture potential is representative of the actual vertical sediment flux within the lake and may vary under calm or turbulent flow conditions (See Figure 3.17, Håkanson and Jansson, 1983). Laboratory and field investigations conclude that cylinders are the preferable shape to avoid over or under-trapping of suspended sediment flux (95-100% of real sedimentation rate; Bloesch and Burns, 1980; Gardner, 1980). This applies in both calm and turbulent flow conditions for particles most likely to be trapped in lake: particles with diameters <500 µm and low Reynolds number (Re < 0.5) or organic-rich particles (low density).

The cylinder height to diameter ratio (the aspect ratio) is also critical in trap design (Bloesch and Burns, 1980). Openings with a diameter <40 mm should be avoided to minimise under-sampling and aspect ratios greater than 15:1 may induce the development of anoxic conditions within the vessel (Håkanson and Jansson, 1983). The general recommendation to ensure particles are held at the base of the vessel is a minimum aspect ratio of 5:1 in calm conditions and 10:1 where more turbulent flow may occur (Hargrave and Burns, 1979; Blomqvist and Kofoed, 1981; Bloesch and Burns, 1980; Bloesch, 1996). The dimensions of some published trap designs are summarised in Table 2.

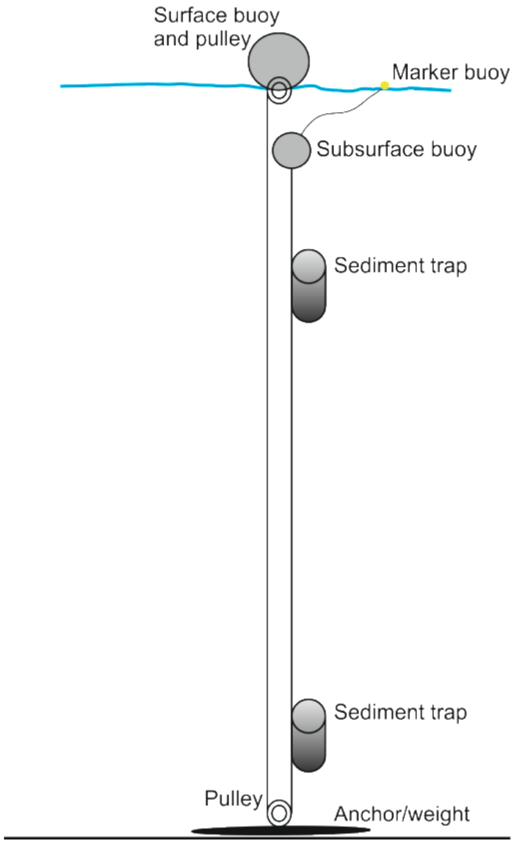

Figure 4. Idealised mooring setup for a sediment trapping programme. Modified from Ohlendorf and Sturm (2001)

The cylindrical body is most commonly constructed from transparent or non-transparent PVC or plexi-glass tubes. Field tests indicate that attaching collars or mesh at the opening should be avoided and lids that close during recovery are not required (Bloesch and Burns, 1980). Ohlendorf and Sturm (2001) installed a stopper at the base of the cylinder to release supernatant water without disturbing the accumulated sediments but this is not required if the basal, removable vessel is sufficiently deep to prevent re-suspension when detaching from the tube during collection (Schillereff, 2015). Attach traps to a mooring cable or pre-stretched plastic rope held taught between an anchor at the lake bed and a surface buoy (Figure 4). Installing the upper buoy below the water surface (Håkanson *et al.* (1989) recommend 0.5 m) ensures the cabling and traps are kept vertical during turbulent wave action or lake level fall (Douglas and Rippey, 2000). Ohlendorf and Sturm (2001) recommend the use of a pulley system between anchor and buoy to minimise re-suspension and a D-ring clasp (Schillereff, 2015) or clamp (Ohlendorf and Sturm, 2001) helps avoid trap tilt (Gardner, 1985). For further details, Sturm (2001) and Schillereff (2015) describe the deployment procedures at Lake Baikal and Brotherswater (Cumbria), respectively.

Table 2. Design parameters and deployment intervals used in published sediment trapping research.

Height (cm)	**Diameter (cm)**	**Aspect Ratio**	**# of joined tubes (distance apart)**	**Sampling Interval**	**Reference**
75	11	6.8:1	2	Variable	Schillereff, 2015
160	20	8:1	1	1.5-3.5 d	Waples and Klump, 2013
45.6	7.6	6		Weekly	Gelda, 2012
65	6	10.8:1	4	Monthly[1]	Tylmann *et al.*, 2011
50.8	10.1	5:1		Annual	McDonald *et al.*, 2010
91.4	8.9	10.3:1	4	7-10 d	Fortino *et al.*, 2009
45.6	7.6	6:1	3	Weekly	Effler *et al.*, 2006
36.4	5.2	7:1	3	Annual	Rose and Monteith, 2005
25.5	5.08	5:1	1	Before and after runoff events	Matisoff *et al.*, 2005
32.4	5.4	6:1	5	14 d	Horppila and Nurminen, 2005
78	15	5.2:1	3	Monthly during ice-free conditions	Chu *et al.*, 2005
80	11	7.3	6	20-41 d	Foster *et al.*, 2003
100	9.1	11:1	2	11 d[1]	Ohlendorf and Sturm, 2001
100	10	10:1	2 (40 cm)		Douglas and Rippey, 2000
100	10	10:1	2	14 d	Raubitschek *et al.*, 1999
50	10	5:1	1		Eadie, 1997
160	20	8:1			Eadie, 1997
60	5.1	11.8:1	4	One year	Flower, 1990
15	9 (12 at collar)		4 (30 cm)	4 m	Chambers and Parker, 1979

[1] During ice-free conditions. d = day; m = month

Sediment trap deployment

Depending on the research question being asked and the lake configuration, traps may be installed at one or multiple water depths and at one or more mooring sites. For example, river-borne sediment plumes diffusing across the lake as either over-, inter- or underflows (Figure 2) may be detected by installing arrays at the sediment surface, near the thermocline and in the upper water column. Paired, replicate traps (Figure 3a) yield insignificant variability in terms of dry weight of collected sediment (±10%; Bloesch and Burns, 1980); their deployment in small lakes or zones of low sedimentation is useful to ensure adequate sample size for further laboratory-based analyses (Chambers and Parker, 1979). Sediment trap arrays can be deployed to great depth (e.g., ~1390 m in Lake Baikal; Sturm, 2001; Ryves *et al.*, 2003).

The research question will most likely guide the frequency of trap collection. Palaeoecological studies may only require annual sampling (e.g., Woodbridge and Roberts, 2010). Systems dominated by low-frequency, intense sediment delivery events (e.g., Arctic lakes with nival hydrological regimes) may require daily (Cockburn and Lamoureux, 2008) or near-daily (Dugan *et al.*, 2009) trap replacement. Investigating internal sedimentation processes will necessitate multiple moorings positioned with regard to the inflow position and basin configuration. Douglas and Rippey (2000) installed paired traps at five locations in Lough Neagh while Lewis *et al.* (2002) employed 33 traps at twelve mooring locations in Bear Lake (arctic Canada).

Other considerations include the risk of contamination from algae growing on external trap casings or the mooring rope (Chu *et al.*, 2005) and the addition of a preserving agent. Bloesch and Burns (1980) and Håkanson *et al.* (1989) concluded that the potential biological effects of added chemicals are significantly negative, yet some researchers continue to add chloroform (Eadie, 1997) or sodium azide (NaN_3; Chang *et al.*, 2013) to avoid sediment decomposition. Injecting oasis foam or a similar reagent to the capturing vessel upon retrieval may enable the stratigraphy to be preserved (Woodbridge and Roberts, 2010).

Mass accumulation rates (MAR; mg cm^{-2} d^{-1}) per sampling interval can be calculated from Equation 1 using dried sediment weights, where m is the total dry mass (mg) in each container, d is the number of days during the sampling interval and r is the radius of the trapping vessel (cm^2).

$$MAR = \frac{m}{d} / \pi r^2 \qquad \text{(Equation 1)}$$

Sequencing sediment traps

Computer-controlled traps offer increased temporal resolution and can shed light on short-lived hydrometeorological controls on sedimentation behaviour as multiple bottles housed within an internal carousel rotate under the cylindrical tube at pre-programmed intervals (Eadie, 1997; Muzzi and Eadie, 2002). Trap and circuit board schematics are published from Baker and Milburn (1983) and Muzzi and Eadie (2002).

Summary and recommendations

Method selection

Choosing to deploy SSC sensors or sediment traps will largely be guided by the research question(s). Sediment traps provide a time-averaged signal, whereas SSC devices can measure at sufficiently high temporal resolution to investigate sub-daily interactions between hydrometeorological events, such as wind, and SS dynamics (e.g., Gilbert and Lamoureux, 2004). Sediment traps are appropriate for monitoring nival flood events (Gilbert and Butler, 2004) that may be logistically challenging to monitor in real-time and may offer opportunities to inspect the internal sedimentology of a flood deposit if sufficient material accumulates in a trapping vessel. Furthermore, captured material can be returned to a laboratory where desk-based instruments with more sensitive detection limits may be available. Conversely, sediment traps do not provide information on the relationship between turbidity and suspended sediment concentrations and SSC sensors alongside current meters should be used instead (e.g., Schiefer and Gilbert, 2008). SSC sensors may also be able to detect particles flocculating in the water column (e.g., Droppo *et al.*, 1997) and may be more appropriate when investigating the influence of short-lived events such as internal waves or turbidity currents on SS dynamics.

Sediment traps stationed at different heights may detect differences in the sediment regime under thermal stratification or evidence that a turbidity current has occurred (e.g., Schillereff, 2015) but SSC techniques will be more effective at discerning their duration, spatial extent across the basin floor and the critical SS threshold at which they are triggered in individual lakes (Gilbert and Butler, 2004; Schiefer and Gilbert, 2008).

Long-term process monitoring

Although case studies are rare, a detailed perspective on depositional mechanisms and the implications for the accumulated basal sediments can be acquired through integrating *in situ* measurements of SSC, turbidity, thermal stratification and other lake processes with sediment trapping and comparisons to adjacent sediment core records (e.g., Gilbert and Butler, 2004; Gilbert *et al.*, 2006). Such an approach can yield unprecedented information on sediment dynamics during discrete floods and the potential for a palaeoflood sedimentary signature to be preserved (Gilbert *et al.*, 2006) and foster greater confidence in palaeoenvironmental reconstructions produced from long lake sediment cores.

Conclusions

A broad range of equipment is available to researchers investigating limnological processes and technological advances are continually being made to improve the temporal and spatial resolution of data collection. However, the complexity of internal lake dynamics necessitates careful consideration of appropriate methods when investigating suspended sediment dynamics. Each type of suspended sediment monitoring device has drawbacks, in particular related to variable particle sizes, and choice should be guided by knowledge of the field site. Implementing a programme of analysis that combines multiple methods of SSC monitoring is ideal but financially and logistically more demanding. Sediment trapping is a time and labour-intensive undertaking that potentially offers valuable insight into hydrometeorological controls on sediment flux, provided the design and deployment protocols are appropriate. The coupling of catchment sediment budget calculations with lake-based sediment trapping could be a useful pathway for future geomorphological research.

Acknowledgements

The author would like to thank Dr Jennifer Clear and Dr Neil Macdonald for commenting on an earlier draft. The constructive comments of two anonymous reviewers are gratefully acknowledged. The author was awarded funding from the School of Environmental Sciences, University of Liverpool to construct and deploy the sediment traps in Brotherswater.

References

Agrawal YC, Pottsmith HC. 2000. Instruments for particle size and settling velocity observations in sediment transport. *Marine Geology*, **168**: 89–114. DOI:10.1016/S0025-3227(00)00044-X

Agrawal YC, Whitmire A, Mikkelsen O A., Pottsmith HC. 2008. Light scattering by random shaped particles and consequences on measuring suspended sediments by laser diffraction. *Journal of Geophysical Research* **113**: C04023. DOI:10.1029/2007JC004403

Andrews SW, Nover DM, Reuter JE, Schladow SG. 2011. Limitations of laser diffraction for measuring fine particles in oligotrophic systems: Pitfalls and potential solutions. *Water Resources Research* **47**: W05523. DOI:10.1029/2010WR009837

Baker ET, Milburn HBI. 1983. An instrument system for the investigation of particle fluxes. *Continental Shelf Research* **1**: 425–435.

Best JL, Kostaschuk R A., Peakall J, Villard P V., Franklin M. 2005. Whole flow field dynamics and velocity pulsing within natural sediment-laden underflows. *Geology* **33**: 765–768. DOI:10.1130/G21516.1

Bloesch J. 1996. Towards a new generation of sediment traps and a better measurement/understanding of settling particle flux in lakes and oceans : A hydrodynamical protocol. *Aquatic Sciences* **58**: 283–296.

Bloesch J, Burns N. 1980. A critical review of sedimentation trap technique. *Schweizerische Zeitschrift für Hydrologie* **42**: 15–55.

Blomqvist S, Håkanson L. 1981. A review on sediment traps in aquatic environments. *Archiv for Hydrobiologie* **91**: 101–132.

Blomqvist S, Kofoed C. 1981. Sediment trapping - a subaquatic in situ experiment. *Limnology and Oceanography* **26**: 585–590.

Chambers K, Parker A. 1979. A modified design for lake-sestion traps and a simple method for relocating them. *Earth Surface Processes and Landforms* **4**: 73–76.

Chang AS, Bertram M A., Ivanochko T, Calvert SE, Dallimore A, Thomson RE. 2013. Annual record of particle fluxes, geochemistry and diatoms in Effingham Inlet, British Columbia, Canada, and the impact of the 1999 La Niña event. *Marine Geology* **337**: 20–34. DOI:10.1016/j.margeo.2013.01.003

Chu G, Liu J, Schettler G, Li J, Sun Q, Gu Z, Lu H, Liu Q, Liu T. 2005. Sediment Fluxes and Varve Formation in Sihailongwan, a Maar Lake from Northeastern China. *Journal of Paleolimnology* **34**: 311–324. DOI:10.1007/s10933-005-4694-0

Cockburn JMH, Lamoureux SF. 2008. Inflow and lake controls on short-term mass accumulation and sedimentary particle size in a High Arctic lake: implications for interpreting varved lacustrine sedimentary records. *Journal of Paleolimnology* **40**: 923–942. DOI:10.1007/s10933-008-9207-5

Dearing JA. 1991. Lake sediment records of erosional processes. *Hydrobiologia* **214**: 99–106.

Douglas RW, Rippey B. 2000. The random redistribution of sediment by wind in a lake. *Limnology and Oceanography* **45**: 686–694.

Droppo I, Leppard G, Flannigan D, Liss S. 1997. The freshwater floc: a functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties. *Water, Air and Soil Pollution* **99**, 43-54.

Dugan HA, Lamoureux SF, Lafrenière MJ, Lewis T. 2009. Hydrological and sediment yield response to summer rainfall in a small high Arctic watershed. *Hydrological Processes* **1526**: 1514–1526.

Eadie BJ. 1997. Probing particle processes in Lake Michigan using sediment traps. *Water, Air and Soil Pollution* **99**: 133–139.

Effler SW, Matthews DA, Kaser JW, Prestigiacomo AR, Smith DG, Prestigiacomo R. 2006. Runoff event impacts on a water supply reservoir: suspended sediment loading, turbid plume behavior, and sediment deposition. *Journal of the American Water Resoures Association* **10595**: 1697–1710.

Felix D, Albayrak I, Boes RM. 2013. Laboratory investigation on measuring suspended sediment by portable laser diffractometer (LISST) focusing on particle shape. *Geo-Marine Letters* **33**: 485–498. DOI: 10.1007/s00367-013-0343-1

Flower RJ. 1990. Seasonal changes in sedimenting material collected by high aspect ratio sediment traps operated in a holomictic eutrophic lake. *Hydrobiologia* **214**: 311–316.

Fortino K, Hershey A, Keyse MD, Whalen S. 2009. Summer sedimentation in six shallow arctic lakes. *Hydrobiologia* **621**: 75-84

Foster GC, Dearing J, Jones R, Crook D, Siddle D, Harvey A, James P, Appleby P, Thompson R, Nicholson J, Loizeau J-L. 2003. Meteorological and land use controls on past and present hydro-geomorphic processes in the pre-alpine environment: an integrated lake-catchment study at the Petit Lac d'Annecy, France. *Hydrological Processes* **17**: 3287–3305. DOI: 10.1002/hyp.1387

Foster IDL, Collins A. L, Naden PS, Sear D A., Jones JI, Zhang Y. 2011. The potential for paleolimnology to determine historic sediment delivery to rivers. *Journal of Paleolimnology* **45**: 287–306. DOI:10.1007/s10933-011-9498-9

Gardner WD. 1980. Sediment trap dynamics and calibration: a laboratory evaluation. *Journal of Marine Research* **38**: 17–39.

Gardner WD. 1985. The effect of tilt on sediment trap efficiency. *Deep-Sea Research* **32**: 349–361.

Gelda R. 2012. Calibration and application of a sediment accumulation rate model – a case study. *Inland Waters* **2**: 23–36. DOI: 10.5268/IW-2.1.454

Gilbert R, Butler R. 2004. The Physical Limnology and Sedimentology of Meziadin Lake, Northern British Columbia, Canada. *Arctic, Antarctic, and Alpine Research* **36**, 33-41.

Gilbert R, Lamoureux S. 2004. Processes affecting deposition of sediment in a small, morphologically complex lake. *Journal of Paleolimnology* **31**, 37-48.

Gilbert R, Crookshanks S, Hodder K, Spagnol J, Stull R. 2006. The Record of an Extreme Flood in the Sediments of Montane Lillooet Lake, British Columbia: Implications for Paleoenvironmental Assessment. *Journal of Paleolimnology* **35**, 737-745.

Gray JR, Gartner JW. 2009. Technological advances in suspended-sediment surrogate monitoring. *Water Resources Research* **45**: W00D29. DOI:10.1029/2008WR007063

Guerrero M, Rüther N, Szupiany RN. 2012. Laboratory validation of acoustic Doppler current profiler (ADCP) techniques for suspended sediment investigations. *Flow Measurement and Instrumentation* **23**: 40–48. DOI:10.1016/j.flowmeasinst.2011.10.003

Guerrero M, Szupiany RN, Amsler M. 2011. Comparison of acoustic backscattering techniques for suspended sediments investigation. *Flow Measurement and Instrumentation* **22**: 392–401. DOI:10.1016/j.flowmeasinst.2011.06.003

Håkanson L, Floderus S, Wallin M. 1989. Sediment trap assemblages - a methodological description. *Hydrobiologia* **176/177**: 481–490.

Håkanson L, Jansson M. 1983. *Principles of Lake Sedimentology*. Blackburn Press, USA.

Hargrave BT, Burns NM. 1979. Assessment of sediment trap collection efficiency. *Limnology and Oceanography* **24**: 1124–1136.

Horppila J, Nurminen L. 2005. Effects of calculation procedure and sampling site on trap method estimates of sediment resuspension in a shallow lake. *Sedimentology* **52**: 903–913. DOI:10.1111/j.1365-3091.2005.00726.x

Hubbart J A., Kellner E, Freeman G. 2014. A case study considering the comparability of mass and volumetric suspended sediment data. *Environmental Earth Sciences* **71**: 4051–4060. DOI:10.1007/s12665-013-2788-y

Kostaschuk R, Best J, Villard P, Peakall J, Franklin M. 2005. Measuring flow velocity and sediment transport with an acoustic Doppler current profiler. *Geomorphology* **68**: 25–37. DOI:10.1016/j.geomorph.2004.07.012

Lamoureux SF. 2005. A sediment accumulation sensor for use in lacustrine and marine sedimentation studies. *Geomorphology* **68**: 17–23. DOI:10.1016/j.geomorph.2004.02.014

Lerman A, Imboden DM, Gat J. 1995. *Physics and Chemistry of Lakes*. Springer-Verlag, Berlin.

Lewis AJ, Rasmussen TC. 1999. Determination of suspended sediment concentrations and particle size distributions using pressure measurements. *Journal of Environmental Quality* **28**: 1490-1496.

Lewis T, Gilbert R, Lamoureux SF. 2002. Spatial and temporal changes in sedimentary processes at proglacial Bear Lake, Devon Island, Nunavut, Canada. *Arctic, Antarctic and Alpine Research* **34**: 119–129.

Loizeau J-L, Arbouille D, Santiago S, Vernet J-P. 1994. Evaluation of a wide range laser diffraction grain size analyser for use with sediments. *Sedimentology* **41**: 353–361.

Ludwig KA, Hanes DM. 1990. A laboratory evaluation of optical backscatterance suspended solids sensors exposed to sand-mud mixtures. *Marine Geology* **94**: 173–179.

McDonald CP, Urban NR, Barkach JH, McCauley D. 2010. Copper profiles in the sediments of a mining-impacted lake. *Journal of Soils and Sediments* **10**: 343–348. DOI:10.1007/s11368-009-0171-0.

Mackereth FJH. 1966. Some chemical observations on post-glacial lake sediments. *Philisophical Transactions of The Royal Society B: Biological Sciences* **250**: 165–213.

Matisoff G, Wilson C, Whiting P. 2005. The 7Be/210Pbxs ratio as an indicator of suspended sediment age or fraction new sediment in suspension. *Earth Surface Processes and Landforms* **30**: 1191-1201.

Mikkelsen O, Pejrup M. 2001. The use of a LISST-100 laser particle sizer for in-situ estimates of floc size, density and settling velocity. *Geo-Marine Letters* **20**: 187–195. DOI:10.1007/s003670100064

Muzzi RW, Eadie BJ. 2002. The Design and Performance of a Sequencing Sediment Trap for Lake Research. *Marine Technology Society Journal* **36**: 23–28. DOI:10.4031/002533202787914025

Ohlendorf C, Sturm M. 2001. Precipitation and dissolution of calcite in a Swiss high alpine lake. *Arctic, Antarctic and Alpine Research* **33**: 410-417.

Onset. 2013. HOBO Water Temperature Pro v2 Logger. Specification Sheet [online] Available from: http://www.onsetcomp.com/files/data-sheet/Onset HOBO Water Temp Pro v2 Data Logger.pdf (Accessed 11 November 2014)

Perks MT. 2014. Section 3.3.6: Suspended sediment sampling. In: Clarke LE, Nield JM (Eds.) *Geomorphological Techniques (Online Edition)*. British Society for Geomorphology: London, UK.

Raubitschek S, Lücke A, Schleser GH. 1999. Sedimentation patterns of diatoms in Lake Holzmaar , Germany - (on the transfer of climate signals to biogenic silica oxygen isotope proxies). *Journal of Paleolimnology* **21**: 437–448.

Reichel G. 1998. Suspended sediment monitoring: use of acoustic Doppler current profiler. In: Herschy RW and Fairbridge RW (Eds.) *Encylopedia of Hydrology and Water Resources* , Kluwer Academic Publishers, The Netherlands: Dordrecht; 638–644.

Rose NL, Monteith DT. 2005. Temporal trends in spheroidal carbonaceous particle deposition derived from annual sediment traps and lake sediment cores and their relationship with non-marine sulphate. *Environmental Pollution* **137**: 151–163. DOI:10.1016/j.envpol.2004.12.022

Ryves DB, Jewson DH, Sturm M, Battarbee RW, Flower RJ, Mackay AW, Granin NG. 2003. Quantitative and qualitative relationships between planktonic diatom communities and diatom assemblages in sedimenting material and surface sediments in Lake Baikal, Siberia. *Limnology and Oceanography* **48**: 1643–1661. DOI:10.4319/lo.2003.48.4.1643

Sassi MG, Hoitink A. JF, Vermeulen B. 2012. Impact of sound attenuation by suspended sediment on ADCP backscatter calibrations. *Water Resources Research* **48**: W09520. DOI:10.1029/2012WR012008

Schiefer E, Gilbert R. 2008. Proglacial sediment trapping in recently formed Silt Lake, Upper Lillooet Valley, Coast Mountains, British Columbia. *Earth Surface Processes and Landforms* **33**, 1542-1556.

Schillereff DN. 2015. *Lake sediment records of flood frequency and magnitude*. Unpublished PhD Thesis, University of Liverpool, 320 pp.

Schillereff DN, Chiverrell RC, Macdonald N, Hooke JM. 2014. Flood stratigraphies in lake sediments: A review. *Earth-Science Reviews* **135**: 17–37. DOI:10.1016/j.earscirev.2014.03.011

Stokes GG. 1851. On the effect of the internal friction of fluids on the motion of pendulums. *Transactions of the Cambridge Philiosophical Society* **IX**: 8.

Sturm M. 2001. Sediment traps for evaluation of particle dynamics in Lake Baikal. CONTINENT Protocol #1. EAWAG, Duebendorf, Switzerland.

Tylmann W, Szpakowska K, Ohlendorf C, Woszczyk M, Zolitschka B. 2011. Conditions for deposition of annually laminated sediments in small meromictic lakes: a case study of Lake Suminko (northern Poland). *Journal of Paleolimnology* **47**: 55–70. DOI:10.1007/s10933-011-9548-3

Waples JT, Klump JV. 2013. Vertical and horizontal particle transport in the coastal waters of a large lake: An assessment by sediment trap and thorium-234 measurements. *Journal of Geophysical*

Research: Oceans **118**: 5376–5397. DOI:10.1002/jgrc.20394

Wood PJ, Armitage PD. 1997. Biological Effects of Fine Sediment in the Lotic Environment. *Environmental Management* **21**: 203–217.

Woodbridge J, Roberts N. 2010. Linking neo- and palaeolimnology: a case study using crater lake diatoms from central Turkey. *Journal of Paleolimnology* **44**: 855–871. DOI:10.1007/s10933-010-9458-9

Wren DG, Barkdoll BD, Kuhnle RA, Derrow RW. 2000. Field techniques for suspended-sediment measurement. *Journal of Hydraulic Engineering* **126**: 97–104.