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Review of methods to measure short time scale sediment accumulation

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Abstract

This review paper aims at providing a list of methods available to measure sediment accumulation in underwater or intertidal environments over short-term periods (in the order of hours to months at the most), both in situ and under laboratory conditions. Methods are classified based on two criteria: (a) whether they measure sediment accumulation or sediment elevation change and (b) whether they allow continuous or discontinuous measurements. The main characteristics of each method are outlined, along with its vertical resolution, its accuracy, its temporal resolution, its spatial coverage capacity, and an indication of its relative cost. Typical examples of applications are also provided. The purpose of this review is to be a starting point for readers who need an overview of existing techniques that measure short-term sediment accumulation, in order to guide and facilitate, for instance, the selection of an appropriate technique for a given application with set requirements.

Keywords: sediment accumulation; elevation change; method; review

1. Introduction

This paper aims at providing a list of methods available to measure sediment accumulation in underwater or intertidal environments over short-term periods (order of hours to months), both in situ and under laboratory conditions. 'Sediment accumulation' and 'sedimentation rates' are terms and concepts widely used in relation to underwater or intertidal environments in geological-, sedimentological-, hydrodynamics-, and biological-related studies. The processes they refer to are controlled by highly complex physical parameters, and are often subject to large temporal and spatial variations. In order to study these variations and understand the processes at work, a variety of methods have been developed to measure sediment accumulation over a short time scale. In this review, we provide an inventory of these methods with their main characteristics and fields of application, to guide potential users in the selection process of the most adequate method for a given application.

1.1. Definition of short time scale accumulation

'Sediment accumulation', 'sediment deposition', and 'sedimentation' are terms that cover a wide range of time scales, and physical, chemical, and geological processes. In aqueous environments, a common starting point may be described as particles

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settling under gravity through the water column and reaching the bottom of the water body, defined as the water/sediment interface. However, the end result of this simple mechanism may vary greatly depending on which time scale it is examined upon, and short-term downward particle fluxes through the water column often differ significantly from long-term net sediment accumulation. For instance, accumulation rates on 1000-year time scale (estimated with a radiocarbon dating method) have been found to be smaller than seasonal to yearly accumulation rates by a factor of 4 (Parkinson et al., 1994; marker horizon method) and by a factor of 10 (Courp and Monaco, 1990; near-bottom sediment traps method). And radiochemical techniques have revealed an order-of-magnitude difference between rates of deposition (defined as emplacement of particles on the seabed) on a 100-day time scale and rates of accumulation (defined as the net sum of many episodes of sediment deposition and removal) on a 100-year time scale on a continental shelf (McKee et al., 1983). Several processes that occur en route to the bottom and/or in the surface mixed layer of sediment may account for these differences, such as decomposition of organic matter, dissolution of some minerals, erosion, resuspension, potential lateral transport by saltation for large particles, and compaction. Each of the above may contribute to net accumulation to various extents depending on the time scale considered (Cahoon and Lynch, 1997).

It is therefore important to define the time scale on which accumulation processes are considered, taking into consideration the context of each study. In the past, the phrase 'short-term time scale' (sometimes called contemporary, modern, or recent time scale) has been used to refer to a period that spans from less than 1 month (Pasternack and Brush, 2001), less than 1 year (Knaus and Van Gent, 1989; Childers et al., 1993; Parkinson et al., 1994; Wijnen and Bakker, 2001), less than 10 years (Cahoon and Lynch, 1997) to less than a 100 years (Nittrouer et al., 1979; Lynch et al., 1989). Courp and Monaco (1990) differentiate 'contemporary' (less than 1 year) from 'recent' or 'short' time scale (less than a 100 years), whilst Parkinson et al. (1994) classify accumulation rates as 'historical' (1–100 years) and 'geological' (hundreds to millions of years). The latter traditionally belongs to the 'long-term time scale', which may refer to early Holocene deposits (Courp and Monaco, 1990; less than 4000 years) or millennial geological processes. These overlaps of denominations and lengths of time illustrate the need for a clear statement on the use of words with regards to time scales.

In this review, the phrase 'short time scale accumulation' refers to particle fluxes to the water/sediment interface over minutes to hours, months at the most. The thickness of accumulated sediment over such short periods is often expected to be small (in the order of microns to millimetres).

1.2. Definition of sediment accumulation

Similarly to qualifiers of time scales, terms related to sediment level changes may reflect a diversity of processes. On one hand, 'vertical sediment accumulation' describes the increase in thickness of a sediment body, caused by addition of material at its upper surface (Larcombe and Woolfe, 1999). It may be separated in a primary flux of particles that settle for the first time, and a secondary flux of resuspended particles that settle for a multiple number of times (Lund-Hansen et al., 1997). McKee et al. (1983) define sediment accumulation as the result of primary and secondary fluxes, or more exactly as 'the net sum of many episodes of sediment deposition and removal'. Sediment deposition itself is defined by the authors as the emplacement of particles on the seabed. On the other hand, 'surface elevation changes' represent variations in water/sediment interface level with respect to a subsurface datum (Childers et al., 1993; Cahoon et al., 1995). The difference between accumulation and elevation change is commonly defined as 'shallow subsidence' as follows (Cahoon and Lynch, 1997):

$$\text{surface elevation change} = \text{vertical accumulation} + \text{shallow subsidence}$$

Shallow subsidence may be caused either by direct surface rise due to vegetation roots pushing the sediment upward (negative subsidence), or by subsurface subsidence due to compaction, dissolution, or decomposition, which shrink the volume of sediment.

It may also be influenced by water flux into the sediment, which incurs shrink and swell effects (Cahoon et al., 1995). Finally, density effects and variations (linked for instance with the level of water saturation) may also affect shallow subsidence processes. Deep subsidence refers to subsidence that occurs below the subsurface datum and may be due to tectonic movements (Cahoon et al., 1995). These tectonic effects are not included in surface elevation changes and are predominantly negligible in the time scales considered in this review.

The phrase 'vertical accretion' has been used in numerous studies but it does not refer to one single concept. For instance, over periods of weeks to months, vertical accretion is defined by Ellison (1993) as the sum of mineral sediment accumulation and peat formation, whilst Cahoon et al. (1995) define it as the sum of sediment deposition and erosion, plant production and decomposition. Alternatively, Callaway et al. (1997) distinguish vertical accretion (defined as a gross linear sediment accumulation) from accumulation (mass-based sedimentation, either organic or mineral), and from net accretion (gross vertical accretion minus relative sea-level rise). McKee et al. (1983) define vertical accretion as positive accumulation, in the sense that deposition (as defined above by these authors) episodes are greater than removal episodes and result in preservation of strata.

These examples introduce some frame of reference to vertical sediment movements, however they also emphasise the need to carefully define the terms associated with accumulation processes for each study. We define 'sediment accumulation' in this review as the particle flux to the water/sediment interface. This flux may result from both vertical and horizontal fluxes, and from both primary and secondary fluxes. It represents short-term oscillations (on a time scale of minutes to months) of bulk particle accumulation velocity at the water/sediment interface. In particular, it does not necessarily equate with water column vertical particle flux, and does not account for medium- and long-term sediment resuspension, sediment decomposition or dissolution, compaction, medium- and long-term erosion, and longer-term net accumulation. Surface elevation change is defined as vertical accumulation (as defined above) plus shallow subsidence, which includes changes due to vegetation roots, compaction, dissolution, and decomposition.

1.3. Classification of methods for measuring short-term sediment accumulation

Various methods have been developed to try and measure both sediment accumulation and elevation changes. Methods that allow measurements of short-term accumulation are presented first (methods with hourly to seasonal temporal resolution are considered in this category), followed by methods that estimate elevation changes over a similar time scale. In addition, methods are classified as discontinuous and quasi-continuous.

Discontinuous methods are most common and require an observer to go on site and take a reading or collect a sample, in order to estimate sediment accumulation. Discontinuous methods only yield an average rate of accumulation over the observation interval, and as a consequence, surveys are either short in duration (order of 24 hours) or have a long observation interval (order of weeks) and do not allow for extensive high frequency time variability analysis. To improve time variability analysis, several techniques have been developed that allow quasi-continuous measurements to relate accumulation processes to small time scale environmental parameters such as tides, currents, or storms (Lawler, 1991; Ridd et al., 2001). These instruments are, in general, more elaborate and more expensive than the discontinuous methods because they involve in situ data loggers. Nevertheless, they are also significantly less labour-intensive and offer sampling frequency limited only by the electronic logging capabilities of instruments, and data can often be recorded for months at sampling frequencies of several minutes.

For each method, vertical resolution, accuracy, temporal resolution, spatial coverage, and cost are indicated whenever available. 'Vertical resolution' (also simply called 'resolution' in the text) is defined as the smallest accumulation increment detectable by a given method. 'Accuracy' is defined as the probability that a measurement be representative of reality. An accuracy of 60 % for instance means that the real value of a parameter is within $\pm$40% of the measurement. 'Temporal resolution' is defined as the smallest possible time interval between two consecutive measurements. 'Spatial coverage' is an indication of the distance covered by one measurement site, as well as the distance over which the method may be used. The cost is estimated as low, medium, and high in relative terms between methods. A sketch of the instrumentation is provided unless the setup is obvious or does not involve any particular equipment on site (such as sample collection), and each method is illustrated with a data sample, except when data cannot be visualised simply (such as a suite of video camera frames). The following enumeration of methods is summarised in Table 1.

2. Measuring sediment accumulation

2.1. Discontinuous methods

2.1.1. Marker horizon method

The marker horizon method consists of spreading, at the start of the study, a layer (or horizon) of material

Table 1
Inventory of methods used to measure short-term sediment accumulation and surface elevation changes

Method	Reference (example)	Vertical resolution	Accuracy	Spatial coverage	Cost	Time resolution
Sediment accumulation						
Marker horizon	Cahoon and Turner (1989)	1 mm	33–86% reported	1 to 10 m	Low to medium	Discontinuous (observation interval)
Anchored tiles	Pasternack and Brush (1998)	0.001 μm (assumed)	NA	1 m	Low	
Ruler	Ridd (1992)	1 mm	NA	NA (laboratory)	Low	
Sediment traps	Butman (1986)	NA	NA	Spot	Low to medium	
SSC changes	Wattayakorn et al. (1990)	NA	Error on calibration	10 m to 1 km (budget)	Medium	
OBS (sediment accumulation sensor)	Ridd et al. (2001), Thomas et al. (2002)	0.2 μm	95% in still water, 70% in flowing water	Spot	High	Continuous (logging interval)
Gravimetric balance	Renagi (1999)	0.2 μm	NA	NA (laboratory)	Medium	
Video camera	Davies (1985)	NA	NA	Spot	High	
Surface elevation change						
Graduated pegs	Spenceley (1982)	1 mm	NA	Spot	Low	Discontinuous (observation interval)
SET	Boumans and Day (1993)	1.5 mm	95%	1 m	Medium	
Radionuclides	Alvisi et al. (2001)	NA	NA	Spot	High	
Echo-sounder	Verlaan and Spanhoff (2000)	1–10 cm	NA	1 km	Medium to high	
OBS (sedimeter)	Erlingsson (1991)	0.1 mm	NA	Spot	High	Continuous (logging interval)
PEEP	Lawler (1991)	2 mm	NA	Spot	High	
Electro-resistivity bed-level sensor	Ridd (1992)	1 mm	NA	Spot	High	

such as feldspar, clay, brick dust, sand or sediment laden with a rare earth element, over the natural sediment surface (Bird and Barson, 1977; Cahoon and Turner, 1989; Knaus and Van Gent, 1989; Stoddart et al., 1989; Wijnen and Bakker, 2001; Wood et al., 1989). At chosen intervals, typically every 6 months, a core is taken at the site and the depth of the horizon below the surface is recorded. A variant to this method is to bury metal plates and measure the depth of sediment on the plate with a ruler to the nearest millimetre (Allen and Duffy, 1998).

The marker horizon method indicates vertical accumulation with a resolution of the order of ± 1 mm, with an accuracy dependent on the absolute accumulation rate. For instance, Cahoon and Lynch (1997) deduced a mean vertical accumulation of 4.4 to 7.2 mm yr^{-1} from measurements done to the nearest millimetre, giving an accuracy of 77% to 86%, respectively, whilst Knaus and Van Gent (1989) obtained an accuracy of 66% and 33% for accumulation rates of 15.2 ± 5.2 and 10.2 ± 6.8 mm yr^{-1}, respectively. Cahoon et al. (1995) used marker horizon to measure vertical accumulation every 3 months and compare it with surface elevation changes (see Fig. 1).

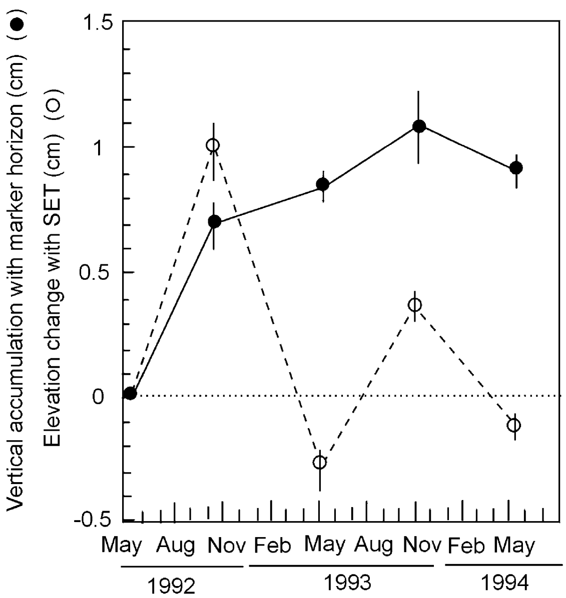

Fig. 1. Three-monthly marker horizon data, showing vertical accumulation, and SET data, showing surface elevation change. Similar data were collected in four marshes simultaneously. Modified from Fig. 4 of Cahoon et al. (1995).

The incorporation of a marker horizon is inexpensive and simple, except when rare earth elements are used, which are usually more expensive and require sophisticated sample analysis. Measurements can thus be made at numerous sites within a survey area, for instance at intervals of hundred metres to kilometres (each measurement site is in the order of 1–10 m), or at numerous geographical locations to compare various environments (e.g., Cahoon et al., (1995) compared four different marshes in one study). However, the method presents several disadvantages, which include: (1) the density of the marker being potentially greater than the medium measured and sinking through the sediment; (2) the large quantity of the marker needed to yield an easily discernible layer; (3) the possible changes in hydrology and life forms in the covered area; (4) the potential disturbance of the layer by bioturbation; (5) smearing by coring when sampling; (6) the possible loss of the marker in freshwater systems; (7) the need to locate the area marked by the horizon with pinpoint accuracy; and (8) the limitation to intertidal areas (Bird and Barson, 1977; Knaus and Van Gent, 1989). Besides, marker horizons do not allow for measurements of less than ca. 1 mm and are limited in temporal resolution, usually used for the detection of seasonal or yearly variations in vertical accumulation rates (Parkinson et al., 1994; Cahoon and Lynch, 1997; Cahoon et al., 2000).

2.1.2. Anchored tile method

The anchored tile method, applicable to intertidal environments, consists in sinking an aluminium rod (1 m long) almost entirely into the ground and capping it with a detachable ceramic tile (ca. 20 × 20 cm), positioned flush with the exposed surface at low tide, and made detachable by gluing an acrylic tube under it (Pasternack and Brush, 1998). The tile is visited at chosen intervals during low tide (typically every 2 weeks) and all accumulated materials on the tile are collected into a clean container, dried, and weighed. As an example of a typical field application, Fig. 2 shows two-weekly vertical accumulation rates obtained with anchored tile, revealing that there is no correlation between accumulation rate and watershed runoff in this case study. A variation of the anchored tile method is the filter pad technique (Reed, 1989), which consists of placing pre-weighed filter

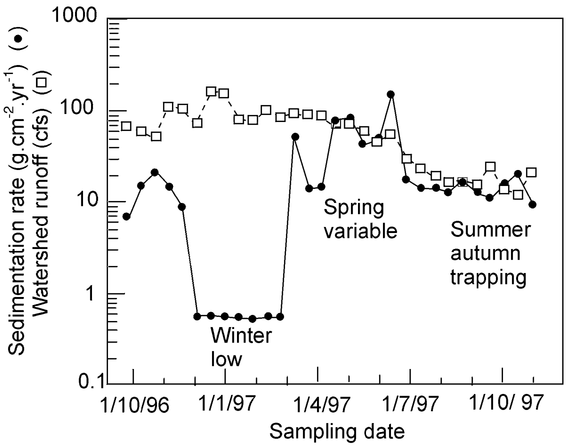

Fig. 2. Two-weekly anchored tile data showing vertical accumulation rates compared with watershed runoff, and revealing no correlation. Modified from Fig. 4 of Pasternack and Brush (2001).

papers at the sediment surface. To prevent adhesion of the existing sediments to the bottom of the 9-cm-diameter pad, it is secured to a plastic disc laid directly on the sediment surface. The pad is removed at each visit of the site and replaced with a clean one. It is then dried, weighed, and the vertical accumulation rate is calculated.

Resolution of accumulation measurements with anchored tiles and filter pads relies on accurate weighing, the errors of which are not explicitly indicated in published studies. However, it can be estimated from the resolution of a standard laboratory balance (usually at least $\pm$ 0.1 mg), which for a tile of 400 cm^2 (respectively a pad of 63 cm^2) gives a resolution of around 0.0002 mg. cm^{-2} (respectively 0.0015 mg .cm^{-2}). For a dry bulk sediment density of 1.3 g. cm^{-3} (assuming a porosity of 50% and a grain density of 2.6, which is a general estimate for surface marine sediment), this gives a vertical resolution in the order of 0.001–0.002 μm, which is a very high resolution. Accuracy will depend on care taken during sediment collection and processing of the samples, and whether the accumulation on a tile is the same as on the surrounding sediment.

Like marker horizons, anchored tiles and filter pads are indicators of vertical accumulation by indicating the amount of material that has accumulated on the tiles/pads between two visits, regardless of subsurface processes. They provide a low-cost method with a high vertical resolution, well suited for intertidal measurements of sediment accumulation (Pasternack and Brush, 1998). Each site provides a spot measurement that represents an area of typical length 10 cm, and thanks to the low-cost numerous sites can be sampled to implement surveys over distances of typically 1 km. However, these methods have not been extended to underwater measurements at this stage and, in a similar way to marker horizons, are limited in temporal resolution by the collection interval. Besides, the potential for site disturbance of the surrounding environment associated with the anchored tiles method is high (from inserting the rod in the sediment, from the presence itself of the relatively large tile, and from the collection process of removing and replacing the tile). The filter pad technique reduces this potential disturbance significantly, provided that care is taken not to step inconsiderately in the sampling area. The difference between the sediment and the tile or the filter paper surface characteristics is believed to have a slight influence on measurements, for instance by preventing resuspension partly once the sediment has dried on the paper. This influence, which is usually unquantified and variable, exists for all similar techniques that collect the accumulating sediment on an artificial surface.

2.1.3. Ruler method

In laboratory experiments involving tanks, fall towers or aquariums, the position of the sediment–water interface has been monitored with a ruler in some studies, mostly to calibrate another method (Ridd, 1992; Blewett et al., 2001). This simple and inexpensive method offers a poor resolution (nearest millimetre at best), a temporal resolution restricted by observation frequency, and is limited to laboratory studies.

2.1.4. Sediment trap method

Sediment traps (also called settling tubes) are used widely to estimate vertical particle movements in riverine and coastal environments. Traps are usually cylindrical or conical tubes closed at the bottom and open at the top, deployed on a frame or rope at a chosen height in the water column, and most often moored to the bottom. After several days to months, the trap is retrieved, the sediment collected in the tube is dried and weighed, and a vertical sediment flux is determined.

Despite attempts to define the 'ideal trap' (Gardner, 1980a), trap designs are not standardised. Cylindrical traps are generally preferred to other shapes, but the adequate trap aspect ratio (trap height to aperture diameter) is a highly debated parameter. Values used in surveys vary greatly from a ratio as low as 0.15 up to 6 (Gardner, 1980b; Monaco et al., 1990; Lund-Hansen et al., 1997; Furukawa et al., 1997; Bale, 1998; Avnimelech et al., 1999; Jones et al., 2001; Ridd et al., 2001). In order to improve temporal resolution, more elaborated traps called time-series or sequential sediment traps have been designed that collect several samples in a deployment period thanks to a rotating system, which replaces the collecting trap at a programmed interval (Bale, 1998; Honjo and Doherty, 1988; Lund-Hansen et al., 1997). Despite the automated design, the sampling frequency remains low (e.g., one per tide or one per day, see Fig. 3 for an example of such data, which is amongst the highest collection frequency obtained with sediment traps).

Sediment traps are classed with methods measuring sediment accumulation rather than elevation change, as they clearly do not account for any subsurface processes. However, trap results are compared loosely by authors to a vertical particle flux at the location of the trap (Hargrave and Burns, 1979; Butman, 1986; Baker et al., 1988; Courp and Monaco, 1990; Buesseler, 1991; Lund-Hansen et al., 1997), a measurement of sediment rain (Brunskill, 1969), a settling flux of particulate matter (Kozerski, 1994), a sedimentation flux (Håkanson et al., 1989; Rosa et al., 1991; Furukawa et al., 1997; Avnimelech et al., 1999) or deposition (Bengtsson et al., 1990). Occasionally, sediment traps are also used to estimate resuspension (Hargrave and Burns, 1979; Håkanson et al., 1989; Lund-Hansen et al., 1997) or simply to collect particles for chemical or physical analysis (Bale, 1998; Jones et al., 2001).

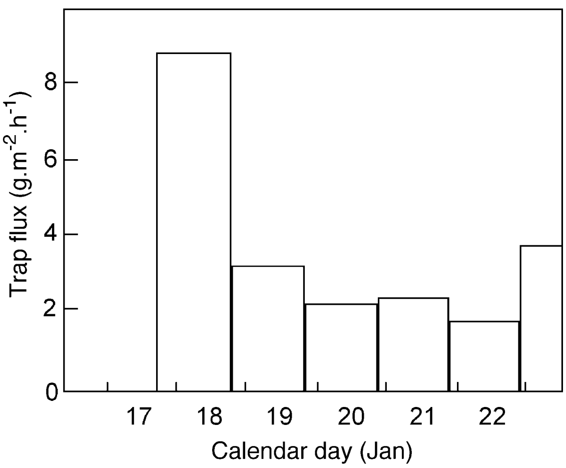

Fig. 3. Daily sediment traps data obtained with sequential sediment traps. Modified from Fig. 3 of Bale (1998).

Sediment traps provide spots measurements and are typically deployed hundreds of metres to kilometres apart. Traps offer some undeniable advantages: they are a priori simple, hardy, inexpensive (unless automated, in which case the cost can be relatively high), and are applicable from intertidal areas (Ridd et al., 2001) to deep waters (Honjo and Doherty, 1988). As such, they have become one of the most widespread methods for estimating sediment accumulation. Nevertheless, the ability of sediment traps to provide an accurate measurement of particle flux has been widely criticised (Buesseler, 1991), particularly in flowing water (Gardner, 1980b; Gust et al., 1992; Kozerski, 1994; Bale, 1998). The bias of trap measurements in flowing water is ascribed to the trap body protruding into the water column and disturbing the surrounding flow hydrodynamics. Numerous laboratory and field studies have attempted to quantify and potentially correct this effect (Hargrave and Burns, 1979; Gardner, 1980b; Kozerski, 1994), but difficulties are numerous, because trap collection efficiency depends at least upon trap geometry, suspended sediment concentration (SSC), size and density of sediment particles, and current velocity and direction (Gardner, 1980b; Butman, 1986). Besides, studies designed to calibrate trap results encounter the obstacle of determining the true accumulation rate accurately (Butman, 1986). Buesseler (1991) has used ^{234}Th activity as an independent method (finding a difference of a factor 3–10 between traps- and ^{234}Th-derived rates), whilst Baker et al. (1988) used drifting traps as a supposedly unbiased reference (finding a difference of a factor 3 between rates derived from moored and drifting traps). The difficulty worsens for very small -scale accumulation (order of microns), and traps are therefore not calibrated in most field studies. It is thus impossible to define the accuracy for the sediment trap method, while the resolution is dependent on the weighing procedures.

2.1.5. Measuring changes in SSC

Sediment accumulation may also be inferred from changes in SSC. This technique has been used both in laboratory (Jones et al., 2001; Ridd et al., 2001) and field surveys (Wolanski et al., 1998) by collecting water samples (Wattayakorn et al., 1990; Lekang et al., 2001) or by using logging instruments (Wolanski et al., 1998). In laboratory studies, SSC is usually measured over time at one location of the flume or tank by collecting water samples regularly (Hargrave and Burns, 1979; Gardner, 1980b). The suspended matter lost between two samples is assumed to have accumulated over the tank surface. An example of such application is shown in Fig. 4a, where the effect of settling treatment is compared with a combination of settling and assimilation of particles by oysters. In the field, SSC and currents are usually monitored together over time at least at two locations of the surveyed area (e.g., at the inlet and at the outlet of a swamp, or at two locations along a creek). The outgoing particle flux from the surveyed area is subtracted from the incoming particle flux, and if the difference is positive (incoming flux greater than

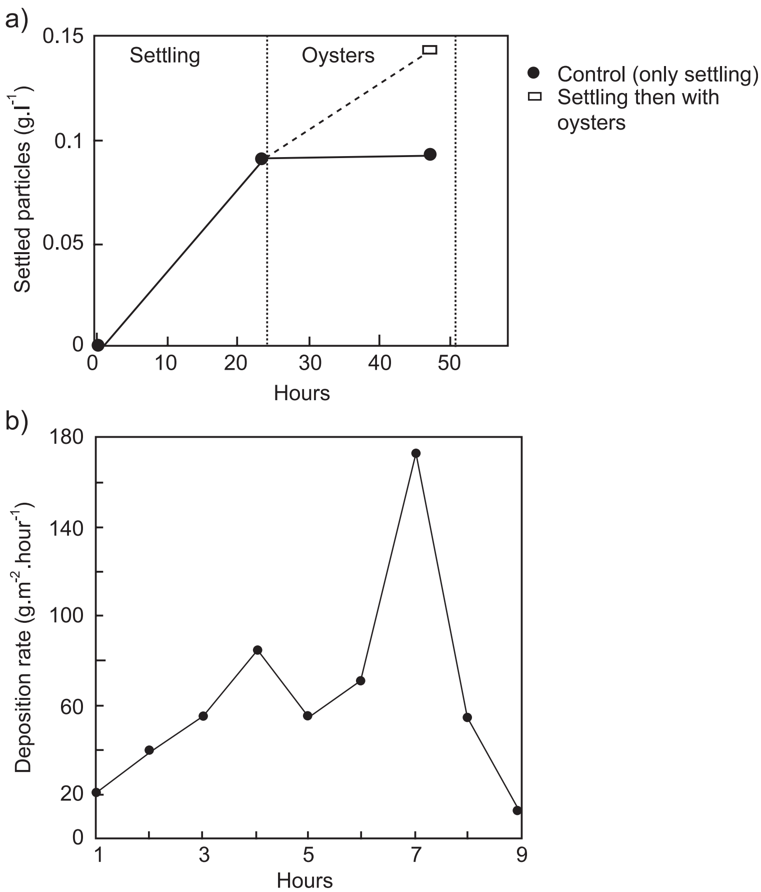

Fig. 4. Accumulation data obtained from SSC changes measurement with samples (a) and self-logging logger (b). Modified from Fig. 3 in Jones et al. (2001) and from Fig. 7 of Halide et al. (2003), respectively.

outgoing flux), the difference between the two fluxes is assumed to have accumulated uniformly over the surveyed area. If the difference is negative, the surveyed area is considered to be a source of suspended matter.

The SSC change method indicates the loss of material in suspension in the water column and assumes that this loss is equal to the amount accumulated at the sediment/water interface. The loss of suspended sediment is averaged over the surface between deployment sites, which can be tens of metres to kilometres apart. It is considered to yield order-of-magnitude estimates rather than exact measurements of sediment accumulation, and vertical resolution and accuracy may not be quantified in general as they depend upon numerous factors. These include accuracy of SSC and current measurements, sampling frequency in time and space, and (non)-uniformity of accumulation over the surveyed area. A high temporal resolution, in the order of minutes, may be achieved when using logging instruments, which makes the SSC method a quasi-continuous method in some applications. Water sampling is usually much cheaper in itself than deploying self-logging instruments, because such instruments are relatively expensive to buy or rent. However, considering the cost of field trips to collect water samples and obtain a data set of a few points in time, this method may be as expensive (or more) as deploying a self-logging instruments during a one-off field trip, that will provide a continuous data set.

2.2. Quasi-continuous methods

2.2.1. Optical backscatter sensors

Optical backscatter sensors (OBS) are used to measure sediment accumulation in two ways. The conventional way consists of calibrating the instrument versus SSC and recording SSC changes quasi-continuously at different locations. Sediment accumulation is then indirectly inferred as described above (Furukawa et al., 1997; Bryce et al., 1998; Wolanski et al., 1998). An example of accumulation data obtained by continuously monitoring SSC changes is shown in Fig. 4b.

The second method involves deploying the OBS facing upward such that particles may accumulate on the sensor (Ridd et al., 2001) (see Fig. 5a). The OBS response in this case increases as particles accumulate on the OBS, and its output is related to the amount of accumulated sediment (rather than to SSC as is the case for a sideways-pointing OBS). The OBS output is recorded in a submersible logger and an automatic wiper cleans the sensor at chosen intervals (Fig. 5a).

This technique has been investigated in laboratory experiments (Renagi, 1999), used in the field by Furukawa et al. (1997) and Ridd et al. (2001) with conventional turbidity OBS sensors, and has led to a new in situ instrument, the sediment accumulation sensor (SAS) (Thomas et al., 2002). Its advantages are a high temporal resolution (order of minutes) combined with a long deployment (order of months), and a high vertical resolution. An example of field application is shown in Fig. 5b, where hourly accumulation rates can be compared with various tidal stages with a small time step for several tidal cycles. Laboratory calibrations reported the vertical resolution to be 0.01 mg cm^{-2} (Ridd et al., 2001; Thomas et al., 2003), although small fluctuations in OBS output cause a reduction in resolution to 0.03 mg cm^{-2} (Renagi, 1999). Using a sediment dry bulk density of 1.3 g cm^{-3}, this corresponds to 0.2 μm. Accuracy was reported to be 95% in still water (Ridd et al., 2001) and 70% in flowing water (Thomas et al., 2003). The effect of particle size on OBS calibration when measuring accumulation has been found to be significantly less than when measuring turbidity (Thomas et al., 2003). Each instrument deployed provides a spot measurement and surveys may include 5–10 instruments for instance, deployed at intervals of hundreds of metres to kilometres. Disadvantages of this technique are its relatively high cost, its dependence on the wiping mechanism (which can be hindered for mechanical reasons or for external reasons, such as interference of animal (e.g., crabs) or obstruction by detritus (e.g., fallen leaves), and its limitation in the thickness of sediment that can accumulate before optical saturation occurs. The sediment thickness that causes optical saturation depends on the sensitivity of each individual instrument but it can be estimated in the order of 0.1 mm (or 20 mg. cm^{-2}) according to Thomas et al. (2003). Finally, this technique suffers from the difference in surface

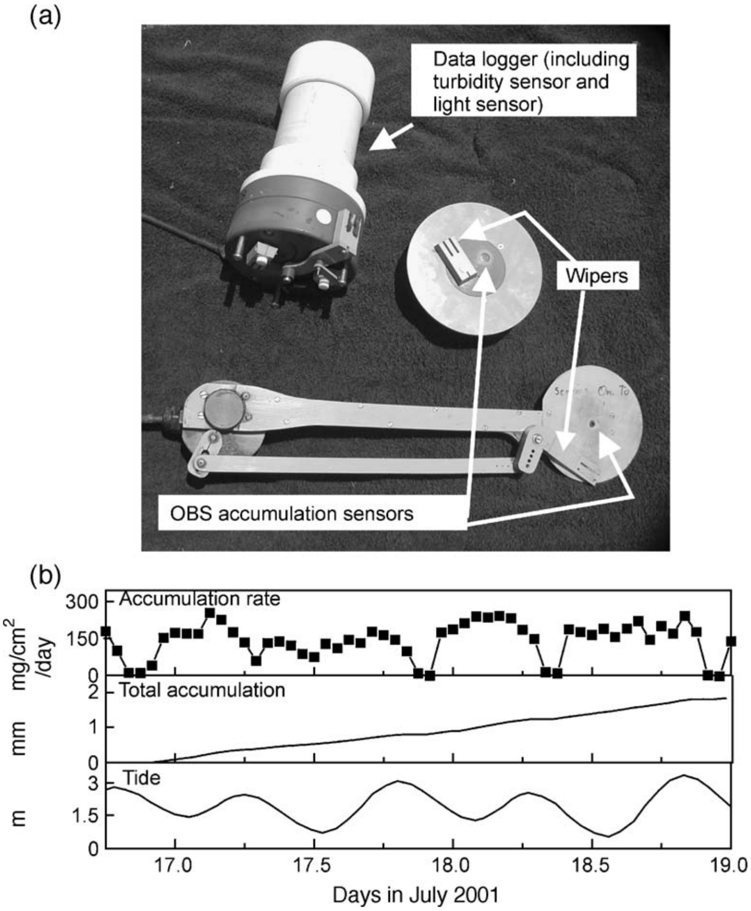

Fig. 5. Hourly accumulation rate obtained with a sediment accumulation sensor (SAS) compared with tidal elevation. This technique allows easy visualisation of total accumulation with both a high temporal and vertical resolution. Modified from Fig. 2 of Thomas et al. (2002).

characteristics between the sensor plate and the surrounding sediment, which may affect the accumulation process locally.

2.2.2. Gravimetric balance method

Weighing balances have been used as a means to measure sediment accumulation in laboratory studies featuring a fall tower (or settlement tower) as featured in Fig. 6. (Rigler et al., 1981; Renagi, 1999; Ridd et al., 2001). In this setup, a balance lies at the bottom of the tower, which is filled with water and suspended sediment. As particles fall out of suspension, they settle on the balance pan and their weight is recorded as a function of time at small time intervals in the order of seconds to minutes.

The resolution is based on the balance characteristics, and Ridd et al. (2001) report a resolution of 0.03 mg. cm^{-2} (or 0.2 μm using a density of 1.3 g. cm^{-3}). The accuracy of the balance was not defined. Despite its high temporal and vertical resolution, the weighing balance method is so far restricted to laboratory experiments. In fall towers, the balance may be replaced by high-energy X-ray measurements of density to position the water/sediment interface with a vertical resolution of 10 mm (Been and Sills, 1981), or by electrodes

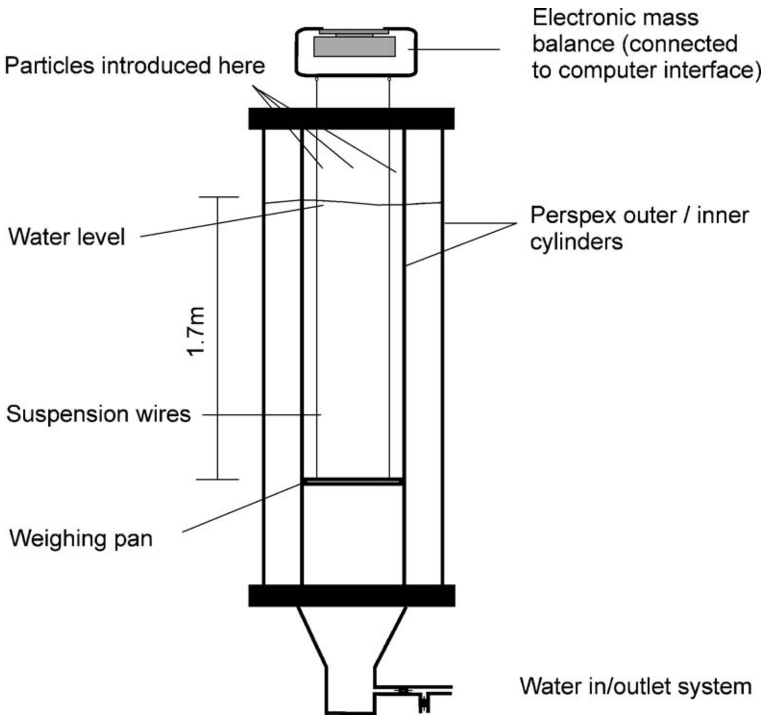

Fig. 6. Fall tower set-up, modified from fig. 2 of Ridd et al. (2001).

mounted along the tower walls (Blewett et al., 2001; no information is provided on resolution or accuracy).

2.2.3. Video camera

Video cameras have been used for visualising periods of sand motion with respect to wave activity (Davies, 1985). This technique is valuable to determine processes affecting the sediment motion on short -time scale (order of seconds) at a given spot, but it does not provide any quantified measurement of accumulation nor can it be used easily for a large spatial coverage due to its high cost and intense data processing.

3. Measuring surface elevation changes

Methods described above measure sediment accumulation above the water/sediment interface. Methods described below measure surface elevation changes, i.e., they integrate the effects of surface (sediment accumulation and erosion) and subsurface processes (sediment compaction, shrinkage, swelling, organic decay).

3.1. Discontinuous techniques

3.1.1. Graduated pegs

Graduated pegs, also called pins or stakes, are commonly used to survey intertidal zones (beaches, mangrove swamps, salt-marshes, etc.). The peg is planted in the ground and the sediment level is read on the instrument graduations by an observer at chosen intervals. Pegs are simple, low-cost, and robust tools. The reference datum for a peg inserted into the sediment is the bottom of the peg and consequently, pegs tend to indicate elevation changes over their length, including subsurface processes (Cahoon and Lynch, 1997). However, peg lengths may vary greatly (from ca. 30 cm to over 2 m) as a function of the expected accumulation range and the energy level of the environment, and the processes considered are often vaguely referred to as accretion or erosion (Spenceley, 1977; Young and Harvey, 1996), sedimentation (Reed, 1988), or accumulation (Brunskill et al., 2001).

Measurements indicate surface elevation changes averaged over the period between two observations, typically every week or month as shown in Fig. 7. Like other discontinuous methods, this restricts the potential for time variability analysis whilst resolution depends on the graduation, usually to the nearest millimetre (Spenceley, 1982). Thanks to their low cost and easy usage, pegs can be planted at short intervals (order of metres) in almost unlimited number, which allows covering large areas (order of kilometres) if adequate. Accuracy is not specified in published surveys but can be estimated to the nearest millimetre. Like most protruding instruments, pegs have been criticised for causing some disturbance of wave and current action in such a way as to generate eddies, which may produce locally anomalous patterns of accretion (Bird, 1986).

3.1.2. Sediment erosion table

A Sediment Eerosion Table (SET) is a portable device designed for intertidal zones surveys (Boumans and Day, 1993; Cahoon et al., 1995; Childers et al., 1993; French et al., 2000). The table is placed into a pre-installed seat pipe cemented permanently in the ground (see Fig. 8 for a sketch of the instrument setup). The seat pipe, driven into the sediment up to refusal (2–9 m, typically 3–6 m), provides a stable

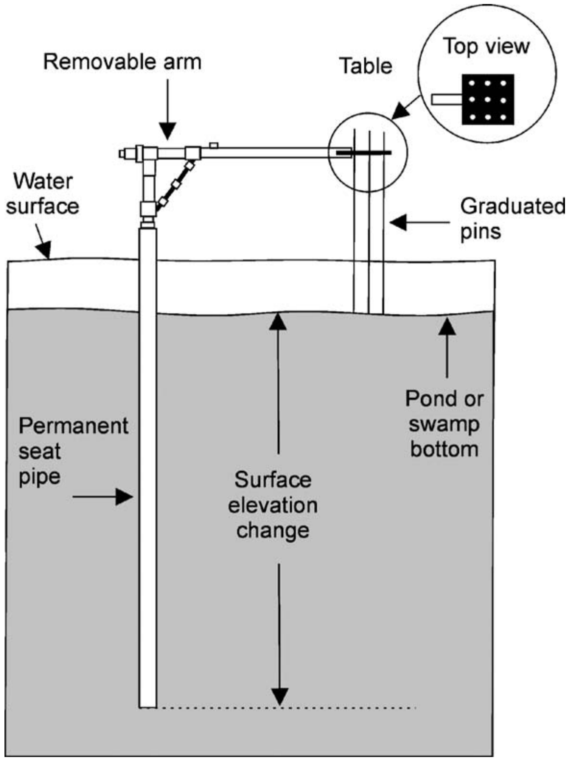

Fig. 8. Sediment elevation table (SET). Modified from Fig. 1 of Cahoon et al. (2002a). Data collected with a SET are shown on Fig. 1.

datum over time. Four to eight notches at regular interval in the pipe rim allow the SET to be locked into different orientations. Once placed into the seat pipe and locked in a given orientation, the SET is

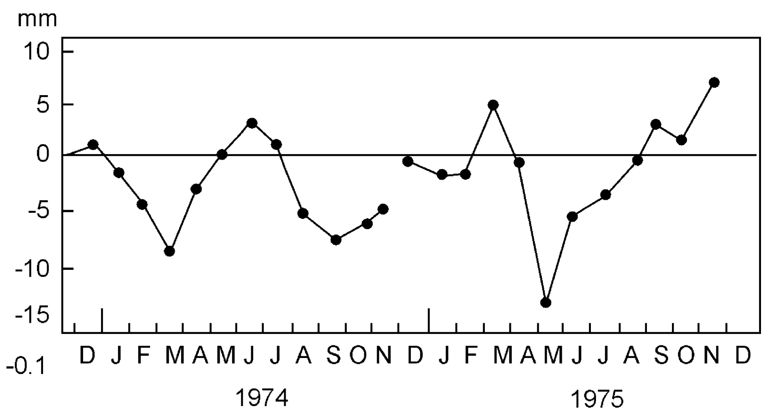

Fig. 7. Monthly data collected with 300 mm long pegs. Modified from Fig. 3 of Spenceley (1982).

carefully leveled, and pins (usually nine of them) are lowered from the table to the ground surface. The user then records the length of each pin above the SET, directly related to the distance between the table and the ground. The operation is repeated at each of the four orientations. This gives a sample size of 36–72 measurements, which provide for a measure of elevation change with a resolution of ± 2 mm (French et al., 2000), ± 1.5 mm according to Boumans and Day (1993) and Cahoon and Lynch (1997), or ± 1.4 mm according to Cahoon et al. (2002a). Boumans and Day (1993) reported a 95% confidence interval of 1.5 mm from repetitive measurements at a given location. An example of surface elevation changes measured with an SET at three-monthly intervals is shown oin Fig. 1 and compared with vertical accumulation measured with the marker horizon method.

A SET can measure both positive and negative elevation changes, and remains relatively low-cost, although it is significantly more expensive than the peg method for instance. However, it is not as simple and robust as pegs, and it requires careful pre-installation and surveying of seat pipes, and leveling of the SET with high accuracy. For these reasons, SETs may be used to survey areas with a distance between measuring sites in the order of hundreds of metres to kilometres, but the number of sites remains limited by the preparation of the seat pipes required (for instance 5–10 sites is a realistic option). It is also crucial to ensure that the seat pipes are not subsiding over the survey period. The SET method is usable in intertidal zones as well as underwater since it is an entirely mechanical device.

The sedimentation–erosion table has been renamed as a surface-elevation table to account for the fact that this method reflects some subsurface changes as well as vertical accumulation, and provides a measurement of elevation changes (Cahoon et al., 2002a). Besides, the method has been improved by developing the rod surface elevation table (RSET) (Cahoon et al., 2002b). The new device is lighter than the original SET, and therefore may be balanced over a shallower rod or seat pipe than the SET seat pipe, or on a deeper but thinner rod or seat pipe than the SET seat pipe. As a consequence, the seat pipe of the RSET allows measurement of elevation change in the shallow fraction of the ground (e.g., the root zone), or it allows measurement of elevation change over a large depth. This improvement enables the measurement of elevation changes over a larger depth range than the SET, and it provides information to separate processes over various thicknesses of sediment. However, the RSET resolution and accuracy are unchanged compared to the SET. The sedimentation–erosion bar (SEB) used by Wijnen and Bakker (2001) is a slightly modified version of the SET but works on the same principle, with the center pole being replaced by three poles that form a triangle, and the plate being replaced with a bar.

3.1.3. Short-term radionuclides

Radionuclides may be used to measure accumulation on any time scale but ^{234}Th (half-life of 24.1 days) and ^{7}Be (half-life of 53.3 days) are the two natural ones used for short time scales in marine and riverine environments, respectively (Alvisi et al., 2001; Cooper et al., 2002). ^{234}Th, the most appropriate tracer in our context, is continuously produced in situ by uranium and radon decay in the water column and completely scavenged onto particles within 1 or 2 days (ECOFLAT, 2002). After sample collection, ^{234}Th activity is counted by gamma spectrometry as described in Frignani and Langone (1991). ^{7}Be is an atmospherically-derived, particle-reactive radionuclide, with its only natural source being its generation in the atmosphere following cosmic ray spallation of nitrogen and argon (Cooper et al., 2002). This isotope has a short life and the element has a short chemical residence time in seawater because of its chemical reactivity with marine particles (Olsen et al., 1986). Therefore, surface bottom sediments in which this radionuclide is detected must be regions where there has been recent particle deposition from the sea surface. Samples of sediment are assayed for gamma emitters, including ^{7}Be, using low-level, high-resolution, lithium-drifted germanium or high-purity germanium detectors (Coopers et al., 2002).

Although temporal resolution of days is theoretically possible (ECOFLAT, 2002), surveys usually provide information on a monthly time scale, and vertical resolution is often reduced by bioturbation (Alvisi et al., 2001). Whilst the use of natural radionuclides is limited by their restricted abundance in the environment and by a given half-life, artificial radionuclides of any half-life may theoretically be added to a site. However, this is not commonly practiced due to legislative constraints on release of nuclides in the environment, and this technique is more often used in restricted man-made systems such as tanks or dams (J. Pfitzner from the Australian Institute of Marine Science, personal communication). Longer half-life natural and artificial radionuclides may also be used under certain circumstances for short-term elevation changes measurements, when specific time releases can be identified (e.g., Chernobyl in 1986). However, accumulation conditions would probably need to be relatively quiescent and accumulation to be relatively high for longer half-life radionuclides to be usable on short-time scale in the order of months at the most. Therefore, this method is more likely to be used in conjunction with another technique than as a primary measurement. Besides, it is an expensive technique due to the cost of processing samples, which is usually the limiting factor of an extensive spatial coverage and a survey area may be very large but sample intervals will also have to be large (e.g., sample interval of hundreds of metres for a typical length of 1 km for the survey area).

3.1.4. Acoustic sensor methods

Echo-sounder transects are commonly used to survey large elevation changes (meter scale), usually in shallow water (order of 20 m), and often to assess infill of some infrastructure such as harbours (Verlaan and Spanhoff, 2000), dams (De Cesare et al., 2001), or dredge and sediment spoil sites (Wolanski and Gibbs, 1992). The comparison of repetitive lines can indicate vertical variations of various sediment layers over time. For instance, in Rotterdam harbour, Verlaan and Spanhoff (2000) used a 210-kHz sounder to detect the water/fluid mud (10–300 g l^{-1}) interface and a 15-kHz sounder to detect a higher density layer of the more sandy original seabed. These transects were done weekly or after storms, and storm deposits of up to 2 m thick were identified in this way.

Echo-sounding has the advantage of yielding two-dimensional information, unlike any other method, and allows the best spatial coverage of all methods. Thanks to this high spatial coverage, it also allows estimating a total weight of sediment over the surveyed area (see Fig. 9) with least averaging, where weekly accumulated weights are compared with weekly averaged wave orbital velocity. However, as illustrated above and with a resolution in the order of 1–10 cm, this method is adequate for surveying large elevation changes only. Furthermore, as it requires a ship, it ranks amongst the expensive methods even though the use of a small craft such as an inflatable, when feasible, can significantly reduce cost.

3.2. Quasi-continuous techniques

3.2.1. Optical backscatter sensors

Erlingsson (1991) developed a ‘sedimeter’ consisting of a vertical array of sideways-pointing infrared transmitters and OBS built-in within a transparent rod (Fig. 10a). The rod is planted in the ground and connected to an underwater logger, and is suitable for intertidal sites as well as continuously submerged sites. As sediment accumulate, compact or erode, more or fewer sensors receive a backscattered signal, indicating the level of the sediment/water interface.

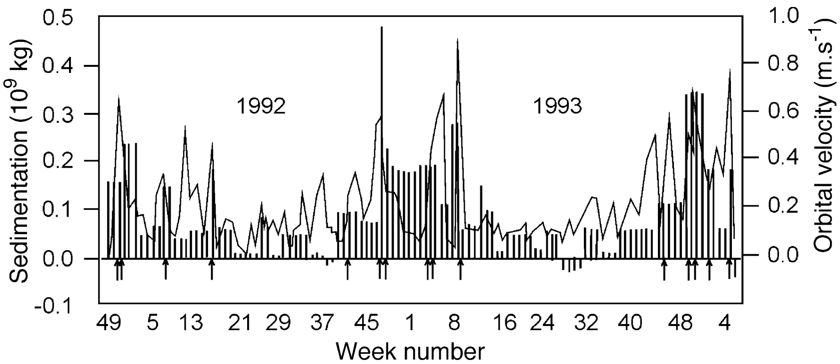

Fig. 9. Weekly amount of accumulated sediment over a given area in a shipping channel deducted from echo-sounder transects, and weekly-average wave orbital velocity at 20 m depth of the one-third highest waves. Modified from Fig. 4 of Verlaan and Spanhoff (2000).

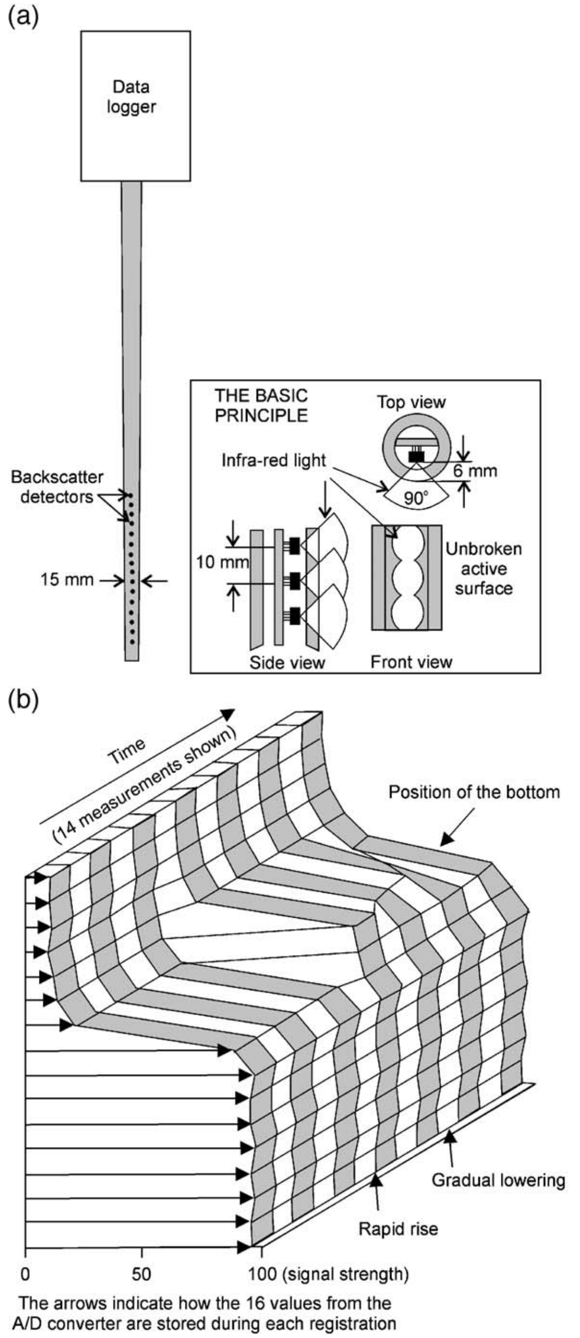

Fig. 10. Sedimeter instrumentation (a) and corresponding data (b). Modified from Figs. 1 and 2 of Erlingsson (1991). The signal strength is indicated as an index value from 0 to 100, and needs to be calibrated in order transform this index to a precise value of bottom elevation.

The sedimeter is suitable for monitoring both accumulation and erosion, yet the latter cannot be differentiated from consolidation processes.

Rapid changes over periods of minutes are detectable with this device, making monitoring of ephemeral sediment layers (e.g., ripples) possible (Fig. 10b). Resolution of 100 μm was achieved in the laboratory, but the accuracy was not specified. Like pegs, the sedimeter is likely to disturb local flow hydrodynamics, although Erlingsson (1991) suggests that this effect introduces a constant offset and is negligible for relative measurements (as opposed to absolute measurements). With a relatively high cost per instrument, due to the self-logging device, and with an instrument required at each measurement location, this technique provides spots measurements with a deployment of ca. five instruments per survey (for instance). Distances between sites may vary from tens of metres to kilometres depending on the objectives of the survey, with the spatial resolution decreasing accordingly.

3.2.2. Photo-electronic erosion pin

Similarly to the sedimeter, the photo-electronic erosion pin (PEEP) consists of a vertical row of photosensitive cells connected in series and enclosed within a waterproofed transparent rod, as shown in Fig. 11a (Lawler, 1991). This technique has been mainly used for surveys of river bank or beach and dune profile changes in the past. The rod is partly inserted vertically into the ground at intertidal or shallow marine sites. As sediment level changes, more or fewer cells are exposed to light, respectively causing the voltage output of the device to increase or decrease. Readings are calibrated depending on ambient light level (an artificial light is used at night).

This device measures accumulation and erosion as well as subsurface processes over the buried section of the instrument. Its resolution was reported to be within ca. 2 mm, whilst accuracy was not specified. PEEP was one of the first instruments to provide quasi-continuous time-series data of sediment elevation changes, and an example of elevation data collected every minutes over more than 2 months is shown in Fig. 11b. As a consequence, it was also the first instrument to allow comparison of elevations changes with tidal and wind forcings on a scale of minutes to hours as illustrated in Mitchell et al.

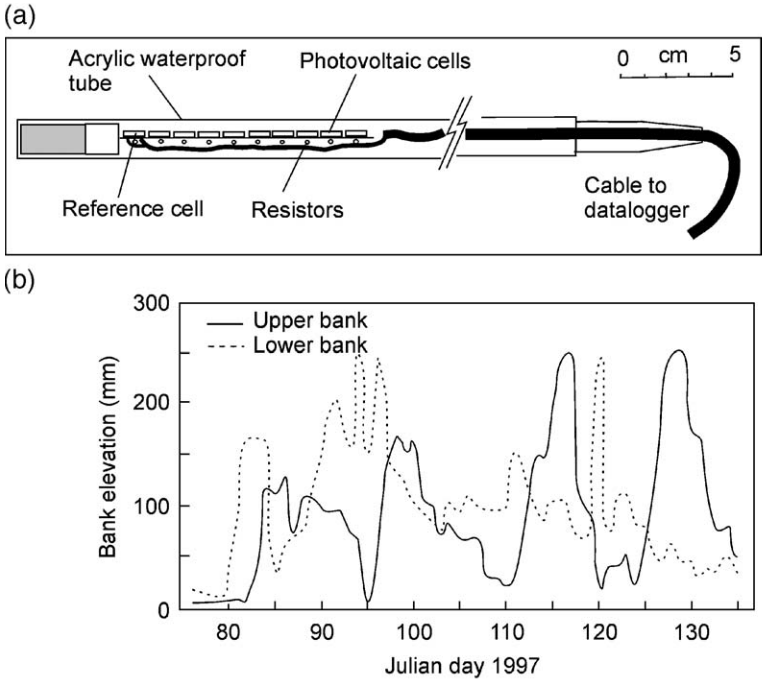

Fig. 11. Photo-electronic erosion pin (PEEP) (a) and corresponding data obtained on an intertidal mudbank (b). Modified from Fig. 1 of Lawler (1991) and from Fig. 3 of Mitchell et al. (1999), respectively.

(1999). However, its resolution is not satisfactory for very small-scale measurements, and scouring was observed around the instrument, due to hydrodynamics disturbance. Finally, long deployments may be limited by fouling over the sensors. Spatial coverage suffers the same limitations as the sedimeter method, i.e., a relatively high cost per instrument (due to the self-logging unit) and spots measurements at each instrument site, with a realistic deployment including 5–10 sites for the survey area.

3.2.3. Conductivity sensors

Ridd (1992) developed a field instrument based on the difference between the electrical conductivity of sediment and seawater, and called an electro-resistivity bed level sensor (BLS). The probe is a rod of variable length (from 10 cm to over 1 m, depending on the expected range of vertical changes) inserted vertically into the sediment and connected to an electronic data logger (Fig. 12a). Sediment level changes are sensed by a set of electrodes mounted on the rod, as the conductivity difference between the water and sediment bodies distorts the voltage field generated by a current source placed close to the interface. This instrument detects downward and upward changes and records elevation changes over the probe length.

Resolution depends on the electrode spacing and is ca. 1–2% of the instrument length. The smallest instrument that has effectively been used to date is a 10-cm rod with a 1–2 mm resolution, although higher resolution is theoretically possible. Accuracy is not specified. The high temporal resolution has been used to survey ripples progression over a tidal cycle as illustrated on Fig. 12b (Larcombe and Ridd, 1995). Spatial coverage also suffers the same limitations as the sedimeter and the PEEP methods described above, i.e., a relatively high cost per instrument (due to the self-logging unit) and spots measurements at each instrument site, with a realistic deployment including 5–10 sites for the survey area. An important limitation of this technique is that it cannot be used reliably in estuaries where the water salinity varies with time.

Blewett et al. (2001) developed a similar electrical impedance technique in conjunction with a settlement column to monitor the sedimentation processes of

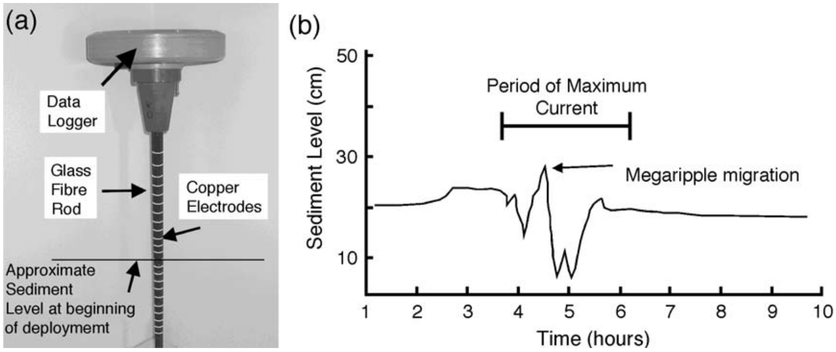

Fig. 12. Electro-resistivity sediment bed level sensor (a) and sand ripples migration measured with the BLS (b) modified from Figs. 1 and 2 of Thomas et al. (2002), respectively.

kaolin particles from a slurry. Electrodes were built flush with the column walls and measurements of the impedance were taken using parallel electric field lines perpendicular to the accumulation direction. This technique, tested in a 3-day laboratory experiment, was proposed to provide an in situ, non-invasive technique to study sedimentation processes (Blewett et al., 2001). However, no information on an instrument designed for the field is available to date. Sampling frequency was 1 hour in the laboratory test, although it could probably be increased. Accuracy is unknown.

4. Conclusion

Methods available to measure sediment accumulation over a short-term period (order of days to months at the most) in situ and in laboratory conditions are reviewed. Methods are classified based on two criteria: (a) whether they measure sediment accumulation or sediment elevation change, and (b) whether they allow continuous or discontinuous measurements. A brief description of the main characteristics of each method is given, along with its vertical resolution, its accuracy, its temporal resolution, its spatial coverage capacity, and an indication of its relative cost. However, the cost indication may be deceptive in cases where a technique may be much more expensive than another one (for instance, self-logging turbidity sensors as opposed to collecting water samples) but also drastically reduces manpower requirements and field costs. In these cases, the overall cost of the survey may sometimes be minimised by using the expensive techniques, which also provide a more comprehensive data set. Nevertheless, there is no ideal technique in general as the selection of a method depends on a combination of scientific, logistical, and financial requirements. Users will thus need to define their objectives and requirements before selecting the most appropriate method, which may include adapting or developing further an existing method.

Amongst methods measuring sediment accumulation, most discontinuous techniques (marker horizon, anchored tiles, ruler, sediment traps, and SSC changes) do not allow for much development or improvement, other than varying the nature of the horizon or the shape of the trap for instance. Anchored tiles could be improved by covering the tiles with a permanent layer of sediment, in order to imitate the natural surface characteristics such as friction and stickiness. This potential improvement also applies for the OBS sediment accumulation sensor in theory. However, because the OBS sensor saturates electronically after a small layer of sediment has accumulated (in the order of 0.1 mm), it is not practical to cover the sensor with a permanent sediment layer. A more realistic approach would be to modify the OBS instrument into a forward scattering sensor, with a transmitter positioned under the sensor plate (as in Fig. 5a) and a receiver unit above the plate. Experimental trials indicate that a forward signal could be detected through a layer of 3–4 mm, hence allowing to pre-coat the plate with a permanent layer of sediment, therewith avoiding effects linked with the difference in surface characteristics. Gravimetric balances provide satisfactory results under laboratory conditions, but their adaptation to field conditions causes numerous problems. Video images have potential for high-speed and high vertical resolution localised measurements, but the extrapolation from spot measurements to spatial averages will remain very limited, due to its very high cost and labour-intensive data analysis.

Amongst methods measuring surface elevation changes, graduated pegs are the technique that offers the least potential for improvement due to their very basic mechanism. SETs have been continuously improved by successive users, in particular to improve accuracy and to adapt the methods to various environments (e.g., vegetated swamps) (Cahoon et al., 2002a). The use of radionuclides offers a high potential for improvement by using various elements with different half-lives. However, this technique also contains a potentially high environmental risk, which will keep limiting its applications under natural conditions, and so will its high cost that is unlikely to decrease significantly. High cost is also a limitation to the echo-sounding method, which otherwise offers a very high potential for comprehensive surveys of surface elevation changes. Successive echo sounder surveys of the sea bed to determine sea bed elevation change have improved dramatically with the introduction of differential ground positioning systems (DGPS). DGPS allow the vertical and horizontal position of the echo sounder mounted on a boat to be determined with great accuracy. Clearly, future improvements in DGPS will further enhance the accuracy of echo sounder surveys. Increasing the frequency of operation of the echo sounder could also improve the resolution and accuracy of echo sounder surveys since the wavelength of sound in water at 210 kHz is in the order of 1 cm, which ultimately places a limit on the accuracy to which the bed can be located. Finally, amongst continuous methods measuring surface elevation changes, improvements are most likely to stem from increase in vertical resolution and a decrease in prices, assuming that their use becomes more and more widespread. The electro-resistivity bed elevation sensor, for instance, has been developed into a prototype that can measure vertical changes in the order of microns, by replacing the vertical rod and suite of ring electrodes with a horizontal grid of thin wires (P. Ridd, personal communication). This method has been developed and calibrated under laboratory conditions at this stage but no field application has been implemented successfully to date.

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