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Cohesive Sediment Flocculation and the Application to Settling Flux Modelling

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1. Introduction

The majority of the particulate matter which accumulates within an estuary is commonly referred to as mud. Mud is typically composed of mineral grains which originate from both fluvial and marine sources, together with biological matter - both living and in various stages of decomposition. It is the combination of these features that make estuarine muds sticky in nature and for this reason these sediment types are referred to generically as cohesive sediment (Whitehouse et al., 2000).

The primary mineral component of cohesive muds are clay minerals. Clays have a plate-like structure, and generally have a diameter of less than 2 μm . Cohesion arises through the combined efforts of both the electrostatic charging of the clay minerals as they pass through brackish to highly saline water, and various biogenic long-chain polymer molecules which adhere to individual particle surfaces, such as sticky mucopolysaccharides. Edzwald and O'Melia (1975) conducted experiments with pure kaolinite, and found that their flocculation efficiency was less than 10%. Where as Kranck (1984) found that the flocculation of mineral particles which contained some organic matter, greatly enhanced the settling velocity of the aggregates (Fig. 1). The efficiency with which the particles coagulate is a reflection of the stability of the suspension (van Leussen, 1994). The statistical occurrence of collisions further increases as the abundance of particles in suspension rise. A suspension is classified as unstable when it becomes fully flocculated, and is stable when all particles remain as individual entities.

From a water quality perspective, cohesive sediments have the propensity to adsorb contaminants (Ackroyd et al., 1986; Stewart and Thomson, 1997). This in turn has a direct effect on water quality and related environmental issues (e.g. Uncles et al., 1998). Accurately predicting the movement of muddy sediments in an estuary therefore is highly desirable. In contrast to non-cohesive sandy sediments, muddy sediments can flocculate (Winterwerp and van Kesteren, 2004) and this poses a serious complication to modellers of estuarine sediment dynamics.

This chapter provides the following:

- An outline of the flocculation process
- Flocculation measurement methods and the importance of data
- Floc settling behaviour
- Examples of cohesive sediment depositional model approaches, including ways of parameterising flocculation

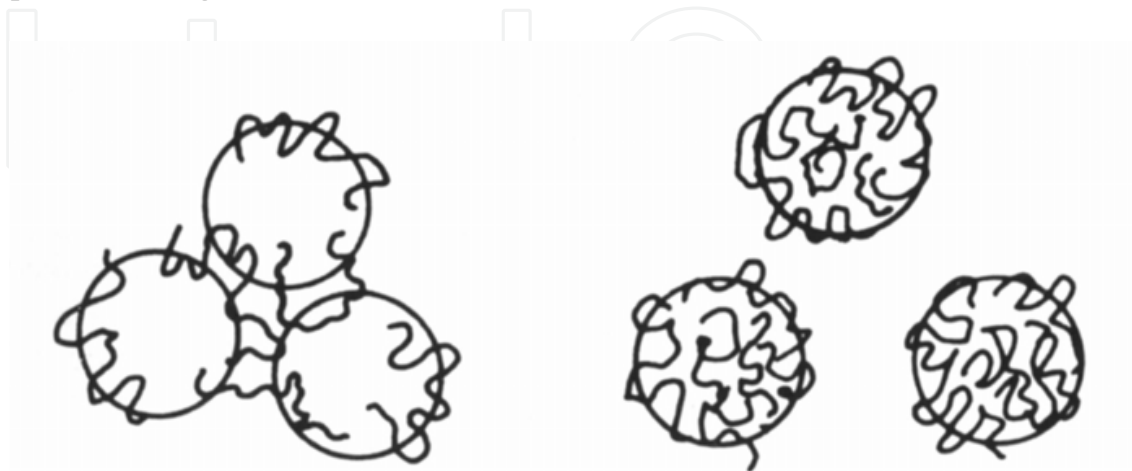


Fig. 1. Flocculation and destabilisation by adsorbed polymers (after Gregory, 1978).

2. Flocculation overview

Cohesive sediments have the potential to flocculate into larger aggregates termed flocs (Winterwerp and van Kesteren, 2004; see example in Fig. 2). Floc sizes (D) can range over four orders of magnitude, from individual clay particles of $1\ \mu\text{m}$ to stringer-type floc structures several centimetres in length. An individual floc may comprise up to 10^6 individual particulates, and as flocs grow in size their effective densities (i.e. bulk density minus the water density), ρ_e , generally decrease (Tambo and Watanabe, 1979; Klimpel and Hogg, 1986; Droppo et al., 2000), but their settling speeds (W_s) rise due to a Stokes' Law relationship (Dyer and Manning, 1998). The general trend exhibited by floc effective densities by a number of authors is shown in Fig 3. A typical floc size vs. settling velocity distribution from the Tamar Estuary (UK) is illustrated in Fig 4. One can immediately see that for a constant W_s , there is a wide range in D and ρ_e . Similarly, for a constant D , there is a large spread in both W_s and ρ_e . Like the floc size, the settling velocities can also typically range over four orders of magnitude, from $0.01\ \text{mm s}^{-1}$ up to several centimetres per second (Lick, 1994).

Kranck and Milligan (1992) observed that under the majority of estuarine conditions, most suspended particulate matter (SPM) within an estuary occurs in the form of flocs. Of the various physical processes which occur during a tidal cycle, flocculation of the sediment is regarded as one of the primary mechanisms which can affect the deposition, erosion and consolidation rates. The flocculation process is dynamically active which is directly affected by its environmental conditions, primarily being dependent on a complex set of interactions between sediment, fluid and flow within which the particles aggregation plays a major role (Manning, 2004a). Flocculation is therefore a principle mechanism which controls how fine sediments are transported throughout an estuary.

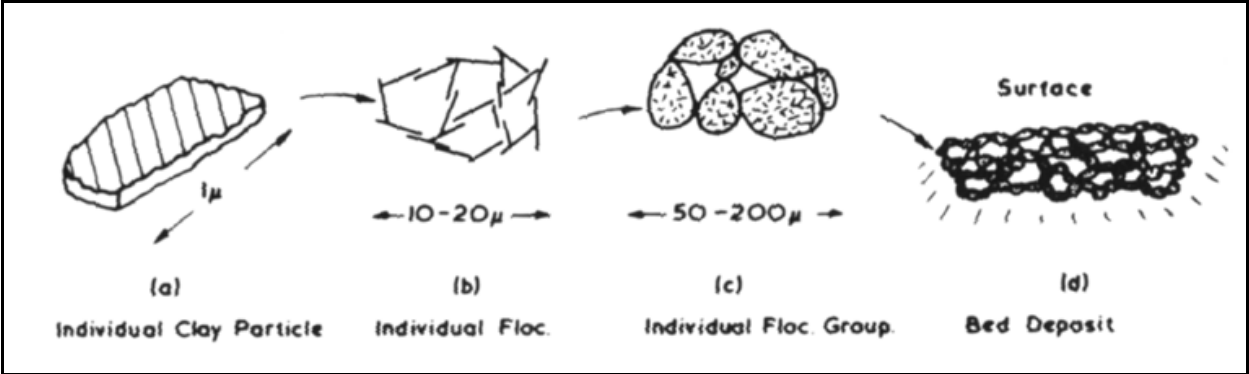


Fig. 2. Sizes of clay particles, flocs and floc groups (after McDowell and O'Connor, 1977)

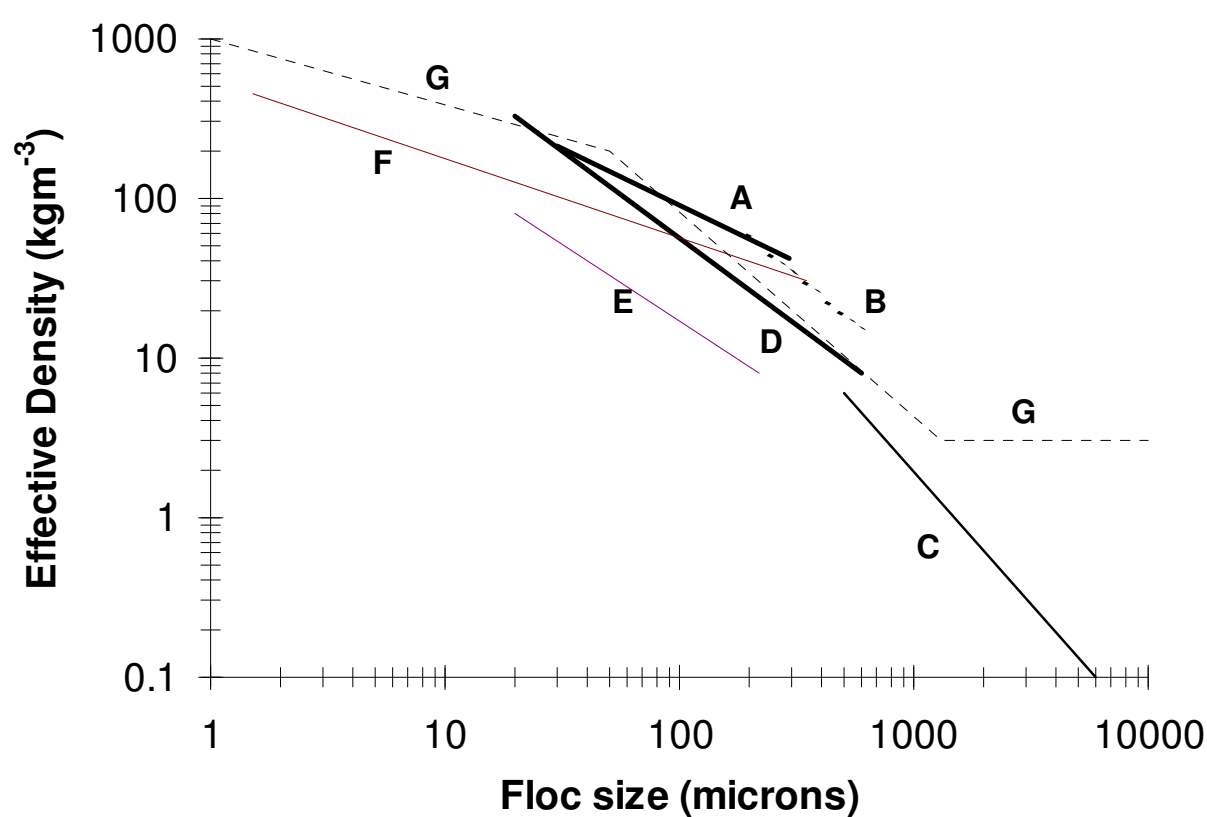


Fig. 3. Comparative results of effective density against floc size. A = Manning and Dyer (1999), B= Al Ani et al. (1991), C = Alldredge and Gotschalk (1988), D = Fennessy et al. (1994b), E= Gibbs (1985), F= McCave (1975), and G = McCave (1984) (from Manning and Dyer, 1999).

The degree of flocculation is highly dependent upon both the SPM concentration and turbulent shear (e.g. Krone, 1962; Parker et al., 1972; McCave, 1984; Burban et al. 1989; van Leussen, 1994; Winterwerp, 1998; Manning, 2004a), and both of these parameters can vary spatially and temporally throughout an estuary. A conceptual model which attempts to explain the linkage between floc structure and floc behaviour in an aquatic environment is provided by Droppo (2001). As a result of dynamic inter-particle collisions, floc growth implies large variations in the sediment settling flux with direct implications on the vertical distribution of sediment loading.

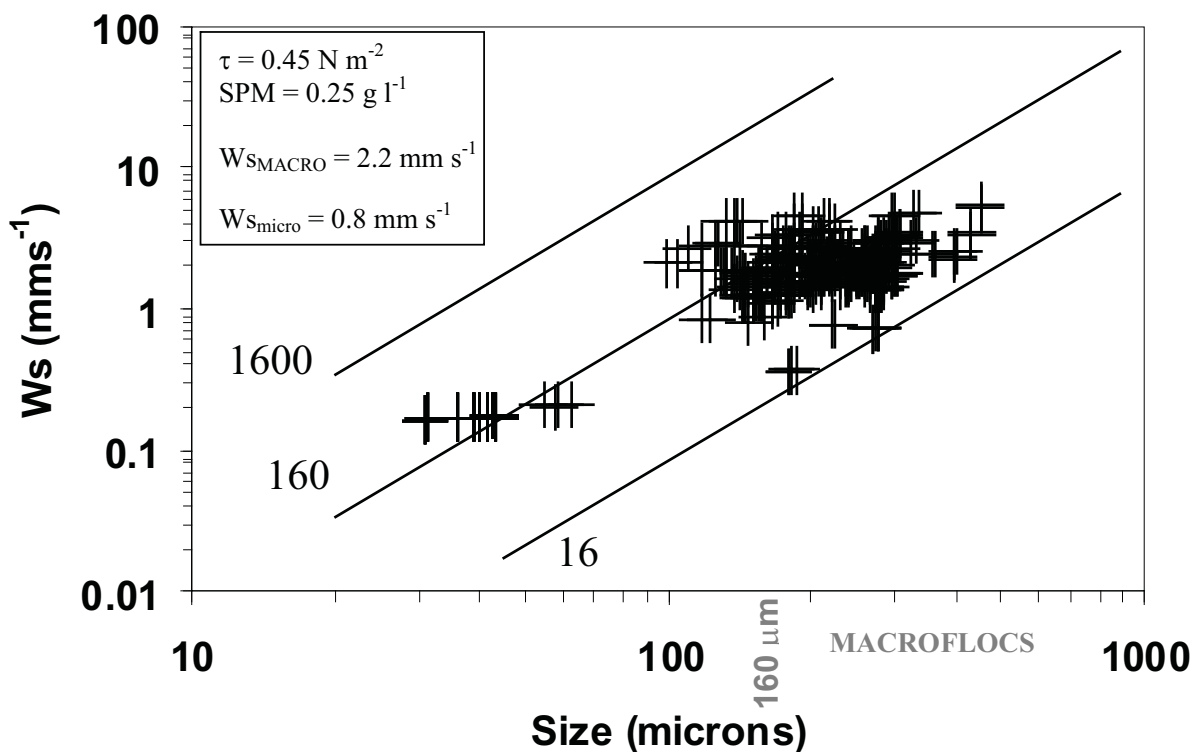


Fig. 4. An example of an INSSEV measured floc population from the Tamar Estuary (UK) illustrating the relationships between floc size and settling velocities of individual flocs during neap tide conditions. The diagonal lines represent values of constant effective density (kg m^{-3}). Macrofloc: microfloc segregation is indicated by the dotted line at $160 \mu\text{m}$ (from Manning, 2004c).

It has been generalised that there are two distinct component groups of flocs: *macroflocs* and *microflocs* (Eisma, 1986; Manning, 2001). Many floc suspensions exist as bi-modally distributed populations (e.g. Manning and Dyer, 2002a; Lee et al., 2010). These two floc fractions form part of Krone's (1963) classic order of aggregation.

Macroflocs (Fig. 5) are large, highly porous ($> 90\%$), fast settling aggregates which are typically the same size as the turbulent Kolmogorov (1941) microscale. Macroflocs ($D > 160 \mu\text{m}$) are recognised as the most important sub-group of flocs, as their fast settling velocities tend to have the most influence on the mass settling flux (Mehta and Lott, 1987). Their fragile, low density structure means they are sensitive to physical disruption during sampling. Macroflocs are progressively broken down as they pass through regions of higher turbulent shear stress, and reduced again to their component microfloc sub-structure (Glasgow and Lucke, 1980). They rapidly attain equilibrium with the local turbulent environment.

The smaller microflocs (Fig. 5; $D < 160 \mu\text{m}$) are generally considered to be the building blocks from which the macroflocs are composed. Microflocs are much more resistant to break-up by turbulent shear. Generally they tend to have slower settling velocities, but exhibit a much wider range in effective densities than the larger macroflocs (e.g. McCave, 1975; Alldredge and Gotschalk, 1988; Fennessy et al., 1994a).

In order for flocculation to occur, suspended particles must come into contact with each other. Van Leussen (1988) theoretically assessed the comparative influence of the three main collision mechanisms: Brownian motion, turbulent shear and differential settling (see Fig. 6),

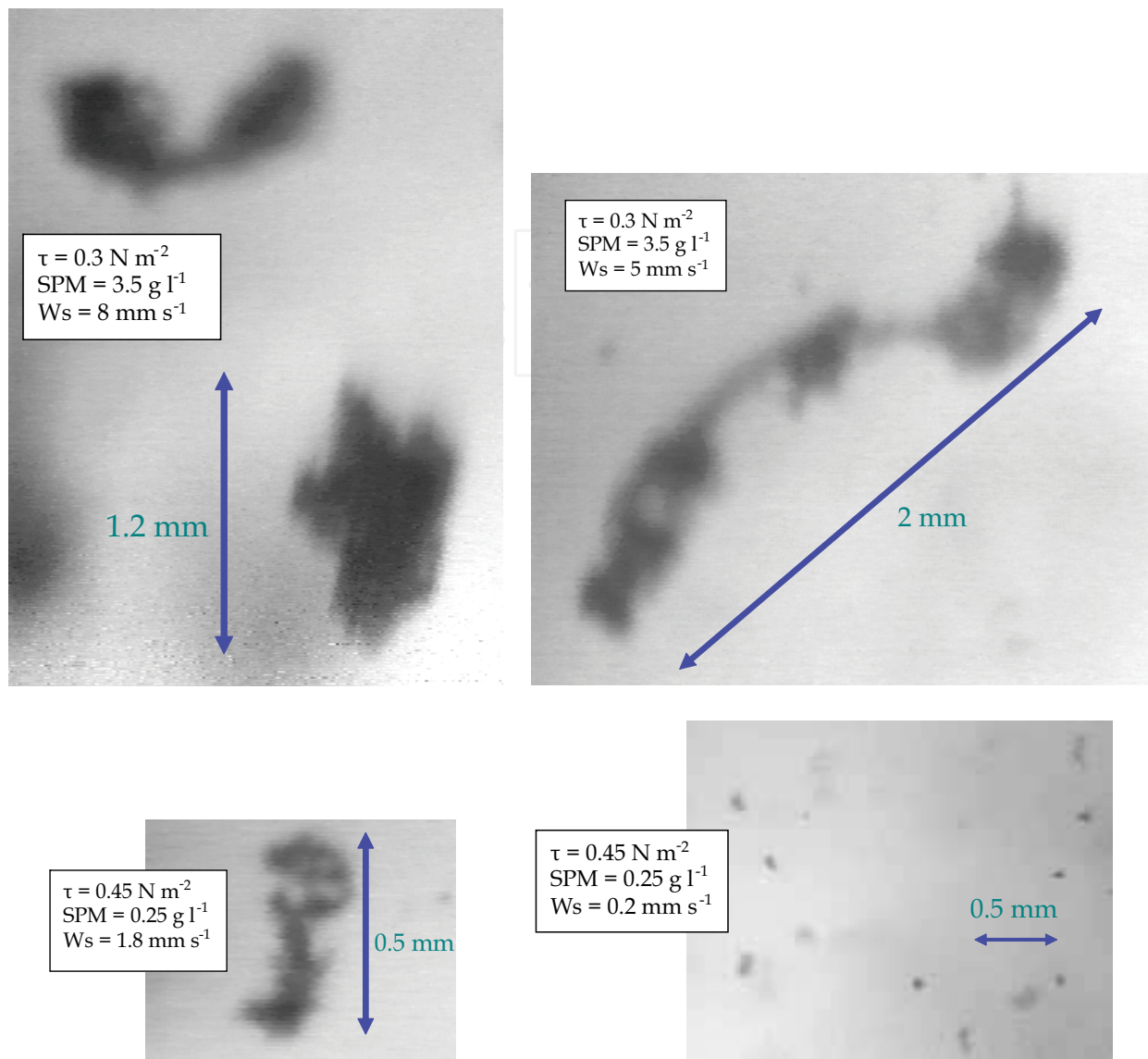


Fig. 5. Illustrative examples of real estuarine floc images. Ambient shear stress, concentration and settling velocity values are provided (from Manning and Dyer, 2002).

and deduced that turbulent shear stresses ranging between 0.03-0.8 Pa, provided the dominant flocculation collision mechanism. Turbulent shear stress can impose a maximum floc size restriction on a floc population in tidal waters (McCave, 1984). Tambo and Hozumi (1979) showed that when the floc diameter was larger than the length-scale of the energy dissipating eddies, the aggregate would break-up. Similarly, Eisma (1986) observed a general agreement between the maximum floc size and the smallest turbulent eddies as categorised by Kolmogorov (1941). Both Puls et al., (1988), and Kranck and Milligan (1992) have hypothesised that both SPM concentration and turbulence are thought to have an effect on the maximum floc size, and the resulting spectra. As SPM concentration increases, the influence of particle collisions can also act as a floc break-up mechanism. Floc break-up by three-particle collisions tends to be the most effective mechanism (Burban et al., 1989). Settling velocity is regarded as the basic parameter used in determining suspended sediment deposition rates in either still or flowing water. Much has been documented on non-cohesive sediments (coarse silts and larger), and it is possible to calculate the settling

velocity of low concentrations in suspension, using well defined expressions (e.g. Stokes' Law), from the relative density, size and shape of the particles, since the only forces involved are gravity and the flow resistance of the particle. However, the settling velocity of flocculated, cohesive sediments in estuaries are significantly greater than the constituent particles. Based on the research of Stolzenbach and Elimelech (1994) and Gregory (1978), Winterwerp and Van Kesteren (2004) concluded that although flocs are porous in composition, they can be treated as impermeable entities when considering their settling speeds.

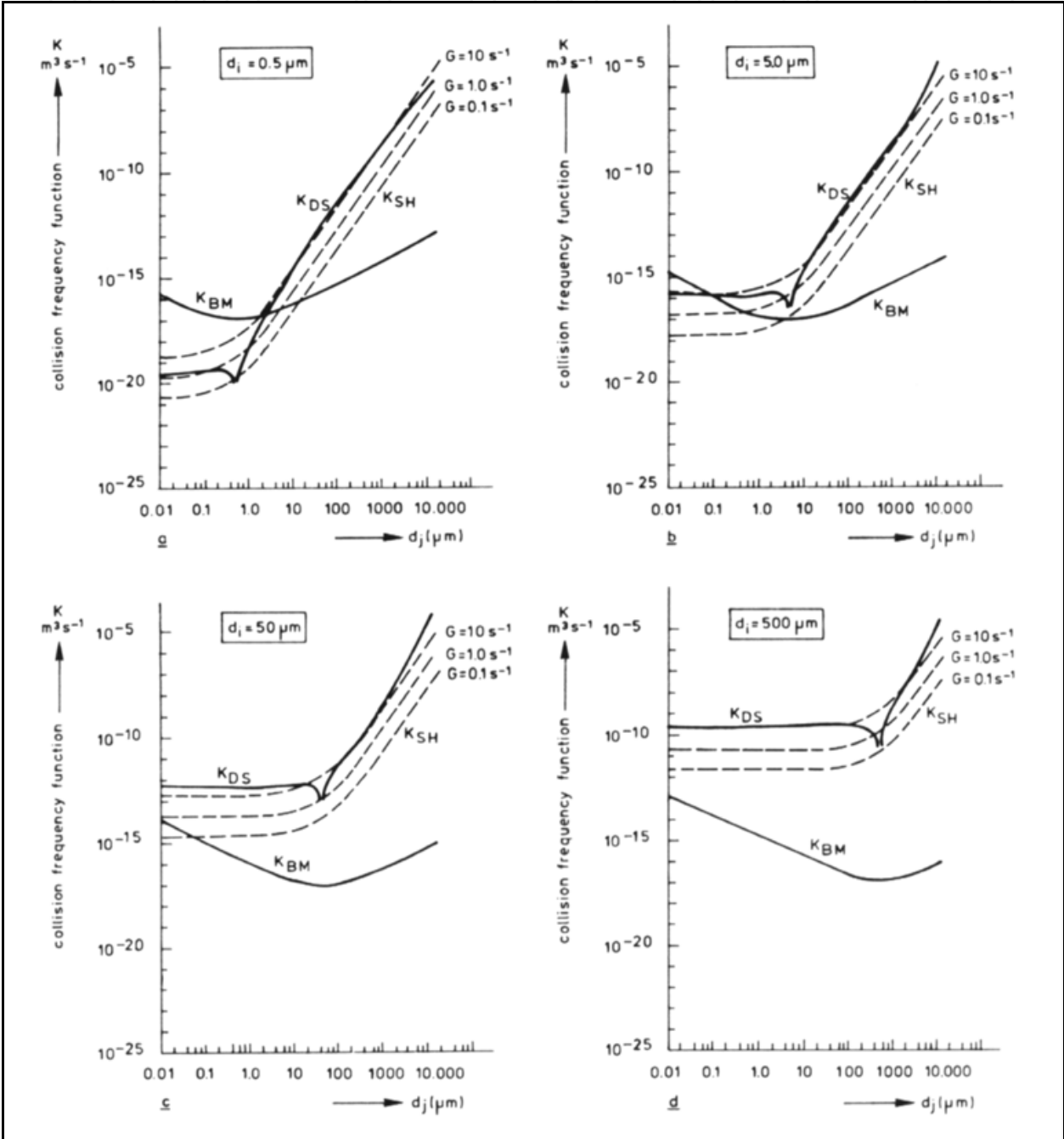


Fig. 6. Comparison of collision mechanisms: Brownian motion (K_{BM}), differential settling (K_{DS}) and turbulent shear (K_{DS}), for different particle diameters (After Van Leussen, 1994).

A knowledge of floc effective density is also important in the calculation of vertical settling fluxes since the majority of the suspended mass is contained in the low density, high settling velocity, large flocs (Mehta and Lott, 1987). Furthermore, the rheological properties of suspended particulate matter are governed by volume concentrations, as opposed to mass concentrations (Dyer, 1989).

3. Flocculation measurement methods and the importance of data

Hayter and Mehta (1982) and Whitehouse et al. (2000) both indicated that many parameters need to be determined in order to fully describe a cohesive sediment type and physical behaviour. Flocs are multi-component, being composed of varying proportions and types of inorganic and organic particles, and the packing (i.e. density) of these grains within a floc can significantly affect their resultant size and settling velocity. It is this complexity that means it is not a simple task to mathematically describe the mud flocculation process on a fundamental basis (Milligan and Hill, 1998; Mikkelsen and Pejrup, 1998). The principle reason for such a poor understanding of cohesive sediment settling fluxes and deposition rates, has been principally due to a lack of reliable floc data, although the situation is now improving. The influence of floc density variations are required for accurate settling flux determination. Therefore a key to rectifying this problem is to use a floc sampling system which directly measures (in-situ) both the simultaneous size and settling velocity of the larger and more fragile flocs.

It is difficult to accurately quantify the influence and occurrence of flocculation, as well as floc break-up, on in-situ estuarine floc distributions. The fragility of large, fastest settling macroflocs, which are easily broken-up upon sampling (Gibbs and Konwar, 1983), has tended to preclude the direct measurement of floc settling and mass characteristics due to instrumentation limitations (Eisma et al., 1997). Floc disruptive devices include field settling tubes (FST), such as the Owen tube (Owen, 1976). These instruments are the original devices used to determine the in situ settling properties of flocculated mud. The Owen tube is the most universally known of all FSTs. It was developed during the 1960's at Hydraulics Research Station Wallingford (now HR Wallingford Ltd) by M.W. Owen (1971, 1976). Collected water samples are extracted from the bottom of the tube at pre-selected time intervals and the settling velocity is inferred from gravimetric analysis (Vanoni, 1975), and tends to significantly under-estimated W_s .

Floc breakage occurs in response to the additional shear created during acquisition (Eisma et al., 1997). The presence of large estuarine macroflocs was initially observed *in-situ* by underwater photography (Eisma et al., 1990). To overcome this problem less invasive techniques for measuring floc size and settling velocity in situ have been developed, for example VIS (van Leussen and Cornelisse, 1994), INSSECT (Mikkelsen et al., 2004), INSSEV (Fennessy et al., 1994b; see Fig. 7), LabSFLOC (Manning, 2006; see Fig. 8), and the HoloCam (Graham and Nimmo Smith, 2010). Unlike particle sizers (e.g. Agrawal and Pottsmith, 2000; Benson and French, 2007; Law et al., 1997), these instruments can provide direct simultaneous measurements of floc size and settling velocity, in-situ, and permit an estimate of individual floc effective density by applying a modified Stokes' Law. These types of measurements make possible the computation of the floc mass distribution across a range of sizes (Fennessy et al., 1997).

Optical devices to measure concentration profiles by Spinrad et al. (1989), Kineke et al. (1989), and McCave and Gross (1991) have sought to quantify the rate of water clearance,

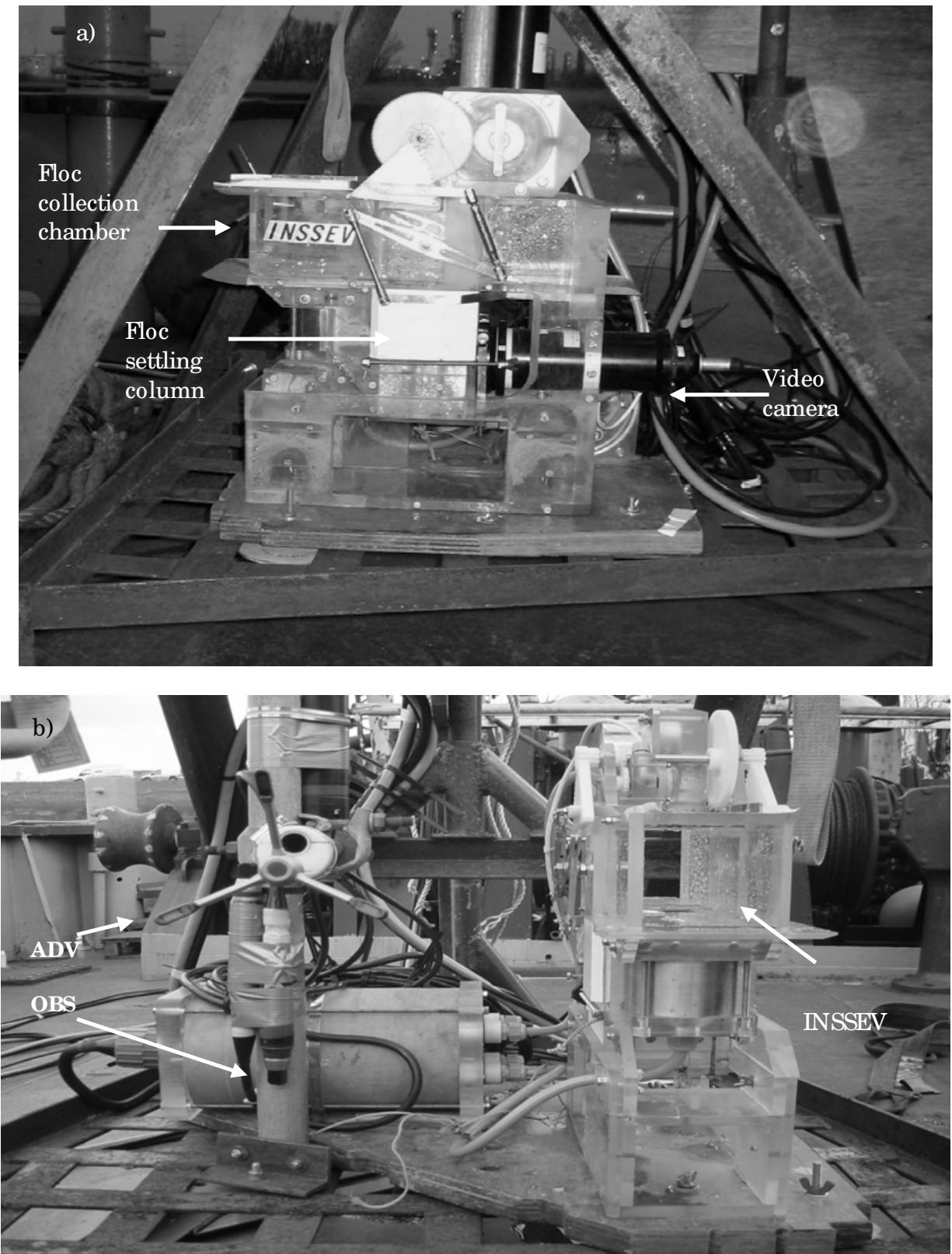


Fig. 7. a) Side view of INSSEV instrument mounted on a metal deployment frame. b) Front view of the INSSEV instrument (*right*), together with optical backscatter (OBS) sensors and an acoustic Doppler velocimeter (ADV) positioned on a vertical pole (*left*). The ADV provides high frequency turbulence data which can be directly related to the floc populations.

but they are unable, like all earlier instrumentation, to measure particle size and settling velocity spectra directly. Whereas sampling devices which directly observe D and W s can provide an insight into the interaction of flocs with both turbulent eddies and SPM concentration variations during a tidal cycle, particularly within the lower layers of the flow where the turbulent shearing is at its greatest (Mehta and Partheniades, 1975). Deploying floc samplers in conjunction with high frequency velocimeters provides scientists a means of accurately acquiring time series of both the spectral distribution of the floc dry mass and settling velocities, together with information on the turbulence fluctuations, directly from within a turbulent estuarine water column. Such site-specific information of floc settling velocity spectra is a prerequisite for accurate physical process parameterisation, especially for the implementation into sediment transport modelling applications (Manning, 2004c).

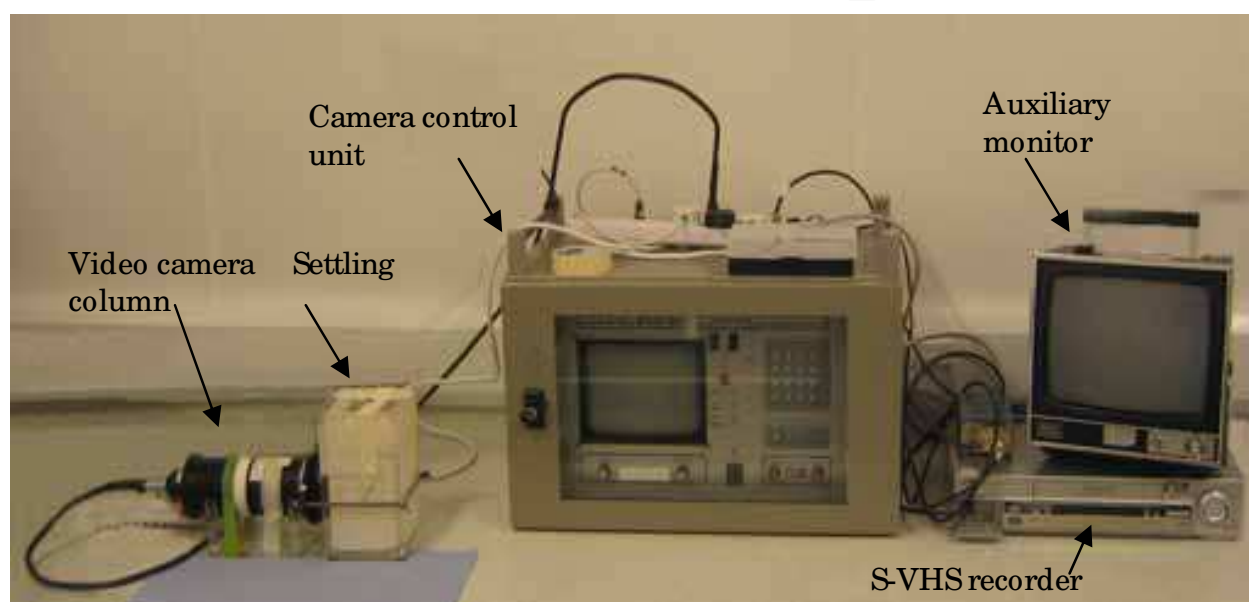


Fig. 8. LabSFLOC set-up (from Manning, 2006).

4. Floc settling behaviour

For non-cohesive sediment, the settling velocity can be regarded as being proportional to the particle size. However, as discussed earlier in this chapter, many estuarine locations tend to be dominated by muddy flocculated sediments and an accurate representation of the vertical sediment settling fluxes for cohesive sediments is problematic. As a result, the sizes and settling velocities of flocs are key parameters in the modelling of cohesive sediment transport in near-shore waters (e.g. Geyer et al., 2000; Cheviet et al., 2002).

Throughout a tidal cycle there are slack water periods (usually around times of high and low water), when the current flow which transports suspended matter in an estuary decreases quite significantly. It is at these times of slack water in the tidal cycle, there tend to be an absence of a significant amount of vertical exchange and allows suspended flocculated matter to deposit to the bed. Stringer flocs have been observed in many European estuaries by underwater cameras (Manning and Dyer, 2002a; Fennessy et al., 1994b) and it has been speculated that they are the result of particle scavenging through differential settling. Particle interaction by differential settling is where larger particles have larger settling velocities, and therefore fall onto relatively smaller particles. Stolzenbach and Elimelech

(1994) have suggested that differential settling is not an important contact mechanism, and may only occur within quiescent waters, particularly slack tide periods.

In still water, the rate of deposition of flocculated sediments is described by the rate of change of sediment mass (m) per unit area, or in other words the gradient dm/dt , where t is time. The depositional rate is equal to the product of the SPM concentration and settling velocity (at any point in time and space), which is known as the mass settling flux (MSF) towards the bed. Where detailed settling information is not available, it is quite common for a median settling velocity, W_{s50} , to be used, although this can produce a misleading representation of the actual settling behaviour of individual floc populations.

Whitehouse et al (2000) note that it is highly probable that a concentration gradient will develop in an estuarine water column in very turbid and tidally active estuaries, e.g. Severn Estuary in the UK (Manning et al., 2009). This means that the near-bed concentration will be greater than the depth-averaged SPM value. As more flocs are deposited to the bed, the near-bed concentration gradient will rise. Thus the amount of SPM higher in water column will progressively decrease with time as more flocculated matter settles to the bed. This will lead to a gradually decrease in the depositional rate. For example, in the Severn Estuary, Whitehouse et al. (2000) found settling fluxes rose to a peak of about $60 \times 10^{-3} \text{ kg m}^{-2}\text{s}^{-1}$ at a SPM of 25 kg m^{-3} . The MSF then rapidly decreases with rising concentration, due to hindered settling effects.

In tidal estuaries, the ambient hydrodynamics very rarely produce perfectly quiescent water column conditions. The mechanisms of the deposition of cohesive sediment in flowing water was originally studied through the use of laboratory flume experiments by Krone (1962), and Einstein and Krone (1962). Further flume experiments were conducted (see Partheniades, 1962; Postma, 1962; Mehta, 1988; Burt and Game, 1985; Delo, 1988). The role of turbulence on settling flocs was also examined by Owen (1971) and Wolanski et al. (1992). Furthermore, field measurements of the deposition of muddy sediments in estuaries during single tides have been undertaken by HR Wallingford (Diserens et al., 1991).

Classically deposition of the cohesive sediment to the bed occurs only when the bottom shear stress falls below some critical value, with the deposition rate proportional to the deficit of shear stress below that critical value. Erosion of cohesive sediment particles from near the estuary bed usually only occur when the bed shear stress rises above some critical value, with the erosion rate depending in some way on the excess of stress above that value. The critical stress for erosion is greater than or equal to the critical stress for deposition, such that an intermediate range of bottom shear stresses can exist for which neither deposition or erosion can occur.

Traditionally the rate of deposition of cohesive sediment from a suspension in flowing water has been modelled using the near-bed SPM concentration (C_b), median settling velocity W_{s50} , the bed shear stress exerted by the flowing water τ_b and a critical bed shear stress for deposition τ_d (Whitehouse et al., 2000). τ_d is defined as the bed shear stress above which there is no deposition of suspended sediment. Lau and Krishnappan (1991) state that classically floc deposition can be identified in terms of a depositional shear stress τ_d , whereby this shear stress provides a threshold indicating that when the ambient shear stress falls below this stress level (i.e. τ_d), the flow is unable to support the matter in suspension and it is deposited.

In reality the whole sediment transport cycle in an estuary is particularly complicated, because it is not necessarily closed, and processes are interdependent. For instance, settling does not always lead to deposition, i.e. when entrainment dominates, and the sediment then

remains in suspension. Sediment tends to respond behind the hydrodynamics of the ambient flow (Dyer, 1995). This lag is created by tidal asymmetry and a phase difference between the SPM concentration and flow velocity; this can produce a residual flux of sediment. For mud deposition, settling lag effects are the most relevant. On the decreasing tide, mud flocs will start to settle once the turbulence in the flow is incapable of maintaining them in suspension. As the flocs settle, they are transported along on the waning current flow, so that they eventually reach the estuary bed some distance up or downstream (depending upon the point in the tidal cycle) from the point at which settling was initiated. This effect is settling lag, and a qualitative model outlining these effects was developed by Postma (1961). A settling lag will sort out the flocs according to their threshold characteristics and settling velocity (Dyer, 1995).

Most previous research indicated that a paradigm of cohesive sediment transport research in that deposition (Dep) and erosion are mutually exclusive (e.g. Ariathurai and Krone, 1976; Officer, 1981; Dyer, 1986; Mehta, 1986, 1988; Partheniades, 1986, 1993; Sheng, 1986; Odd, 1988; Mehta et al., 1989; Uncles and Stephens, 1989). Sanford and Halka (1993) analysed a series of field measurements under tidal conditions in Chesapeake Bay. They observed that the suspended sediment concentration started to decrease when the flow velocity started to decrease. This behaviour could not be simulated by Krone's (1962) depositional formula, when used in conjunction with an erosion formula. Krone's (1962) formula predicted that the SPM concentration could not decrease before the ambient flow velocity, and thus the bed shear stress, fell below its τ_d ($\tau_b < \tau_d$). However, Sanford and Halka (1993) were able to model the observed concentration pattern only when they applied a continuous depositional formula. This is for the case where $\text{Dep} = W_s \cdot C_b$. Sanford and Halka's (1993) research concluded that the paradigm of mutually exclusive deposition and erosion of cohesive sediment, is not valid for real estuarine scenarios, but is valid under laboratory conditions.

Winterwerp (2007) suggested that four elements comprise the deposition of cohesive sediments, which are: i) simultaneous erosion and deposition, ii) erosion rate, iii) bed shear stress, and iv) flocculation. Using this four-point framework, Winterwerp (2007) re-analysed Krone's (1962) original flume results and advocates that a critical shear stress for deposition does not exist. Instead this τ_d stress represents a critical shear stress for erosion of freshly deposited cohesive sediment, i.e. resuspension. Winterwerp's (2007) concludes that the use of Krone's deposition formula and Partheniades erosion formula for the modelling of the water-bed exchange processes (e.g. Ariathuria and Arulanandan, 1978), does not correctly represent the physics. Thus Winterwerp recommended that in order to model the sedimentation flux for applications at low mud SPM concentrations, only the depositional flux itself is required: $\text{Dep} = W_s \cdot C_b$.

This approach concurs with the findings of Sanford and Halka (1993). For higher concentration suspensions, the flocculation process becomes more important. Similarly sediment-turbulence interaction can become significant through the formation of CBS or fluid mud, which can affect the bed shear stress through turbulence damping and drag reduction. However, both Le Hir et al. (2001) and Winterwerp (2002) indicate that the sedimentation flux is still correctly described by $\text{Dep} = W_s \cdot C_b$, even at higher concentrations. The implication of Winterwerp's approach to deposition was reported by Spearman and Manning (2008).

In contrast, Maa et al. (2008) maintain that both τ_b (a hydrodynamic parameter) and τ_d (a sediment parameter) are the main controlling parameters for determining cohesive sediment deposition. Therefore further research is required in this area.

5. Examples of the application of different floc depositional models

Computer simulation models are commonly the chosen tools with which estuarine management groups attempt to predict sediment transport rates for tasks such as routine maintenance dredging, through to estimating the potential impacts new port related construction would have on an existing hydrodynamical regime. In order for these numerical models to provide sufficiently meaningful results, they require a good scientific understanding of the phenomena under consideration, and these processes need to be adequately described (i.e. parameterised) by the model coding.

Of particular importance, a quantitative understanding of the dynamics of the vertical structure of cohesive sediments in suspensions is essential for an accurate estuarine sedimentation model (Kirby, 1986; van Leussen, 1991). This requires an understanding of the physical processes related to the entrainment, advection and deposition of muddy sediments. One physical process which has caused particular difficulty is the modelling and mathematical description of the vertical mass settling flux of sediment, which becomes the depositional flux near to slack water. The MSF is the product of the concentration and the settling velocity. Manning and Bass (2006) have found that mass settling fluxes can vary over four or five orders of magnitude during a tidal cycle in meso- and macrotidal (Davies, 1964) estuaries, therefore a realistic representation of flux variations is crucial to an accurate depositional model.

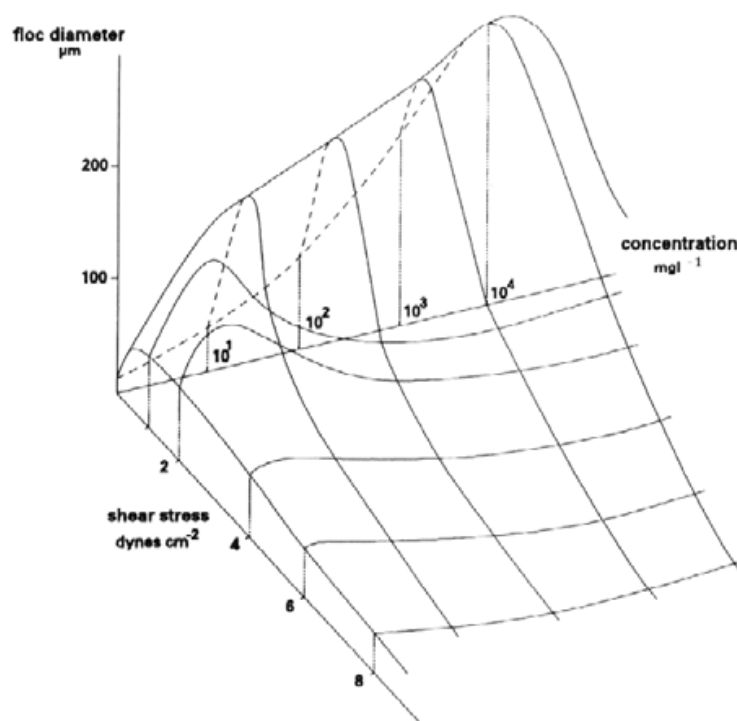


Fig. 9. Conceptual diagram showing the relationship between floc modal diameter, suspended sediment concentration and shear stress (Dyer, 1989).

The specification of the flocculation term within numerical models depends upon the sophistication of the model. Dyer (1989) proposed a conceptual relationship between D (W_s), SPM and τ (Fig. 9), but until recently was largely unproven. Therefore the simplest parameterisation is a settling velocity value which remains constant in both time and space.

Constant W_s of $0.5\text{--}1\text{ mm s}^{-1}$ have historically been used to represent mud settling, although these are now known to significantly under-estimate of macrofloc fall rates. Peterson et al. (2002) in contrast employed a constant W_s of 5 mm s^{-1} for the Tamar Estuary (UK), which tended to over-predict depositional rates. These fixed settling values are typically selected on an arbitrary basis and adjusted by model calibration. The next step has been to use gravimetric data provided by field settling tube experiments to relate flocculation to SPM concentration. Empirical results have shown a general exponential relationship between either the mean or median floc settling velocity (W_{s50}) and SPM for concentrations ranging up to 10 g l^{-1} (Fig. 10). However, both of these parameterisation techniques do not include the important and influential effects of turbulence (Manning, 2004a). Beyond 10 g l^{-1} , the settling of flocs becomes hindered and their terminal velocities progressively slow with rising turbidity (see Fig. 11).

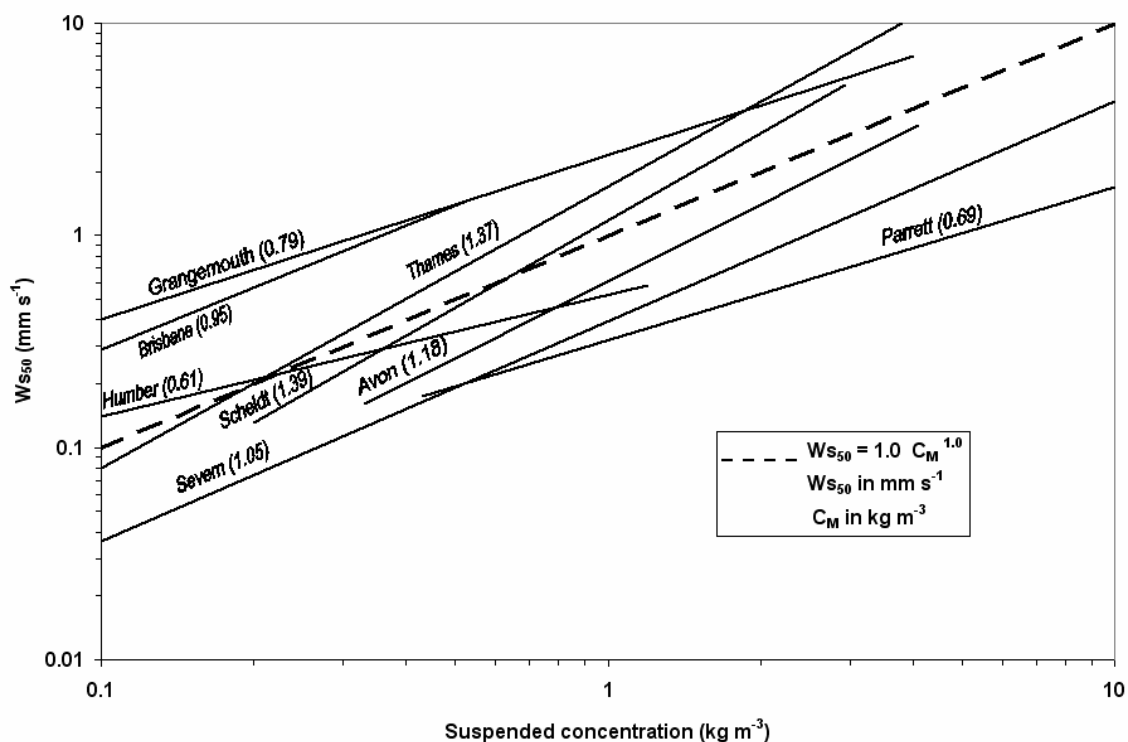


Fig. 10. Owen tube determined median settling velocity as a function of suspended sediment concentration (C_M) for different estuaries. The dotted line represents an exponent of unity (Redrawn from Delo and Ockenden, 1992).

More recently, a number of authors have proposed simple theoretical formulae inter-relating a number of floc characteristics which can then be calibrated by empirical study. Such an approach has been used by van Leussen (1994), who has utilised a formula which modifies the settling velocity in still water, by a growth factor due to turbulence and then divided by a turbulent disruption factor. This is a qualitative simplification of the Argaman and Kaufman (1970) model originally developed for the sanitation industry, with only a limited number of inter-related parameters, and hence does not provide a complete description of floc characteristics within a particular turbulent environment. Even so, Malcherek (1995) applied van Leussen's (1994) heuristic approach to the Wesser Estuary in Germany (Malcherek et al., 1996) with some degrees of success.

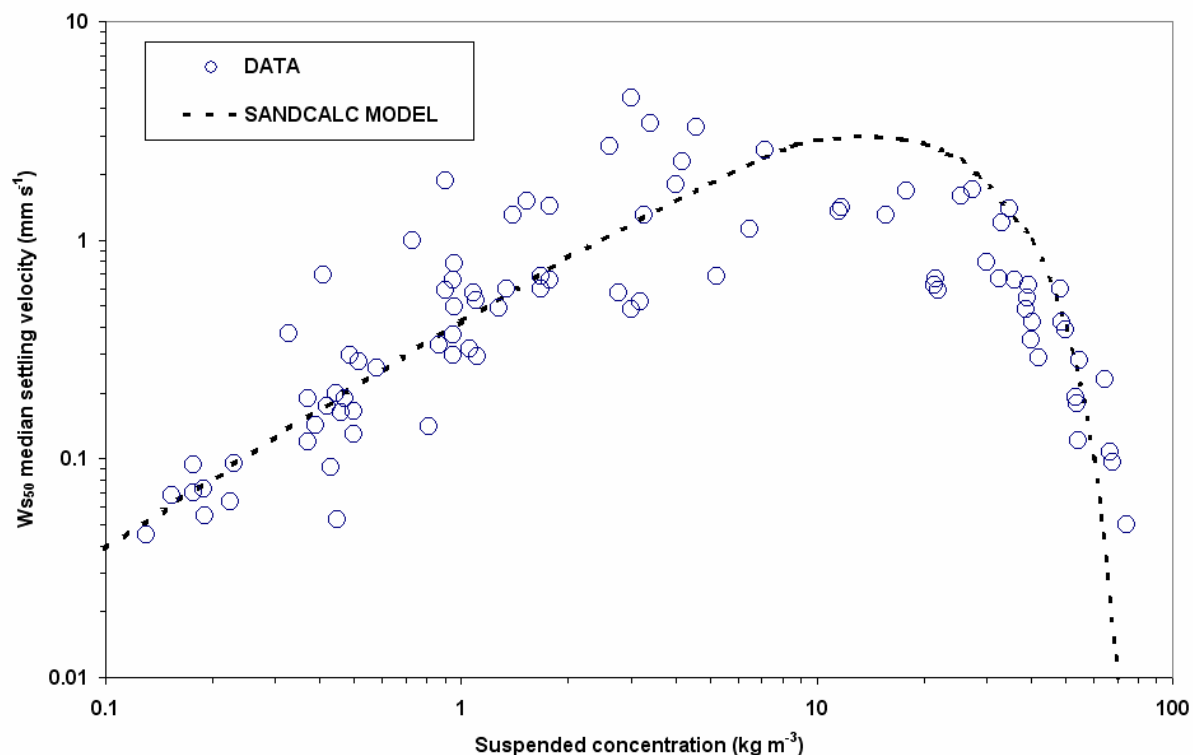


Fig. 11. Median settling velocity of Severn Estuary mud as a function of SPM concentration. The Owen tube data is from Odd and Roger (1986). The solid line represents the hindered settling effect based on the the *SandCalc* sediment transport computational software algorithm (Redrawn from from Soulsby, 2000).

A number of authors have attempted to observe how the floc diameter changes in turbulent environments. For example, Lick et al (1993) derived an empirical relationship based on laboratory measurements using a flocculator. They found the floc diameter varied as a function of the product of the SPM concentration and a turbulence parameter. However, this type of formulation says very little about the important floc settling or dry mass properties. An approach which has recently gained much interest by mathematicians, is the fractal representation of flocs (e.g. Chen and Eisma, 1995; Winterwerp, 1999). Population balance approaches to flocculation modelling can also require floc fractal information (e.g. Maggi, 2005; Mietta et al., 2008; Verney et al., 2010). Fractal theory is dependent on the successive aggregation of self-similar flocs producing a structure that is independent of the scale considered. This is similar to Krone's (1963) order of aggregation. Winterwerp (1998) obtained a relationship, based on research by Kranenburg (1994), relating floc settling to the: floc size, primary particle diameter and the fractal dimension (n_f). Fractal dimensions of 1.4 are representative of fragile aggregates, whilst values of 2.5 indicate strongly bonded estuarine flocs. However, in order to make a fractal based model solvable analytically within a numerical simulation, a mean n_f of 2 is commonly assumed and this ignores important floc density variations. A less complex version of Winterwerp's (1998) original fractal flocculation model since been developed by Winterwerp et al. (2006) and has been incorporated into a Delft 3-D model to examine sediment transport in the Lower Scheldt Estuary.

Most floc settling velocity parameterisations do not include a component which represents floc density and hence floc mass flux variations. Also most floc parameterisations produce a single mean fall rate in time and space. However, a conclusion drawn from an

Intercomparison Experiment of various flocc measuring devices conducted in the Elbe estuary (Dyer et al., 1996), was that a single mean or median settling velocity *did not* adequately represent an entire flocc spectrum, especially in considerations of a flux to the bed. Dyer et al. (1996) recommended that the best approach for accurately representing the settling characteristics of a flocc population was to split a flocc distribution into two or more components, each with their own mean settling velocity. Both Eisma (1986) and Manning (2001) suggest a more realistic and accurate generalisation of flocc patterns can be derived from the larger macrofloc and smaller microfloc sized fractions.

Significant advances into the modelling of flocculated cohesive sediment were made during the recent Defra funded EstProc (Estuary Processes Research) project (Estuary Process Consortium, 2005), where Manning (2004b; 2008) developed a series of algorithms. Manning's algorithms for settling velocity is based entirely on empirical observations made in situ using un-intrusive flocc data collected with the INSSEV instrument (Fennessy et al., 1994; Manning and Dyer, 2002b) together with turbulence data, both acquired from a wide range of estuarine conditions. The Manning settling model includes aspects of flocc mass representation and dual settling velocities, both of which vary in response to shear stress (τ) and SPM concentration changes.

The Manning algorithms were derived using a parametric multiple regression statistical analysis of key parameters which were generated from the raw spectral flocc data (Manning, 2004b; 2008). The algorithms are based on the concept of macrofloc settling ($w_{s,macro}$) and the settling of the smaller microfloc size fraction ($w_{s,micro}$), and the ratio of macrofloc to microfloc mass present in each flocc population termed the SPM_{ratio} (Manning, 2004c). The algorithms are illustrated in Fig. 12. The two fractions were demarcated at 160 μm (Manning, 2001). The representation of flocc population settling characteristics by dividing distributions into bi-modal fraction, each with their own mean settling velocity, as advised by Dyer et al. (1996). Since the development of the MFSV, Baugh and Manning (2007) have subsequently implemented the Manning algorithms into a Telemac 3-D numerical model of the Thames Estuary, and the parameterisation is now being used routinely for projects in the Coasts and Estuaries Group at HR Wallingford. Their findings of the 1-D case studies (see Figs 13 and 14.) found the MFSV model could reproduce 93% of the total mass settling flux observed over a spring tidal cycle. This increased to a near-perfect match within the turbidity maximum zone. A constant W_s of 0.5 mm s⁻¹ only estimated 15% of the flux within the turbidity maximum zone (TMZ), whereas a fixed 5 mm s⁻¹ settling rate over-predicted the TMZ mass flux by 47%. Both a power law W_s – SPM representation and van Leussen method did not fare much better, typically estimating less than half the observed flux during the various tidal and sub-tidal cycle periods. When the Manning settling flux model was applied to a highly saturated benthic suspension layer with SPM concentrations approaching 6 g l⁻¹, it calculated 96% of the observed flux. In contrast, the van Leussen approach only predicted a third of the total observed flux within a concentrated benthic suspension layer.

During 3-D model testing, Baugh and Manning (2007) reported the use of a constant settling velocity did not result in the representation of any of the observed structure of suspended concentrations (Fig. 15). The use of a linear settling velocity was a great improvement, firstly in that it introduced an element of vertical variation in the predicted suspended concentration. Secondly, the linear formulation also resulted in higher concentrations occurring on the inside of the river bend during the ebb tide and on the outside of the bend on the flood tide as observed. The use of the Manning algorithms further improved the

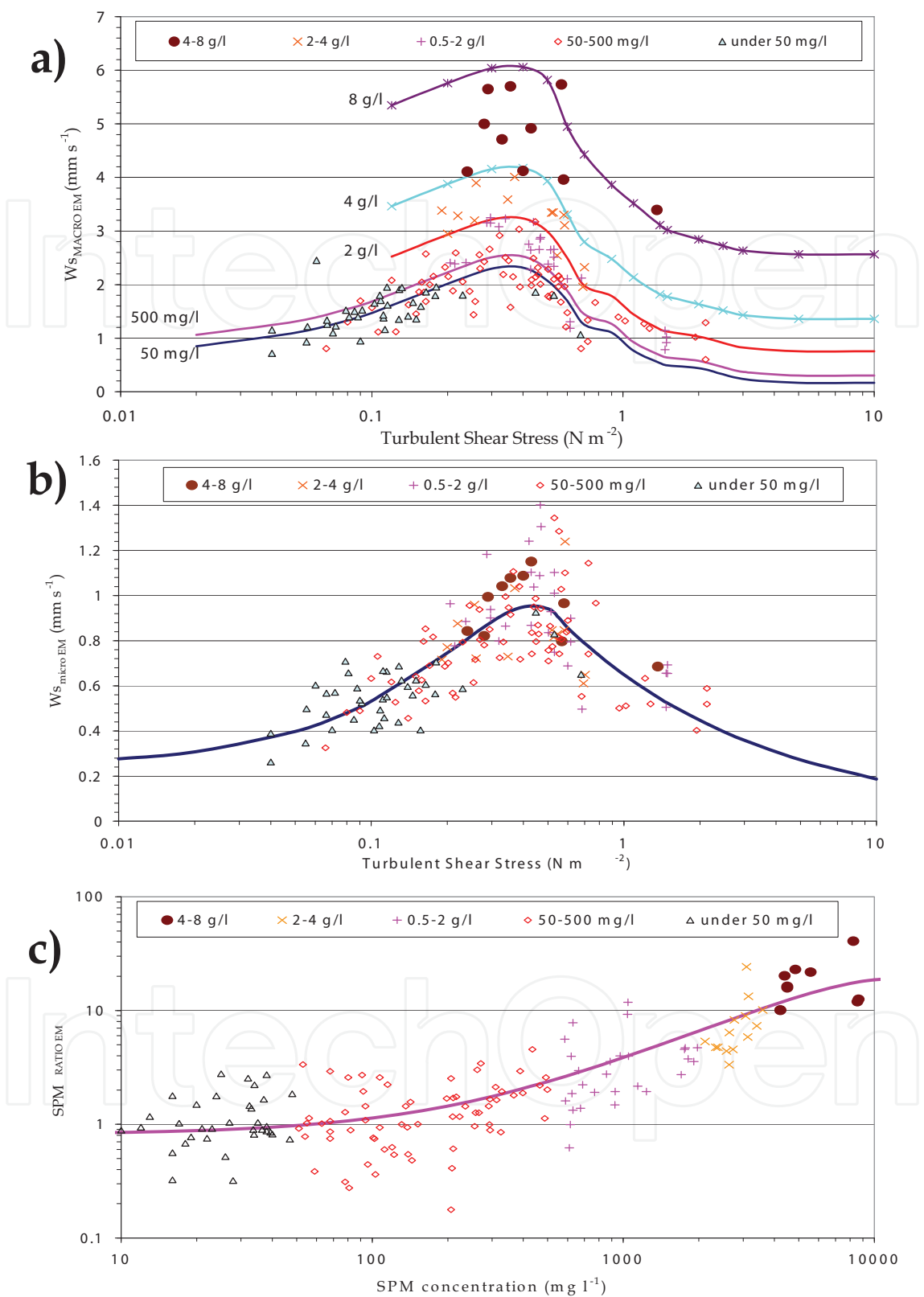


Fig. 12. Representative plots of the statistically generated regression curves, together with the experimental data points, illustrating the three contributing components for the empirical flocculation model: a) W_{s_macro} at various constant SPM values plotted against τ ; b) W_{s_micro} plotted against τ ; and c) SPMratio plotted against SPM (from Manning and Dyer, 2007).

representation of the observed distribution by increasing the level of vertical variation in suspended concentration. The Manning algorithm also introduced an area of higher concentration on the inside of the bend during the flood tide, as was observed. Similarly, Spearman (2004) reported significant improvements in a 3-D numerical mud transport simulation on tidal flats when Manning’s settling model was included. Soulsby and Manning (see Soulsby et al., 2010 in prep.) have since derived a more physics-based flocculation model. This model is based on the key mass settling flux flocculation characteristics exhibited by the original Manning algorithms, but intends to provide a more generic, floc modelling solution, through a reduction in the number of coefficients used during calibration.

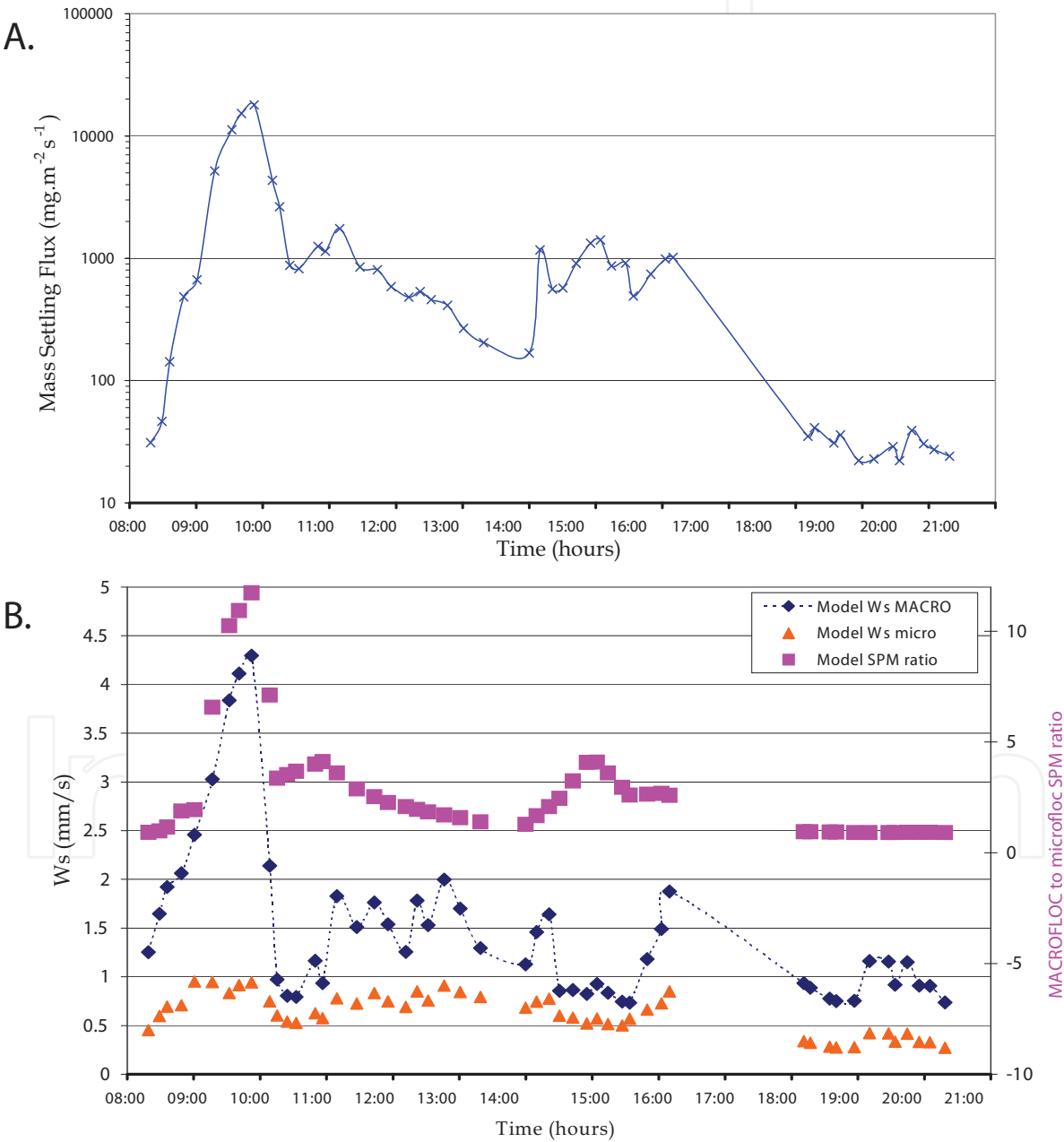


Fig. 13. A) Observed mass settling flux time series, B) Manning model component algorithm outputs for the tidal cycle (from Baugh and Manning, 2007).

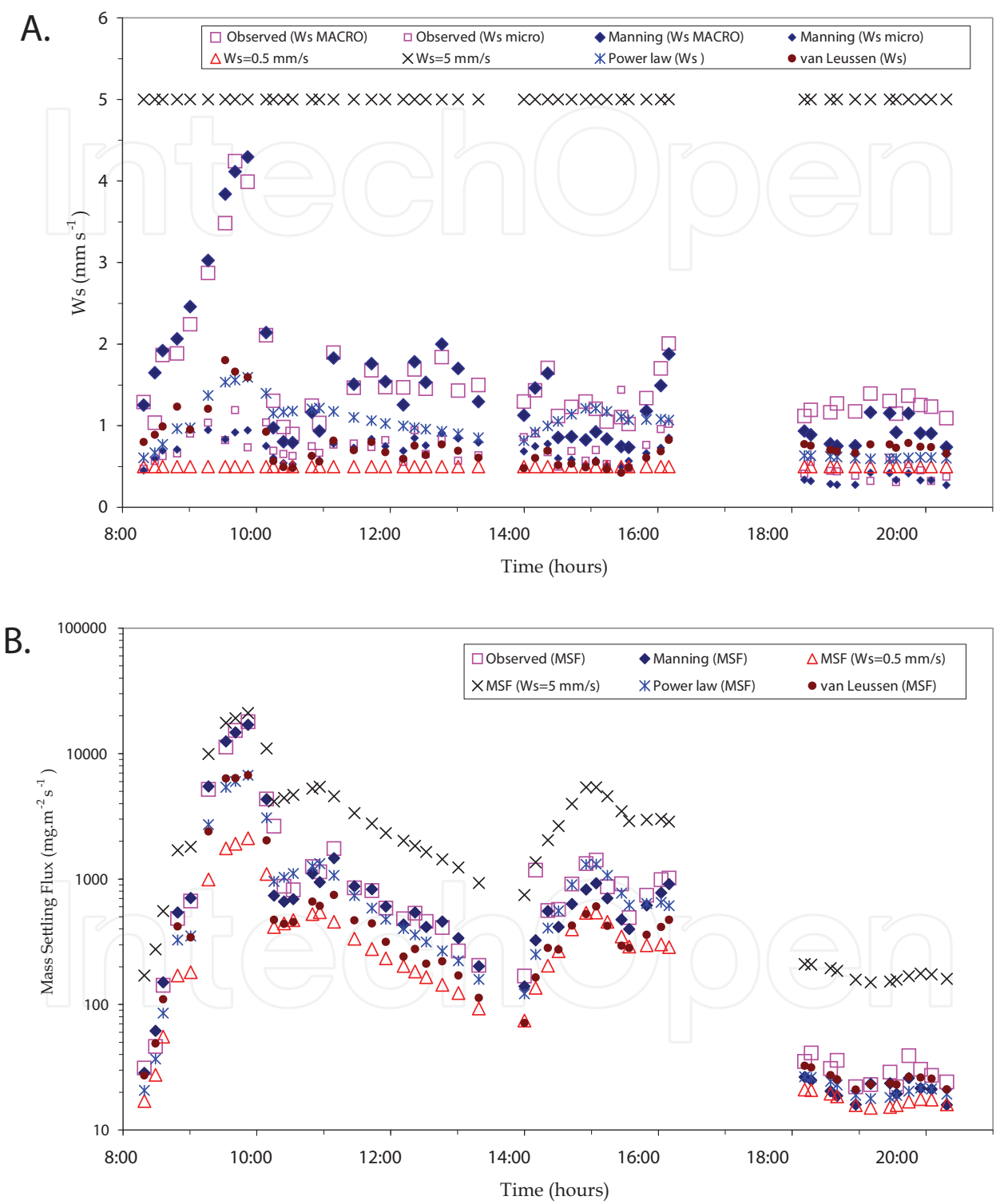


Fig. 14. Tidal cycle time series comparison of observed and predicted values of: A) settling velocity, B) mass settling flux (from Baugh and Manning, 2007).

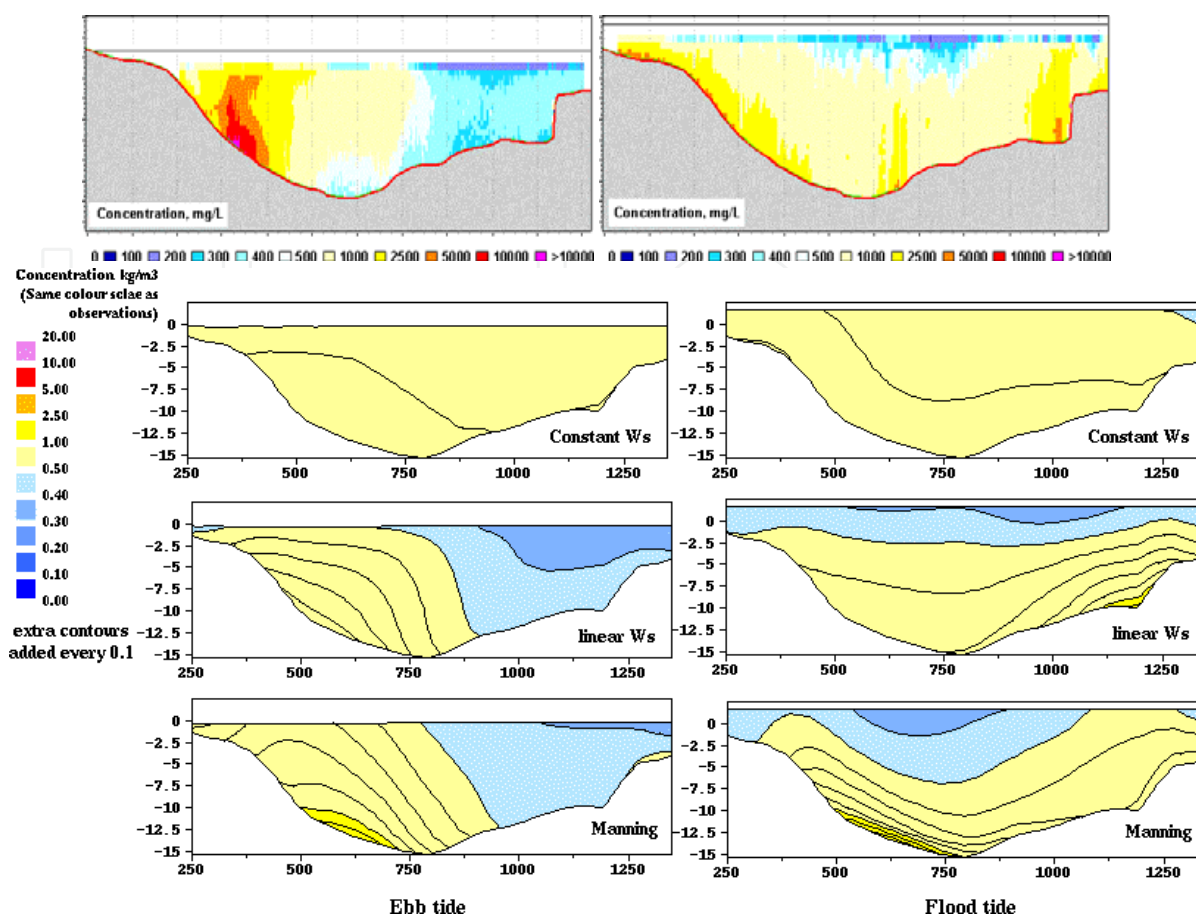


Fig. 15. Comparison of observed sediment concentrations across the river section (top) and predicted sediment concentrations using different assumptions about the settling velocity (from Baugh and Manning, 2007).

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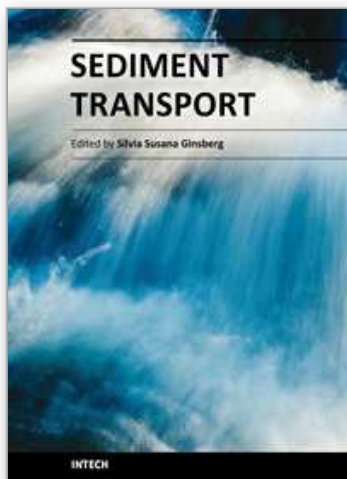
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Sediment transport is a book that covers a wide variety of subject matters. It combines the personal and professional experience of the authors on solid particles transport and related problems, whose expertise is focused in aqueous systems and in laboratory flumes. This includes a series of chapters on hydrodynamics and their relationship with sediment transport and morphological development. The different contributions deal with issues such as the sediment transport modeling; sediment dynamics in stream confluence or river diversion, in meandering channels, at interconnected tidal channels system; changes in sediment transport under fine materials, cohesive materials and ice cover; environmental remediation of contaminated fine sediments. This is an invaluable interdisciplinary textbook and an important contribution to the sediment transport field. I strongly recommend this textbook to those in charge of conducting research on engineering issues or wishing to deal with equally important scientific problems.

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