Marine Geology 277 (2010) 1–10

Contents lists available at ScienceDirect

Marine Geology

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

Observations of particle density and scattering in the Tamar Estuary

K.M. Braithwaite [a,*], D.G. Bowers [a], W.A.M. Nimmo Smith [b], G.W. Graham [b], Y.C. Agrawal [c], O.A. Mikkelsen [c]

[a] School of Ocean Sciences, Bangor University, Menai Bridge, UK, LL59 5AB
[b] School of Earth, Ocean and Environmental Sciences, University of Plymouth, UK, PL4 8AA
[c] Sequoia Scientific, Inc., Bellevue, Washington, USA

A R T I C L E   I N F O

Article history:
Received 12 June 2009
Received in revised form 30 June 2010
Accepted 30 June 2010
Available online 17 July 2010

Communicated by J.T. Wells

Keywords:
particle size
particle density
flocculation
LISST
fractal dimension

A B S T R A C T

To investigate the relationships between the optical scattering and the physical properties of suspended sediments such as size and density, the absorption and scattering coefficients (a and b), mass concentration and particle size spectra have been measured at 30 stations along a transect of the Tamar Estuary and Plymouth Sound. The apparent density of the suspended sediment (ρ_a), which dropped significantly in the upper reaches of the estuary, was found to vary negatively as a function of both the chlorophyll concentration and median particle size by volume (D_v).
A relationship of the form, $\rho_i = (\rho_p / D_p^{-\alpha})\, D_i^{-\alpha}$ relating the density of individual particle size fractions (ρ_i) of diameter D_i has been assumed and used to predict the total apparent density of the size spectrum. By comparing this to the measured apparent density, the size and density of the primary particles (D_p and ρ_p) and value of α (a measure of the fractal dimension) which in combination produce the best fit of predicted to actual ρ have been found. They were found to be 3.9 µm, 1787 kg m^{-3} and 0.65, respectively. These values were closely reproduced by repeating this method for the specific scattering coefficient (b^*) which was determined by applying Mie theory to the measured particle size spectra for a refractive index consistent with that used by the LISST instrument. Using the calculated values of D_p and ρ_p the best fit value for the fractal dimension was determined for each station. The fractal dimension is shown to be strongly correlated with the apparent density and varies significantly from 2.05 in turbid, chlorophyll-rich Tamar water to 2.56 in the clearer water out in Plymouth Sound. Results suggest that the relationship between fractal dimension and particle density is robust and can be used to predict primary particle size and density from bulk properties. Until now these values, which are important for aggregation models have not been easily determined.

1. Introduction

Sediments are a dynamic constituent of the ocean, shelf seas and estuaries. The vertical and spatial distribution, size and composition of the suspended matter and bed sediments are constantly changing in response to high and low frequency processes. While tides produce regular patterns of resuspension, deposition and advection, wind events give rise to random resuspension events. Changes in the seasons are also reflected in the sediments. Lower wind speeds reduce random resuspension, while the evolution of thermal stratification due to increased solar heating produces clearer surface waters. Biological activity, enhanced during the summer months introduces a diversity of phytoplankton which in turn modifies the inorganic sediments, enhancing flocculation, leading to the formation of larger particles, increasing settling and reducing the total suspended sediment load during the summer months (Jones et al., 1998).

Increased turbidity has been shown to have a negative effect on marine flora and fauna, with plankton photosynthesis directly limited by increased suspended particulate matter (SPM) concentrations (Tett, 1990). Much of the microbial activity in the water column also occurs on the surface of particulate matter, especially fine particles, as they offer a large surface area per unit mass (Hoppe, 1984). These fine particles are also optically important as they are responsible for the greatest proportion of scattering of light which in turn determines the transit of light through the water column and so productivity.

Using the optical properties of the surface waters, satellite images have been used to show the spatial distribution of SPM and chlorophyll in the oceans (Weeks and Simpson, 1991; Bowers et al., 1998, 2002). While there are several methods and instrumentation widely used for the determination of optical properties such as the scattering coefficient (b), the absorption coefficient (a) and attenuation (c), the determination of the compositional properties of sediments are much more challenging. In addition to the particle size, the density (ρ) and refractive index (n) of particles make a large contribution to the observed variation in scattering (Bowers et al., 2009). The apparent density (ρ_a) can be estimated from gravimetric

* Corresponding author. Tel.: +44 1248 382274; fax: +44 1248 716367.
E-mail address: k.m.braithwaite@bangor.ac.uk (K.M. Braithwaite).

0025-3227/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2010.06.008

measurements of mass concentration and volume concentration, using an instrument such as a LISST (Mikkelsen and Pejrup, 2001). The apparent (or effective density) is the ratio of dry weight to wet volume of particles and in this way is different from the actual density of the particles.

In this paper we aim to improve our understanding of the factors which control our ability to predict particle size from optical scattering. This link between the specific scattering coefficient (b^*) and the particle size has the potential to enable us to map particle size from space using remote sensing reflectance. We seek to build on the findings of Bowers et al. (2009) who observed that almost 64% of the variance in the mineral specific scattering coefficient could be explained by changes in particle density (mass concentration/volume concentration), while only 15% of the variance was down to changes in the particle diameter.

In order to improve our ability to predict particle size from space, we further investigate the relationship between scattering and particle size and density. While Bowers et al. (2009) considered the bulk density, in this paper we will propose a relationship to relate the density of individual particle sizes to the density of an entire particle size spectra. We aim to evaluate the way in which particle size varies with density and gain a better understanding of the other factors which influence particle size.

2. Regional setting

The Tamar Estuary is situated on the southwest coast of England forming a boundary between the counties of Devon and Cornwall (Fig. 1). Composing of the Tamar river and two tidal sub-estuaries, the main channel enters the sea at Plymouth Sound some 31 km from the

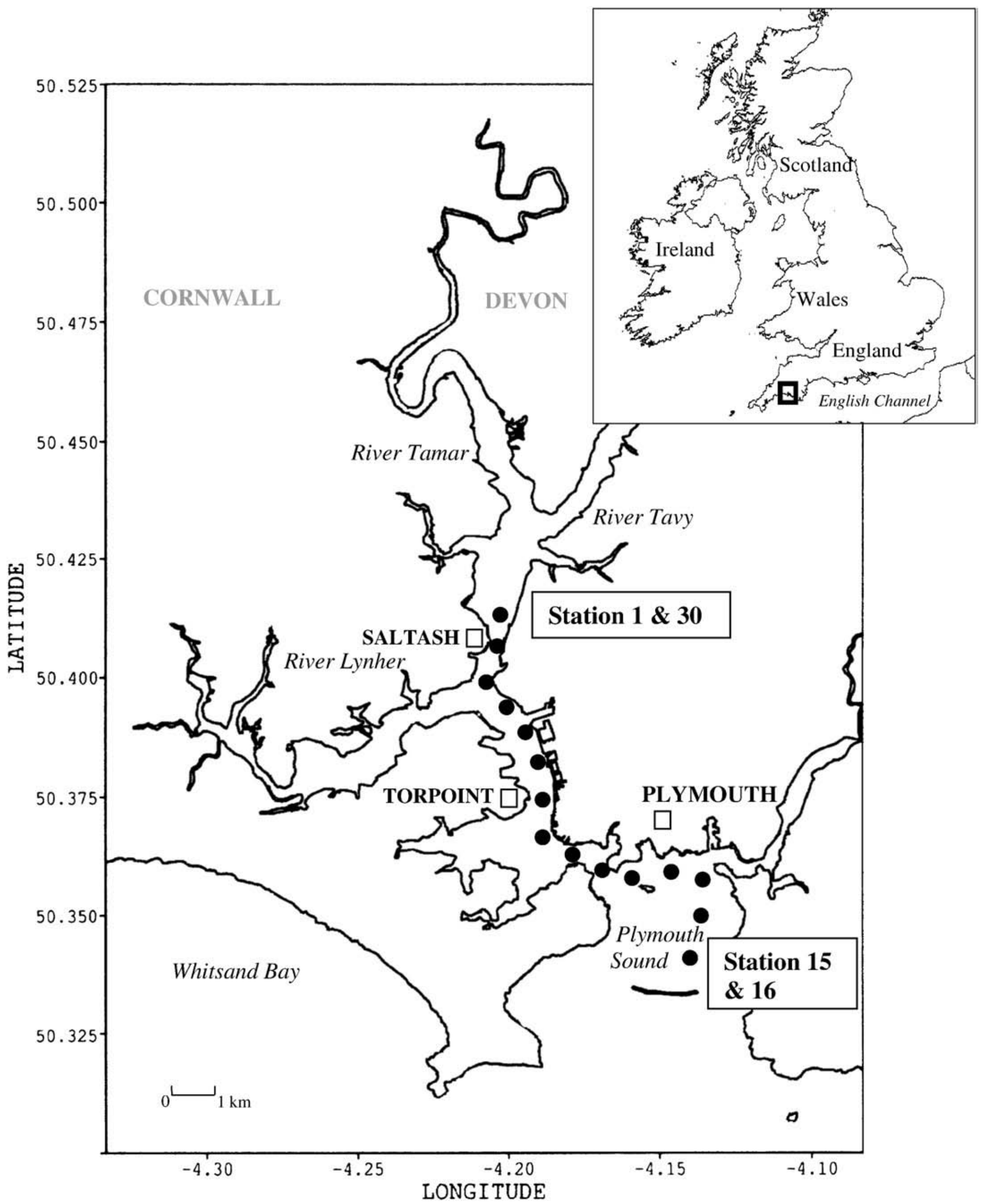

Fig. 1. Map of the observational area and location of the stations sampled (dark circles). The transect starts at station 1 at the furthermost point up-river. Station numbers are then consecutive down the estuary towards Plymouth Sound. Station 15 and 16 are at the same location. Station numbers 16 to 30 are then consecutive up the estuary towards the head of the estuary.