Marine Geology 367 (2015) 94–104

Contents lists available at ScienceDirect

Marine Geology

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

Classifying seabed sediment type using simulated tidal-induced bed shear stress

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ARTICLE INFO

Article history:
Received 19 November 2014
Received in revised form 22 May 2015
Accepted 26 May 2015
Available online 30 May 2015

Keywords:
Seabed sediments
Sediment transport
Tidal modelling
Bed shear stress
ROMS
Irish Sea

ABSTRACT

An ability to estimate the large-scale spatial variability of seabed sediment type in the absence of extensive observational data is valuable for many applications. In some physical (e.g., morphodynamic) models, knowledge of seabed sediment type is important for inputting spatially-varying bed roughness, and in biological studies, an ability to estimate the distribution of seabed sediment benefits habitat mapping (e.g., scallop dredging). Although shelf sea sediment motion is complex, driven by a combination of tidal currents, waves, and wind-driven currents, in many tidally energetic seas, such as the Irish Sea, long-term seabed sediment transport is dominated by tidal currents. We compare observations of seabed sediment grain size from 242 Irish Sea seabed samples with simulated tidal-induced bed shear stress from a three-dimensional tidal model (ROMS) to quantitatively define the relationship between observed grain size and simulated bed shear stress. With focus on the median grain size of well-sorted seabed sediment samples, we present predictive maps of the distribution of seabed sediment classes in the Irish Sea, ranging from mud to gravel. When compared with the distribution of well-sorted sediment classifications (mud, sand and gravel) from the British Geological Survey digital seabed sediment map of Irish Sea sediments (DigSBS250), this 'grain size tidal current proxy' (GSTCP) correctly estimates the observed seabed sediment classification in over 73% of the area.

1. Introduction

The large-scale redistribution of sediments in shelf sea regions by hydrodynamical processes has direct implications for geological basin and coastal evolution. Seabed sediments also determine the turbidity of water, provide a substrate for marine benthic organisms, host organic matter and are involved in biogeochemical exchanges. Shelf sea sediment motion under the influence of tides, waves and wind-driven currents is a complex phenomenon, the relative contributions of which can change on complex spatial and temporal scales (van der Molen, 2002; Porter-Smith et al., 2004; Neill et al., 2010).

In a tide-dominated shelf sea such as the Irish Sea, sediment transport in the nearshore (coastal) zone can be dominated by wave action, whereas farther offshore the characteristics of seabed sediment distribution are more indicative of the tidal current conditions of a region (e.g., van Dijk and Kleinhans, 2005; Van Landeghem et al., 2009b). A number of studies have used the distribution of peak bed shear stress vectors from tidal models to infer sediment transport pathways and the location of bedload partings around the British Isles (Pingree and Griffiths, 1979; Austin, 1991; Harris and Collins, 1991; Aldridge, 1997; Hall and Davies, 2004; Neill and Scourse, 2009) as well as for the evolution of bathymetric features such as tidal sand ridges (e.g., Huthnance, 1982; Hulscher et al., 1993), in particular in the Celtic and Irish Seas (e.g., Belderson et al., 1986; Scourse et al., 2009; Van Landeghem et al., 2009a). Pingree and Griffiths (1979) were the first to model the correlation between sand transport paths and the peak bed shear stress vectors caused by the combined $M_2 + M_4$ tidal currents for many areas on the UK shelf. They found that the direction of bedload transport correlates with the peak bottom bed shear stress vectors ($M_2 + M_4$), and most sand transport occurs in response to the peak current speed over a tidal cycle.

Although the relationship between near-bed hydrodynamics and seabed sediment textures in tidally-dominated areas have been examined (e.g., Uncles, 1983; Knebel and Poppe, 2000; Signell et al., 2000), there remains a need to define and quantify a relationship between a range of simulated current speeds (or bed shear stresses) and a range of seabed sediment types applicable at regional scales. Such a relationship would be valuable for several applications, such as informing expensive field campaigns, or spatial scales for sampling, for incorporating spatially varying drag coefficients into hydrodynamic models, and for habitat mapping (e.g., for scallop dredging) (Robinson et al., 2011).

The aim of this study is to quantify the relationship between simulated (numerically modelled) tidal-induced bed shear stress and observed seabed sediment grain size distribution in the Irish Sea. This relationship is used to develop a proxy, which we refer to hereafter as the 'grain size

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http://dx.doi.org/10.1016/j.margeo.2015.05.010

tidal current proxy' (GSTCP), for predicting large-scale distribution in seabed sediment type in the Irish Sea. The study region is introduced in Section 2. In Section 3, the tidal model is described, and the seabed sediment data are presented in Section 3.2, along with a description of the sub-selection of the observational data (Section 3.3). A first-order approximation of the relationship between the simulated bed shear stress and observed seabed sediment grain size is presented in detail in Section 4. The applications and limitations of this proxy are discussed in Section 5.

1.1. Sediment transport theory

The effects of currents, waves or by combined current and wave motion on sediment dynamics take place primarily through the friction exerted on the seabed. This frictional force is referred to as the bed shear stress (τ_0) and is expressed as the force exerted by the flow per unit area of bed in terms of the density of water (ρ) and the frictional velocity (u_*) such that:

$$\tau_0 = \rho u_*^2 \tag{1}$$

Sediment transport (of non-cohesive sediments) occurs when the bed shear stress exceeds the threshold of motion, τ_{cr}, or threshold Shields parameter (θ_{cr}) (Shields, 1936), which is a dimensionless form of the bed shear stress and is dependent upon the median grain size, d_{50}:

$$\theta_{cr} = \frac{\tau_{cr}}{g(\rho_s - \rho)d_{50}} \tag{2}$$

where g is the gravitational acceleration and ρ_s is the grain density. The threshold Shields parameter can be plotted against the dimensionless grain size, D_*, to produce the well-known Shields curve (Shields, 1936), which describes the threshold of motion beneath waves and/or currents. The dimensionless grain size is given by:

$$D_* = \left[\frac{g(s-1)^{1/3}}{\nu^2}\right] d_{50} \tag{3}$$

where v is the kinematic viscosity of water and s is the ratio of grain to water density.

Sediment transport occurs through bedload and suspended load transport, and varies depending on the forcing mechanism e.g., whether it is wave-, current- or wind-induced motion, or a combination of mechanisms inducing the motion. Numerous empirically-derived sediment transport formulae are available for total-load sediment transport by currents (e.g., Engelund and Hansen, 1972; van Rijn, 1984a,b,c), waves (e.g., Bailard, 1981) and combined currents and waves (e.g., Bailard, 1981; Soulsby, 1997) in the marine environment. However, these equations have inherent limitations, such as restrictions on applicable water depths, or ranges of grain sizes, and as such are inappropriate for application to regional scales, such as the Irish Sea. Many numerical modelling studies (e.g., Pingree and Griffiths, 1979; Harris and Collins, 1991; Aldridge, 1997; van der Molen, 2002; van der Molen et al., 2004; Griffin et al., 2008; Warner et al., 2008b, 2010) and combined modelling and observational studies (e.g., Harris and Wiberg, 1997; Wiberg et al., 2002) have been conducted in attempts to understand the role of tides and waves on sediment transport in coastal regions. This is the first study aimed at generating maps of estimated sediment grain size distribution on regional scales using both observations and numerical modelling techniques.

2. Case study: Irish Sea

It has long been realised that higher-than-average intensity of energy dissipation occurs in the shallow shelf seas around the UK (Flather, 1976; Simpson and Bowers, 1981), with approximately 5 to 6% of the total global tidal dissipation occurring in the Northwest European shelf seas, making it the second most energetic shelf in the world, second only to Hudson Bay (Egbert and Ray, 2001; Egbert, 2004). The Irish Sea (Fig. 1), positioned centrally within the Northwest European shelf seas, is a semi-enclosed body of water, with water depths generally < 150 m, and with a north–south trending 250 m deep channel to the northwest of the Isle of Man, between Scotland and Ireland. The tides in the Irish Sea are semi-diurnal (Pingree and Griffiths, 1978), and are dominated by the M_2 and S_2 tidal constituents. Some of the tidal wave, which propagates from the North Atlantic onto the Northwest European shelf, enters the North Sea (from the north) and through the English Channel from the southwest, while some energy passes into the Irish Sea, most of which propagates south to north (Pugh, 1987). The tidal range in the Severn Estuary (in the Bristol Channel) reaches a maximum of ~12 m, the second largest in the world after the Bay of Fundy.

The tidally-dominated Irish Sea is an ideal case study for comparison of observed grain sizes and simulated bed shear stresses given the abundance of existing research and information on the composition of the seabed sediment distribution (e.g., Wilson et al., 2001; Holmes and Tappin, 2005; Blyth-Skyrme et al., 2008; Robinson et al., 2009; Van Landeghem et al., 2009a), as well as extensive surveys by the British Geological Survey (BGS). Irish Sea sediments represent redistributed glacial (or glaciofluvial) materials characterised by a wide range of grain sizes which have the potential to be fractionated by bed shear stress. There is a significant diversity of seabed sediment classifications within the Irish Sea (Fig. 2), including areas of exposed bedrock (mostly limited to the northwest of Anglesey) and patches of semi-consolidated Pleistocene deposits, both covered in places only by thin transient patches of unconsolidated sediment. The majority of the seabed consists

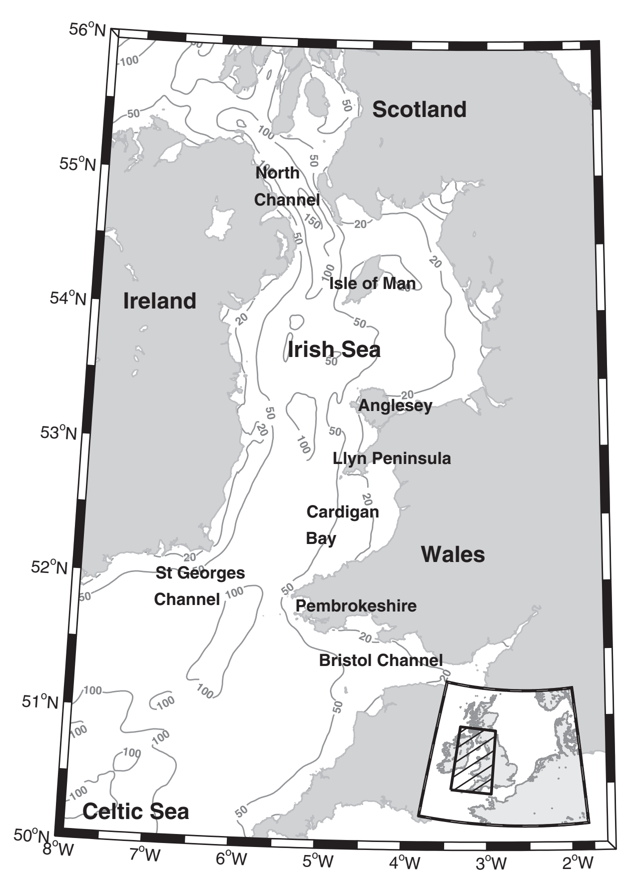

Fig. 1. Bathymetry of the Irish Sea, with water depth (mean sea level) contours in metres. Insert map: the position of the Irish Sea on the Northwest European Shelf.