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Mobility of maerl-siliciclastic mixtures: Impact of waves, currents and storm events

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ABSTRACT

Maerl beds are free-living, non-geniculate coralline algae habitats which form biogenic reefs with high micro-scale complexity supporting a diversity and abundance of rare epifauna and epiflora. These habitats are highly mobile in shallow marine environments where substantial maerl beds co-exist with siliciclastic sediment, exemplified by our study site of Galway Bay. Coupled hydrodynamic-wave-sediment transport models have been used to explore the transport patterns of maerl-siliciclastic sediment during calm summer conditions and severe winter storms. The sediment distribution is strongly influenced by storm waves even in water depths greater than 100 m. Maerl is present at the periphery of wave-induced residual current gyres during storm conditions. A combined wave-current Sediment Mobility Index during storm conditions shows correlation with multibeam backscatter and surficial sediment distribution. A combined wave-current Mobilization Frequency Index during storm conditions acts as a physical surrogate for the presence of maerl-siliciclastic mixtures in Galway Bay. Both indices can provide useful integrated oceanographic and sediment information to complement coupled numerical hydrodynamic, sediment transport and erosion-deposition models.

1. Introduction

An understanding of the dynamic equilibrium between erosion and deposition of a sedimentary system is crucial for the identification of sediment transport. This is of relevance to a range of coastal and estuarine activities including morphodynamics, marine conservation, offshore engineering and marine renewable energy (Van Rijn, 1993). This has led to the development of coupled hydrodynamic-wave-sediment transport models for computing the rate of sediment transport due to a combination of waves and currents (Warner et al., 2008; Brown and Wolf, 2009; Bever and MacWilliams, 2013; Hoeke et al., 2013). The dominant physical processes embedded into these models are wind-induced surface gravity waves, tidal currents, and wave-induced currents which take into account radiation stress gradients associated with the horizontal momentum of the waves (Longuet-Higgins and Stewart, 1964; Basco et al., 1982). These are the key forcing functions governing sediment transport in the benthic boundary layer (Jones et al., 2007).

Even in the presence of high-resolution data on the spatial and temporal variations in the wind and wave climate and *in situ* physical properties of seafloor sediment, there is a lack of confidence in the theory and application of sediment transport modelling (Wilcock, 2001; Idier et al., 2010). This is particularly the case when considering uncertainty in cumulative sediment transport due to variations in estimates of sediment input and output as well as estimates of the storage at the sediment source (Schmelter et al., 2012). The quantitative outputs of sediment transport rates may therefore not be reliable. In this study, we recognise the value and limitations of sediment transport models and use sediment mobility modelling as a complementary tool for investigating sediment transport from coupled hydrodynamic-wave-sediment modelling outputs.

Sediment mobility, defined in its simplest form as the percentage of time that grains of a particular size are mobile within a tidal cycle, is an intuitive and practical concept to present sediment transport information based on hydrodynamic modelling (Idier et al., 2010). Sediment mobility models typically utilise the critical bed shear stress above which incipient motion, mobility, erosion and deposition of sediment occur near the seafloor. Harris

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and Coleman (1998) utilised a global wave model to estimate global shelf sediment mobility based on empirical threshold speed equations. Porter-Smith et al. (2004) used a similar approach of shear stress threshold exceedance to define regions of the continental shelf with sediment mobility estimations based on wave and tidal energy inputs. Hemer (2006), recognising the need to integrate the magnitude and frequency of seafloor disturbance and sediment mobility due to combined-flow shear stresses, proposed three approaches, all of which have been incorporated, reviewed and standardised by Li et al. (2015). Griffin et al. (2008) considered the mobility of sediment based on its grain size distribution rather than the mean grain size. Dalyander et al. (2013) took into account non-linear effects of wave-current interactions by utilising a coupled hydrodynamic-wave model. Li et al. (2015) defined three sediment mobility indices: Mobilization Frequency Index (MFI), Sediment Mobility Index (SMI) and Seabed Disturbance Index (SDI). The MFI takes account of the frequency of seabed disturbance events, the SMI takes account of the magnitude and frequency of disturbance events, and the SDI requires analysis of the whole spectrum of disturbance events. In this paper, we combine the MFI and SMI with coupled hydrodynamic modelling to assess sediment transport characteristics of maerl-siliciclastic mixtures.

Sediment mobility of maerl is an important biophysical variable which could be used as a predictor for species occurrence. "Surrogacy" is defined in the context of benthic habitat mapping studies as a biophysical variable that can be quantitatively mapped to benthic species occurrence (Harris, 2012b). An abiotic or physical surrogate may be a direct or indirect variable affecting the presence or absence of a particular species in a particular space at a particular time. Sediment mobility is affected by geomorphic processes, ocean currents and storm events so it influences sediment rugosity, grain size and turbidity (Harris, 2012b). It is therefore a biophysical variable which can govern the potential and realised hydrodynamic niche of marine organisms and may be considered to be a physical surrogate for benthic species occurrence. It can be used as an eco-geographical variable within habitat suitability models for the prediction of spatial patterns of benthic ecosystems (Guisan and Zimmermann, 2000; Kostylev and Hannah, 2007). Harris and Hughes (2012) examined the mobilization of sediment on Australia's continental shelf and defined an ecological disturbance index which also considers the recurrence interval of disturbance with respect to ecological succession timescales.

1.1. *Maerl*

This paper is concerned with modelling the mobility of mixtures of maerl and siliciclastic sediment. Maerl (rhodolith) gravel beds are free-living coralline red algae that occur in mobile biogenic sediment deposits in the euphotic zone of shallow marine environments. Its heterogeneous spatial distribution is a consequence of its sensitivity to light intensity, high currents, moderate wave action, low sedimentation and high salinity (Birkett et al., 1998). This often results in autochthonous beds, banks and the formation of subaqueous dunes ~0.3 m - 2 m high, probably due to oscillatory wave-induced currents (Bosence, 1976). They are often found between islands and adjacent to channels where there are enhanced tidal currents and suppressed waves (Scoffin, 1988; Birkett et al., 1998).

Maerl beds are one of four main macrophyte-dominated benthic communities in the world (Foster, 2001; Basso et al., 2015). They play a primary role as carbonate producers and rhodolith beds are globally significant carbon sinks (Amado-Filho et al., 2012; Adey et al., 2015; Moura et al., 2016). They are of ecological significance with two species, *Lithothamnium corallioides* and *Phymatolithon calcareum*, protected under Annex V of the EC Habitats Directive, with indirect protection under Annex I (EC Council Directive 92/43/EEC). Maerl beds are on the Oslo and Paris (OSPAR) Convention's List of Threatened and/or Declining Species and Habitats (Hall-Spencer et al., 2010). Their spatial distribution contributes to the evidence base for "Seafloor Integrity" and "Hydrographical conditions" Good Environmental Status descriptors in the Marine Strategy Framework Directive (EC Council Directive, 2008/56/EC) as biogenic maerl is considered to alter the structure of the seafloor ecosystem (Rice et al., 2012). In Ireland, De Grave (1999) found eel grass-covered live maerl banks in the shallow, low energy parts of Galway Bay and maerl debris facies with varying proportions of sand, mud and shell gravel in high energy areas.

Rhodoliths are known to grow intermittently with a seasonal growth pattern and highest rates in the summer (Adey and Mc Kibbin, 1970; Bosence, 1983). Growth rates have been measured to be 0.55 mm yr^{-1} for *Phymatolithon calcareum* and 0.10 mm yr^{-1} for *Lithothamnion corallioides* (Adey and Mc Kibbin, 1970; Birkett et al., 1998). Growth rate is inversely related to crust thickness (Steneck, 1986) and maerl species are climax colonisers in conditions of high wave energy in the absence of grazers (Adey and Vassar, 1975). Taberner and Bosence (1985) investigated the co-occurrence of corals and coralline algae, where coralline algae were found to overgrow the corals in the Eocene. A taxonomic gradation has been observed from the rhodolith nucleus to the outer layer due to ecological succession or extrinsic successional control, including changes in hydrodynamics (Bosence, 1983; Gherardi and Bosence, 1999; Aguirre et al., 2017). Freiwald and Henrich (1994) discuss the ecological succession of coralline algal frameworks from the crust stage to an increasingly branched thicket stage to increasing bio-erosion of the framework-base (Fig.13 in Freiwald and Henrich (1994)).

An understanding of the hydrodynamics associated with maerl habitats is also important for re-constructing palaeo-environmental processes and quantifying the range of present, realised ecological niches of maerl (Bassi et al., 2012). Hinojosa-Arango et al. (2009) studied the impact of disturbance on the rich species assemblages associated with maerl in Northern Ireland by comparing a wave-disturbed and a sheltered maerl bed. Campos and Dominguez (2010) obtained sediment mobility on the continental shelf off Brazil using a threshold exceedance approach to locate where the observed orbital velocity exceeds the critical orbital velocity to mobilise sediment. De Falco et al. (2011) utilised a three dimensional hydrodynamic model to study the impact of the hydrodynamic regime on modern maerl carbonate biogenic sedimentation patterns in the western Mediterranean.

The hydrodynamic parameters of maerl have received little attention from the research community. For sand and maerl gravel mixtures, the critical threshold velocity for incipient motion is a function of the maerl grain diameter (Harris et al., 1996) and its mobility depends upon the different hydrodynamic processes in shallow wave-dominated maerl beds, deep wave-dominated beds and current-dominated beds (Marrack, 1999). There is clear evidence of strong interactions amongst hydraulic energy, maerl grain morphology and sediment mobility (Nelson, 2009; Riosmena-Rodríguez et al., 2011). Maerl have lower settling velocity (Joshi et al., 2014) and lower critical bed shear stress than quartz grains of the same diameter.

This study focuses on coupled hydrodynamic-sediment transport modelling of a spatially-heterogeneous mixture of maerl gravel and siliciclastic sediment in Galway Bay, containing about two-thirds of all gravel beaches/dunes of dead and live maerl in Ireland (De Grave and Whitaker, 1999). It addresses the following questions: What is the relative importance of the different physical processes operating in Galway Bay, such as wave action, tidal currents, wave-induced currents, for the mobility of maerl-siliciclastic