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Empirical model to estimate permeability of surface sediments in the German Bight (North Sea)

Andreas Neumann [a,*], Jürgen Möbius [b], H. Christian Hass [c], Walter Puls [a], Jana Friedrich [a]

[a] *Helmholtz-Zentrum Geesthacht, Institut für Küstenforschung, Max-Planck-Straße 1, D-21502 Geesthacht, Germany*
[b] *Universität Hamburg, Institut für Geologie, Bundesstraße 55, D-20146 Hamburg, Germany*
[c] *Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung, Wattenmeerstation, Hafenstraße 43, D-25992 List, Germany*

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ABSTRACT

As the determinant of solute and particle fluxes through sediments, quantifying sediment permeability is vital step in understanding of the exchange phenomena between the water column and sediment as permeability determines the mode and intensity of solute and particle fluxes. Reliable estimates of sediment permeability are therefore a constraint on the accurate implementation of benthic biogeochemical models. This is particularly true for the North Sea, as field data are scarce and available grain-size-based models fail to represent the full range of sediment types. In this study, we combine measurements of sediment permeability and grain size analysis with a generic permeability model to establish a high-resolution permeability map of the sediment in the German Bight (North Sea). Our results show a good agreement between model-based prediction and measurements of permeability, even for a wide range of permeability values.

1. Introduction

Sediment permeability describes the resistance to flow of water through the sediment (Bear, 1972). Permeability is thereby a key characteristic of surface sediment as it governs the exchange of solutes (e.g. Elliott and Brooks, 1997, Precht et al., 2004) and particles (e.g. Huettel et al., 1996, Huettel and Rusch, 2000). Sediment permeability also governs early diagenetic pathways and the spatial distribution of permeability is of great importance when answering many biogeochemical questions. For example, flushing of permeable surface sediment with oxygenated bottom water favors oxygen consuming microbial and chemical reactions such as aerobic decomposition of organic matter, nitrification and sulphide oxidation. By contrast, stagnant pore water in impermeable sediment promotes reducing reactions such as denitrification, sulphate reduction and methanogenesis, as well as anaerobic decomposition pathways.

Unfortunately, direct measurements of sediment permeability are still scarce in the southern North Sea. The distribution of pervious and impervious sediment, a constraint for the implementation of biogeochemical models, is not known in detail yet. A sound representation of sediment physical properties in coupled pelagic-benthic biogeochemical models is a prerequisite to translate point benthic flux measurements into spatial/regional flux estimates, for example, in ecosystem service assessment.

Obtaining direct measurements of sediment permeability at a spatial resolution equivalent to current ecosystem models is usually not feasible, so permeability has to be deduced from other, known parameters. Fortunately, the grain size distribution in the German Bight is already mapped with very high spatial resolution (Figge, 1981) and estimating permeability on measured grain size is a common practice. However, the grain size map (Fig. 1A) reveals that the German Bight sediments comprise a wide variety of sediment types; including cohesive mud with high silt content in deeper areas such as the submerged valley of the Palaeo Elbe (Fig. 1B) as well as coarse sand and gravel along the coast. This variety of sediment types present in the study area implies that existing simple permeability models such as Krumbein and Monk (1943) or Soulsby (1997) are insufficient here as they are only valid for specific sediment types. More complex permeability models such as the Carman-Kozeny model (CK, Glover et al., 2006), the JKS-model (Johnson et al., 1986; Glover and Walker, 2009), or the RGPZ-model (Glover et al., 2006) use specific sediment parameters (e.g. pore dimension, connectedness or topology), which are not available for all sediment types. Moreover, the Cozeny-Karman model was recently discredited by e.g. Walker and Glover (2010) as it takes not account for the porosity component that is not contributing to the flow.

But although the complex permeability models (CK, JKS, RGPZ) are not applicable in this study due to a lack of data for the specific sediment parameters, they may help to explain why the simple models fail to predict the permeability for a wide range of sediment types. Permeability of a sediment or rock (K) is generally controlled by the characteristics of the pore space network such as pore dimensions, topology, or

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* Corresponding author.
E-mail address: andreas.neumann@hzg.de (A. Neumann).

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Notation

a	sediment packing constant, unitless
d_{eff}	effective grain diameter, m
D_{15}, D_{50}	grain size of the 15th/50th percentile, m
EEZ	Exclusive Economic Zone
F	formation resistivity factor, unitless
G	geometric mean grain size, m
K	permeability, m^2
m	cementation exponent, unitless
r_{eff}	effective pore radius, m
ϕ	porosity, unitless
$s(d_{eff})$	empirical structure function, represents am^2F^3, unitless

connectedness (Eq. (1)) as shown by Schwartz et al. (1989), Avellaneda and Torquato (1991), Kostek et al. (1992), Bernabé and Revil (1995), and Glover et al. (2006).

$$K = \frac{r_{eff}^2}{8F} = \frac{r_{eff}^2 \chi \varphi}{8} \quad (1)$$

The effective pore radius (r_{eff}) cannot be regarded as an actual geometric measure but as a characteristic length scale. The formation resistivity factor (F) represents the effective electric resistivity and combines information about porosity (ϕ), connectedness (χ) and electric tortuosity (τ) via $F = \phi^{-m} = \tau\phi^{-1} = (\chi\phi)^{-1}$ (Glover and Walker, 2009). The exponent m is often called the cementation exponent for historical reasons and describes the sensitivity of connectedness to variations of porosity (Glover, 2009). The characterisation of the pore network, from

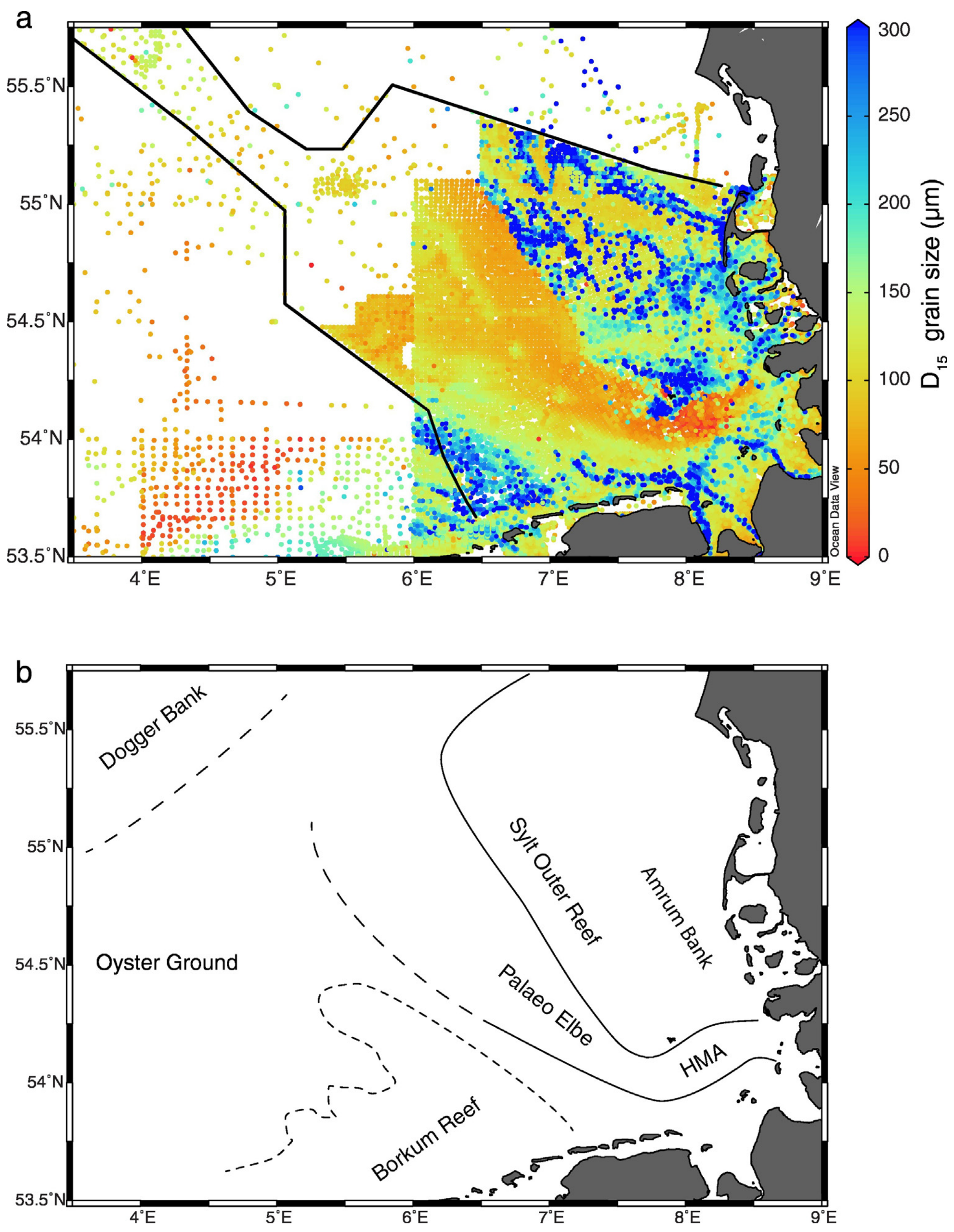

Fig. 1. A: Spatial distribution of sediment samples and D_{15} grain size values used for calculation of permeability map. Each dot represents an individual sediment sample. The solid, black, polygonal outline indicates the German Exclusive Economic Zone. B: Schematic map of bathymetric structures. Features in shallow water such as Dogger Bank, Borkum Reef, and Sylt Outer Reef consist of coarser sediment (blue and green hue in panel A; features in greater water depth such as Oyster Ground, Helgoland Mud Area (HMA) or the Paleo Elbe consist of finer sediment (yellow and orange hue in A). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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