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Turbulenter Transport und Vermischung von submarinem Grundwasseraustritt: Der Einfluss grober Sedimentklassen in gemischten Meeresböden

Turbulent transport and mixing of submarine groundwater discharge: Investigating the influence of large sediment size classes in mixed seabeds

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Marine boundary layers, permeable beds, Reynolds flux, oscillatory flow, PIV, LIF

Abstract

In coastal ocean sciences, submarine groundwater discharge describes a long underestimated phenomenon of water flux from the sediment into the water column. Just over a decade ago it gained recognition as an important transport mechanism of nutrients, metals, and organic matter to the coastal ocean. However, quantifying its impact remains challenging. One aspect to investigate in more detail is the transport of SGD in the water column. It is dominated by advection, therefore highly dependent on different boundary conditions, such as swell and bottom topography. This study addresses the influence of ensembles of protruding stones from a mixed seabed on the flow field, transport, and mixing in the benthic boundary layer. Synchronous Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) measurements show that the presence and size of protruding elements do not just affect the velocity fields, but also the concentration fields of a benthos originated passive tracer to an astounding degree. The role of near-bed separated vortices will be discussed in relation to its impact on turbulent transport, Prandtl mixing lengths, and the fluxes across the seabed interface.

Introduction

Submarine groundwater discharge (SGD) - the seaward flow of water through the seabed – has gained growing recognition in recent years for its importance in the coastal zone. SGD serves as a critical source of nutrients for benthic organisms on a local scale [Lecher and Mackey 2018] and even its large-scale impact on the nutrient and chemical budgets of the coastal ocean is assumed to be in comparable dimension to that of river runoff [Szymczycha and Pempkowiak 2016, Taniguchi et al. 2019]. However, uncertainties and knowledge gaps persist in understanding the full extent of SGD's influence across various scales. One way to address this is by conducting more detailed studies on the flow within the benthic boundary layer. On the local scale, the magnitude of the vertical transport of SGD directly influences the biogeochemical processes in the benthic area. On larger scales, quantifying the contribution of the pressure gradient at the seabed induced by small-scale characteristics of the flow field could reduce some uncertainties of the net flux assessment.

Therefore, there is a need to study the flow in the benthic boundary layer and how it affects the transport of SGD into and within the water column. Several parameters influence the flow field in the benthic boundary layer, most notably the swell and bottom structure. Kandler et al. [2021] and Brede et al. [2022] have investigated the flow over different ripple structures that form in sandy sediment. However, the sediment of seabeds is not always homogeneous, consisting only of sand. Instead, it often contains a heterogeneous mixture of different sediment size classes, thus being referred to as a mixed seabed. Particularly the large size classes alter the bottom structure significantly and, as a result, change the flow field most drastically. Hence, our study aims to investigate the influence of larger sediment size classes on the transport and mixing processes in the benthic boundary layer, contributing to our understanding of submarine groundwater discharge. Several experimental studies investigated currents [Hardy et al. 2016, Mohajeri et al. 2016], waves [Sleath 1987, Thompson et al. 2012], and wave-current interaction [Faraci et al. 2021] over gravel beds. In contrast, the flow over mixed beds remains uninvestigated for the most part. Additionally, the turbulent transport from the seabed is hardly ever integrated directly into the experimental studies.
Lastly, SGD seepage rates are typically in the order of centimetres per day, which can, for example, be taken from the measurements of Racasa et al. [2021] and Kreuzburg et al. [2023] in the Southern and Western Baltic Sea. Thereby, the SGD flux does not disrupt the benthic flow field in a significant way. It rather is one-way coupled to the flow and can be considered a passive tracer. Therefore, due to its passive nature, studying the transport of SGD under the influence of turbulent shear flow gives more general information about the transport and mixing in marine boundary layers.

Theory

The transport of a passive tracer in the flow field is given by the product of the velocity vector with the scalar quantity (here: concentration c). Applying Reynolds decomposition, this quantity separates into the contribution of the mean flow and of the turbulent transport, also known as Reynolds flux. Under the assumption of a purely oscillatory flow, the contribution of the mean flow falls to zero, resulting in turbulent transport being the main contributor to the net flux.

$$Flux = \overline{u_\iota c} = \overline{\overline{u_\iota}\,\overline{c}} + \overline{u'_\iota c'}$$

Prandtl's mixing length model describes a proportional relation between the correlation of fluctuations and the vertical gradients of the mean values. Their proportionality coefficient can be taken as the square of a length scale that is called the mixing length. The relation of the mixing length of a passive scalar can be written as

$$\langle w'c'\rangle = {l_c}^2 \frac{\partial\langle u\rangle}{\partial z}\cdot\frac{\partial\langle c\rangle}{\partial z}$$

Though this formulation is of empirical nature, the mixing length can be an insightful variable to quantify the mixing process and model turbulent transport on larger scales.

Methods

The presented experiments were performed in a wave tank in the flow lab of the Institute of Fluid Mechanics at the University of Rostock. The experimental setup is shown in Figure 1.
The tank's dimensions are a length of 4 m, a width of 0.8 m and a height of 1 m. The static water level was set at a height of 0.3 m for all the measurements. The waves were generated by a Piston-type wave maker. This wave maker consists of a plate, that moves back and forth in the flow direction. By doing this, it is able to generate shallow waves in the tank setup. The generated waves have a maximum velocity of 0.26 m s^{-1} and a wave period of 3.28 s. These

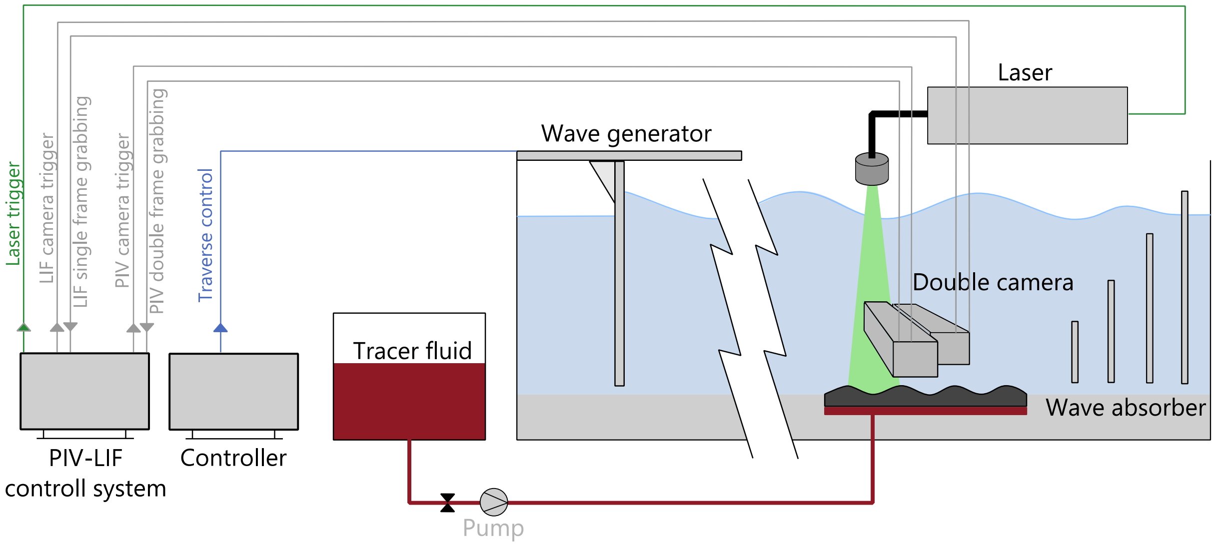

Figure 1 Experimental setup

properties were adapted from field observations [Karow 2019], where typical wave amplitudes and periods were observed at the sea surface. From these observations, flow conditions and characteristic flow properties at the bottom in the shallow and intermediate zone were derived.

A recess at the bottom of the wave tank facilitates the placement of different seabed models. These seabed models consist of a foam layer with the dimensions of 690 x 600 x 50 mm on a perforated plate with a fixture to easily swap and mount each model to the bottom of the tank. One model was kept like this for reference and will be referred to as REF or flat bed in the following. The other models have another layer on top of the foam bed that consists of 3D-printed solid clusters, which model ensembles of larger, protruding stones. The base for this was one cluster, that was repeated throughout the seabed. The design of the cluster was semi-empirical. As a starting point of the modeling process, the stones were simplified as ellipsoids. Empirical field observations (topographic scans, collected samples) served as a base for this assumption. The ellipsoids are mainly oriented with their shortest axis in the vertical direction and their longest axis perpendicular to the wave direction. Instead of being randomly distributed, the stones are rather gathered in a particular cluster, similar to the spatial clusters observed by Hassan and Church [2000].

The cluster was then scaled using a scale factor of 1.0, 1.25, and 1.5. These seabed models will therefore be referred to as S1.0, S1.25, and S1.5 or summarized as mixed beds in the following. Since the scaling was uniform in all directions, the only difference between these seabed models is the size of the ellipsoids, while other bottom characteristics such as packing pattern, packing density, bottom coverage, and effective slope were kept constant, eliminating their influence on the flow characteristics during these experiments. An overview of the different bottom structure properties is given in Table 2.

To simulate discharge of groundwater from the seabed in the experimental setup, a tracer fluid was pumped underneath the seabed model. The fluid perfused the seabed model and emerged into the water column. Due to a fluorescent additive, rhodamine 6G, contained in the tracer fluid, the distribution of the tracer fluid in the water column could be measured by Planar Laser Induced Fluorescence (PLIF).

For the PLIF measurements, we determined a calibration curve for the correlation of rhodamine 6G concentration with its fluorescent effect under a laser light sheet with the intensity of the camera output.

Table 1 Bottom structure properties of different seabed models

	Mean height [mm]	Max height [mm]	Corey shape factor of ellipsoids [ ]	Effective slope in flow direction [ ]	Area covered by ellipsoids [%]
Flat bed (REF)	0	0	-	-	0
Mixed bed, Scale factor 1.0 (S1.0)	2.5	8	0.49 – 0.52	0.26	55
Mixed bed, S1.25	3.0	10	0.49 – 0.52	0.26	55
Mixed bed, S1.5	3.8	12	0.49 – 0.52	0.26	55

Additionally to the PLIF measurements, a second camera was used to measure the velocity field with Particle Image Velocimetry (PIV). Glass spheres of a diameter of 29 µm were added to the water in the wave tank. Since these particles reflect the laser light directly, at a different wavelength from the rhodamine fluorescence, optical filters were placed in front of both cameras. This allowed for simultaneous PIV and PLIF measurements without one method interfering with the results of the other.

The grid resolution for the PIV evaluation was 16x16 pixels, resulting in a resolution of 1.84 mm of the velocity vector field. The concentration map of the PLIF results was then resampled to the same resolution to correlate the quantities directly.

In each measurement sequence, 10 000 velocity and concentration maps were obtained at a measurement frequency of 15 Hz. Phase-specific Reynolds decomposition was applied and the fluctuations were correlated.

Results and Discussion

Phase-specific mean velocity profiles are depicted in Figure 2. The velocity profiles over the different seabed models show that there is no difference in the velocity values far away from the bottom, which indicates that the wave forcing dominates the flow in this region. However, in the boundary layers, there is a significant difference between the flat and mixed beds. All velocity profiles show the typical shape of a wave boundary layer with a velocity peak close to the bottom followed by a slight indent when wave velocity increases. Then, as the wave velocity regresses, this shape changes and the velocity peak and indent disappear. However, the difference between the beds lies in the excursions of the boundary layers. The mixed beds show higher peak velocities which can be explained by the acceleration when passing the protruding elements. Then, flow separation was observed for all mixed beds, resulting in an upwards shift for the velocity peaks at the maximum followed by a decrease of near-bed velocities due to the separated vortices

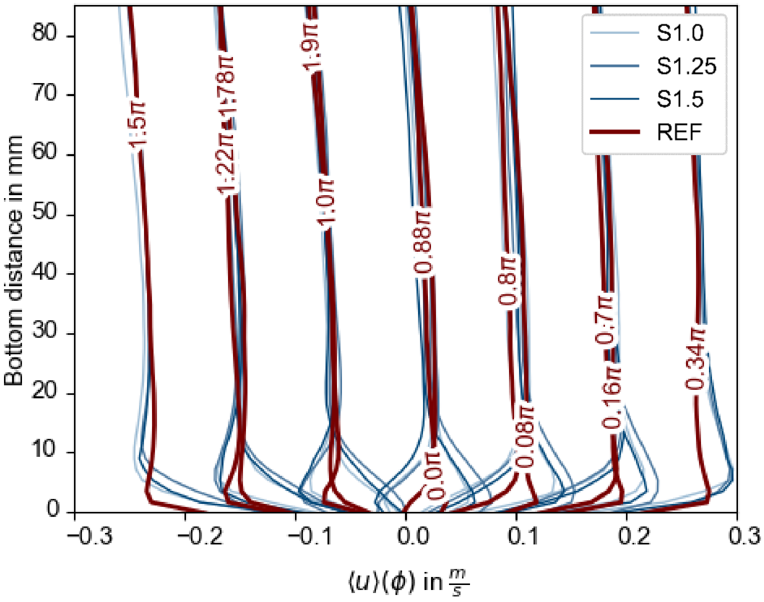

Figure 2 Phase-specific velocity profiles

taking energy away from the main flow. The importance of these separated vortices will be discussed further in the following.

Figure 3 shows the mean concentration for specific phases over all different seabed models. The spatial distribution of concentration changes considerably with phase, but is highly dependent on the bottom structure as well.

One particular effect that can be observed here is the influence of wave pumping over the flat bed. Underneath a wave trough, the hydrostatic pressure at the bottom is lower due to the lower water level which allows for more tracer to escape from the seabed compared to the higher water level at the wave crest. The progression of the concentration levels over the wave phase can be explained by this effect.

The mixed beds, however, show patterns of a different characteristic. Here, the concentration is particularly high in areas where vortices are formed near the bed due to flow separation. The high velocity in the vortices leads to a local pressure drop at the bottom and causes an increased tracer flux out of the seabed. For the different mixed beds, it is apparent that the area of high concentration levels increases with the growing scale factor. This indicates that the tracer flux grows with the scale factor of the protruding elements by governing the size of the separated vortices.

Figure 4 depicts the time-averaged vertical turbulent transport profiles over the different seabed models. In addition, the RMS-profiles of both, the vertical velocity fluctuations w’ and the concentration fluctuations c’, are plotted to dissect their respective influence. The RMS values of the concentration fluctuations align with the observations made in the phase-specific concentration maps. For the mixed beds, the concentration fluctuations grow with the scale factor of the protruding elements. The flat bed shows relatively high concentration fluctuations, comparable with the mixed bed with the largest scale factor, S1.5.

The vertical velocity fluctuations near the bottom boundary are higher for the mixed beds than for the flat bed. Though the curves eventually meet at a certain distance away from the bed, similar to the phase-specific mean velocity profiles in Figure 2, showing again that the wave forcing dictates the flow in these regions.

In combination, the concentration and vertical velocity fluctuations affect the turbulent transport in the following way. The velocity fluctuations significantly affect the shape of the turbulent transport profiles. The increased velocity fluctuations over the mixed beds lead to an upwards shift of the peak of the turbulent transport. This is mainly notable when comparing the flat bed to one of the mixed beds. Nevertheless, there is a slight difference in the shape of the mixed bed’s profiles that stems from different w’-values, but the influence of the concentration fluctuations is much more notable. To conclude, although turbulence levels (w’-RMS values) are higher in the presence of protruding elements compared to a flat bed, the different concentration levels affect the magnitude of turbulent transport significantly. Therefore, higher turbulence does not necessarily imply higher turbulent transport.

The mixing length of a passive scalar is plotted over the bottom distance in Figure. The most notable difference to observe here is in the slope from the bottom. The mixed beds exhibit a much steeper slope from the bottom than the flat bed, which indicates more mixing in the boundary layer over the mixed beds. Outside of the boundary layer, all profiles eventually reach a mixing length value of roughly 50 mm. While this common outer layer value does not perfectly align between the scenarios, which can be attributed to the empirical nature of the mixing length, it should be noted here, that the bias of the different concentration levels is successfully eliminated in the mixing lengths that are derived from the vertical turbulent transport. This proves its suitability as a measure of mixing in the flow field.

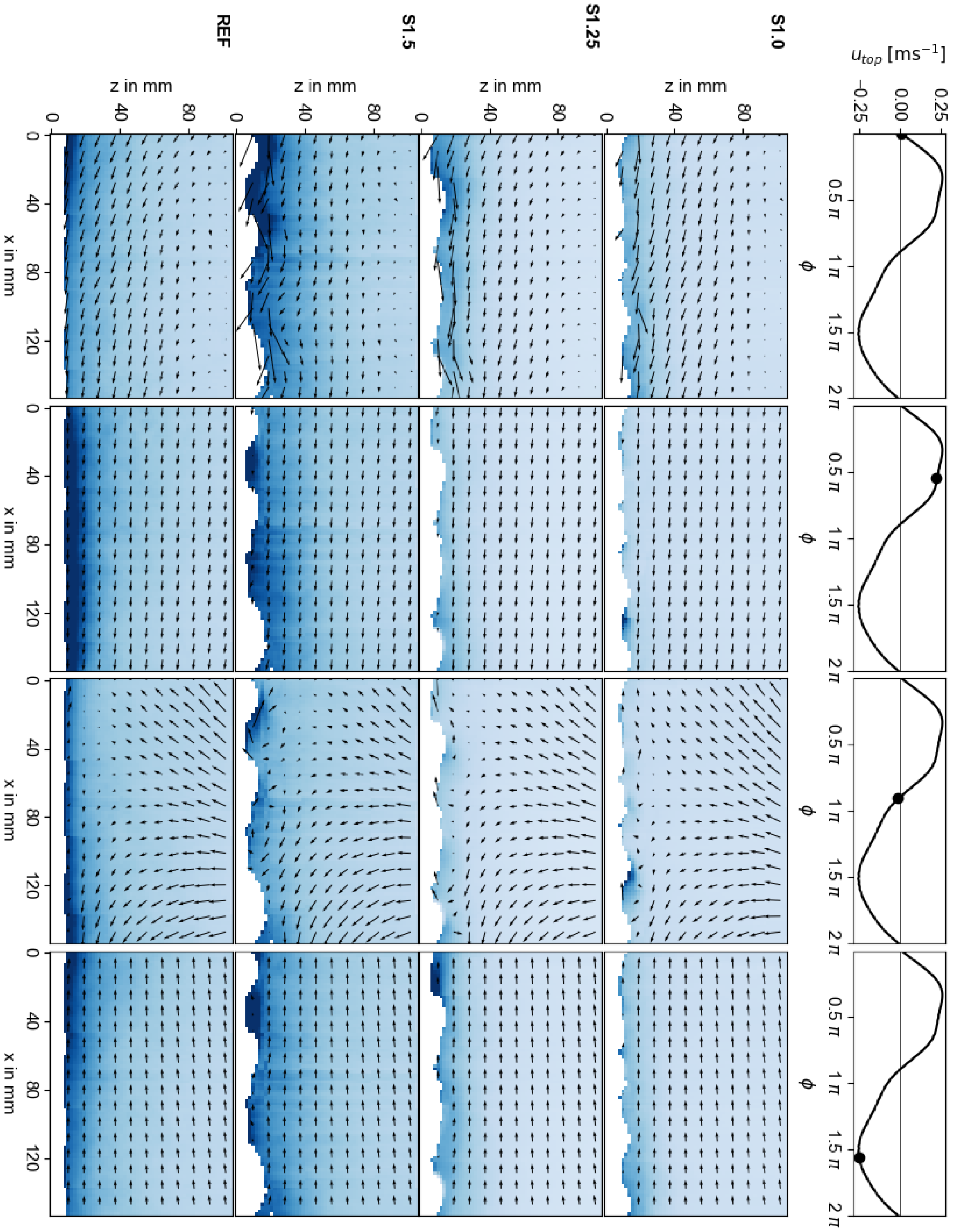

Figure 3 Phase-averaged concentration fields for characteristic phases

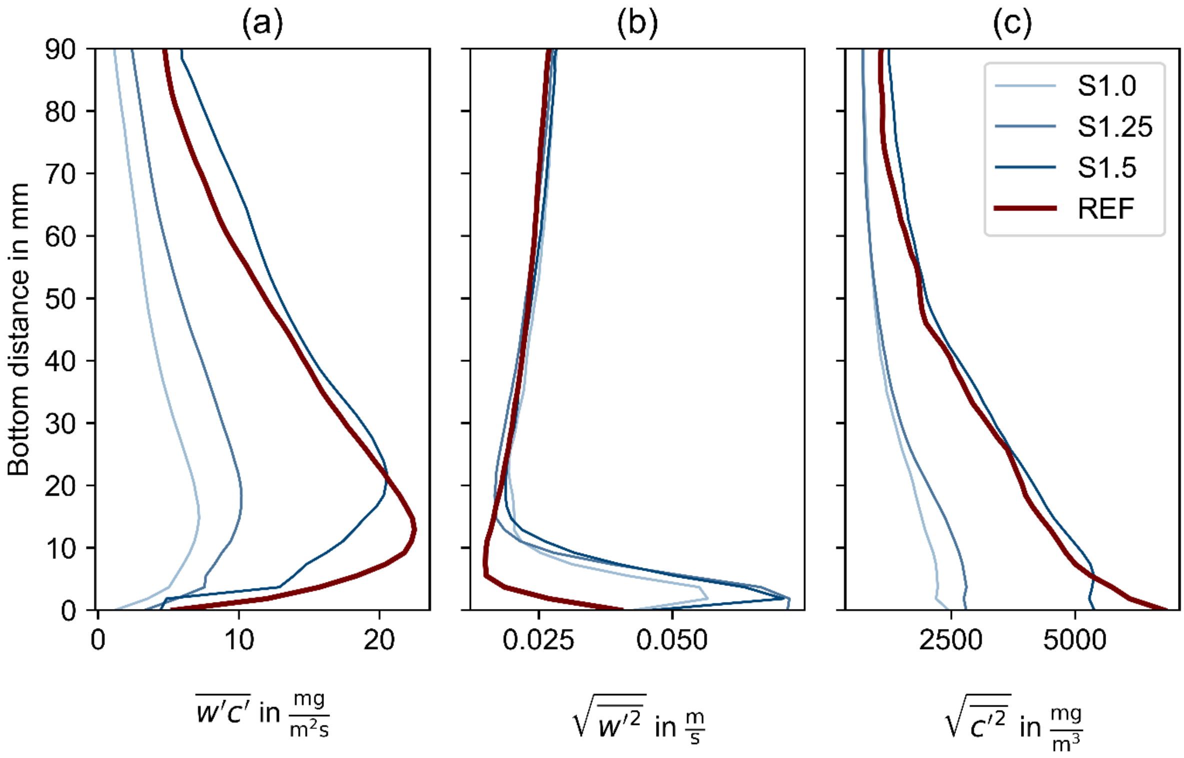

Figure 4 (a) Turbulent transport profiles, (b) RMS profiles of vertical velocity fluctuations, (c) RMS profiles of concentration fluctuations over bottom distance for each bed

Conclusions

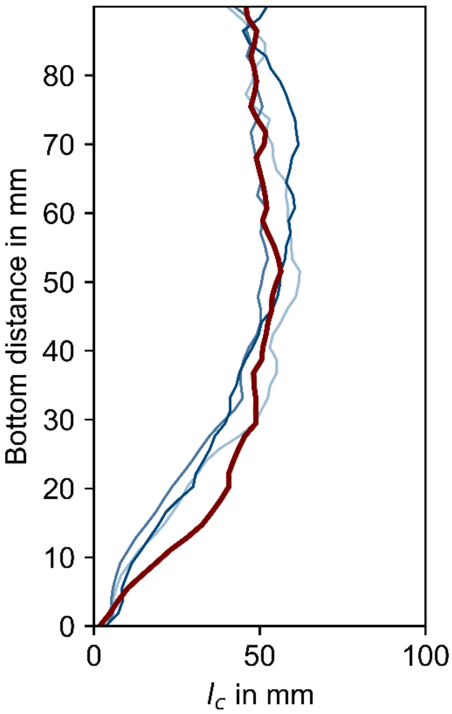

Figure 5 Mixing length profiles of a passive scalar over bottom distance for each bed

When comparing the flow over a flat bed to the flow over a mixed bed with protruding stones, clear difference can be noted. Over the mixed beds, the boundary layer was extended and higher velocity fluctuations occurred. Surprisingly, when comparing the size of the protruding elements, a much greater difference between the scenarios laid in the concentration fields. To explain this observation, we described a mechanism, where the pressure drop induced by separated vortices led to an increased flux of tracer out of the bed in that area. The impact of this mechanism grows with the size of the protruding elements and differs from the wave pumping mechanism occurring over flat beds. The results implicate that it is necessary to distinguish different types of bottom structures and their effect on the transport and mixing of submarine groundwater discharge.

The mean velocities, velocity fluctuations and mixing lengths showed that for such strong wave forcing there is no distinguishable difference in the outer layer. Nonetheless, the different beds affected the boundary layer, which showed critical effects on tracer flux into the water column and the turbulent transport in the water column. Therefore, in applications with transport from the seabed, the bottom structure should be considered a critical factor.

Acknowledgements

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