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The effect of bottom roughness on scalar transport in aquatic ecosystems: Implications for reproduction and recruitment in the benthos

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HIGHLIGHTS

- The effect of roughness geometry on scalar (i.e., gametes) transport was examined.
- Height (k), spacing (λ) and shape (round, triangular, and square bars) were examined.
- Relative scalar transport (RT) was measured to assess retention vs. downstream transport.
- Flow matched the prediction for λ/k; RT was determined and differed for round shapes.
- Spatial configuration determines if the scalar is retained or transported downstream.

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ABSTRACT

Bottom roughness can influence gamete and larval transport in benthic organisms. For example the ratio of the roughness spacing (λ) and roughness height (k) determines the type of roughness flow regime created in two dimensional (2D) flows: $\lambda/k<8$ results in skimming flow; $\lambda/k\sim8$ results in wake interference flow; and $\lambda/k>8$ results in isolated roughness flow. Computational fluid dynamic modeling (COMSOL K–ε) was used to examine the effect of roughness geometry (e.g., a gradient in angularity provided by square, triangular and round 2D bottom roughness elements) on the prediction of roughness flow regime using biologically relevant λ/k ratios. In addition, a continuously released scalar (a proxy for gametes and larvae) in a coupled convection-diffusion model was used to determine the relationship among roughness geometry, λ/k ratios, and scalar transport (relative scalar transport, RT=ratio of scalar measured downstream in a series of roughness elements placed in tandem). The modeled roughness flow regimes fit closely with theoretical predictions using the square and triangle geometries, but the round geometry required a lower λ/k ratio than expected for skimming flow. Relative transport of the scalar was consistent with the modeled flow regimes, however significant differences in RT were found among the roughness flows for each geometry, and significantly lower RT values were observed for skimming flow in the round geometry. The λ/k ratio provides an accurate means of classifying flow in and around the roughness elements, whereas RT indicates the nature of scalar transport and retention. These results indicate that the spatial configuration of bottom roughness is an important determinant of gamete/larval transport in terms of whether the scalar will be retained among roughness elements or transported downstream.

1. Introduction

For many benthic organisms, hydrodynamic conditions are critical for the release of gametes and settlement of larvae in the near-bed region as well as their dispersal in the water column, because most gametes/larvae act as passive particles entrained in environmental flows (Abelson and Denny, 1997; Pineda et al., 2007; Nishihara and Ackerman, 2013). Much research has focused on the role of turbulence in gamete/larval transport, as turbulence facilitates the encounter between eggs and sperm, and the dispersal and/or settlement of larvae onto the bed (Denny and Shibata, 1989; Crimaldi et al., 2002; Quinn and Ackerman, 2012, 2014). Turbulence caused by bed

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roughness is one of the primary factors controlling flow and transport near the bottom (Nowell and Jumars, 1984; Crimaldi et al., 2002; Hendriks et al., 2006) and the importance of local small-scale hydrodynamics to these processes has been recognized (Yund et al., 2007; Reidenbach et al., 2009).

Mathematical and conceptual models have reached contradictory conclusions concerning the effect of bottom roughness on larval settlement. Specifically, Eckman's (1990) one-dimensional model theorized that larval flux and settlement would increase with the density of roughness elements, whereas Crimaldi et al. (2002) predicted that increased density of roughness elements would reduce larval settlement. Quinn and Ackerman (2012, 2014) suggested from empirical results that simple metrics, such as roughness density, are not sufficient to characterize near-bed flows, rather the spatial configuration of the roughness elements are required to understand the hydrodynamics and transport in these complex near-bed regions.

The relationships between the spatial configuration of bottom roughness and the nature of near-bed flows are extremely complex but can be idealized in two-dimensions (2D) for simple bedforms such as transverse bars (reviewed in Schindler and Ackerman, 2010). These near-bed flow regimes can be predicted by the roughness height (k), water depth (d), the longitudinal distance between roughness elements, or roughness spacing (λ; i.e., wavelength), and roughness groove width (j; the space between the roughness elements) using the approach developed for pipe roughness by Morris (1955); Fig. 1, which has been applied to streambed roughness previously (Young, 1992; Davis and Barmuta, 1989; reviewed in Schindler and Ackerman, 2010). Roughness spacing (λ) and roughness height (k) are of particular importance in 2D transverse bars where λ/k (Roughness Index) can be used to characterize three types of near-bed 'roughness flow regimes' (Morris, 1955; Fig. 1). For flows where $\lambda/k<8$, the fluid in the spaces between the roughness elements are disconnected from the faster moving flow above them resulting in (1) skimming flow (Leonardi et al., 2003, 2004). With flows of $\lambda/k\sim 8$, the wakes downstream of each roughness element interact with each other, resulting in (2) wake-interference flow. Lastly, for flows with $\lambda/k>8$, the wakes downstream of the roughness elements are intermittent and dissipate before reaching the next roughness elements downstream, leading to (3) isolated-roughness flow (Djenidi et al., 2008; Schindler and Ackerman, 2010).

Whereas the hydrodynamics of near-bed regions caused by these idealized 2D roughness elements can be characterized, the determination of scalar transport in them remains to be determined. The purpose of this study is, therefore, to examine the λ/k prediction for flow over different types of roughness geometry and to examine the downstream transport and retention of a released scalar under these flow regimes. The released scalar is used to model the transport of gametes or larvae from a benthic population in a near-bed environment. By relating gamete/larval transport to bottom roughness, the role of physical parameters on biological processes involving benthic populations can be better understood.

2. Methods

2.1. Flow environment

COMSOL multiphysics (version 3.4, COMSOL Inc.) computational fluid dynamic modeling program was used to examine how different bottom roughness parameters influence benthic hydrodynamics and subsequent scalar transport (a proxy for sperm and larval transport). Specifically, we used a 2D K–ε model, a type of Reynolds-averaged Navier–Stokes (RANS) model based on Reynolds decomposition (i.e., time average versus fluctuations; Davidson, 2004), to model the turbulent flow conditions given by

$$\rho(\mathbf{u}\times\nabla)K=P_K-\rho\varepsilon\ +\nabla\times\left[\left(\mu+\frac{\mu_t}{\sigma_K}\right)\nabla K\right] \tag{1}$$

$$\rho(\mathbf{u}\times\nabla)\varepsilon=C_{\varepsilon 1}\frac{\varepsilon}{K}P_K-C_{\varepsilon 2}\rho\frac{\varepsilon^2}{K}+\nabla\times\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] \tag{2}$$

where ρ is the density, $\mathbf{u}$ is the velocity vector, P_K is the production of turbulent kinetic energy, μ is the dynamic viscosity, ∇ is the Laplacian operator, and the unknowns are K the turbulent kinetic

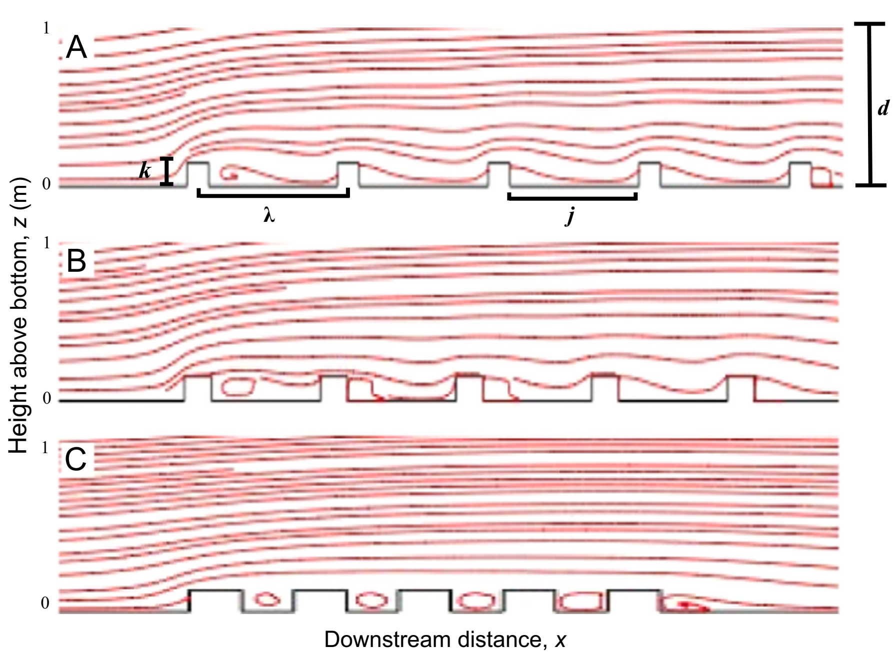

Fig. 1. COMSOL streamline plots illustrating the three main flow regime types over square 2D transverse roughness elements: (A) isolated roughness over $\lambda/k=12$; (B) skimming flow over $\lambda/k=3.3$; and (C) wake interference flow over $\lambda/k=8.3$. Also shown on (A) are the roughness parameters of roughness height (k), water depth (d), the longitudinal distance between roughness elements or roughness spacing (λ; wavelength), and roughness groove width (j; space between the roughness elements). Note that the panels represent a portion of the model domain that illustrates the streamlines around the roughness element rather than the entire domain.