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Flow transition from open-to-closed channels in rivers: implications for plastic accumulation and ice jams

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Introduction

Plastic waste results from human innovation, emerging from our development and use of synthetic materials called plastics. However, because of their long-lasting durability, plastics do not break down quickly and safely in the environment after the duration of intended use. This causes plastic waste to accumulate in the environment, threatening valuable ecosystems and human health (Thompson et al., 2024). Therefore, reducing and mitigating plastic pollution is an urgent priority.

Rivers are considered the main conveyor of plastic debris toward the ocean (Thompson et al., 2024). Once the plastic debris enters the ocean, it becomes more challenging to track and collect them due to a highly dynamic nature of the oceanic processes and wind transport (DiBenedetto, 2025). Hence, collecting macroplastic debris from the river will facilitate clean-up procedure before they reach the ocean.

On the other hand, mismanaged macroplastic debris also harms urban drainage system due to the accumulation at hydraulic structures. These debris accumulations affect the performance of hydraulic structures and result in additional flooding. Hence, understanding the accumulation process of plastic debris is crucial to better design hydraulic structures. It should be noted that ice-jams in rivers can cause similar problems to hydraulic structures.

To analyse the research problem, we subdivided the accumulation process into three subprocesses as shown in Fig. 1: (1) the overall stability of the accumulation layer, also called the carpet, (2) the flow response (e.g. mean flow velocity profile, boundary shear stresses) to the presence of the carpet, and (3) detailed analysis of hydrodynamic forces (lift and drag) acting on the individual particles located in different horizontal and vertical positions with respect to the carpet.

In this study, we are interested in how the particles are influenced by the flow transition induced by the debris carpet or ice jams within a turbulent flow, leading to the following research question: "How does the accumulation affect the hydrodynamic forces, drag and lift forces, acting on the individual particles in the vicinity of the transition point and underneath the layer?"

Research Methods

To better understand the flow physics in such a transition from an open channel to a closed channel, we employed Direct Numerical Simulation (DNS) coupled with the volume penalization technique. Different roughnesses of the top cover were studied with the combination of smooth bottom wall in this research.

To investigate the impact of such a flow transition on the hydrodynamics forces acting on the particles, using DNS method we simulated different scenarios in which a particle is positioned at different vertical and horizontal positions in the computational domain with respect to the carpet as shown in Fig. 2.

Results and Discussion

At the transition, the bottom shear stress forms a hump-shaped profile, and gradually approaches a constant value at the fully developed flow condition of the closed channel section. This hump-shaped shear stress profile is attributed to flow acceleration caused by the cross-sectional contraction, as well as the downward streamline deflection induced by the carpet geometry. As for the top carpet boundary, the shear stress at the transition is significantly large compared to the stress along the whole carpet, and it decreases to the constant value of fully developed flow condition.

Due to the asymmetric roughnesses at the top and bottom boundaries, the location of streamwise maximum velocity is found to be different from the location of zero shear stress. Therefore, the practical consequence of the rough top boundary can be seen in the river bed erosion under the debris accumulation or ice-jams.

Regarding the effect of the carpet on particle forces, a particle far upstream or downstream of the carpet shows a constant mean drag force and lift force, being independent of the hor-

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izontal position. A particle near the leading edge of the carpet experiences a relatively large downward force (or negative lift force) due to flow contraction at the transition point, therefore being very vulnerable to particle erosion. Moreover, due to flow separation at this location, the particle also experiences extreme fluctuation forces, which can also trigger the erosion. Vortex shedding, commonly occurring in flows past a sphere, is also observed around the emerged sphere far upstream of the carpet. However, the vortex shedding no longer occurs for the particle in the vicinity of the carpet, which leads to more unpredictable irregular force fluctuations.

Spheres located in the position of a fully developed flow underneath the carpet show smaller drag and lift forces, where the spheres of interest are shielded around the spheres of the carpet. Therefore, these shielded particles are less vulnerable to particle erosion compared to the particles at the flow transition.

Future Perspectives

The acquired knowledge in this study on flow transition and an asymmetric closed channel can be beneficial to not only collecting the floating debris accumulation but also mitigation of bed erosion in the channel. Lessons learned can be used for the role of driftwood and ice-covers with respect to the interactions with hydraulic infrastructures. Knowledge of the mixing process underneath the carpet will also enhance our understanding of the transport of nutrients and energy essential to riverine ecosystems.

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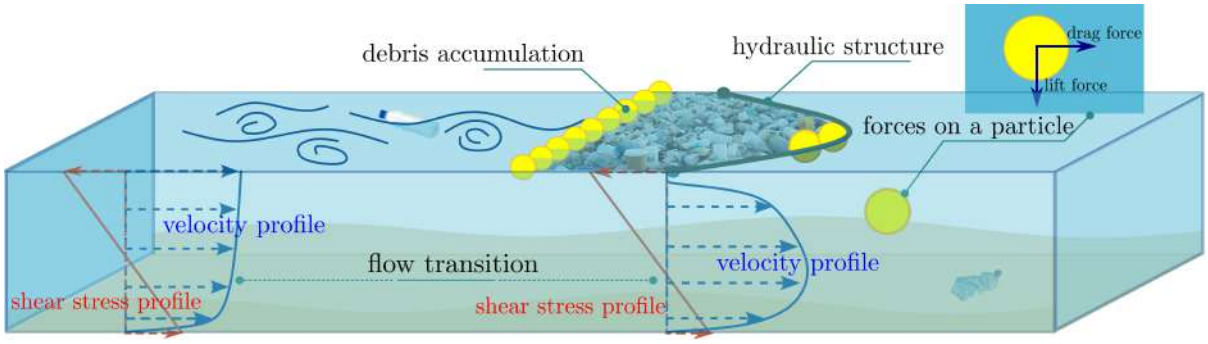


Figure 1: Three subprocesses of the debris accumulation at a hydraulic structure: (1) overall stability of the accumulation layer or the carpet, (2) flow response due to the presence of the accumulation layer, and (3) quantification of hydrodynamic forces action on the particle in different configurations with respect to the accumulation layer.

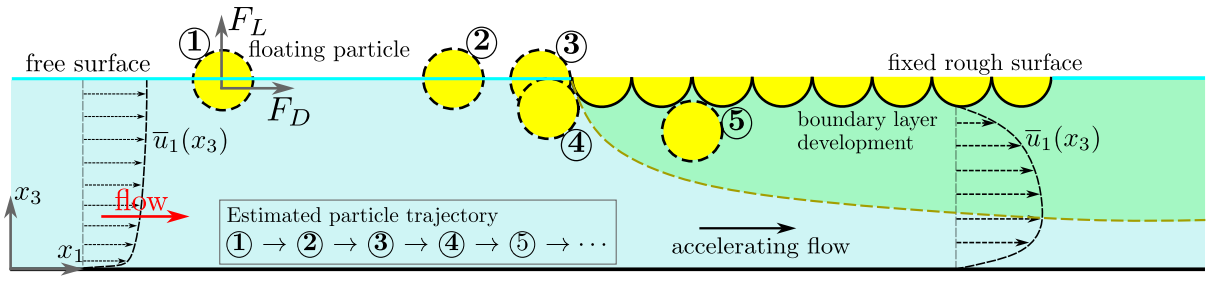


Figure 2: Conceptual sketch for a particle at different positions with respect to a floating carpet. A floating particle is considered to advect in the mean flow direction from position 1 to 5 through encountering a flow transition from the open to closed channel.