Effect of a cylinder on the transport of a solute released downstream of a step

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ABSTRACT: Rivers are vital for ecosystems as they provide habitats for aquatic life. The presence of step-like structures on river or lake bottoms is of interest in environmental studies due to the localized recirculation zones and transverse flows. Additionally, wooden logs as cylindrical obstacles lodged downstream of the step, further altering flow characteristics. This can result in the accumulation of solutes, such as contaminants and nutrients. Numerical simulations using OpenFOAM were conducted to investigate the impact of a cylinder downstream of a step on solute releasing from the bottom corner. Two-dimensional simulations were conducted at a Reynolds number based on step height (Re_h) of 100 with a Schmidt number (Sc) of 500. Solute distribution in the fluid, Residence Time Distribution (RTD), and hydraulic efficiency indicators at different locations in the domain were comparatively studied. The study revealed that a cylindrical obstacle downstream of a step-like structure significantly influences the solute transport, causing it to be washed rapidly away from the recirculation zone.

1 INTRODUCTION

Variations in riverbed elevation can induce heterogeneous flow patterns. Some morphological irregularities in the riverbeds, such as cavities, steps, and bedforms (called step-like geometry), have flow fields with shearing and flow separation at the edge that can produce recirculating downstream of the edge (Gualtieri, 2008, Jackson et al., 2013). When these step-like formations are implemented for purposes such as flood control, energy dissipation, or erosion control, they have the potential to modify flow patterns. In environmental contexts, recirculation zones and transverse flows downstream of step-like geometries play crucial roles in stream ecology, creating dead zones for the mainstream current. This alteration in natural flow dynamics may result in the downstream accumulation of sediment and solute, encompassing pollutants and heavy metals.

In a stream, some cylindrical objects such as wood may become lodged near or within expansions, significantly influencing flow dynamics in step channels and giving rise to intricate flow patterns. In recent years, cylinders have also been used in the modification of backward-facing step flows (Kumar and Dhiman, 2012, Abdollahpour et al., 2022a, Abdollahpour et al., 2022b). The cylinder creates a large drag due to the periodic separation and causes some differences in the pressure between the downstream and upstream. Characteristics of this flow are the separation and reattachment of the boundary layers, wake interactions, vortex breakdown, and merging (Nguyen et al., 2021).

In the last decades, solute transport processes and exchange mechanisms in recirculation zones have received increased attention in environmental hydraulics (EH). Numerous studies on solute dispersion in around a dead zone (Lees et al., 2000, Gualtieri, 2008, Gualtieri et al., 2010, Gualtieri, 2010, Sokáč et al., 2018, Sokáč et al., 2019, Wu and Yu, 2021, Faraji and Mazaheri, 2022); cavities flow (Chang et al., 2007, Gualtieri, 2009, Jackson et al., 2015, Navas-Montilla et al., 2021); backward-facing step flow (Min et al., 2020, Charlwood et al., 2023) have been conducted.

Computational Fluid Dynamics (CFD) is applied in EH for investigating complex flow dynamics and flow patterns, sediment transport, and assessing aquatic habitat quality (Blocken and Gualtieri, 2012). The importance of solute transport in EH is underscored by its relevance in various applications, such as the management of pollutants in rivers, lakes, and coastal zones. Understanding the transport processes in complex geometries can lead to the development of more effective and efficient mitigation strategies for environmental problems. While mean flow and turbulence characteristics with cylindrical obstacles have been studied (Abdollahpour et al., 2023a, Abdollahpour et al., 2023b), there is no systematic investigationon the release of a solute from a square region with a cylinder placed downstream of a step-like geometry The present research studied that case using using the open-source CFD toolbox OpenFOAM. The solute concentration and its evolution over time the are critical for predicting how a solute can impact on aquatic ecosystems .

2 MATERIAL AND METHODS

Numerical simulations were performed using the open-source code Open-Source Field Operation and Manipulation (OpenFOAM). For flow field validation, we considered classically step flow following the geometry experimentally studied by (Armaly et al., 1983, Wang et al., 2019) which was already presented by (Abdollahpour et al., 2023a). To study the effect of cylinder placement on a solute releasing from the square region at the step corner, two geometries were considered step (namely S1) and step with cylinder (namely S2). For the S2, a cylinder with a diameter (D) was considered at one cylinder-diameter distance from the step edge (X=D) in the x-direction (Figure 1). For validation of the solute concentration, we considered the characteristics followed by (Min et al., 2020). The solute is initially confined to a region adjacent to the step, with a square cross-section and dimensions equal to the height of the step. The sketch of the step with the solute source downstream of the step is presented in Figure 1.

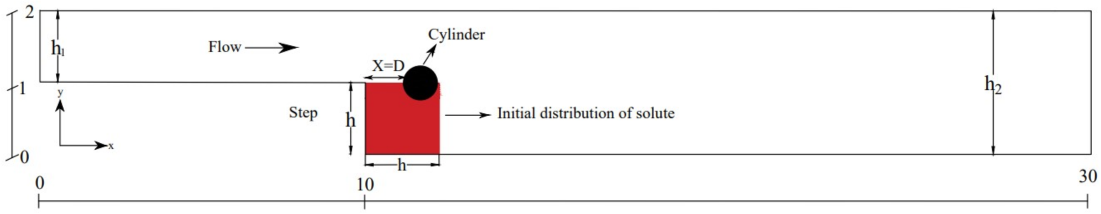


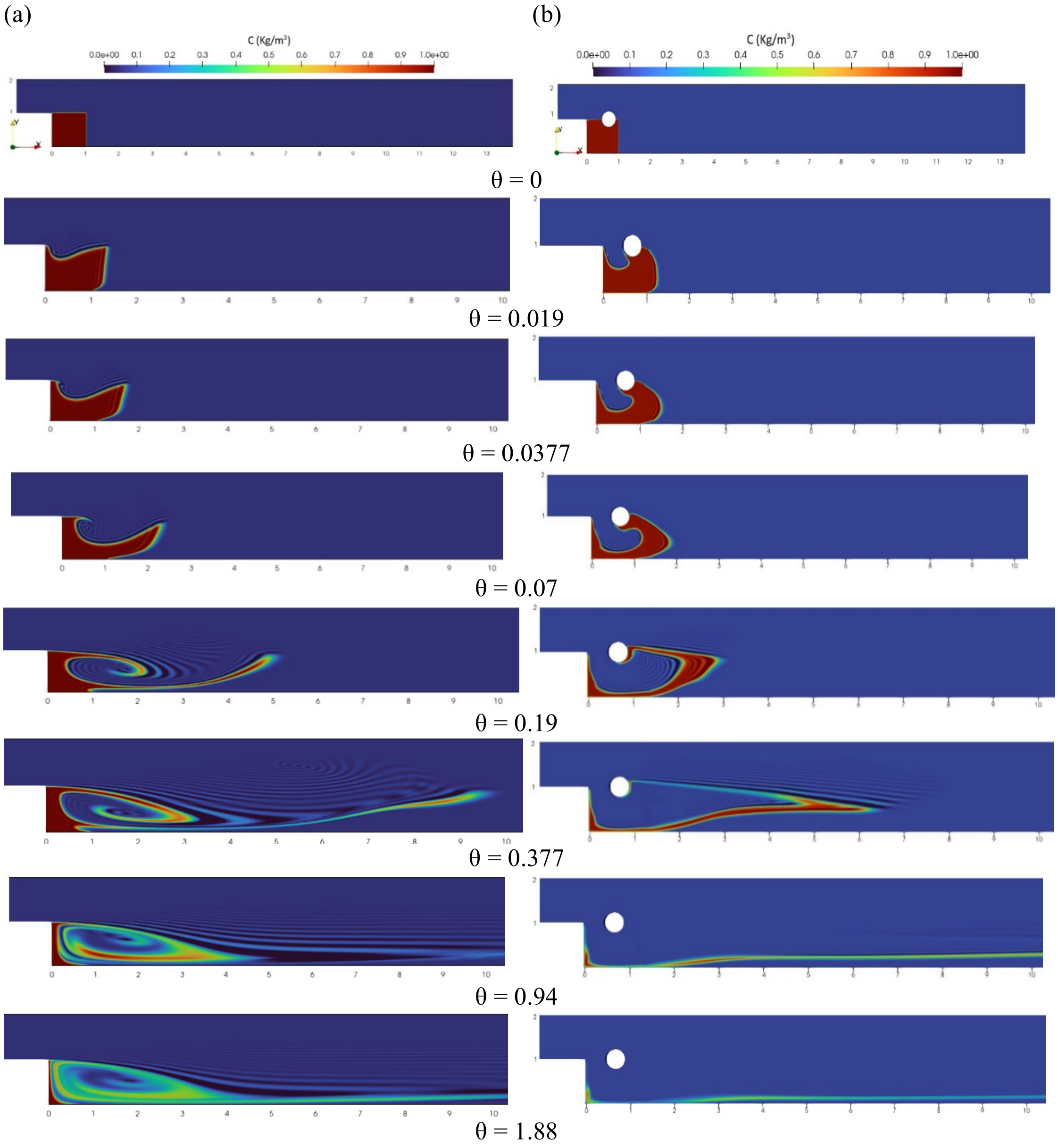
Figure 1. A sketch of the numerical domain with the solute source placed at the step corner. h and h_1 represent the step height and inlet-section height, respectively. D is the cylinder diameter and X is the distance of the cylinder from the step.

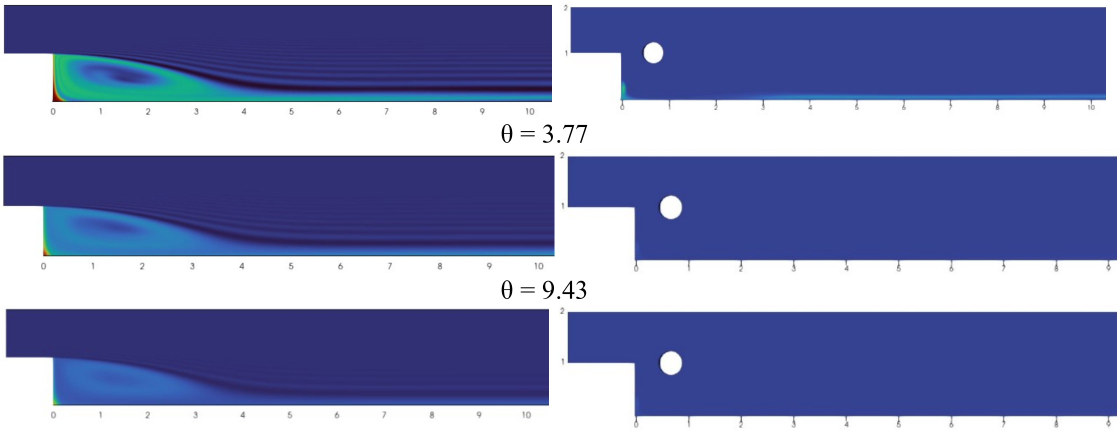
Water at 4◦ C with a density of ρ=1000 Kg/m^3 was selected as fluid. The Reynolds number based on the step height (h) and the inlet velocity (U) was defined as Re_h=Uh/υ=100. An area of concentration was considered as a non-reactive solute with a Schmidt number of 500; (Sc= υ/D =500); where D is the diffusion coefficient. This range of Schmidt numbers is representative of various environmental solutes. The advection-diffusion equation (ADE) is widely applicable to a variety of physical, chemical, and biological processes. It is well-known that the Navier-Stokes equations for mass and momentum conservation are applied to calculate the velocity field of the water.. In this study, the ADE was coupled to the Navier-Stokes equations to provide the spatial distribution of solute. We conducted some numerical simulations to analyse the influence of the cylinder on solute transport within a region adjacent to the step. The results of this analysis are presented in the following section.

3 RESULTS

3.1. Solute temporal distribution

The study of solute transport focused on a region adjacent to the step, characterized by a square cross-section with dimensions equal to the height of the step. The solute distribution was tracked at various time intervals for S1 and S2. The temporal evolution of the solute distribution for S1 and S2 are shown in Figure 2. The dimensionless time scale was defined as $\theta = t/t_{HRT}$, where t_{HRT} is the theoretical mean residence time, defined as the ratio of the volume of the domain to the flow discharge.





θ = 3.77

θ = 9.43

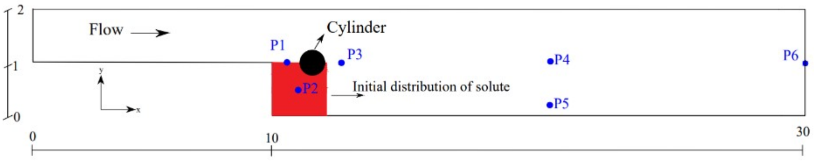
θ = 18.86

Figure 2. Solute distribution at different time steps a) S1 b) S2

For the classical step (S1), the flow pattern involves several different flow regions. Notably, a recirculation zone is formed on the bottom wall (Armaly et al., 1983). As shown in Figure 2-a, the solute decreased due to a downwardly directed flow downstream of the step, and a large part of the solute was carried slightly downstream. A starting vortex formed below the top corner of a step, accompanied by a strong downward flow slightly downstream. Over time, the vortex expanded, and the solute plume was advected downstream, with diffusion effects becoming more prominent. Due to reverse flow, solute was advected downstream, but a portion of it was trapped in the primary recirculation zone. The recirculation zone elongated over time, accompanied by a reversal of flow within the recirculation, leading to the expansion of the region characterized by reverse flow, notably in the core of the primary recirculation. The effects of the cylinder on this process were investigated, and Figure 2-b depicts the temporal evolution of the solute distribution. In Figure 2-b, a cylinder was positioned downstream of the step. As outlined by (Abdollahpour et al., 2023b), no recirculation zones were observed at Re_h=100. For the S2, the process of transport was changed and at the beginning, some portion of the solute was directed towards the below of the cylinder, and a large portion of it continued to move in the x-direction. In S2, a large amount of the tracer left the geometry.

3.2. Residence Time Distribution (RTD)

The Residence Time Distribution (RTD) is defined as the probability distribution of time that fluid materials stay inside unit operations in a continuous flow system (Danckwerts, 1953). The RTD function plays a crucial role in understanding solute transport within water systems. The RTD curves at five different locations in the S1 and S2 were considered (Figure 3). Point 1 is immediately downstream of the step, whereas points 2 and 3 are in the recirculation zones and the cylinder wake, point 4 is in the middle of the channel, and point 5 is in the outlet of the channel.



Point	X	Y
P1	10.225	1
P2	10.5	1
P3	11.33	1
P4	20	1
P5	20	0.15
P6	30	1

Figure 3. Location of points where the temporal distribution of the solute was analysed (not to scale)

The temporal distribution of the dimensionless solute concentration, which is defined as C/C_0, where C_0 is the solute concentration in the square area at the initial time (t=0), and C_0 is set to 1, is presented in Figures 4 and 5 for S1 and S2, respectively.

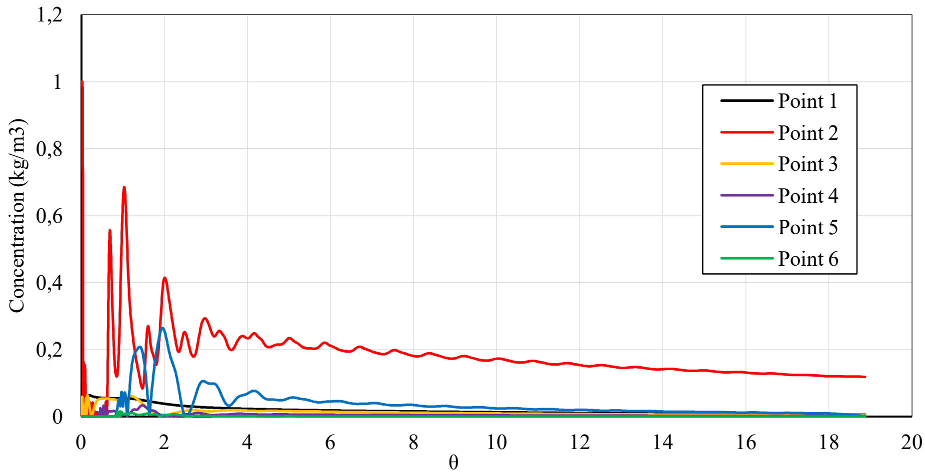


Figure 4. Solute concentration at different points over time for S1

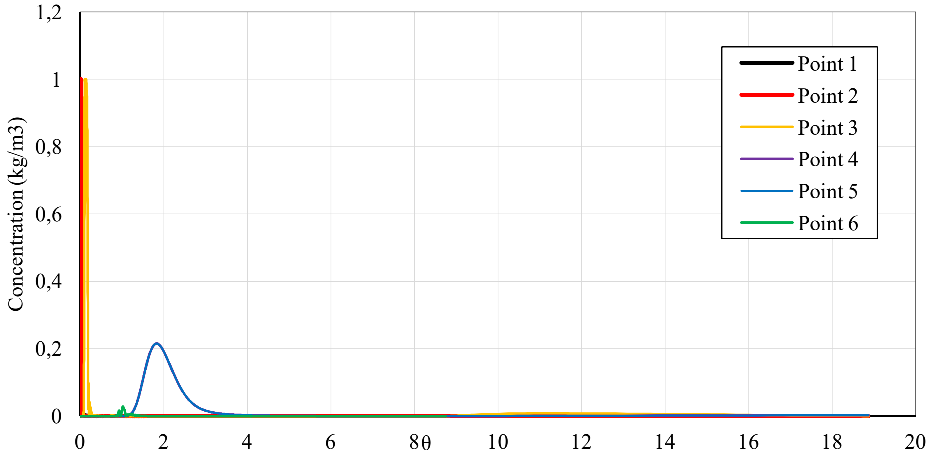


Figure 5. Solute concentration at different points over time for S2

For S1, the solute originates at the corner of the step, where point 1 is located at the top edge of this area. Since flow separation occurs at the step and reattaches to the bottom wall, there is a negligible amount of solute at point 1. Within the core of the recirculation zone, the solute remained high over time at point 2. It is noteworthy that low concentration at points 3, 4, and 5 during the discharge process indicated that the solute, after being trapped in the recirculation zone, reached the outlet through the lower wall. This suggests that the recirculation zone plays a crucial role in the transport of solute. The concentration in the recirculation zone is significantly higher than in other regions, indicating that the recirculation zone acts as a trap for the solute. The low concentration at points 3, 4, and 6 suggests that the tracer plume is transported through the lower wall. For the S2, the solute was affected by the cylinder located downstream of the step. At point 1, the solute concentration was negligible, like in S1. While, within the core of the recirculation zone, a large portion of the flow continued to move from point 2, and this area was washed out very quickly. Differences in concentration were found at point 3, where an increase in solute concentration was observed but for a short time, suggesting that the wake of the cylinder quickly washed out the plume below the cylinder. Like S1, solute was transported through the lower wall at points 3, 4, and 6, indicating that the recirculation zone can act as a source of solute downstream of the step.

Figure 6 shows the curve concentration for the S1 and S2 at the outlet which F(t) represents the cumulative distribution function of RTD.

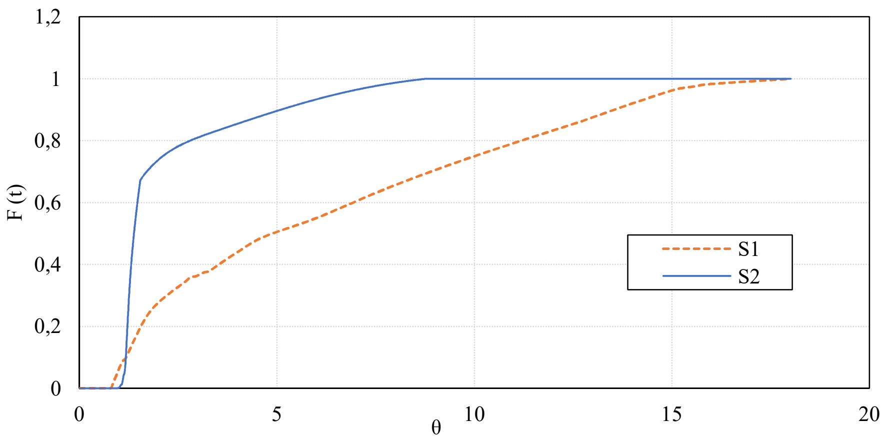


Figure 6. Cumulative residence time distribution (RTD) at the outlet vs dimensionless time (θ)

It was found that in S2, the solute peak arrived before the solute peak for S1. In S2, a sharp peak in the RTD curve revealed flow short-circuiting, indicating a shorter pass-through time due to the cylinder. The delayed peak of S1 was associated with the release of the solute trapped in the recirculation zones. This trapped solute left the geometry slowly.

The concentration field in both S1 and S2 was studied using the RTD function, which is an indicator used to evaluate hydraulic efficiency in water systems. Different indicators derived from the RTD curve can be used to describe the mixing of a solute. The value of indicators for S1 and S2 are listed in Table 1. The indicators, such as $\theta_{10,}$ $\theta_{50,}$ and θ_{90} show the time in which 10 %, 50 %, and 90% of the solute reached the outlet. The indicator M_{90-10} is the time elapsed between t_{10} and t_{90} and M_{75-25} is the time elapsed between t_{25} and t_{75}. Analysing the M_{90-10} and M_{75-25} indicators in solute transport provides insights into the dynamics of solute movement. By normalizing concentration values, the RTD function allows us to focus on the temporal aspects of solute movement, independent of absolute concentration levels. Smaller value ranges indicate rapid movement, while larger ranges suggest heightened dispersion and prolonged solute residence.

Table 1. Hydraulic efficiency indicators for the S1 and S2

Indicators	**S1**	**S2**
$\boldsymbol{\theta_{10}}$	0.39	0.374
$\boldsymbol{\theta_{90}}$	4.31	1.62
$\mathbf{S_{50}}$	0.49	0.135
$\mathbf{M_{90-10}}$	1.23	0.39
$\mathbf{M_{75-25}}$	0.81	0.09

The results showed that the values of θ_{10} in S2 were smaller than those in S1, indicating a short circuit between the inlet and the outlet. In S1, the value of θ_{90} was higher than that of S2, indicating retention of the tracer inside the recirculation zone. The comparison of M_{90-10} and M_{75-25} between S1 and S2 indicated that some portions of the solute were trapped in geometry in S1, resulting in higher values of these indicators for S1.

4 DISCUSSION AND CONCLUSIONS

In the present study, two geometries were comparatively considered, namely the classical step (S1) and a step with a cylinder placed downstream of the step (S2), The numerical study investigated the influence of a cylinder downstream of a step on the transport of a solute released from a square area placed at the step corner. The cylinder modified the solute distribution as it was washed-out solute being trapped in the recirculation zone. It was found that for S1 the solute concentration peaked before than for S2. In addition, the step with the cylinder induced a shorter residence time for the trapped solute, a higher degree of short-circuiting, and an earlier observation time for the tracer at the outlet. This research enhances our current understanding of solute transport process downstream of step-like geometries.

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