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CFD analysis of bioenergetics metric at a step with horizontal cylinder

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Abstract

The flow over a step in an open channel can create complex flow patterns and recirculation zones. In this study, the impact of a cylinder located downstream of a step in a three-dimensional channel was numerically investigated using computational fluid dynamics (CFD). Such a cylinder placed at different locations downstream of the step can significantly affect the recirculation zone, leading to the formation of a second recirculation zone. In addition, the cylinder may have an impact on hydraulic complexity and turbulence levels in streams. In river ecology, habitat quality is correlated with the substrate and the flow characteristics, which are related to the hydraulic complexity within a stream. In this study, the bioenergetics metric M_2, which approximates the drag forces imposed on aquatic organisms moving between two locations, was used to identify bioenergetics patterns in the flow over the step. The presence of the cylinder caused an increase in metric M_2, suggesting that obstacles can significantly impact the local flow structure and thus potentially affect the availability of suitable habitats for aquatic organisms.

Keywords: Ecohydraulics, Numerical simulation, Step channel, Cylinder, Bioenergetics metric

1. INTRODUCTION

Rivers can develop spatially varying flows, referred to as nonuniform flow, due to spatial variation in bedform elevation (Gualtieri 2008, Gualtieri et al. 2017). 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 (Jackson et al. 2013). Recirculation zones and transverse flows downstream of step-like geometry typically play an important role in stream ecology, as they can increase the residence time of organic matter and nutrients and enhance deposition processes. Defining habitat for fish, and other aquatic organisms may be evaluated through hydraulic characteristics such as flow depth, velocity gradients, vortices, and recirculation (Crowder and Diplas 2000a, Crowder and Diplas 2002). Velocity gradients, along with other microhabitat parameters such as flow depth, are important across all scales and can influence physical habitat as well as biological activity. Fish and other aquatic organisms can adjust their behavior in terms of spawning, feeding, and access to refugia by reacting to the velocity patterns present in high flows (Gualtieri et al. 2020).

Many studies have attempted to quantify the complexity and hydraulic habitat features in streams (Shields and Rigby 2005, Kozarek et al. 2010, Fischer et al. 2020); river confluences (Gualtieri et al. 2017, Gualtieri et al. 2018, Gualtieri et al. 2020, Luis and Pasternack 2023); downstream of engineered log jams (L'Hommedieu et al. 2020); near boulders (Crowder and Diplas 2000b, Golpira et al. 2022). Moreover, research has established a correlation between hydraulic complexity metrics of a habitat and ecological factors such as the availability of preferred habitats, spawning grounds, and feeding locations (Crowder and Diplas 2002, 2006, Yu et al. 2008, Zhu et al. 2013).

Constructed channels such as step channels, bottom cavities, and lateral cavities that emulate natural features often incorporate structures that enhance habitat complexity, resulting in improved food availability for fish (Scrimgeour et al. 2014).

Crowder and Diplas (2000b, 2002) introduced spatial metrics to quantify the level of hydraulic complexity in streams and describe its relationship with the preferred habitats of fish. In particular, the bioenergetics metric M_2, provides a measure of how much more energy an aquatic organism must expend moving from a location with lower velocity to a location with higher velocity, and can be used to identify bioenergetics patterns in the flow structure. Evaluating hydrodynamic interaction between step-like geometry and the surrounding environment is crucial for promoting river ecosystems. It causes localized velocity gradients that significantly impact aquatic habitats, making its evaluation essential for designing successful management strategies and evaluating overall ecosystem impact. Failure to understand this interplay can lead to unintended consequences such as altered flow patterns, sediment transport, and changes in aquatic habitat quality. In addition, the presence of obstacles in aquatic environments can significantly impact fish behavior and swimming performance. Several studies have examined fish behavior in the presence of cylinders and other hydrodynamic perturbations (Liao et al. 2003, Liao 2004, Xiao et al. 2011, Ducrocq et al. 2017, Ke et al. 2021, Ke et al. 2022). Their results demonstrated that fish may modify their body kinematics and adopt movement patterns to navigate their environment.

In the stream, some cylindrical obstacles like wood may be trapped near or inside the expansions. They can have a significant impact on the flow dynamics in step-like channels, creating complex flow patterns (Gualtieri 2005). Computational fluid dynamics (CFD) is widely used in environmental fluid mechanics to study complex flow dynamics in rivers and predict flow dynamics, sediment transport, and aquatic habitat quality (Blocken and Gualtieri 2012). This approach can provide insights into bioenergetics metrics with different cylindrical obstacle placements. While mean and turbulent flow characteristics with cylindrical obstacles have been studied (Abdollahpour et al. 2023a, b), there is no systematic examination of how proposed bioenergetics metrics vary with different cylindrical obstacle placements downstream of step-like geometries.

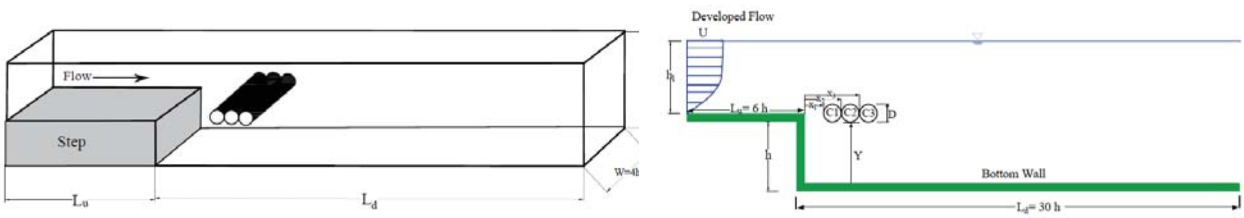
The objective of this study is to analyze the effect of different cylinder placements downstream of a step, on local variations of the bioenergetics metric and recirculation zones. In the present study, three-dimensional numerical simulations were performed using OpenFOAM, an open-source CFD code. The bioenergetics metric M_2 was calculated based on the simulated velocity field. The results of this study might provide valuable insights into the impact of cylindrical obstacles on both recirculation zones and hydraulic complexity of aquatic ecosystems, in a step-like geometry.

2. MATERIAL AND METHODS

2.1. Numerical Model

Numerical simulations were performed using the open-source code OpenFOAM (Open-Source Field Operation and Manipulation). The most common approach to simulate turbulent flow, i.e., a numerical simulation based on the Reynolds-Averaged Navier-Stokes equations (RANS) was used. For validation, we considered the three-dimensional step flow following the geometry experimentally studied by Wang et al. [1] with an expansion ratio ($ER = h_2/h_1 = 2$).

To study the effect of cylinder placement on the local variations of the bioenergetics metric, two geometries were considered: step flow (namely SF1) and a step flow with cylinder (namely SF2). For the geometry SF2, a cylinder at different locations shifted horizontally downstream of the step was considered. The top half of the cylinder was above the top surface (mid-plane) of the step. The sketch of the layout of the numerical simulation is presented in Figure 1. The domain downstream of the step was considered to L_d = 30 h for both cases SF1 and SF2. L_u and L_d are lengths upstream of the step and downstream of the step. A cylinder was placed at three different locations in the x-direction from the step edge. The different configurations of tests are presented in Table 1.



(a) (b)

Figure 1. (a) Sketch of the numerical simulation layout (b) Profile view of the computational domain (not to scale). For test SF2, the cylinder was placed at different distances from the step edge in the x-direction. h and h_1 represent the step height and inlet-section height, respectively. D is the cylinder diameter and x_1, x_2, and x_3 are the distances of the cylinder from the step.

Table 1. Configurations of tests SF1 and SF2. x represents the distance of the cylinder from the step in the x-direction, y represents the distance of the cylinder from the bottom wall in the y-direction and D is the cylinder diameter

Run	x	y	Remarks
SF1	-	-	Step without cylinder
SF2 – C1	X1=1 D	$h-\frac{D}{2}$	Step with cylinder
SF2 – C2	X2=2 D	$h-\frac{D}{2}$	Step with cylinder
SF2 – C3	X3=3 D	$h-\frac{D}{2}$	Step with cylinder

In this study, boundary conditions (BC) were assigned at the inlet, the outlet, and the walls including the cylinder. The boundary conditions applied to SF1 and SF2 were adopted for consistency. The bottom and cylinder walls were treated as solid walls to account for the no-slip BC, while for the upper wall symmetry BC was considered. To initialize the flow, a fully developed flow condition was set at the inlet. These boundary conditions were carefully selected to accurately simulate the flow behavior and provide reliable results for the study. For the simulation, water with density ρ=997 kg/m³ and kinematic viscosity (υ) 0.893×10^{-6} Pa.s was selected as fluid. The Reynolds number based on the step height (h) is defined as $Re_h = \frac{Uh}{\upsilon}$. According to Armaly et al. 1983, in the step flow, the turbulent flow occurs for step-height Reynolds number Re_h > 4,950. So, the step-height Reynolds number was 9,000. Three-dimensional RANS simulations were performed using the standard k-ε turbulence model.

2.2. Calculation of the bioenergetics metric M_2

Hydraulic complexity metric is defined as spatial variation in flow patterns, which may include eddies, transverse flows, and other flows causing velocity gradients. Velocity gradients in nonuniform flows are found in flow separation and recirculation zones which are associated with the flow complexity within the stream. They are likely impacting and utilized by fish and other aquatic organisms (Crowder and Diplas 2000a, Crowder and Diplas 2000b, 2002, Gualtieri et al. 2020). In numerical simulations, the bioenergetics metric, M_2, can be calculated using a mesh-based approach, where the simulation domain is discretized into a finite number of computational cells or elements. The geometric properties of each cell, such as width, depth, and slope, are then calculated using established numerical methods and algorithms, which can consider variations in channel geometry and flow conditions. The calculated properties are subsequently used to determine the overall metric M_2, which can be used to assess the channel's habitat suitability, sediment transport capacity, and other important hydraulic characteristics. The metric M_2 indicates the average rate of change in kinetic energy per unit mass and unit length between two points, which is defined as (Crowder and Diplas 2000b):

$$M_2 = 2V_{avg} \frac{\left| V_2 - V_1 / \Delta s \right|}{V_{min}^2} \quad [1]$$

where V_2 and V_1 are velocity magnitudes measured at points 1 and 2, Δs apart from each other, V_{avg} is the average velocity magnitude between points 1 and 2 (mesh cells), and V_{min} is the minimum value of V_2 and V_1.

Following the implementation of the methodology described the recirculation zone and metric M_2 of step flow with and without cylinder were analyzed through a comprehensive numerical simulation. The outcomes of this analysis are presented in the ensuing section, which provides a discussion of the characteristics of the recirculation zone, as well as a quantitative measure of the channel's hydraulic complexity based on various geometric features.

3. RESULTS

3.1. Recirculation zone

The most important characteristics of the flow over the step are separation and reattachment. The adverse pressure gradient due to the sudden expansion at the edge of the step caused flow separation. In turbulent flow, the flow separated at the sharp corner of the step and reattached downstream at the bottom wall. A sketch of the flow over a step is shown in Figure 2.

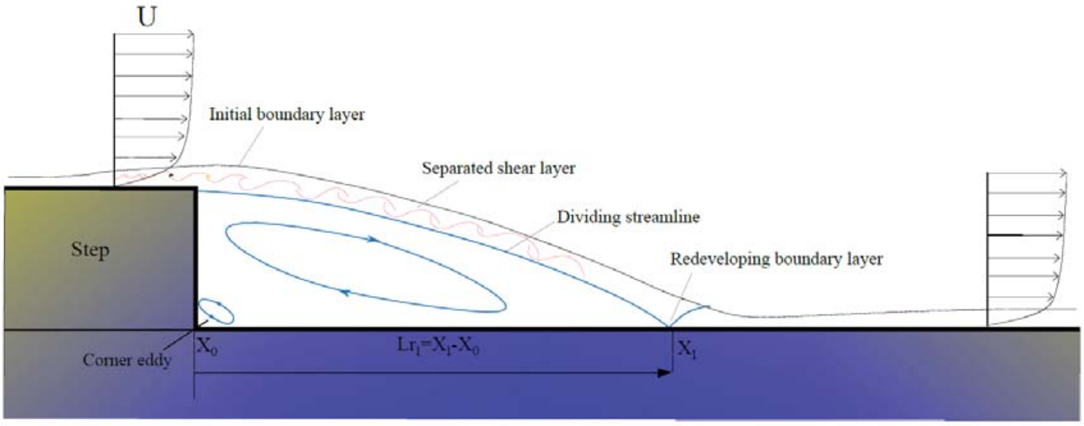


Figure 2. Detailed flow features over the step in turbulent flow

In the present study, the Line Integral Convolution (LIC) method was used to obtain flow field contours at different cases of flow over the step. The LIC method proposed by Cabral and Leedom (1993), offers advantages for visualizing vector fields, particularly in irregular structures, where fluid and structure interactions can create recirculation. The LIC visualization method was used on all runs, as shown in Figure 3, to obtain contours at different runs.

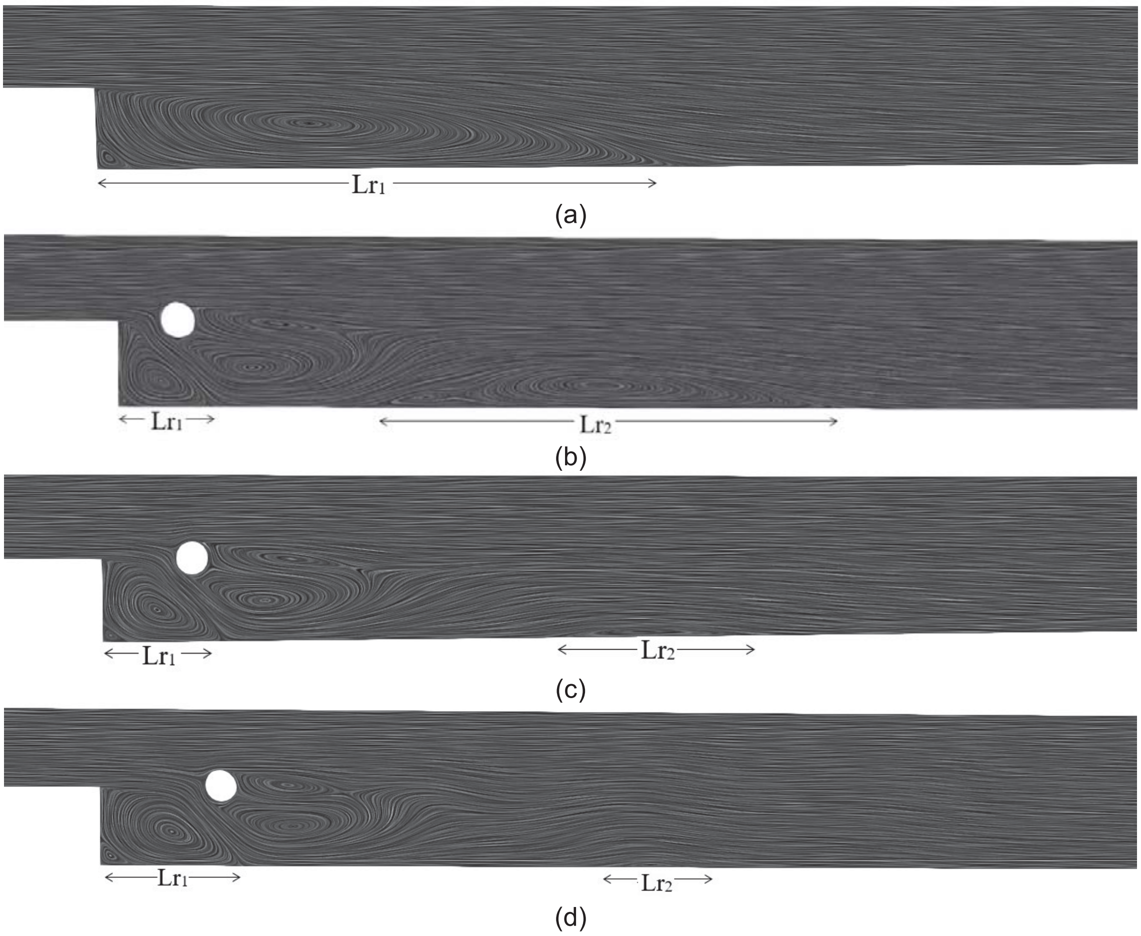


Figure 3. LIC Flow visualization of recirculation zone downstream of step a) SF1 b) SF2 – C1 c) SF2 – C1 d) SF2 – C1

In the turbulent step flow (SF1), the flow separated at the sharp corner of the step and reattached to the bottom wall. This is the primary recirculation zone having a length of Lr_1 (Figure 3-a). However, as a cylinder was installed at different locations downstream of the step, a second recirculating zone (Lr_2) was observed. As shown in Figure 4, the cylinder pushed the primary recirculation region upstream to the corner of the step and its size increased as the distance of the cylinder increased in the x-direction. Table 2 lists the value of the normalized location of starting and ending recirculation zones in SF1 and SF2.

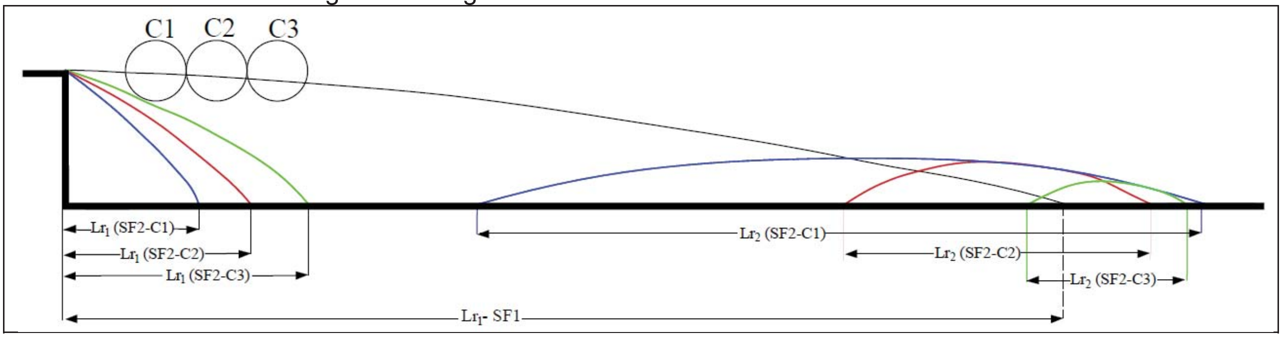


Figure 4. Reattachment and recirculation zones downstream of step for test SF2 compared with that of SF1

Table 2. Value of dimensionless reattachment lengths (Lr_1/h and Lr_2/h) of the SF2 test at different locations of cylinder compared with that of SF1

	SF1	SF2 – C1	SF2 – C2	SF2 – C3
Lr_1/h	7.5	1.05	1.45	1.85
Lr_2/h	-	5.7	2.31	1.35

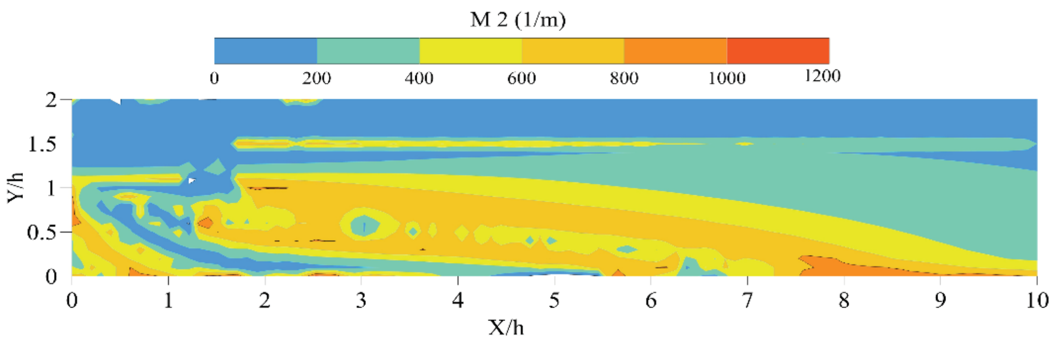
The results showed that as a cylinder placed downstream of the step produced a second recirculation zone, the flow was directly incident on the cylinder; these vortices were thought to approach the wall, and the second recirculation zone was formed due to the sharp change in flow direction caused by the eddies. The second recirculation zone was caused by vortices shedding from the edge of the step (Abdollahpour et al. 2022).

In the recirculation zone, the flow is reversed, which can affect the swimming behavior of fish. Fish swimming in the recirculation zone may experience increased drag and reduced swimming efficiency, as they have to overcome the eddies formed by the flow reversal. The size and strength of the recirculation zone, which in turn may affect the swimming behavior of fish, can vary depending on the geometry of the step and the flow conditions.

3.2. Bioenergetics metric M_2

Maps of metric M_2 at the different horizontal locations of the cylinder downstream of the step were generated. To reduce the computational time, we limited the zone to the critical area where the flow behavior is most complex and where deviations from the desired hydraulic performance are most likely to occur.

a)



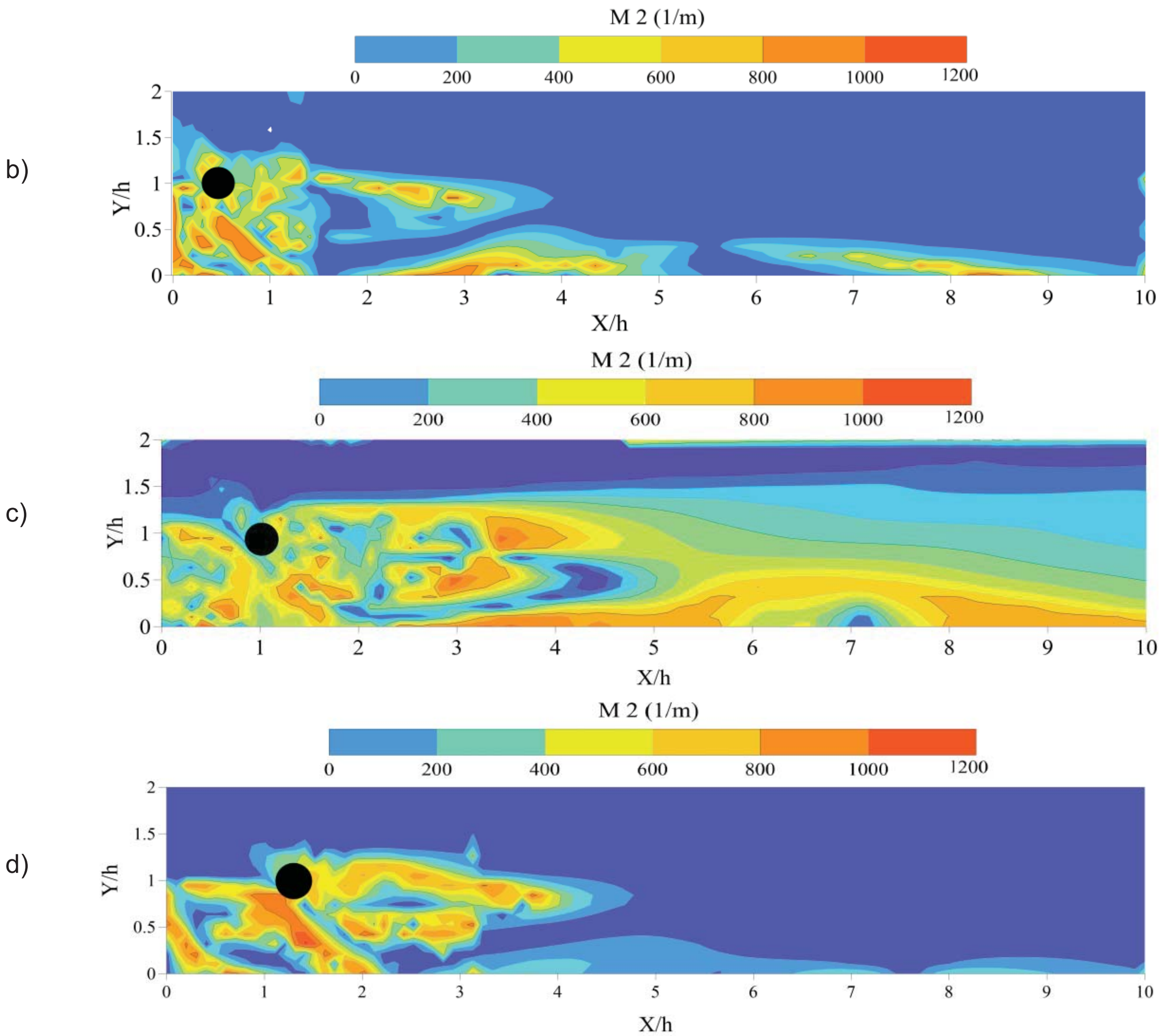


Figure 5. Map of the metric M_2 a) SF1 b) SF2 - C1 c) SF2 – C2 d) SF2 – C3

Figure 5-a shows the metric M_2 distribution in SF1, where a region with high M_2 was observed in the vicinity of the reattachment point and the corner of the step. This region indicates a complex flow structure with significant energy gradients and recirculation zones. Figures 5-b, c, and d show the M_2 distribution for tests SF2, where a cylinder was placed downstream of the step at different locations. In all runs of SF2, regions with high M_2 values were observed downstream of the cylinder, specifically in the wake of the cylinder. This indicates that adding a cylinder downstream of the step increased the value of metric M_2. However, for test SF2-C3 the extension of M_2 impact can be reduced compared to the other cases, in particular to SF1.

The variations in the metric M2 reflect changes in energy and energy expenditure levels for organisms moving in a specific direction of flow. It can also locate potential feeding and resting stations and help determine suitable fish habitats based on their energy needs (Crowder and Diplas 2000b). Such results suggest that the presence of an obstacle in a flow field can significantly influence the flow structure and increase hydraulic complexity. Regions with significant energy gradients and recirculation can be used to specify suitable habitats, such as spawning and feeding grounds, for aquatic organisms. Fish adopt a pattern of body motion called the Kármán gait when swimming behind an obstacle such as a cylinder, to reduce locomotor costs by capturing energy from the low-pressure, high-vorticity regions in the cylinder wake (Liao et al. 2003, Liao 2004). The presence of an obstacle downstream of the step can alter the velocity and turbulence characteristics of the flow past the obstacle. As a result, fish may experience increased drag due to the turbulent flow, resulting in reduced swimming efficiency and higher energy costs. However, some fish species may use the region with a high value of M_2 to their advantage by reducing their energy expenditure during swimming.

4. CONCLUSIONS

This study investigates the effects of placing a cylindrical obstacle downstream of a step (SF2) on the recirculation zone and bioenergetics metric M_2. The presence of a cylinder can significantly impact the formation and dynamics of the recirculation zone, potentially leading to the formation of a second recirculation zone. This can affect the habitat conditions for aquatic organisms, as flow dynamics are closely tied to the substrate properties of fluvial ecological systems. The distribution of metric M2 was analyzed with and without a cylinder, revealing a complex flow structure with high energy gradients and recirculation zones near the reattachment point and the corner of the step. The presence of a cylinder increased the value of metric M2, demonstrating that obstacles in the flow field of the step-like geometry can significantly influence the flow structure and increase hydraulic complexity. This can affect fish behavior and swimming performance. Further research is needed to extend knowledge about the effects of recirculation zones and the metric M_2 on fish behavior and develop effective strategies for managing fish movement in aquaculture systems.

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