Ali Hamza, 2026, 14:1
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

# Computational Fluid Dynamics Analysis of Meandering Open Channel Flow Influenced by Circular Vegetation Patches

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**Abstract- This study explores how circular vegetation patches effect flow characteristics in a meandering open channel functional under steady conditions. Two channel setup were considered for assessment one with a smooth bed and no vegetation and another incorporating rigid circular vegetation patches located along consecutive bends. The comparison tells that the introduction of vegetation considerably alters the flow pattern. A clear reduction in extreme velocity around 55% was observed along with the creation of wake regions behind the areas which contributed to energy loss and flow reducing. In calculation the presence of vegetation controlled to a significant weakening in turbulence related parameters. Turbulence intensity reduced by nearly 40% while turbulent kinetic energy was reduced by nearly 50%. These reductions advise that vegetation plays an effective role in damping large scale turbulent waves even though local mixing still happens near the vegetation foundations. Overall the vegetated arrangement established greater movement stability higher hydraulic resistance and a relocation of turbulent energy throughout the channel. The findings emphasize the standing of vegetation in promoting eco-hydraulic balance reducing the chances of erosion and supporting environmentally sustainable river.**

**Keywords: Meandering channel, vegetation patch, turbulence, CFD, flow resistance, k–ε model.**

## I. INTRODUCTION

Flow behavior in meandering open channels is primarily governed by channel curvature, secondary circulation, and boundary resistance, which together control velocity distribution, sediment transport, and energy dissipation. The curvature of a meandering channel induces helical motion, shifting high velocities toward the outer banks and promoting sediment deposition along the inner banks (Abad & Garcia, et al. 2009). The presence of vegetation further modifies this behavior by increasing hydraulic roughness and generating turbulence through stem-induced drag. According to Nepf et al. (2012), emergent vegetation converts mean-flow energy into turbulence, enhancing mixing and energy dissipation within the flow. Previous studies have highlighted the significant influence of vegetation on open-channel hydraulics. Jahra et al. (2010) and Lugina et al. (2021) reported that vegetation in curved channels alters secondary circulation and increases form drag, leading to a reduction in mean velocity. Similarly, Lopez and Garcia et al. (2001) and Tanino and Nepf et al. (2008) observed that vegetation density and arrangement strongly affect velocity distribution and turbulent kinetic energy (TKE). Anjum et al. (2018) and Anjum et al. (2024) demonstrated that circular vegetation patches generate wake turbulence and substantially reduce streamwise velocity, while Anjum and Tanaka (2019) and Ahmad et al. (2020) found that vertically layered or discontinuous vegetation arrangements further complicate flow structures in open channels. Ghani et al. (2019) and Mohamed et al. (2020) also reported that vegetation-induced turbulence alters the hydrodynamic balance by increasing drag and energy dissipation, ultimately influencing flow resistance and stability.

More recent reviews and numerical analyses have expanded understanding of vegetated flow systems. Li et al. (2023) provided an extensive review of flow structures in emergent vegetation, emphasizing the role of patch density and spatial configuration. Maji et al. (2020) similarly highlighted how vegetation-induced turbulence affects free-surface flow dynamics. Aydogdu (2025) and Raeisifar et al. (2025) reported that vegetation not only alters near-bed flow but also redistributes turbulent energy, stabilizing the flow field in both straight and curved channels. Collectively, these studies underline the importance of vegetation in modifying open-channel hydrodynamics and the need for more focused analysis on combined effects of meandering geometry and discrete vegetation patterns.

Despite these valuable contributions, most existing research has focused on either straight channels or uniformly vegetated conditions. The combined effects of meandering channel geometry and discrete circular vegetation patches on three-dimensional turbulent flow remain insufficiently explored. The interaction between curvature-induced secondary circulation and vegetation generated turbulence creates complex flow behavior that affects velocity distribution, turbulence characteristics, and hydraulic stability. Therefore, a detailed investigation is needed to evaluate how circular vegetation patches placed at successive bends influence flow structure, energy dissipation, and overall hydraulic performance in meandering channels.

The main objective of this study is to numerically investigate the influence of circular vegetation patches on flow behavior in a meandering open channel. The research focuses on analyzing variations in velocity distribution, turbulence intensity, and turbulent kinetic energy (TKE) caused by vegetation. Two configurations a smooth meandering channel and a vegetated channel with rigid circular patches positioned at successive bends are compared to evaluate how vegetation alters flow resistance, enhances energy dissipation, and contributes to overall hydraulic stability within meandering channel systems.

## II. RESEARCH METHODOLOGY

### Geometric Conditions

The computational domain represents a laboratory-scale meandering open channel designed to replicate controlled hydraulic conditions under subcritical flow (Fig. 1a). The channel has a total length of 13 m, a width of 0.39 m, and a flow depth of 0.5 m. The meandering planform consists of two symmetric bends connected by straight transition sections, forming a moderate sinuosity similar to natural alluvial channels. The curvature of each bend was carefully designed to generate secondary circulation while maintaining flow stability. The channel bed and sidewalls were modeled as rigid, smooth, and impermeable surfaces, ensuring consistent hydraulic resistance and eliminating bed deformation or sediment transport effects. Two rigid circular vegetation patches, each with a diameter of 0.03 m and a height equal to the flow depth (0.5 m), were positioned along the inner banks of the first and second bends to simulate emergent vegetation conditions (Fig. 1b). The patches were represented as solid cylinders fixed to the bed, introducing local flow obstruction and wake turbulence typical of vegetation–flow interactions. The spatial arrangement of these patches allowed evaluation of localized velocity reduction, turbulence amplification, and wake interactions in curved flow regions.

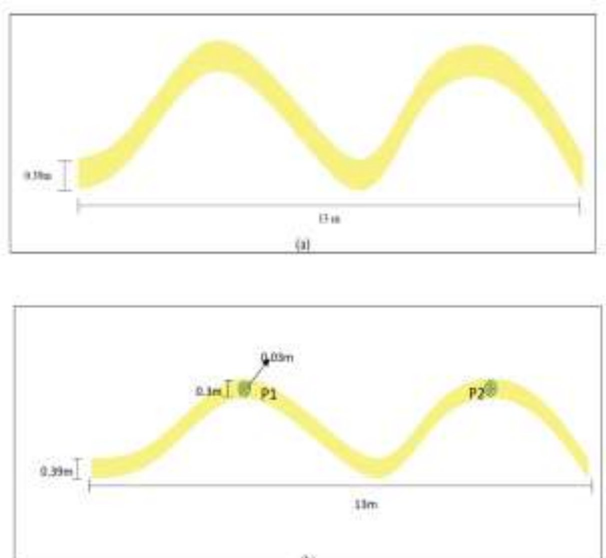


Fig.1 a) Simple Meandering open channel & Fig. 1 (b) Vegetated Meandering Open channel

**Boundary Condition**

Realistic boundary conditions were applied to accurately reproduce the turbulent open-channel flow in the computational model (Fig. 2). At the inlet, a velocity inlet boundary condition was defined corresponding to a discharge rate of 0.0202 $m^3/s$, producing an average velocity of 0.1036m/s. The turbulence intensity at the inlet was set to 5%, and the turbulent length scale was estimated from the hydraulic diameter of the channel section. The outlet was modeled as a pressure outlet with zero gauge pressure, allowing free discharge and preventing artificial backflow or recirculation. The bed and sidewalls of the channel were treated as no slip walls, enforcing zero velocity at the boundaries to account for wall shear and frictional effects. The free surface at the top of the flow domain was modeled as a symmetry plane, assuming negligible shear and normal stress, which approximates a stress-free water surface. The vegetation patches were defined as stationary solid obstacles with no slip conditions on their surfaces to replicate the hydrodynamic drag and wake formation caused by rigid emergent stems. The simulation was initialized with uniform velocity and turbulence parameters, and the simple algorithm was used for pressure velocity coupling until residuals dropped below $1 \times 10^{-6}$, ensuring numerical convergence and mass balance within 0.5%.

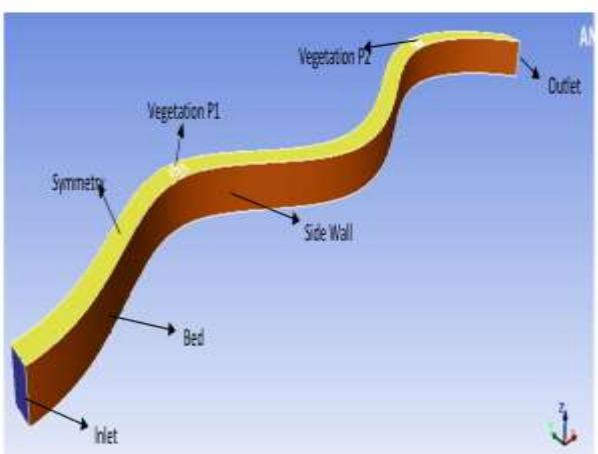


Fig.2 Boundary Condition meandering open channel

## III. RESULTS AND DISCUSSION

**Velocity Contours**

Fig. 3 compares the velocity distribution in (a) a smooth and (b) a vegetated meandering open channel. In the smooth channel, higher velocities up to 0.13 m/s are concentrated along the outer bends due to curvature induced centrifugal forces, while lower velocities (<0.05 m/s) occur near the inner banks. In contrast, the vegetated channel shows a marked velocity reduction, with maximum values around 0.31 m/s and strong deceleration zones forming behind the vegetation patches. These wake regions exhibit velocities below 0.05 m/s, indicating significant energy loss and flow recirculation. The vegetation increases hydraulic resistance, shifts high velocity cores toward the outer banks, and enhances flow asymmetry, confirming its strong influence on energy dissipation and channel stability. The vegetation induced drag redirects high velocity cores toward the outer banks and enlarges low velocity regions, enhancing energy dissipation and hydraulic resistance. These results agree with Lugina et al. (2021) and Anjum et al. (2024), confirming that vegetation redistributes flow momentum and stabilizes meandering channel hydrodynamics.

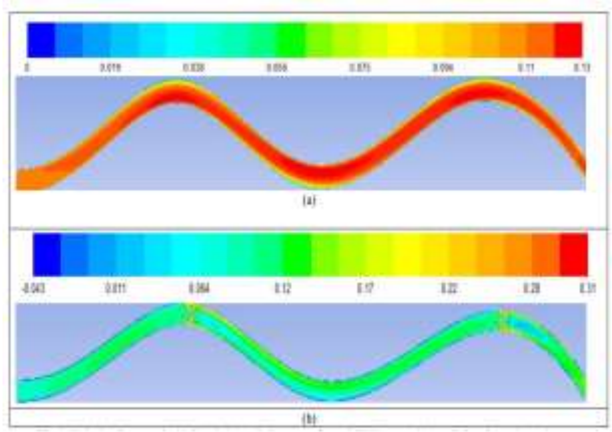

Fig. 3 Velocity Contours in (a) Simple Meandering open channel (b) Vegetated Meandering Open channel

**Turbulence Kinetic Energy**

Fig. 4 illustrates the spatial distribution of turbulent kinetic energy (TKE) for (a) the smooth and (b) the vegetated meandering open channel. In the smooth channel, TKE values range between $2.7\times10^{-5}$ and $9.5\times10^{-4}$ m$^2$/s$^2$, with him. In contrast, the vegetated channel exhibits distinct regions of intensified turbulence downstream of the vegetation patches, where TKE values rise up to $5.2\times10^{-3}$ m$^2$/s$^2$. These premises 50%, reflecting the damping influence of vegetation on large-scale turbulent structures (Nepf, 2012; Tanino & Nepf, 2008). The vegetation increases form drag and dissipates kinetic energy through enhanced resistance, leading to reduced turbulent mixing and a more stable velocity field. Similar results were reported by Shimizu and Tsujimoto (1994), who demonstrated that emergent vegetation significantly reduces turbulent energy and flow velocity in open channel flows. Overall, the presence of vegetation alters the turbulence dynamics by suppressing large scale eddies and promoting localized wake turbulence, resulting in improved flow stability and energy dissipation within the meandering channel.

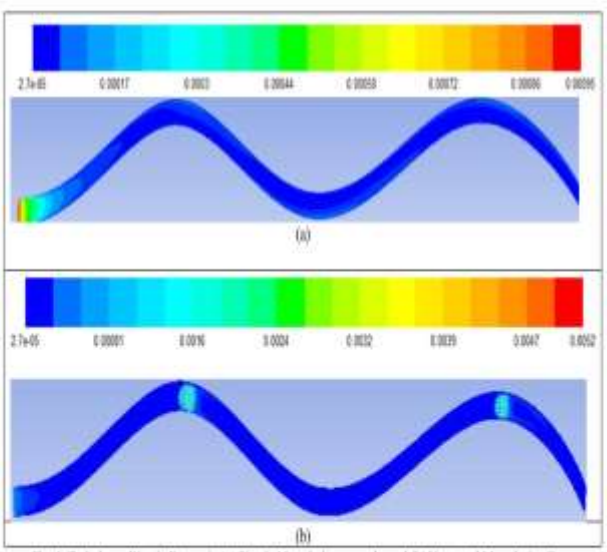

Fig.4 Turbulence Kinetic Energy in (a) Simple Meandering open channel(b)Vegetated Meandering Open channel

**Turbulence Intensity**

Fig. 5 illustrates the turbulence intensity distribution for the two cases. (a) In the smooth channel, turbulence intensity varies between 4.1% and 22%, (b) In the vegetated channel, turbulence intensity increases sharply near the vegetation patches, reaching localized peaks up to 57% due to wake generation and flow separation. However, the mean turbulence intensity across the flow domain decreases by about 40%, demonstrating that vegetation suppresses large-scale turbulence while promoting small-scale fluctuations near stems (Anjum et al. 2018; Jahra et al. 2010). This redistribution of turbulence enhances hydraulic resistance and dissipates flow energy, leading to improved channel stability and reduced erosive potential along outer banks.

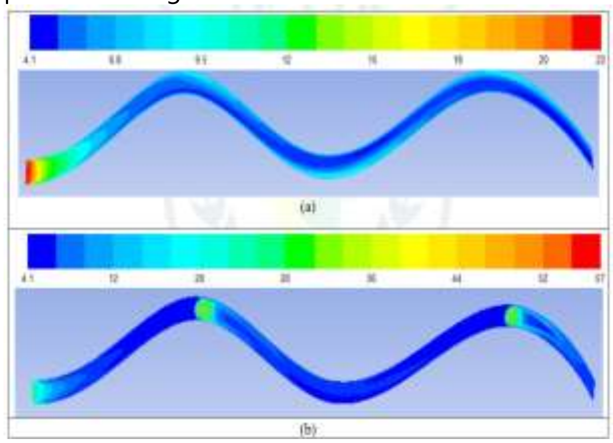

Figure.5 Turbulence Intensity in (a) Simple Meandering open channel (b) Vegetated Meandering Open channel

## IV. CONCLUSION

This study numerically examined the influence of circular vegetation patches on flow behavior in a meandering open channel using the standard k–ε turbulence model in ANSYS Fluent. Two cases were analyzed: a smooth meandering channel and a vegetated channel with rigid circular patches placed at successive bends. The results showed that vegetation significantly modified the flow structure. The maximum velocity decreased by about 55%, with distinct wake zones forming behind the patches, indicating strong energy dissipation and localized recirculation. The there was reduced by nearly 50%, reflecting the damping of large-scale turbulence, while crowd decree 40%, with localized peaks near the vegetation stems due to wake effects. Overall, vegetation increased hydraulic resistance, redistributed turbulent energy, and enhanced flow stability within the meandering channel. These findings highlight the effectiveness of vegetation in improving energy dissipation, reducing erosion potential, and promoting hydraulic stability in natural and engineered water channels.

**Acknowledgements**
The writers would like to express their sincere appreciation to Dr. Naveed Anjum for his valuable guidance, continuous support, and insightful suggestions throughout the course of this research. His expertise in open channel hydraulics and computational fluid dynamics greatly contributed to the successful completion of this study. The authors are also thankful to the Department of Civil Engineering, Khwaja Fareed University of Engineering and Information Technology (KFUEIT) for providing the necessary computational facilities and a conducive research environment to carry out the numerical simulations using ANSYS Fluent. Special appreciation is extended to colleagues and peers for their constructive discussions and technical assistance during model development and result interpretation. Finally, the authors acknowledge the support and encouragement received from family members, which played an important role in the completion of this research work.

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