Numerical Investigation of Flow Characteristics in an Open Channel in the Presence of Floating Vegetation Islands (FVIs)

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A project submitted in partial fulfillment for the requirement of the degree of
Bachelor of Science in Civil Engineering

Department of Civil Engineering

Faculty of Chemical, Civil & Environmental Engineering

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DECLARATION

We Jawad Ashraf, Shahzad Akram, Haseeb-Ur-Rehman, and Muhammad Junaid hereby state that our BS thesis titled "Numerical Investigation of Flow Characteristics in an Open Channel in the Presence of Floating Vegetation Islands" is our own work and has not been submitted previously by us for taking any degree from Khwaja Fared University of Engineering & Information Technology, Rahim Yar Khan or anywhere else in the country/world.

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We Jawad Ashraf, Shahzad Akram, Haseeb-Ur-Rehman, and Muhammad Junaid solemnly declare that the research work presented in the thesis titled "Numerical Investigation of Flow Characteristics in an Open Channel in the Presence of Floating Vegetation Islands" is our own work is solely our research work with no significant contribution from any other person. Small contribution/ help wherever taken has been duly acknowledged and that complete thesis has been written by us.

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CERTIFICATION OF APPROVAL

This report under the title of “Numerical Investigation of Flow Characteristics in an Open Channel in the Presence of Floating Vegetation Islands” is accepted hereby at the Department of Civil Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan in partial fulfillment of the requirements for the degree of “BS Civil Engineering”.

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ACKNOWLEDGEMENTS

In the name of Allah, the Most Merciful and Compassionate, we are grateful to have had the opportunity to complete this project on the numerical investigation of flow characteristics in an open channel in the presence of floating vegetation islands at Khwaja Fareed University of Engineering and Information Technology. We want to express our sincere gratitude to our supervisor, Engr. Dr. Naveed Anjum, for their unwavering support, valuable guidance, and constant motivation throughout this project. We would also like to thank the faculty and staff at the university for providing us with the knowledge and resources we needed to succeed. We are grateful to our family and friends for their love, encouragement, and support, without which this project would not have been possible.

We would also like to extend our thanks to the experts and participants who generously shared their time and knowledge to assist us in this project. Lastly, we would like to acknowledge our fellow students for their camaraderie and assistance throughout our academic career. We are grateful to all those who contributed to this project's success, and we pray that Allah continues to bless us all with success and prosperity.

"Whoever does good, whether male or female, and is a believer, we will certainly make him live a good life, and We will certainly give them their reward for the best of what they used to do."

- Quran 16:97

ABSTRACT

The existence of Floating Vegetation Islands (FVIs), especially the unanchored root canopy beneath it, significantly disrupts the internal structure of fluid while increasing the complexity of the flow pattern. Therefore, this paper aims to investigate the flow dynamics in the presence of FVIs in an open channel. In this study, a three-dimensional (3-D) computational fluid dynamics (CFD) approach was adopted using the FLUENT software tool. The numerical model's validation was affirmed through the utilization of experimental data. The parameter of varying vegetation density for FVI patches was considered. The mean flow and turbulent characteristics at various positions and cross-sections are presented in detail. The findings revealed that stream-wise velocities of flow decreased by a percentage difference of 100% within the canopy region (CR) when compared to the free region (FR), with this effect becoming more pronounced as FVIs' density increased. Whereas the velocity of flow increased up to 200% in the GR (the gap between the channel bed and FVIs canopy) below the canopy column. The results also revealed notable differences in flow velocities between the CR and GR. This disparity resulted in S-shaped velocity profiles through FVIs, while exhibited logarithmic shape velocity profiles resulted from minor flow fluctuations in alternate FR. Consequently, turbulence increased up to 25 times in the CR of dense vegetation i.e., Case 1 with a density of 0.01447 cylinders/cm^2, in comparison to sparse vegetation i.e., Case 3 with a density of 0.0029 cylinders/cm^2. The percentage of discharge passing through the alternate FR is found to be 100-300% greater than that passing through the CR. The study highlighted the impacts of FVIs in open channel flows for effective management of aquatic ecosystems.

COMPLEX ENGINEERING PROBLEM CERTIFICATION

(To be filled by supervisor)

This is to certify that final year project namely ____

_____________supervised by _______________________________ is fulfilling the attributes of complex engineering problem and the level achieved has been well depicted below which can be examined through the brief abstract of the project.

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1. Introduction

Flow dynamics in open channels play a pivotal role in comprehending the intricate behaviors of water bodies, permeating a broad spectrum of disciplines encompassing hydrology and environmental engineering. The orchestration of fluid motion, sediment conveyance, and nutrient circulation within these channels bears profound ramifications for effective water resource management and the vitality of ecosystems. The intricate interplay of these phenomena governs the intricate dynamics of aquatic ecosystems. Amidst this multifaceted landscape, a compelling element comes to the forefront: the influence of natural elements, particularly FVIs, on the hydrodynamic characteristics of these aquatic systems.

Figure 1.1: Artificial Floating Vegetation Islands

The underpinning significance of open channel flows lies in their pervasive influence on numerous environmental processes. These flows are the conduits through which water navigates terrains, altering landscapes as it traverses diverse topographies. This interplay not only molds the physical features of the land but also shapes the intricate relationships between water, sediment, and nutrients. Open channels function as dynamic arenas in which the hydrodynamics of water play a pivotal role in determining resource distribution and the overall ecological well-being of organisms reliant on these ecosystems

The juncture of fluid motion, sediment transportation, and nutrient cycling, exemplified by open channel flows, holds the key to understanding how aquatic environments function as integrated systems. The flow within these channels drives the transport of various suspended particles, including fine sediments and organic materials. This phenomenon actively sculpts the structure of riverbeds, banks, and deltas, playing a pivotal role in shaping habitats and controlling the presence of vital elements in aquatic ecosystems.

Nutrient cycling, another pivotal facet influenced by flow dynamics, governs the transfer of essential elements like nitrogen and phosphorus. These nutrients are vital building blocks of life, playing roles in the growth of aquatic flora and the intricate trophic interactions that characterize aquatic food webs. The transport of nutrients, driven by flow, has ramifications beyond individual organisms, echoing across ecosystems and underpinning the sustainability of aquatic life.

Within this intricate tapestry, our attention turns to the impact of FVIs (as shown in Figure 1.1). These natural features, composed of clusters of floating plants, bring a fascinating yet intricate dynamic to open channel flows. The juxtaposition of these islands with the currents transforms the flow dynamics, creating a distinctive interaction that blends hydrodynamics with ecological subtleties. As the water meanders around these islands, the flow patterns craft intricate stories of resistance, turbulence, and redirection.

The inclusion of FVIs within the discourse of open channel flows is a testament to the complex interplay between nature's elements. The dynamic forces exerted by these FVIs ripple through the water and change its dynamics. The intermingling of these two forces – the elemental flow of water and the subtle yet potent influence of FVIs – paints an enthralling canvas of interactions. As we delve deeper into this realm, the fundamental processes and mechanisms that govern these interactions take center stage, beckoning for further exploration and understanding.

1.1. Background

The background of this research is rooted in the fundamental importance of open channel flows within the domain of environmental sciences and engineering. Open channel flows, referring to the movement of water within natural or artificial channels with free surfaces, hold critical significance due to their far-reaching impacts on various ecological and hydrological processes. These processes, encompassing sediment transport, nutrient cycling, and aquatic ecosystem dynamics, collectively shape the behavior of water bodies and the well-being of associated habitats.

Water, as a universal solvent, plays a central role in the functioning of ecosystems. It transports nutrients, sediments, and organic matter, thereby shaping the physical features of aquatic landscapes. These features, including riverbed morphology and floodplain architecture, provide habitats for a plethora of organisms, from microorganisms to fish species. Furthermore, the movement of water contributes to the dispersion of essential nutrients, which in turn sustains the intricate food webs that underpin aquatic life.

Sediment transport is an inherent part of open channel flows, influencing the geomorphology of water bodies. The velocity of the flowing water determines the capacity to erode, transport, and deposit sediments of varying sizes. This interplay between water and sediment shapes the morphology of rivers, streams, and other watercourses over time. Erosion and deposition processes contribute to changes in the course of rivers and the development of deltas, exerting a cascading influence on habitats and hydrological dynamics.

Figure 1.2: Naturally Occurring Floating Vegetation Islands

Nutrient cycling within aquatic ecosystems is intricately linked to the flow of water. The movement of nutrients, such as nitrogen and phosphorus, within water bodies, is influenced by the flow velocity and patterns. These nutrients are vital for the growth of aquatic vegetation and microorganisms, serving as the foundation of the aquatic food web. The interaction between flow dynamics and nutrient availability has far-reaching consequences, impacting both the abundance and diversity of aquatic organisms.

The influence of FVIs on flow dynamics encompasses alterations in flow patterns, resistance to water movement, and the generation of turbulence (as shown in Figure 1.2). The intricate interplay between water currents and FVIs gives rise to intriguing questions about the mechanics of this interaction and its implications for both ecological and engineering perspectives.

As the investigation into the interaction between flow dynamics and FVIs unfolds, the potential practical applications become apparent. Understanding how FVIs affect flow patterns could pave the way for innovative approaches in water resource management, river restoration, and environmental engineering. Additionally, harnessing the insights gained from this study could offer sustainable solutions for challenges such as nutrient removal from water bodies or the creation of habitat diversity within aquatic environments.

The background of this research resides in the intricate interplay between open channel flows and the presence of FVIs (as shown in Figure 1.3). The holistic comprehension of this interaction has implications that span from ecology to engineering. By delving into this dynamic relationship, it aims to uncover insights that can contribute to the advancement of water management strategies, ecological conservation, and the sustainable utilization of natural resources.

Figure 1.3: Floating Vegetation in an Urban Canal

1.4 Fluid Dynamics

Fluid dynamics and hydrodynamics form the cornerstone of understanding the movement and behavior of fluids, particularly in the context of open channels and water bodies. Fluid dynamics is the study of how fluids, like water, move and interact with their surroundings, while hydrodynamics specifically focuses on the behavior of fluids in motion, encompassing factors such as flow patterns, velocities, and pressures.

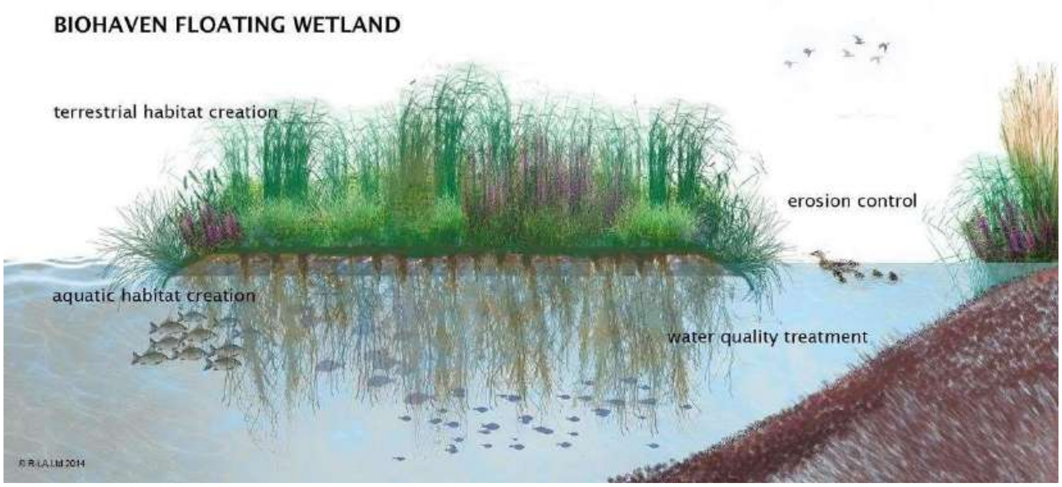


Figure 1.4: Impact of FVIs on Ecohydrology

In the realm of open channel flows, fluid dynamics is essential for deciphering the intricate patterns of water movement. The principles of fluid dynamics provide a framework for comprehending how water responds to external forces, such as gravity and friction, as it flows through channels of varying shapes and sizes (as shown in Figure 1.4). These principles are governed by fundamental equations, including the continuity equation and the Navier-Stokes equations, which describe how fluid flow is affected by factors like velocity, pressure, and viscosity.

Hydrodynamics extends the understanding of fluid dynamics by delving into the specifics of fluid behavior within dynamic environments. In open channels, the interaction between the flowing water and the channel boundaries gives rise to a diverse array of hydrodynamic phenomena. These phenomena include the formation of eddies, vortices, and turbulence, which greatly influence flow patterns and water mixing. Hydrodynamics also considers the impact of fluid properties, such as density and viscosity, on the overall flow dynamics.

In this context, the behavior of fluid within open channels is influenced not only by the channel's geometry but also by the presence of FVIs. The movement of water around FVIs introduces additional complexities to the hydrodynamic processes. FVIs act as obstacles that disrupt the smooth flow of water, leading to changes in flow velocities, pressure distributions, and the formation of turbulent eddies. Understanding these hydrodynamic interactions is vital for predicting the effects of FVIs on flow patterns and overall water dynamics.

Hydrodynamics also plays a pivotal role in unraveling how FVIs impact sediment transport and nutrient cycling. The altered flow patterns induced by FVIs influence the movement of sediments, leading to deposition and erosion in distinct zones. Similarly, the interaction between water currents and FVIs affects the dispersion of nutrients, thereby influencing the availability of essential elements for aquatic life. These hydrodynamic intricacies have implications for both ecological processes and the design of engineering solutions aimed at managing water quality and flow dynamics.

Fluid dynamics and hydrodynamics provide the foundational understanding of how fluids, particularly water, move and interact within open channels. These principles are crucial for comprehending the behavior of water bodies, sediment transport, and nutrient cycling. When combined with the unique context of FVIs, hydrodynamics becomes a powerful tool for unraveling the complex interplay between flowing water, FVIs, and the dynamic processes that shape aquatic environments. By investigating these hydrodynamic interactions, we aim to uncover insights that can inform effective strategies for managing water resources, preserving ecosystems, and addressing environmental challenges.

Open Channel Concept: An open channel is a natural or man-made structure that allows the flow of fluids (usually water) through it. Open channels are commonly found in rivers, streams, and irrigation systems, and are used to convey water from one location to another.


Figure 1.5

Figure 1.6

Figure 1.5, 1.6: open channel and FVIs illustration

The physical structure of FVIs is dynamic and intricate. They typically consist of a dense matrix of emergent macrophytes, such as grasses, reeds, sedges, and other aquatic plants, intertwined with floating vegetation mats and debris. These components are often rooted in the channel bed or along its banks, forming a cohesive and flexible platform that can drift, rotate, and change shape under the influence of hydrodynamic forces. This flexible arrangement allows FVIs to adapt to changing water levels and flow conditions, thereby impacting the surrounding fluid dynamics.

Open channels, on the other hand, represent conduits through which water flows, encompassing a wide range of water bodies, from natural rivers and streams to engineered canals and irrigation ditches (as shown in Figure 1.5, 1.6). The behavior of flowing water in open channels is governed by fundamental principles of fluid dynamics, which include considerations of flow velocity, turbulence, sediment transport, and interactions with boundaries.

The interaction between FVIs and open channel flows introduces a complex set of hydrodynamic phenomena. FVIs act as hydraulic roughness elements, altering the friction between the water and the channel bed. As water flows around and through FVIs, it encounters changes in flow velocity, direction, and turbulence. This interaction generates vortices, wakes, and shedding behavior, all of which have profound effects on the overall flow patterns within the open channel.

Two main types of FVIs can be distinguished based on their spatial arrangement and behavior within open channels: stationary and mobile FVIs.

Stationary FVIs are anchored in place due to rooted vegetation, substrate entanglement, or interactions with channel boundaries. These structures remain relatively fixed, causing variations in flow patterns primarily through their roughness effects and localized hydraulic adjustments.

On the other hand, **mobile FVIs** are capable of drifting or rotating within the channel due to hydrodynamic forces. These mobile structures dynamically modify flow patterns as they change their orientation and position, thereby introducing further complexity to flow dynamics.

The hydrodynamic interactions between FVIs and open channel flows have a cascade of effects on various ecological processes. Sediment transport is altered as FVIs create areas of sediment accumulation and scour, impacting channel morphology and stability. Nutrient cycling is also influenced, with FVIs serving as focal points for sediment deposition and nutrient uptake by vegetation. Additionally, FVIs provide habitats for diverse aquatic organisms, influencing biodiversity, habitat availability, and species interactions.

Figure 1.7: FVIs are collected by a trap in an Open Channel

1.6 Statement of Problem

The dynamic behavior of water flow in open channels is a critical aspect of various fields, ranging from environmental science and hydrology to civil engineering. However, the presence of natural elements, such as FVIs, introduces intricate challenges to the study of flow characteristics and their implications. While extensive research has been conducted on open channel flows and hydrodynamics, there remains a significant gap in understanding the specific interactions between flowing water and FVIs. This gap represents the central statement of the problem addressed by this research.

Research Questions

In these intricate dynamics of flow and vegetation, questions arise that beckon exploration.

1. How do FVIs reshape flow patterns, turbulence, and the movement of waterborne particles?
2. What roles do the densities of FVIs play in this interplay between FVIs and flow dynamics?
3. Can the dynamics of momentum exchange – the subtle push and pull between water and FVIs– be harnessed for practical applications, such as nutrient removal or habitat restoration?

The primary issue at hand revolves around the need to comprehensively investigate the impact of FVIs on flow dynamics within open channels. Although there is a wealth of knowledge regarding fluid behavior in open channels, the unique hydrodynamic effects introduced by FVIs remain relatively understudied. These FVIs are inherently heterogeneous structures that disrupt the natural flow patterns of water, giving rise to turbulence, eddies, and other complex phenomena. The lack of a holistic understanding of these interactions hinders our ability to predict and manage the consequences of FVIs on various aspects of water behavior.

The specific challenges stemming from this problem can be categorized as follows:

- **Limited Understanding of Flow Alterations:** The intricate flow alterations caused by FVIs are not well-documented. It is unclear how these islands influence flow velocities, pressure distributions, and turbulence levels within open channels. Understanding these alterations is crucial for predicting water movement and potential flow-related hazards.
- **Complex Hydrodynamic Interactions:** FVIs introduce a multitude of hydrodynamic interactions with flowing water. These interactions involve phenomena such as vortices, wakes, and shedding behavior. The complexity of these interactions necessitates a thorough investigation to decipher their underlying mechanics and implications.
- **Sediment Transport and Nutrient Cycling Effects:** The presence of FVIs has implications for sediment transport and nutrient cycling within open channels. The disruption of flow patterns around FVIs can lead to sediment deposition and erosion in specific areas, influencing channel morphology and aquatic habitats. Additionally, the altered flow dynamics can impact the distribution of nutrients, affecting water quality and ecosystem health.

Addressing these challenges requires a systematic and thorough investigation into the interactions between FVIs and open channel flow dynamics. The outcomes of such research not only contribute to the advancement of fluid mechanics and hydrodynamics but also have far-reaching implications for water resource management, ecological preservation, and engineering practices.

Scope of Research

This research aims to bridge the existing knowledge gap by providing a comprehensive analysis of the hydrodynamic effects of FVIs on flow characteristics, nutrient cycling, and their broader implications. This investigation will pave the way for informed decision-making and sustainable practices in the management of water bodies and open channels.

The proposed research aims to fill this critical knowledge gap by conducting a systematic investigation into the hydrodynamic interactions between FVIs and open channel flows. Through numerical simulations and analytical techniques, this study will shed light on the intricacies of FVI-induced alterations, providing insights into how these alterations impact flow velocities, turbulence levels, sediment transport, and nutrient cycling.

By addressing these issues, this research seeks to contribute to the scientific community's understanding of fluid dynamics within open channels and the unique effects introduced by FVIs. The findings hold the potential to inform water resource management strategies, guide engineering projects, and facilitate ecologically sustainable practices. Ultimately, this research strives to pave the way for effective decision-making and management strategies that consider the complex interplay between natural elements and hydrodynamic processes within open channels.

1.7 Objectives

The primary aim of this research is to comprehensively investigate the intricate interplay between flow dynamics, momentum exchange, and nutrient removal in open channels, particularly in the presence of FVIs. By delving into these aspects, the study seeks to enhance our understanding of the complex interactions that govern aquatic ecosystems and water resource management.

- **Investigation of Flow Characteristics:** One of the core research objectives is to meticulously examine the various flow characteristics within open channels. These characteristics include flow velocity, turbulence intensity, and discharge rates. Understanding the variations in flow velocity across different zones of the channel, both in the presence and absence of FVIs, is essential. The study will also analyze turbulence intensity, which signifies the degree of flow irregularity and fluctuations. By systematically measuring discharge rates, the research aims to quantify the volumetric flow of water, providing insights into how FVIs influence the channel's hydrodynamic behavior.
- **Exploration of Momentum Exchange Phenomenon:** The research aims to unravel the phenomenon of momentum exchange at the interface between the canopy region (occupied by FVIs) and the free region of the open channel. This phenomenon arises due to the interaction between the kinetic energy of flowing water and the resistance posed by FVIs. By studying this exchange, the study will illuminate how FVIs disrupt flow patterns, leading to the shedding of vortices and wakes. Investigating the momentum exchange phenomenon provides crucial insights into the hydrodynamic mechanisms that underlie

flow behavior and turbulence around FVIs.

- **Analysis of Nutrient Removal:** Another significant research objective is to explore the role of FVIs in nutrient removal from the water. FVIs serve as critical interfaces for nutrient uptake by vegetation and interaction with water. By examining nutrient concentrations within the presence of FVIs, the study aims to quantify the extent to which these structures enhance nutrient removal. Understanding how FVIs facilitate nutrient uptake by vegetation sheds light on their potential contribution to water quality improvement and ecological balance.
- **Effect of FVI Density on Flow:** The research also seeks to investigate how the density of FVIs influences flow dynamics and hydrodynamics. Different densities of FVIs can have varying effects on flow patterns, turbulence, and momentum exchange. By systematically altering the density of FVIs and observing the resulting changes in flow characteristics, the study aims to discern any trends or correlations between FVI density and its hydrodynamic impact.
- **Validation and Comparison:** A key research objective involves validating and comparing numerical simulations with experimental data. This process ensures the accuracy and reliability of the computational models used to study flow characteristics and hydrodynamics around FVIs. By comparing numerical results with real-world measurements, the study aims to verify the applicability of the simulation techniques and enhance our confidence in the findings.
- **Identification of Optimal Conditions for Nutrient Removal:** Building on the investigation of nutrient removal, the research seeks to identify the optimal conditions under which FVIs can effectively contribute to nutrient uptake and water quality improvement. By correlating FVI density, flow characteristics, and nutrient concentrations, the study aims to provide practical recommendations for harnessing FVIs' potential in nutrient removal strategies.
- **Enhancement of Sustainable Practices:** Through its research objectives, this study aims to enhance the development and implementation of sustainable practices in aquatic

ecosystem management. By providing a comprehensive understanding of FVIs' impact on flow dynamics and nutrient cycling, the research contributes to the advancement of ecoengineering solutions that align with environmental conservation and restoration goals.

The research objectives encompass a diverse range of inquiries, each contributing to a holistic understanding of flow dynamics, momentum exchange, nutrient removal, and the role of FVIs in open channels. By addressing these objectives, the study aspires to unravel the intricate mechanisms that shape aquatic environments and offer valuable insights into harnessing the potential of FVIs for sustainable water resource management and ecosystem health. Through rigorous investigation, validation, and interpretation, this research seeks to advance both scientific knowledge and practical applications in the realm of aquatic ecosystem dynamics.

1.8 Novelty and Expected Contributions of the Research

In the realm of scientific exploration, novelty is the cornerstone of progress. This FYP embarks on a pioneering journey to unravel the intricate interplay between flow characteristics, hydrodynamics, and the presence of FVIs within open channels. The research stands as a distinctive endeavor, offering novel insights and anticipated contributions to the state of the art in several significant dimensions.

1. **Integrating Hydrodynamics and FVIs:** The novelty of this research lies in its holistic approach, merging the realms of hydrodynamics and the presence of FVIs. While individual studies have explored either flow characteristics or the influence of FVIs, this research pioneers the integration of these two domains. By deciphering how FVIs shape flow patterns, turbulence, and nutrient dynamics, the research bridges a critical knowledge gap and provides a comprehensive understanding of aquatic ecosystem dynamics.

2. **Momentum Exchange Mechanism Clarification:** The investigation into the momentum exchange phenomenon marks a significant stride in contributing to the state of the art. While previous research has acknowledged the presence of this phenomenon, the research aims to delve deeper into its underlying mechanisms. By shedding light on the shedding of vortices, wake formation, and fluctuations in flow dynamics, this study will offer unprecedented clarity on the dynamics of momentum exchange at the boundary between canopy and free-flow regions.

3. **Unveiling Nutrient Removal Potential:** The anticipated contribution of this research extends to the realm of environmental sustainability. By exploring how FVIs influence nutrient removal from water bodies, the study introduces a pioneering dimension to the application of FVIs as eco-engineering tools. While FVIs' role in flow dynamics has been studied, their potential for enhancing nutrient uptake and improving water quality remains relatively unexplored. The research is poised to illuminate pathways for harnessing FVIs to optimize nutrient cycling and promote ecosystem health.

4. **FVI Density's Impact on Flow and Nutrient Uptake:** The research's novelty is further amplified by its exploration of FVI density's influence on hydrodynamics and nutrient uptake. While FVIs' presence has been acknowledged, understanding the nuanced impact of varying FVI densities on flow behavior and nutrient assimilation is relatively uncharted territory. By systematically investigating this relationship, the research will contribute valuable insights into designing FVI-based strategies for targeted nutrient removal and ecosystem restoration.

5. **Computational Fluid Dynamics (CFD) Visualization:** The research's innovative use of CFD modeling for visualization and analysis sets it apart in the field. The integration of CFD allows for the creation of virtual scenarios, enabling the exploration of complex hydrodynamic processes in a controlled environment. This integration enhances the accuracy and depth of the research's findings, providing a sophisticated platform to study intricate flow behavior in the presence of FVIs.

6. **Guiding Practical Applications:** The anticipated contributions extend beyond academic realms to practical implications. The insights garnered from this research are expected to guide practitioners, water resource managers, and environmental policymakers. By offering recommendations on FVI implementation for water quality improvement and ecological restoration, the research strives to bridge the gap between scientific discovery and real-world applications, fostering sustainable management of aquatic ecosystems.

The novelty of this research stems from its multifaceted exploration of the interplay between flow dynamics, hydrodynamics, and the presence of FVIs. Through its integrated approach, elucidation of momentum exchange, investigation into nutrient removal mechanisms, examination of FVI density's impact, and use of advanced CFD visualization, the study is poised to enrich the state of the art. The anticipated contributions, ranging from fundamental insights to practical applications, have the potential to reshape the way we perceive and harness FVIs for enhancing water quality, nutrient cycling, and ecosystem sustainability. As the research unfurls its findings, it promises to carve a unique niche in the landscape of aquatic ecosystem dynamics and environmental science.

2. Literature Review

The study of channel flow characteristics in the presence of FVIs is an important topic in the field of hydraulic engineering (fluid mechanics), as it has important implications for the management and design of natural and artificial water channels. In this chapter, we review the existing literature on this topic, focusing on the numerical methods used to study channel flow characteristics and the key findings of previous research.

Vegetation canopies can be submerged, emergent, or suspended and are frequently found in aquatic environments. Submerged or emergent canopies are attached to the bottom of the water, whereas suspended canopies often remain afloat on the water's surface. i.e., Eichhornia crassipes, Lemna spp., Nymphaea spp., and Salvinia molesta are some common examples of naturally occurring FVIs (Wagner et al. 1998; Lange et al. 2018; Les et al. 1999). Open channels are important components of the hydrological cycle because they transport water for irrigation systems, drainage networks, and water supply systems. The presence of FVIs in open channels can have a significant impact on flow characteristics such as velocity patterns, turbulence characteristics, and Reynolds stresses. FVIs are a natural occurrence that can cause significant problems with water flow in open channels, leading to issues such as flooding and erosion (Sofia et al. 2020).

Numerous studies have investigated the dynamics of flow in the presence of emerging vegetation in open channels (Kasiteropoulou et al. 2017; Anjum et al. 2018; Anjum et al. 2019; Huai et al. 2012). Thorne et al. (1977) investigated that flow around a single submerged cylinder increases the drag on the cylinder and reduces the circulation around the cylinder. These vortices and eddies can significantly alter the flow patterns and the transport of pollutants and sediment in the flow (Rauch et al. 2003). The presence of vegetation in channels also reduces the erosion of the banks by increasing the resistance to the flow and altering the flow patterns in the vicinity of the banks. The presence of FVIs exerts a notable influence on flow velocity, inducing a state of reduced flow velocity by quickly covering the water's surface. The drag force caused by FVIs can significantly alter the flow patterns and dissipate the energy of the flow (Chaudhary et al. 2013). FVIs can improve the quality of water by accumulating the toxins from polluted water which is called biological treatment. FVIs are also helpful in nutrient removal (Li and Katul 2020). The U.S. Environmental Protection Agency also investigated the nutrient removal by FVIs to alleviate the problem of algal blooms in water bodies. However, it is necessary to develop a deep understanding of the alterations in flow structure resulting from the interplay between root canopies and open channel flow.

The latest research studies have focused on using numerical models and investigated that FVIs can significantly alter the flow dynamics which can lead to scouring and erosion in channels (Kim et al. 2020; Xue et al. 2019). FVIs can alter the flow conditions near the top water surface, with the flow acceleration and deceleration being stronger on the leeward side of the FVIs. FVIs caused an increase in Reynolds stress, which affects the mixing and transport of heat and mass (Wang et al. 2008). Zhang et al. (2013) used a large-eddy simulation model to investigate the flow around a group of FVIs in a shallow lake and found that the FVIs had a significant effect on the flow patterns and vortex structures. Chen et al. (2018) used a coupled hydrodynamic model to investigate that the FVI disturbed the flow dynamics by increasing turbulence in the vegetation zone. Yu et al. (2022) investigated the interaction between emerged vegetation and flow dynamics and concluded that flow patterns are extremely sensitive to the size and density of the vegetation (Huai et al. 2017; Huai et al. 2018). Therefore, it is necessary to investigate the impacts of FVI density and height on the velocity of flow, turbulence characteristics, and Reynolds stresses.

A two-dimensional numerical model investigated the hydrodynamic impacts of FVIs in a tidal channel and found that the presence of FVIs significantly influenced the flow patterns and velocity distributions in the tidal channel (Alameddine et al. 2017). A three-dimensional numerical model investigated the influence of FVIs on flow resistance and erosion processes in a tidal channel and witnessed a significant reduction in flow resistance, increasing the channel flow speed (Zhang et al. 2019). The presence of the FVIs results in an increase in turbulence intensity in the water body resulting in the formation of counter-rotating vortices (Huang et al. 2018; Wang et al. 2019). Moreover, the roughness of the vegetation has been shown to influence the flow patterns around the islands (Huai et al. 2016). Numerous studies have utilized numerical modeling to study the flow characteristics around FVIs and concluded that FVIs greatly impacted the flow field, resulting in changes in velocity patterns and turbulence (Huai et al. 2017; Chaudhary et al. 2020; Huai et al. 2016; Huai et al. 2018). Truong et al. (2019) investigated the Kelvin-Helmholtz instabilities, which are typically brought on by velocity differences between the root canopy and the GR. These instabilities result in a shear layer and accompanying coherent vortex structures at the bottom of root canopies, which ultimately causes momentum exchange. However, there is a lack of research on the 3-D models to investigate the characteristics of flow in the presence of discontinuous FVI patches while considering the density parameter.

2.1 Research studies on FVIs

It has always been observed in laboratories and fields that the presence of vegetation in a flow can significantly alter the characteristics of the flow. Vegetation can provide resistance to the flow, change the direction of the flow, and create eddies and vortices. Understanding the flow characteristics in the presence of vegetation is important for a variety of applications, including the design of hydraulic structures, the prediction of erosion and sediment transport, and the management of aquatic ecosystems.

One of the best studies on the flow characteristics in the presence of vegetation was conducted by Thorne and Raju (1977). They examined the flow around a single submerged cylinder and a group of cylinders. They found that the presence of vegetation significantly increased the drag on the cylinder and reduced the circulation around the cylinder. These results were consistent with the findings of other researchers.

More recent studies have focused on the flow characteristics in more complex vegetation configurations. For example, Rauch and Lauer (2003) examined the flow around a single vegetated bank and a group of vegetated banks. They found that the presence of vegetation increased the resistance to the flow and altered the flow patterns in the vicinity of the banks. In addition, they found that the presence of vegetation reduced the erosion of the banks, due to the increased resistance to the flow.

The effect of vegetation on the flow characteristics is not only limited to submerged vegetation. Terrestrial vegetation can also significantly alter the flow characteristics. For example, Chaudhary et al. (2013) studied the flow characteristics in a channel with riparian vegetation. They found that the presence of vegetation increased the resistance to the flow and reduced the flow velocity in the channel. In addition, they found that the presence of vegetation increased the occurrence of vortex structures in the flow.

One of the main mechanisms through which vegetation influences the flow characteristics is the drag force exerted on the flow by the vegetation. The drag force is a function of the diameter, length, and spacing of the vegetation, as well as the velocity and viscosity of the flow. The drag force can significantly alter the flow patterns and the energy dissipation in the flow.

Vegetation can also alter the flow characteristics through the creation of vortices and eddies. These vortices and eddies can significantly alter the flow patterns and the transport of sediment and pollutants in the flow (Rauch and Lauer 2003). The formation of vortices and eddies is influenced by the geometry of the vegetation and the flow conditions.

In addition to the effects of vegetation on the flow characteristics, there are also feedbacks between the flow and the vegetation. For example, the flow can influence the growth and survival of the vegetation, and the vegetation can alter the flow conditions and the erosion and sediment transport in the flow (Chaudhary et al. 2013). These feedbacks can significantly influence the development and stability of aquatic ecosystems.

The investigation of flow characteristics in the presence of vegetation is an active area of research, with many recent studies focusing on the effects of vegetation on the flow patterns, erosion and sediment transport, and aquatic ecosystems. Understanding the flow characteristics in the presence of vegetation is important for a variety of applications, including the design of hydraulic structures, the prediction of erosion and sediment transport, and the management of aquatic ecosystems.

2.2 Research studies on submerged vegetation

One of the latest studies found that when the short vegetation became submerged during high flows, an inflection points in the velocity distribution occurred resulting in a significant mixing layer over the top of submerged vegetation due to the vertical exchange of momentum between the top of the submerged canopy and the overlying flow. When both the short and tall vegetation remained emergent during low flows, the mean flow characteristics showed almost uniform distribution along the depth of flow.

One of their studies in Japan investigated the flow structure and energy reduction of tsunami currents (approaching the inland region) through the coastal forest. They also did a comparison of flow structures through a continuous and discontinuous forest and concluded that downstream depth was not significantly affected due to variation in forest configuration or gap length between the forest models.

(Anjum, & Tanaka, 2019) presented a study that revealed the effectiveness of the combination of short and tall vegetation and the inflection point in flow was observed to be associated over the top of shorter submerged vegetation, which suggests that the flow has a maximum effect of momentum exchange in this region.

2.3 Research studies suspended vegetation

Several previous studies have investigated the effect of FVIs on channel flow characteristics. In general, these studies have found that the presence of FVIs can significantly alter the flow patterns and hydrodynamic forces in a channel.

FVIs are natural structures consisting of roots and canopies that often float on the surfaces of open channels. They vary in density, root length, and canopy size, and have significant implications for water flow in these channels, including increased flood risk and erosion. FVIs introduce hydraulic resistance, reducing the conveyance channel's flood-carrying capacity. Moreover, FVIs play a crucial role in river ecosystems by influencing flow dynamics and sediment transport (Hartstein and Stevens 2005; Huai et al. 2016; F. Zhao et al. 2017).

While previous research has extensively investigated the effects of emergent vegetation on flow characteristics in open channels (Anjum et al. 2019c; Anjum et al. 2018), limited attention has been given to the impact of FVIs on flow patterns (Huai et al. 2012; Anjum et al. 2019a). Analytical models have been proposed to analyze streamwise velocity distribution in channels with vegetation (Huai et al. 2014), and experimental investigations have explored the interaction and effects of adjacent vegetation patches on flow features (Meire et al. 2014; Anjum et al. 2019b). Numerical simulations have been utilized to study mean flow structure and the interaction of emerged, submerged, and layered patches in open-channel flow by notable researchers (Huai et al. 2017; Chaudhary et al. 2020; Huai et al. 2016; Huai et al. 2018).

Ghani et al. (2019) examined flow dynamics in the presence of circular staggered vegetation patches, highlighting the influence of neighboring patches and emphasizing that larger blockages result in higher flow velocities and turbulence characteristics. This study addresses a significant research gap concerning the velocity behavior of flow in the presence of FVIs in open channels. While previous research has focused on emergent vegetation, the distinct characteristics and effects of FVIs have been largely overlooked. By employing advanced modeling and simulation techniques, this research aims to comprehensively investigate the velocity parameter of flow through FVIs using Computational Fluid Dynamics (CFD) coupled with Reynolds Stress 7 Equation model.

One of the earliest numerical studies on the flow characteristics around FVIs was conducted by Wang et al. (2008), who employed a two-dimensional viscous flow model to simulate the flow around an isolated FVI. They found that the FVI significantly altered the flow structure and velocity near the water surface, with the flow acceleration and deceleration being stronger on the leeward side of the FVI. They also observed that the FVI caused an increase in the turbulent intensity and Reynolds stress, which could affect the mixing and transport of heat and mass.

Recent research has focused on using numerical models to investigate the flow characteristics in the presence of FVIs. One study (Kim et al. 2020) used a two-dimensional hydrodynamic model to examine the flow patterns around an FVI in a shallow pond. The model results showed that the FVI caused an increase in the flow velocity and a decrease in the water depth on the lee side of the island, leading to increased scouring and erosion. (Xue et al. 2019) used a three-dimensional numerical model to investigate the flow characteristics around an FVI in a natural river. The model results showed that the FVI caused an increase in the flow velocity and an increase in the water depth in the lee side of the island, leading to increased sediment deposition and habitat creation.

Zhang et al. (2013) used a large-eddy simulation model to investigate the flow around a group of FVIs in a shallow lake. They found that the FVIs caused a significant increase in the turbulent kinetic energy and Reynolds stress, which could affect the sediment transport and water quality in the lake. In addition, they observed that the FVIs had a significant effect on the flow patterns and vortex structures, which could alter the exchange of heat and mass between the air and water.

Some investigators used a coupled hydrodynamic and sediment transport model to examine the flow characteristics around an FVI in a shallow lake. The model results showed that the FVI caused an increase in the flow velocity and a decrease in the water depth in the lee side of the island, leading to increased erosion and sediment transport. These studies demonstrate that FVIs can significantly alter the flow characteristics in freshwater systems, leading to both erosion and sediment deposition.

One of the highly cited studies on the topic of numerical investigation of flow characteristics in the presence of FVIs is "Hydrodynamic and water quality impacts of FVIs in a tidal channel" by Alameddine et al. (2017). This study utilized a two-dimensional numerical model to investigate the hydrodynamic and water quality impacts of FVIs in a tidal channel. In this research the authors found out that the presence of FVIs significantly influenced the flow patterns and velocity distributions in the tidal channel. Specifically, the islands caused an increase in velocity and shear stress near the bottom of the channel, as well as an increase in the volume of water exchanged between the channel and the surrounding wetlands. These results suggest that FVIs can play a role in improving water quality by increasing the exchange of water between the channel and the wetlands, which can help to flush out pollutants and nutrients.

Another highly cited study on this topic is "The influence of FVIs on flow resistance and erosion processes in a tidal channel" by Zhang et al. (2019). This study utilized a three-dimensional numerical model to investigate the influence of FVIs on flow resistance and erosion processes in a tidal channel. The authors found that the presence of FVIs caused a significant reduction in flow resistance, resulting in an increase in the channel flow speed. Additionally, the islands reduced the erosion rate of the channel bed, suggesting that they may be an effective tool for mitigating erosion in tidal channels. These studies demonstrate the importance of numerical modeling in the understanding the flow characteristics and impacts of FVIs in tidal channels. Further research is needed to fully understand the potential benefits and limitations of these islands as a tool for improving water quality and mitigating erosion in tidal environments

A study was conducted by Huang et al. (2018) examined the effect of FVIs on the flow field in a rectangular channel. The study found that the presence of the islands resulted in a decrease in velocity and an increase in turbulence intensity in the water body. The authors also observed that the islands had a significant effect on the flow field, resulting in the formation of counter-rotating vortices and an increase in the flow separation region.

Another study by Wang et al. (2019) focused on the effect of FVIs on the flow and pollutant removal in a river. The authors found that the presence of the islands resulted in an increase in flow resistance and a decrease in flow velocity, leading to improved pollutant removal efficiency. The study also found that the islands had a significant impact on the flow field, resulting in the formation of complex vortices and an increase in the flow separation region.

Another research article by Chaudhary et al. (2020) focused on the examination of the effect of island geometry on flow patterns and pollutant removal efficiency in a rectangular channel. The authors found that the shape and size of the islands greatly impacted the flow field, resulting in changes in velocity, turbulence intensity, and pollutant removal efficiency.

Numerical modeling has been widely used to study the flow characteristics around FVIs (Huai et al., 2017). These models allow for the prediction of flow patterns and the estimation of the forces acting on the islands (Huai et al., 2016). However, the complex geometry and motion of the islands make the numerical simulation of flow characteristics a challenging task (Huai et al., 2018).

One of the key factors affecting the flow characteristics around FVIs is the vegetation density (Huai et al., 2017). A higher vegetation density can lead to a reduction in the flow velocity and an increase in the drag force acting on the islands (Huai et al., 2018). In addition, the roughness of the vegetation has been shown to influence the flow patterns around the islands (Huai et al., 2016).

Another important factor is the size and shape of the islands. A study found that the flow patterns around rectangular islands were significantly different from those around circular islands. Similarly, the size of the islands has been shown to affect the flow characteristics, with larger islands experiencing higher drag forces and lower flow velocities (Huai et al. 2017).

In summary of wenxin huai published research, the flow characteristics around FVIs are influenced by a variety of factors, including vegetation density, roughness, size, and shape. Numerical modeling has been an effective tool for studying these characteristics and predicting the forces acting on the islands. Further research is needed to better understand the complex interactions between the flow and the islands and to optimize the design of FVIs for specific purposes.

2.4 Research Gap

Despite the importance of understanding flow characteristics in the presence of FVIs, comprehensive research studies on this topic are lacking. The majority of previous research has concentrated on the effects of submerged vegetation on flow patterns in an open channel, while the others have focused only on the velocity, and turbulence parameters of flow in the presence of suspended and emerging vegetation. However, there is a lack of understanding about the impact of the density of FVIs on flow dynamics, the momentum exchange phenomenon taking place, and nutrient removal. Therefore, the primary aim of this study is to investigate the flow characteristics in an open channel in the presence of varying densities of FVIs using numerical simulation CFD technique. This research study will provide an understanding of momentum exchange and nutrient removal by FVIs. This research will provide more comprehensive insights into the effects of FVIs on open channel flow velocity, and turbulence characteristics.

Reasons for research gaps

One reason for this gap in the research is the complexity of modeling the flow around FVIs. FVIs can move and rotate in the flow, and they can also interact with each other. Modeling these interactions accurately requires advanced numerical techniques and computational resources.

Another reason for the gap in the research is the lack of field data on the flow characteristics in the presence of FVIs. While there have been several field studies on the flow characteristics in the presence of submerged vegetation and riparian vegetation, there are few field studies on the flow characteristics in the presence of FVIs. This lack of field data makes it difficult to validate numerical models and to understand the underlying mechanisms of the flow around FVIs

Despite these challenges, the numerical investigation of flow in an open channel in the presence of FVIsis important for a variety of applications. For example, FVIs can be used for erosion control, sediment trapping, and water treatment. Understanding the flow characteristics in the presence of FVIs is essential for the design and management of these systems.

2.5 Complex Engineering Problem

Studying FVIs within open channels is essential for understanding their role in shaping aquatic ecosystems. Advanced numerical simulations and field observations have become valuable tools in unraveling the complex hydrodynamics of FVIs (as shown in Figure 1.7). Furthermore, they aid in predicting the behavior of FVIs, helping us understand their mobility and its implications for flow dynamics. The **complex engineering problem** addressed by this final year project is “how to manage water flow in open channels in the presence of FVIs?” FVIs can significantly impact the way water flows, which can lead to changes in sediment transport, velocity of flow, and pollutant dispersion. Therefore, it's essential to understand the effect of FVIs on water flow to develop effective and sustainable water management systems. By investigating the changes in water velocity and turbulence caused by FVIs and analyzing the impact of different factors such as vegetation density, height, and flow rate, this project aims to provide valuable insights for improving the design and management of open channel systems.

Inline Sustainable Development Goals:

This FYP is linked to two Sustainable Development Goals (SDGs). Firstly, the project is related to ***SDG 6: “Clean Water and Sanitation,”*** which aims to ensure the availability and sustainable management of water and sanitation for all. By understanding the impact of floating vegetation on open channel flow, we can improve water management practices and contribute to achieving this goal.

Secondly, the project is linked to ***SDG 13: "Climate Action,"*** which calls for urgent action to combat climate change and its impacts. By studying the impact of floating vegetation on water flow, we can develop more efficient and sustainable water management practices, which can contribute to mitigating the impact of climate change on water resources. To achieve these goals, this research project aims to conduct numerical simulations of open channel flow characteristics using ANSYS FLUENT software.

Required approaches for further research

There are several potential approaches that could be taken to address this research gap. One approach would be to develop advanced numerical models that can accurately simulate the flow around FVIs. These models could be based on CFD or other numerical techniques, and they could incorporate the effects of vegetation geometry, flow conditions, and interactions between islands.

Another approach would be to collect field data on the flow characteristics in the presence of FVIs. This could be done through the use of flow sensors, pressure gauges, and other measurement devices. The data collected could be used to validate numerical models and to better understand the underlying mechanisms of the flow around FVIs.

A third approach would be to combine numerical modeling and field data to study the flow characteristics in the presence of FVIs. This could involve the use of CFD models to simulate the flow around FVIs and the comparison of the results with field data. This approach would allow for a more comprehensive understanding of the flow characteristics in the presence of these structures.

In addition to these approaches, there are also several other research directions that could be explored in the investigation of flow in an open channel in the presence of FVIs. For example, further research could be conducted on the effect of vegetation geometry, flow conditions, and interactions between islands on the flow characteristics. Other research directions could include the effects of FVIs on erosion and sediment transport, the influence of FVIs on water quality, and the use of FVIs for erosion control and water treatment.

3. Methodology

Numerical investigation of flow characteristics in an open channel in the presence of FVIs can be achieved using CFD techniques (modeling, and simulations). CFD involves the use of numerical methods to solve the governing equations of fluid flow and transport phenomena. In the case of an open channel with FVIs, the CFD model should consider the effects of the vegetation on the flow field, including drag and lift forces as well as the influence of the vegetation on the local flow velocity and turbulence.

3.1 Modeling Approach

H_g(mm)	L(mm)	B(mm)	Q(L/s)	H(mm)	U(m/s)
100	200	50	10.1	200	0.08

Table 3.1: Geometric and hydraulic conditions of flow for the experimental run, where: "Hg" is the gap between the bed and canopy; "L" is stream-wise, and "B" is cross-stream Spacing between cylinders respectively; "Q" is the flow rate; "H" is the water depth; and "U" is the average mean velocity.

3.1.1 Experimental data for validation

The experimental data of Plew (2011) was used for validation of the CFD model. Plew (2011) performed experiments in a deep rectangular flume in the hydraulic laboratory of Wuhan, the dimensions of the flume length, width, and height are 20 m, 0.6 m, and 0.5 m respectively. The water depth in the flume was 0.2 m, which was controlled by the tailgate at the downstream end of the flume. Rigid cylinders of plexiglass bars with 0.8 cm diameter at a gap of 5 cm were placed in the flume to represent vegetation. The arrangement of cylinders was linear, 8 m long and 0.6 m wide. A micro acoustic Doppler velocimeter (ADV) was utilized to measure the momentary velocities. The hydraulic and geometric conditions of the experiment are summarized in Table 3.1.

3.1.2 Validation of the Numerical Model

To validate the numerical data, the same cross-section channel as in the CFD domain with reduced length was used to run simulations for validation case. A comparison of computational and experimental data was performed to validate the mean velocity u/Uo velocities within canopy region, and free region (as shown in Figure 3.1). “u” represents the stream-wise velocity, while the Uo represents the mean transverse velocity of flow. Initially the value of u/Uo-Numerical was 1.08m/s, and u/Uo-Experimental was 1.13m/s in free region. When the flow entered into the canopy region the velocity of flow started decreasing and minimum observed value of u/UoNumerical was 0.70m/s, and u/Uo-Experimental was 0.73 m/s. Both experimental and numerical results show that the mean flow velocities are significantly reduced in the vegetation part of the FVIs patches, but the velocities are higher in the free regions. This suggests that the presence of FVIs on the open channel's surface can provide noticeable resistance to the flow and affect the discharge-carrying capacity of the channel. The results show that the computational data agrees closely with the experimental data, proving the current numerical model's validity. However, there is a minor difference of 3-4% between the computational and experimental results was observed in the form of a slight overestimation of the velocity values, which could be due to an RSM simplification error (as shown in Figure 3.2).

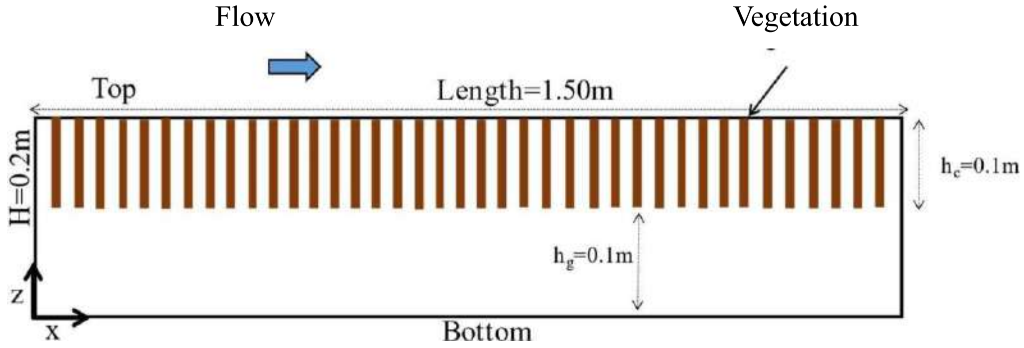


Figure 3.1:Vertical section of schematic diagram of experimental setup (Plew, 2010) of rectangular flume with FVI patches for the validation of CFD models

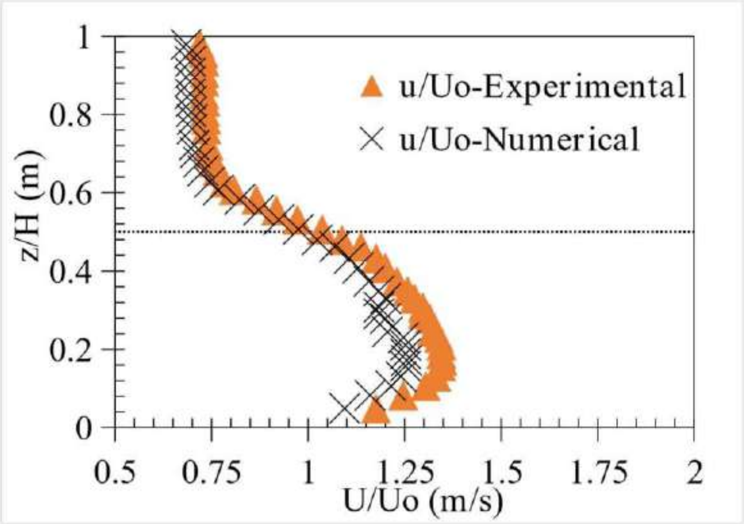
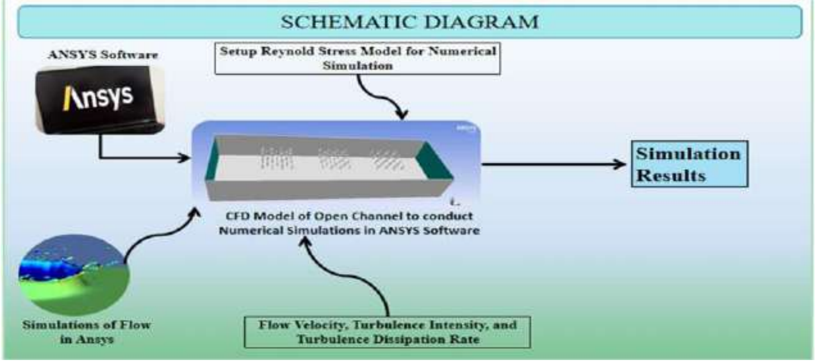


Figure 3.2: comparative analysis of experimental and numerical mean velocity profile u/Uo

3.1.3 Numerical Simulations

To simulate the flow characteristics in the presence of FVIs, we used the ANSYS Fluent software package, which is a popular CFD software package for accurately simulating complex fluid flows. To conduct the simulations, we used the Reynolds Stress Model (RSM), a highly advanced turbulence model capable of accurately predicting turbulence and its effect on flow characteristics. The model is based on the Reynolds-Averaged Navier-Stokes (RANS) 7 equations and considers both Reynolds stresses and mean flow properties. The RSM formulation provides a comprehensive framework for understanding the complex turbulence phenomena and accurately predicting the flow characteristics in our investigation. Furthermore, the utilization of this advanced numerical simulation approach enhances the reliability and accuracy of the results obtained in this study. The use of this model will allow to accurately predict the flow characteristics and gain valuable insights into the complex interactions between the flow and the FVIs.



3.2 Definition of Domain

The first step in the CFD methodology is to define the problem domain and boundary conditions. This involves determining the size and shape of the open channel, as well as the location and size of the FVIs. The boundary conditions should include the flow rate, water depth, and any other relevant parameters such as the vegetation density and roughness. Therefore, we modeled a 3 dimensional rectangular domain with a length of 1.5 meters, height of 0.24 meters, and width of 0.5 meters and these dimensions are according to the CFD model of open channel which was used to validate our numerical data. We used solid cylinders as a FVIs. We extruded 75 circular cylinders for Case 1; 45 cylinders for case 2; and 15 cylinders for case 3; on the top surface of 3D rectangular channel to represent FVIs. These cylinders were extruded in three square shape patches with height of 0.05 meter in each patch. The diameter of circular cylinders was 0.008m (0.8cm). The arrangement of cylinders is staggered. The domain is a single body with cylinders extruded with cut material property of ANSYS.

3.2.1 Numerical Model details

A 3D CFD model was generated to simulate the complex flow in an open channel with FVIs. Geometry was simplified, i.e., to avoid large mesh structures and reduce computational costs channel length was reduced (as shown in Figure 3.3). Three different models of FVIs in the open channel were created, for which the domain was 1.5 meters in length, 0.24 meters in height, and 0.5 meters in width (as demonstrated in Table 3.2). The schematic diagrams of the vertical section and top view for Case 1 are shown in Figures 3.4 and 3.5. The main difference between the models was the difference in canopy density of FVIs, which was 0.01447 cylinders/cm^2 in the first case, 0.00870 cylinders/cm2 in the second case, and it was 0.0029 cylinders/cm2 in the third case. We used solid cylinders to represent the root canopies, with 75, 45, and 15 circular cylinders extruded on the top surface of the rectangular channel in three square-shaped patches in cases 1, 2, and 3, respectively. Each patch of canopies contained 25, 15, and 5 cylinders in a staggered arrangement in cases 1, 2, and 3, respectively. In the actual field, plant roots can take on a variety of complicated shapes depending on the plant type and climatic conditions. However, it can be difficult and time-consuming to accurately model this complexity in numerical simulations, therefore FVIs are modeled in circular shapes to streamline the modeling process and concentrate on the main hydrodynamic effects of

Sr. No.	L (cm)	B (cm)	α	d (cm)	FVIs Density (cm^{-2})	Q (L/s)	z (cm)	U (m/s)
Case 1	18.2	18.2	1	0.8	0.01447	28.2	24	0.24
Case 2	18.2	18.2	1	0.8	0.00870	28.2	24	0.24
Case 3	18.2	18.2	1	0.8	0.0029	28.2	24	0.24

Table 3.2: CFD Model details for Case 1, 2, and 3

FVIs on open channel flow (Poggi et al. 2018; Van der Welle et al. 2015; Nepf 2012). However, it can be difficult and time-consuming to accurately model this complexity in numerical simulations, therefore FVIs are modeled in circular shapes in order to streamline the modeling process and concentrate on the main hydrodynamic effects of FVIs on open channel flow (Poggi et al., 2018; van der Welle et al., 2015; Nepf, 2012). We set up

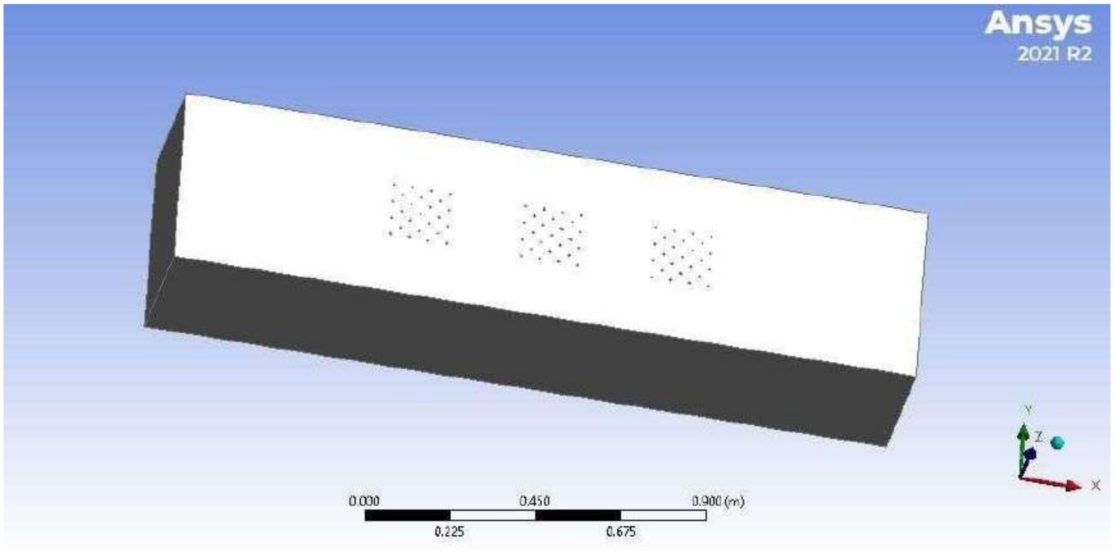


Figure 3.3: CFD model to conduct numerical simulations

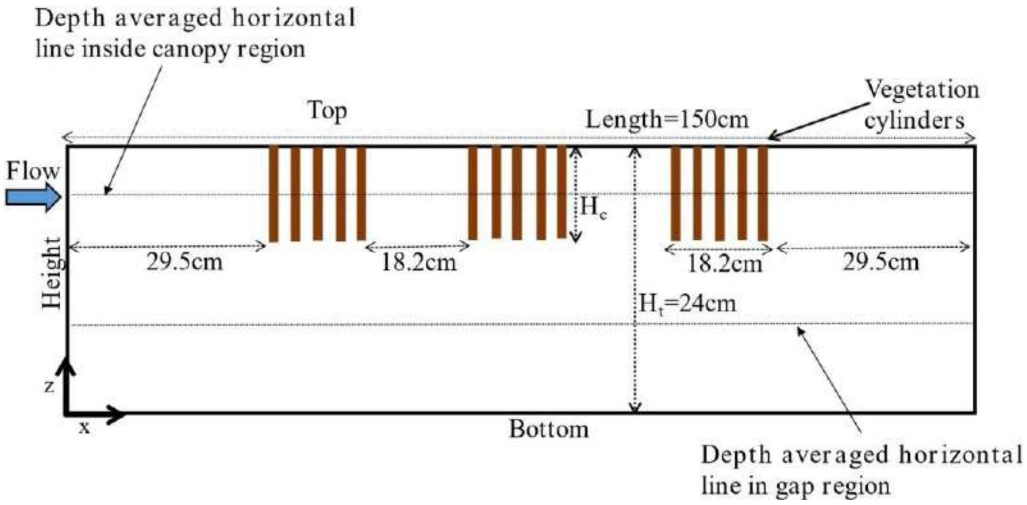


Figure 3.4: Schematic diagram of CFD model

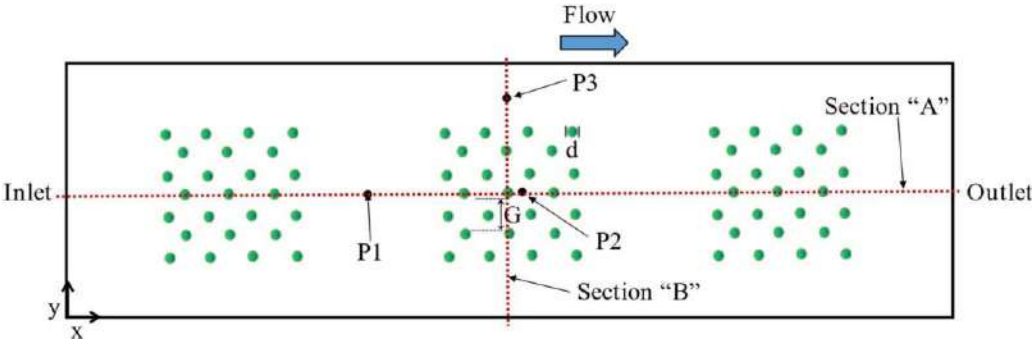


Figure 3.5: Top view of FVIs patches arrangements and vertical lines locations

three cases with varying densities of FVIs for ANSYS Fluent Simulations for more accurate Numerical Investigations.

3.3 Numerical Model Setup

The meshing process of the CFD model was conducted using FLUENT software, and the mesh was refined to include approximately 0.7 million nodes. The Tri-Pave unstructured mesh option was employed, which divided the domain into fine tetrahedral elements to ensure an accurate representation of the geometry. To validate the quality of the numerical model, a mesh independence test was performed. After the modeling and meshing of the CFD model, FLUENT was utilized for the simulation and post-processing of the numerical investigation. The RSM-7 Equation model was employed to simulate the flow dynamics within the model.

For the setup of boundary conditions, the top surface of the channel was set to symmetry, the side walls were set to stationary no-slip condition, and the inlet and outlets were assigned periodic boundary conditions. The schematic diagram of the boundaries of the CFD model is (shown in Figure 3.6). Additionally, the circular solid cylinders representing the FVIs were treated as solid walls in the boundary conditions set up. To couple the pressure and velocity fields during the simulations, the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) approach was utilized. An iterative process was carried out with a convergence criterion set to $1\text{x}10^{-6}$ to ensure accurate results for the CFD investigation.

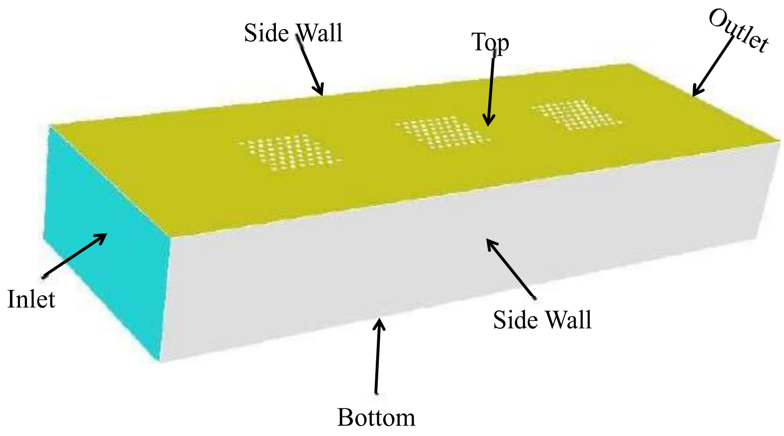


Figure 3.6: Schematic diagram of boundary conditions of CFD model

3.3.1 Meshing

The process of meshing refers to the process of dividing a finite element model into smaller, interconnected elements that can be analyzed using computer algorithms (as shown in Figure 3.7). The resulting mesh is a collection of small geometric elements, such as triangles or quadrilaterals, that approximate the shape of the model and capture the behavior of the model under different loading conditions. Meshing is a crucial step in finite element analysis because it determines the accuracy and efficiency of the analysis. The quality of the mesh can significantly affect the accuracy of the results, so it is important to carefully consider the type, size, and distribution of the elements in the mesh.

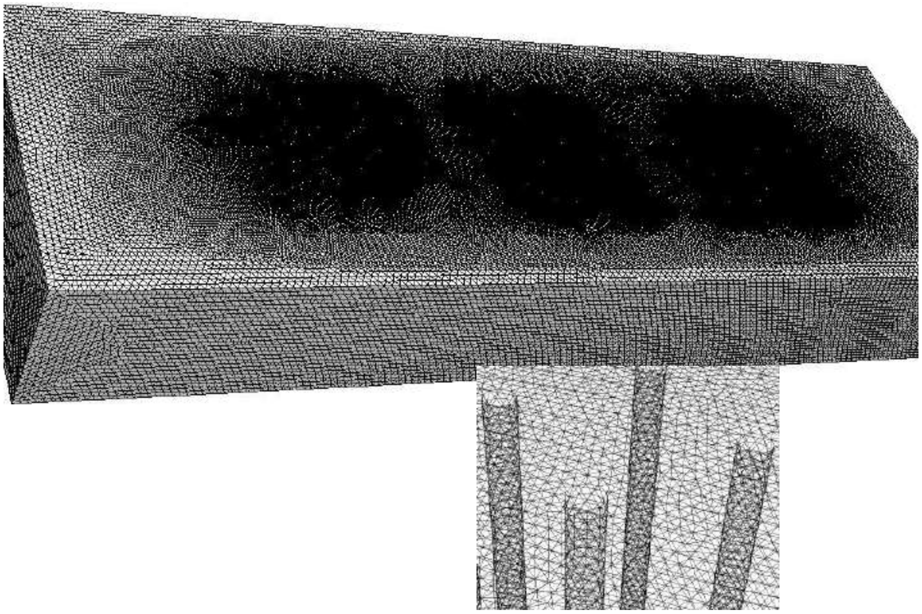
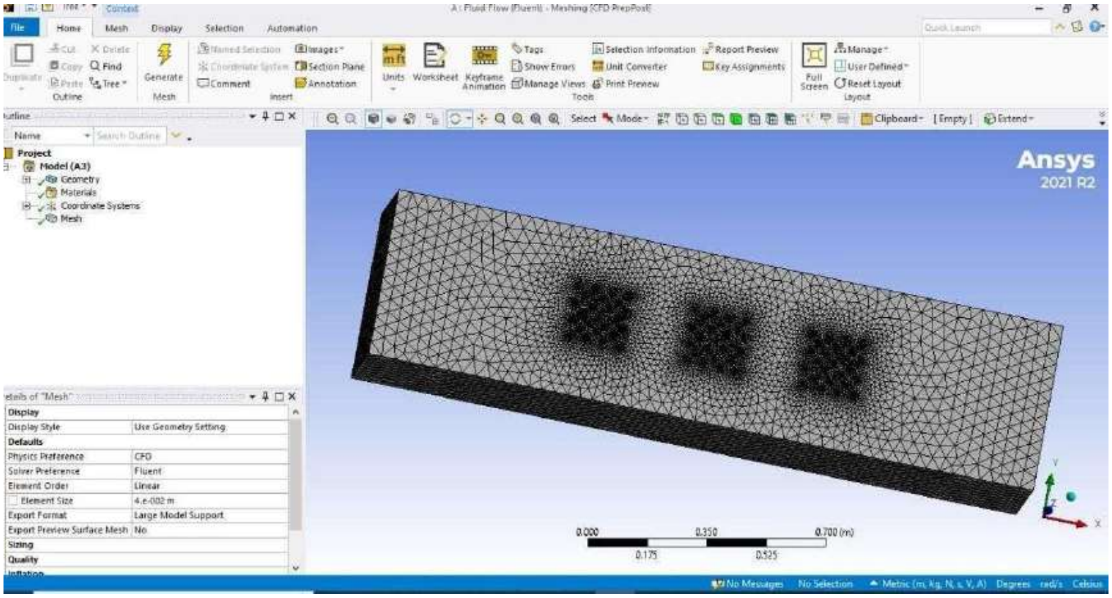


Figure 3.7: Meshed structure of domain with close view

Therefore, as a next step, the CFD 3D model was discretized using a suitable mesh generation technique of ANSYS fluent. The mesh was fine enough to accurately capture the flow phenomena in the presence of the vegetation islands, but not so fine as to significantly increase the computational time and cost. We used the recommended settings of fluent with element size of 0.03m and maximum size of 0.03m to create a triangular mesh of approximately 1.5 million number of nodes of our domain. Cylinders were extruded by cut materials therefore, they automatically meshed as solid bodies. After the meshing of the 3D channel model, we created named sections of our rectangular channel so that we can easily apply boundary conditions to these sections in the setup of ANSYS fluent. The minimum sizing of our CFD model was 4×10^{-3} which existed around the area of the cylinder. The flow in the channel is simulated using the finite volume method implemented in ANSYS Fluent. The k-ε turbulence model is used to account for the turbulent flow in the channel.

In ANSYS Fluent, we used a suitable mesh generation technique to simulate the flow characteristics in the presence of vegetation islands. The mesh was fine enough to accurately capture the flow phenomena around every smaller dimension of the CFD model, but not so fine that it significantly increased computational time and cost. A triangular mesh was created with up to 0.6 million nodes for Case: 1, 0.4 million nodes for Case: 2, and up to 0.3 million nodes for Case: 3. The minimum element size was 0.017m, and the maximum size was also 0.017m (referred to as Figure 3.7). To improve the accuracy of the numerical simulations, we set the curvature and defeature size in ANSYS Meshing to 0.0017m. To accurately measure the minimum element size of meshing we used the following formula: Min. Element Size= smaller Dimension of Channel/5 (ANSYS Fluent Guide Manual)

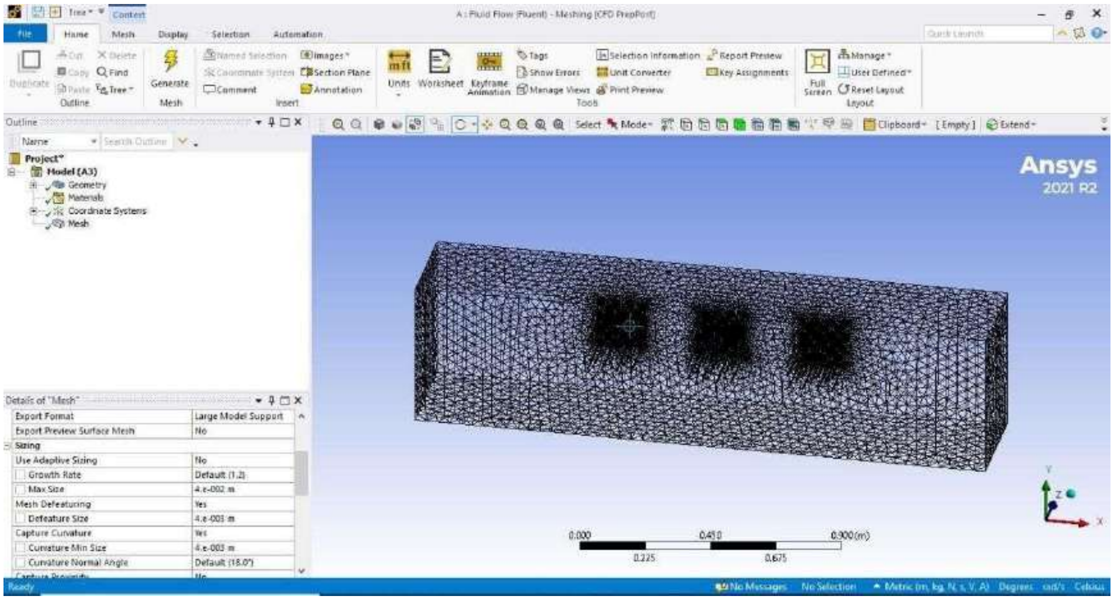
The smaller dimension in all three CFD domains was the diameter of cylinders which is 0.8cm (0.008m). Therefore, a small element size of 0.005m for the solid bodies was selected for meshing, which allowed us to precisely capture the intricate details of the vegetation and their impact on the flow characteristics, resulting in more reliable simulation results (as shown in Figure 3.8 and 3.9). Subsequently, the ANSYS Fluent will capture the geometry's details more precisely and reduce the impact of numerical errors on our results. In ANSYS Meshing, a fine meshing technique. A minimum sizing of 7×10^{-3} was used around the cylinder's area. Before finalizing the mesh node numbers, a mesh independence test was run to ensure satisfactory results.



Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
☐ Element Size	4.e-002 m
Export Format	Large Model Support
Export Preview Surface Mesh	No
Sizing	
Quality	
Inflation	

Figure 3.8: Meshed CFD model of FYP research



Details of "Mesh"

Export Format	Large Model Support
Export Preview Surface Mesh	No
Sizing	
Use Adaptive Sizing	No
Growth Rate	Default (1.2)
Max Size	4.e-002 m
Mesh Defeaturing	Yes
Defeature Size	4.e-003 m
Capture Curvature	Yes
Curvature Min Size	4.e-003 m
Curvature Normal Angle	Default (18.0°)
Capture Proximity	No

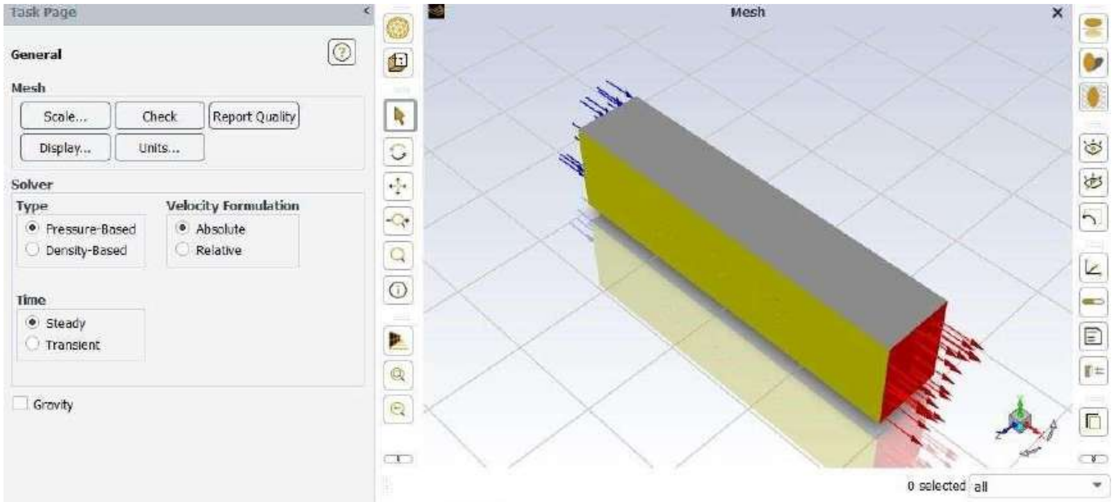
Figure 3.9: Meshed CFD model in ANSYS Fluent

3.4 Boundary conditions

After mesh generation solid stationary- no slip wall conditions were set to simulate the side walls, bottom, and circular cylinders of the CFD domain. The inlet was configured as a velocity inlet, and the outlet as a pressure outlet. A periodic boundary condition was applied on inlet and outlets of CFD models to investigate the flow dynamics in a comparatively smaller domain (referred to as Figure 14). The inlet velocity was fixed at 0.24m/s, and the inlet pressure is kept constant. The outlet pressure is fixed, and the velocity at the outlet is calculated using the RSM. The channel walls, as well as the cylinders and walls, are set to be no-slip solid wall boundaries. A symmetric boundary condition was assigned to the top surface of CFD channel. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) pressure velocity coupling technique with flux type RheiChow: distance-based was utilized to solve the governing equations of fluid flow, including the continuity equation, momentum equation, and energy equation. The SIMPLE algorithm is a popular method for numerically investigating flow characteristics in open channels. The convergence criteria for the solution calculation for all residuals were set to 1x10-6.

3.5 Setting up the boundary conditions

Once the CFD model is meshed, the next step is to set up our numerical model for iterations, and simulations, and to get the expected results. In setting up our CFD model first of all we checked the model, and continued to the next conditions by using a steady setup with no gravity check (as demonstrated in 3.10 and 3.11). The channel is filled with water with a density of 1000 kg/m3 and a kinematic viscosity of 1 x 10-6 m2/s. The flow in the channel is assumed to be steady and laminar We used Reynolds Stress Model (RSM) 7-equation for our numerical calculation.



General

Solver

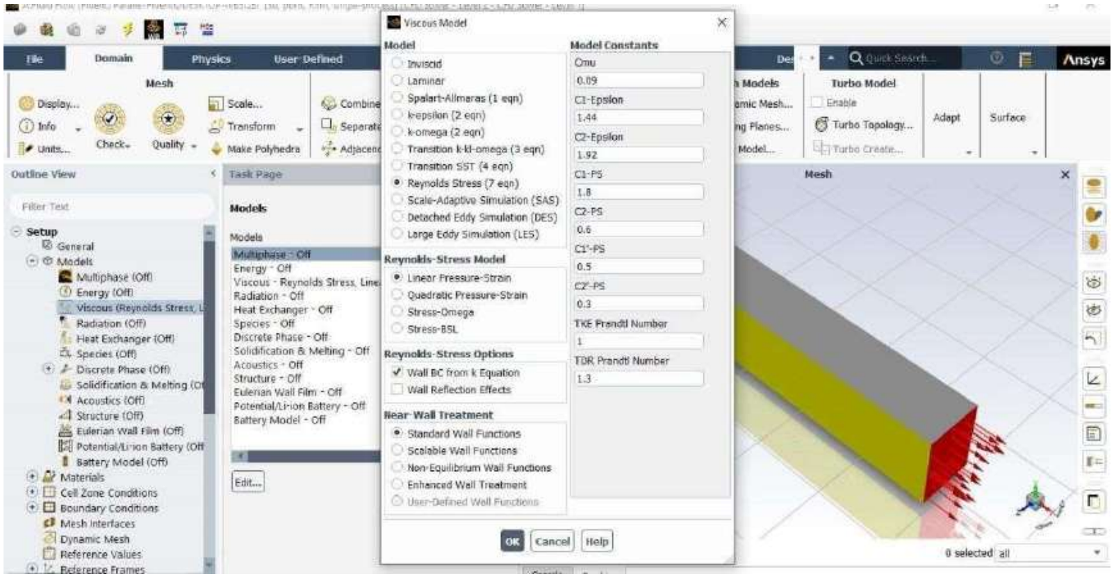
Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
● Steady
○ Transient

☐ Gravity

Figure 3.10 Setting up Conditions



Viscous Model

Model
○ Inviscid
○ Laminar
○ Spalart-Allmaras (1 eqn)
○ k-epsilon (2 eqn)
○ k-omega (2 eqn)
○ Transition k-kl-omega (3 eqn)
○ Transition SST (4 eqn)
● Reynolds Stress (7 eqn)
○ Scale-Adaptive Simulation (SAS)
○ Detached Eddy Simulation (DES)
○ Large Eddy Simulation (LES)

Reynolds-Stress Model
● Linear Pressure-Strain
○ Quadratic Pressure-Strain
○ Stress-Omega
○ Stress-BSL

Reynolds-Stress Options
☑ Wall BC from k Equation
☐ Wall Reflection Effects

Near-Wall Treatment
● Standard Wall Functions
○ Scalable Wall Functions
○ Non-Equilibrium Wall Functions
○ Enhanced Wall Treatment
○ User-Defined Wall Functions

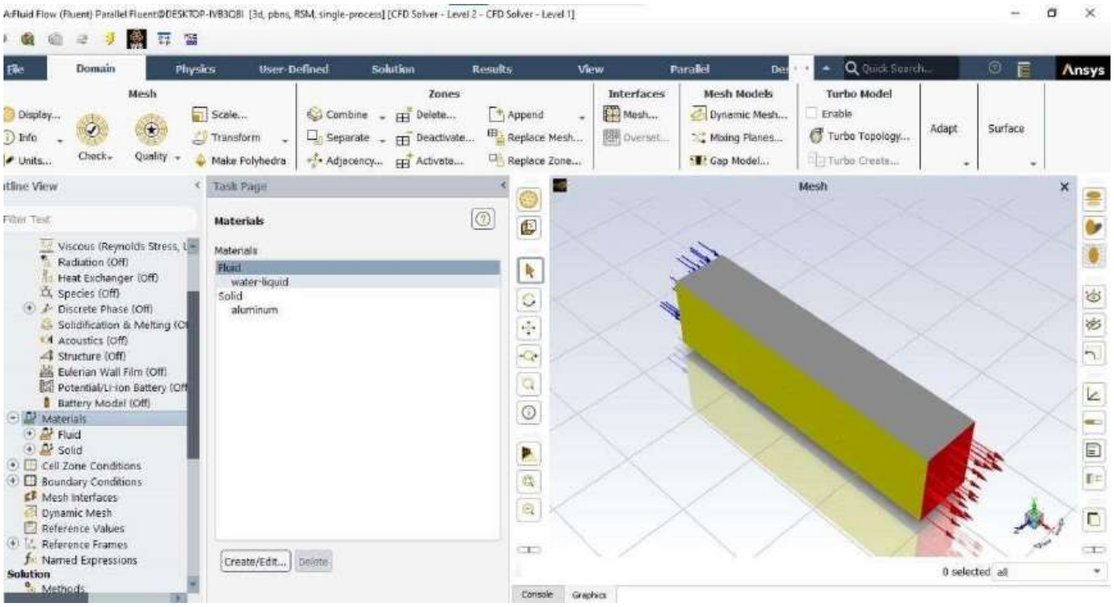
Model Constants
Cmu: 0.09
C1-Epsilon: 1.44
C2-Epsilon: 1.92
C1-PS: 1.8
C2-PS: 0.6
C1'-PS: 0.5
C2'-PS: 0.3
TKE Prandtl Number: 1
TDR Prandtl Number: 1.3

Figure 3.11: Turning on the Reynolds Stress (7 eq) Model

3.6 Boundary conditions

We assigned solid stationary wall conditions to side walls, bottom, and solid cylinders of our domain. Inlet of our domain was setup as a velocity inlet and outlet is setup as a pressure outlet. The boundary condition of top surface of domain is symmetry. We used SIMPLE pressure velocity coupling technique with flux type Rhei-Chow: distance based. The SIMPLE (Semi-Implicit Method for Pressure Linked Equations) technique is an algorithm which is commonly used in numerical investigation of flow characteristics in open channels. It is used to solve the governing equations of fluid flow, including the continuity equation, the momentum equation, and the energy equation (as shown in Figure 3.12). The SIMPLE technique iteratively solving these equations using a combination of explicit and implicit time-stepping schemes, which allows for stable and accurate numerical solutions.

We setup Pressure=0.1, Density=1, Body forces=1, Turbulence kinetic energy=0.5, Turbulence dissipation rate=0.5, Turbulence viscosity=1, and Reynolds stresses=0.5 in solution controls (as shown in 3.13 and 3.14). We used the standard initialization method for the calculation process and set the reference frame relative to the cell zone.

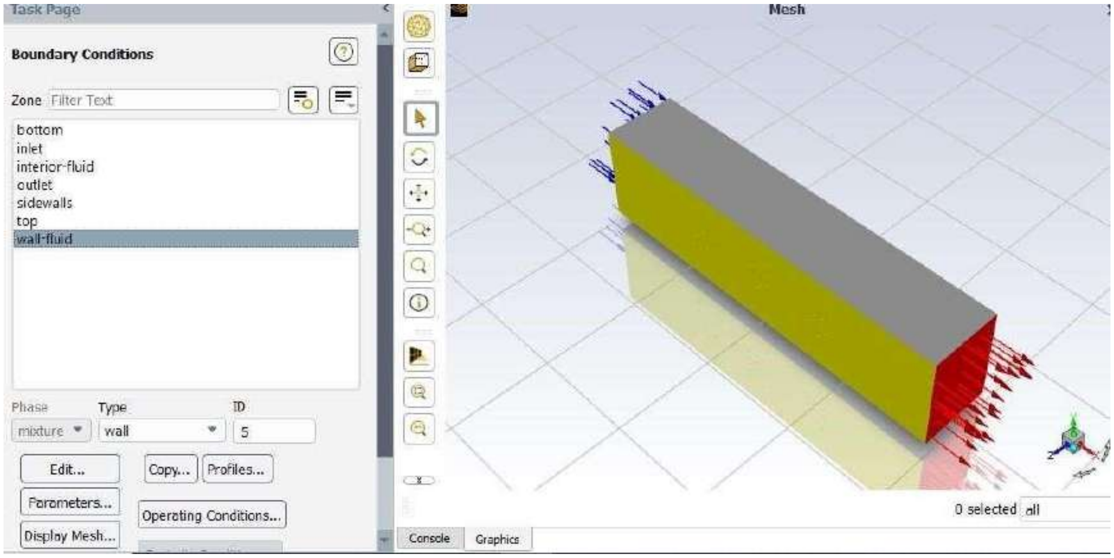


A:Fluid Flow (Fluent) Parallel Fluent@DESKTOP-IVB3QBI [3d, pbns, RSM, single-process] [CFD Solver - Level 2 - CFD Solver - Level 1]

Materials

Fluid
water-liquid
Solid
aluminum

Figure 3.12: Removed Air and Added up Water-Liquid in Material Section



Boundary Conditions

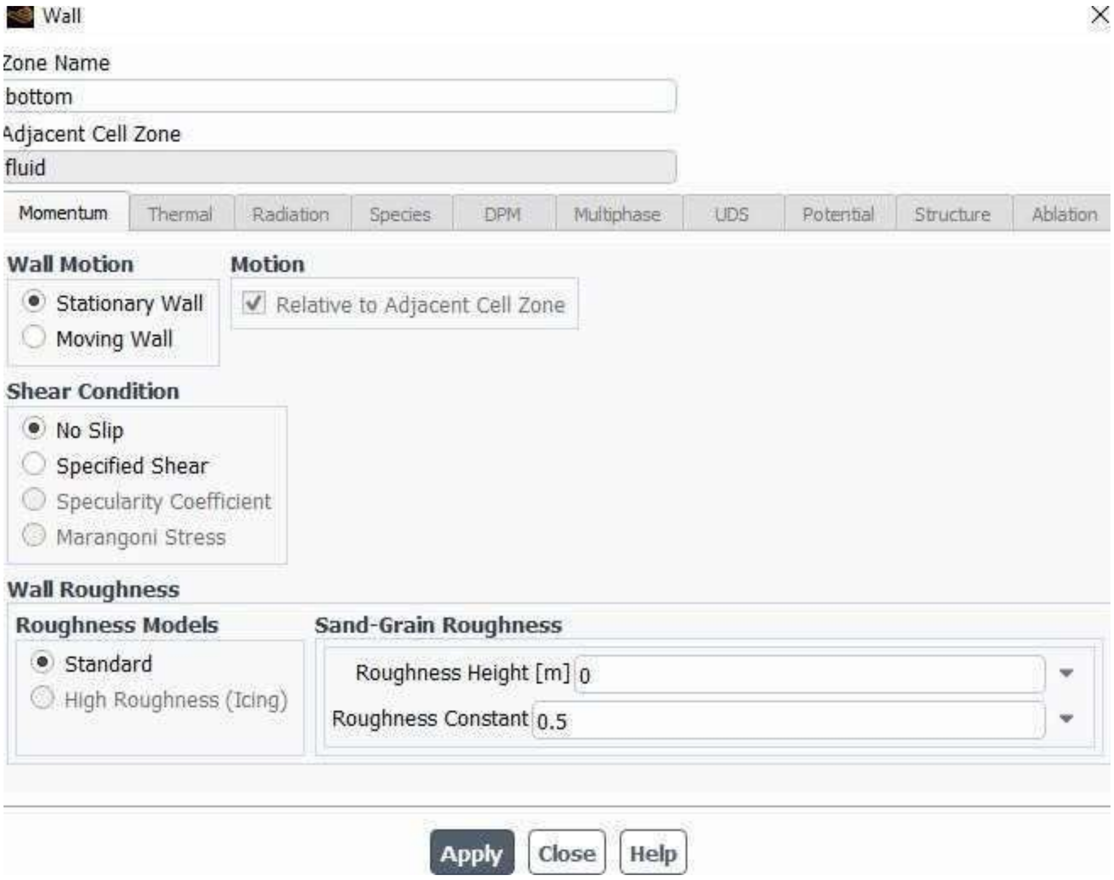
Zone Filter Text

bottom
inlet
interior-fluid
outlet
sidewalls
top
wall-fluid

Phase: mixture
Type: wall
ID: 5

0 selected all

Figure 3.13: Setting up boundary conditions in ANSYS



Zone Name: bottom

Adjacent Cell Zone: fluid

Wall Motion

● Stationary Wall
○ Moving Wall

Motion

☑ Relative to Adjacent Cell Zone

Shear Condition

● No Slip
○ Specified Shear
○ Specularity Coefficient
○ Marangoni Stress

Wall Roughness

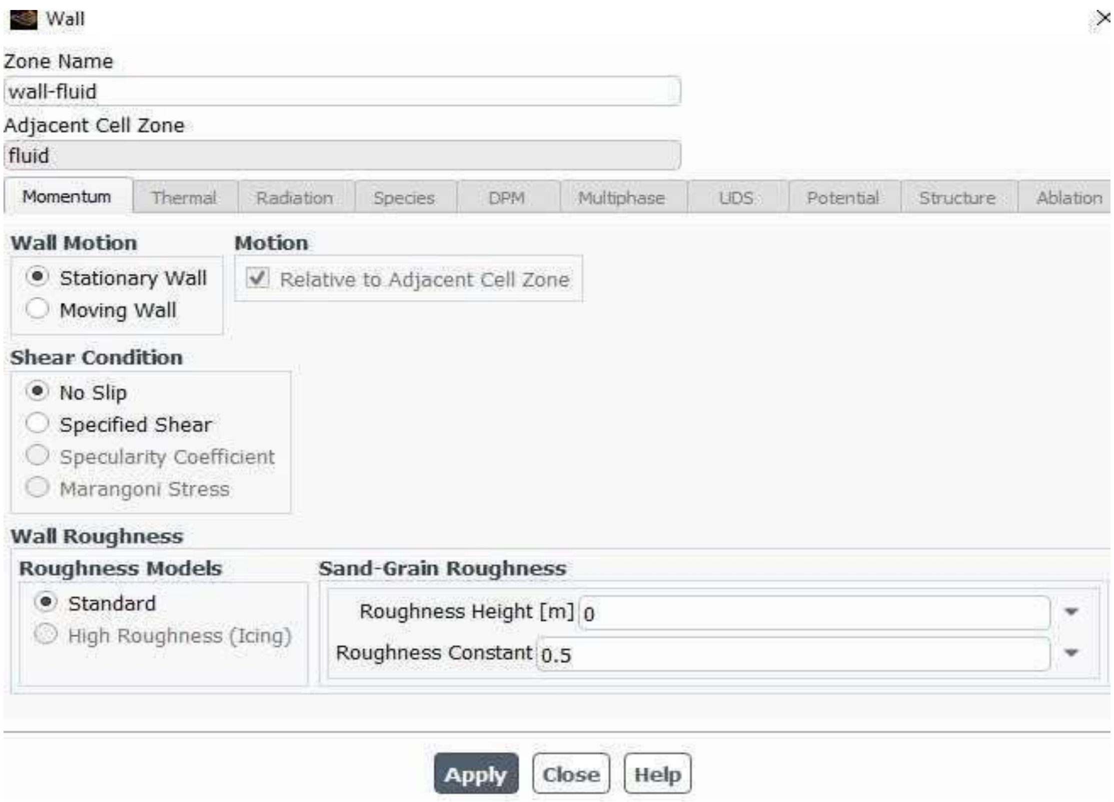
Roughness Models

● Standard
○ High Roughness (Icing)

Sand-Grain Roughness

Roughness Height [m] 0
Roughness Constant 0.5

Figure 3.14: Boundary Conditions for Bottom



Zone Name
wall-fluid
Adjacent Cell Zone
fluid

Wall Motion
● Stationary Wall
○ Moving Wall

Motion
☑ Relative to Adjacent Cell Zone

Shear Condition
● No Slip
○ Specified Shear
○ Specularity Coefficient
○ Marangoni Stress

Wall Roughness

Roughness Models
● Standard
○ High Roughness (Icing)

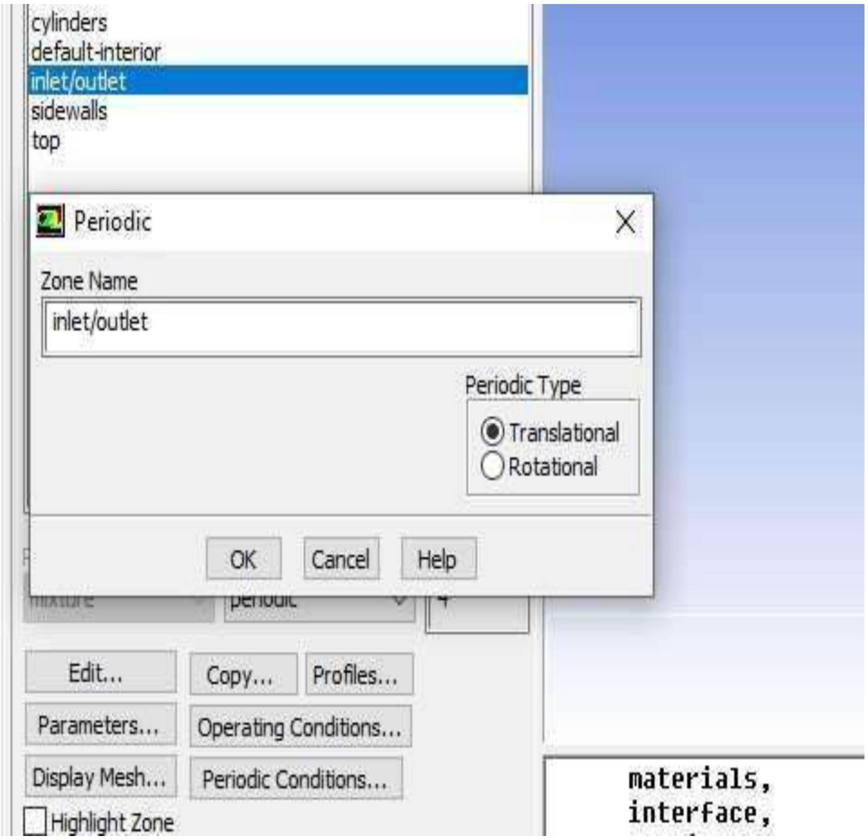
Sand-Grain Roughness
Roughness Height [m] 0
Roughness Constant 0.5

Figure 3.15: Boundary Conditions for Cylinders

3.7 Inlet Detail

The flow in the channel is driven by a constant flow rate. The inlet velocity is fixed at 0.12m/s, and the pressure at the inlet is set to a constant value. The outlet pressure is set to a constant value, and the velocity at the outlet is calculated using the continuity equation. The walls of the channel and the vegetation islands are assumed to be no-slip boundaries (as shown in Figure 3.16).

After setting up all the values as per our planned methodology we initialize the calculation process for 10,000 iterations. After the iteration process, we calculated the results in the form of velocity contours graphs, XY graphs, and animations.



cylinders
default-interior
inlet/outlet
sidewalls
top

Periodic

Zone Name: inlet/outlet

Periodic Type
● Translational
○ Rotational

mixture
periodic

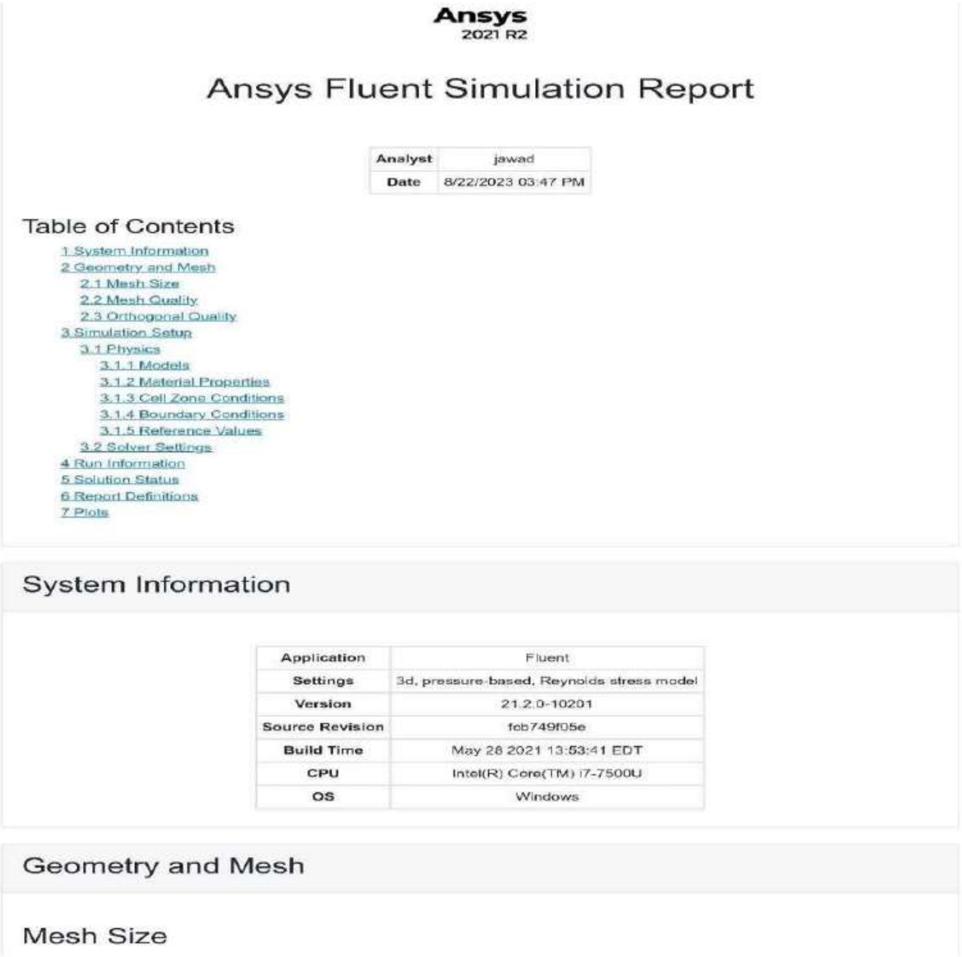
materials,
interface,

Figure 3.16: Inlet periodic conditions screenshot

4. Results and Discussions

In this chapter, the results of our investigation into the flow characteristics of an open channel in the presence of FVIs are presented. Our objective was to numerically simulate the flow patterns around and through FVIs using the CFD technique in ANSYS Fluent Software and gain a better understanding of the effects of these islands on the flow velocity of the channel.

When all the setting up and iteration processes of CFD model are completed in ANSYS Fluent, then the next step of Numerical Investigation is Post Processing. In Post-Processing the results of simulations are processed in the form of Graphs, Histograms, Simulations Reports, and Contours.



Ansys
2021 R2

Ansys Fluent Simulation Report

Analyst	jawad
Date	8/22/2023 03:47 PM

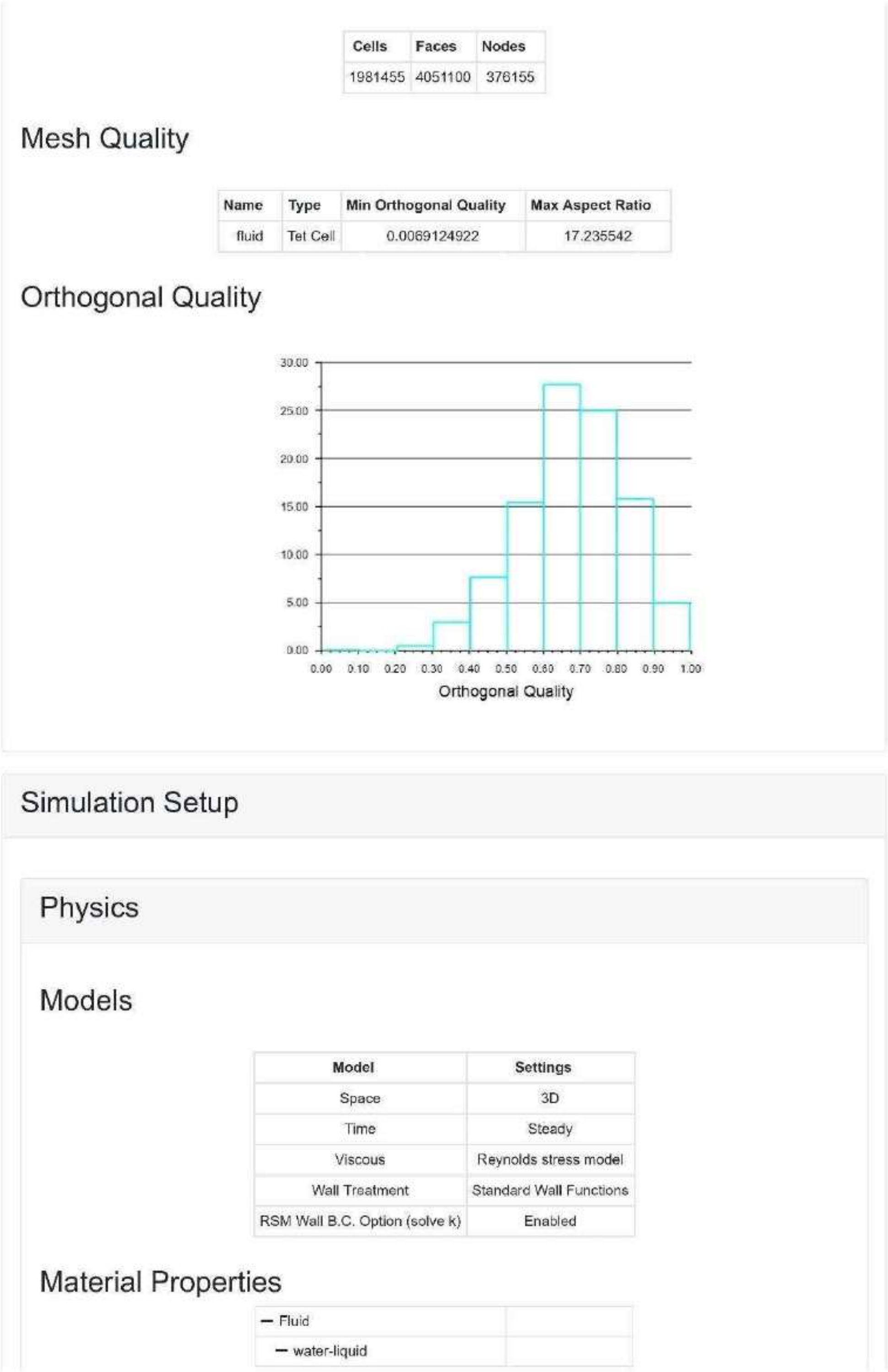
Table of Contents

System Information

Application	Fluent
Settings	3d, pressure-based, Reynolds stress model
Version	21.2.0-10201
Source Revision	fcb749f05e
Build Time	May 28 2021 13:53:41 EDT
CPU	Intel(R) Core(TM) i7-7500U
OS	Windows

Geometry and Mesh

Mesh Size



Cells	Faces	Nodes
1981455	4051100	376155

Mesh Quality

Name	Type	Min Orthogonal Quality	Max Aspect Ratio
fluid	Tet Cell	0.0069124922	17.235542

Orthogonal Quality

Simulation Setup

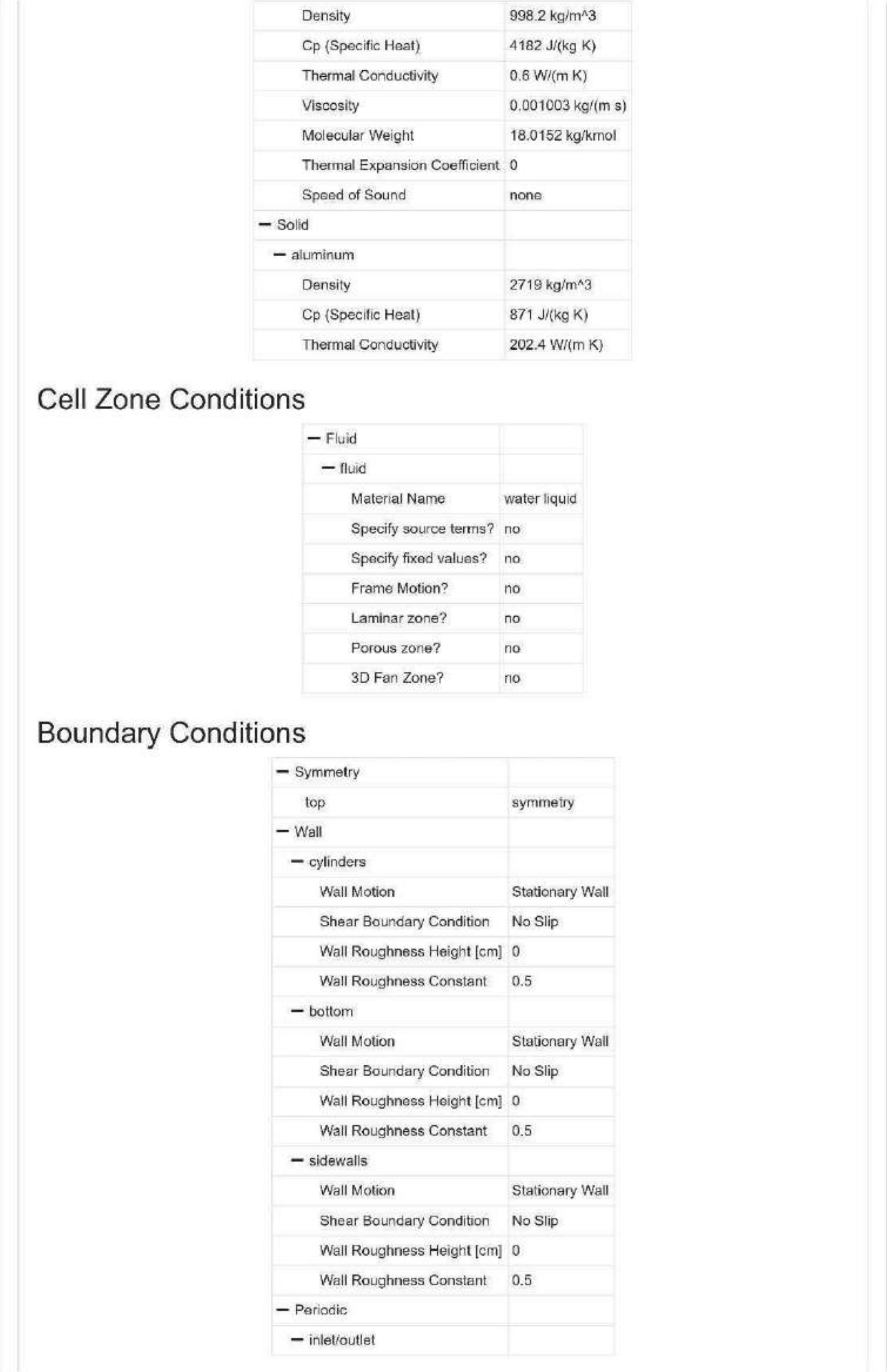
Physics

Models

Model	Settings
Space	3D
Time	Steady
Viscous	Reynolds stress model
Wall Treatment	Standard Wall Functions
RSM Wall B.C. Option (solve k)	Enabled

Material Properties

− Fluid	
− water-liquid	



Density	998.2 kg/m^3
Cp (Specific Heat)	4182 J/(kg K)
Thermal Conductivity	0.6 W/(m K)
Viscosity	0.001003 kg/(m s)
Molecular Weight	18.0152 kg/kmol
Thermal Expansion Coefficient	0
Speed of Sound	none
− Solid	
− aluminum	
Density	2719 kg/m^3
Cp (Specific Heat)	871 J/(kg K)
Thermal Conductivity	202.4 W/(m K)

Cell Zone Conditions

− Fluid	
− fluid	
Material Name	water liquid
Specify source terms?	no
Specify fixed values?	no
Frame Motion?	no
Laminar zone?	no
Porous zone?	no
3D Fan Zone?	no

Boundary Conditions

− Symmetry	
top	symmetry
− Wall	
− cylinders	
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Roughness Height [cm]	0
Wall Roughness Constant	0.5
− bottom	
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Roughness Height [cm]	0
Wall Roughness Constant	0.5
− sidewalls	
Wall Motion	Stationary Wall
Shear Boundary Condition	No Slip
Wall Roughness Height [cm]	0
Wall Roughness Constant	0.5
− Periodic	
− inlet/outlet	

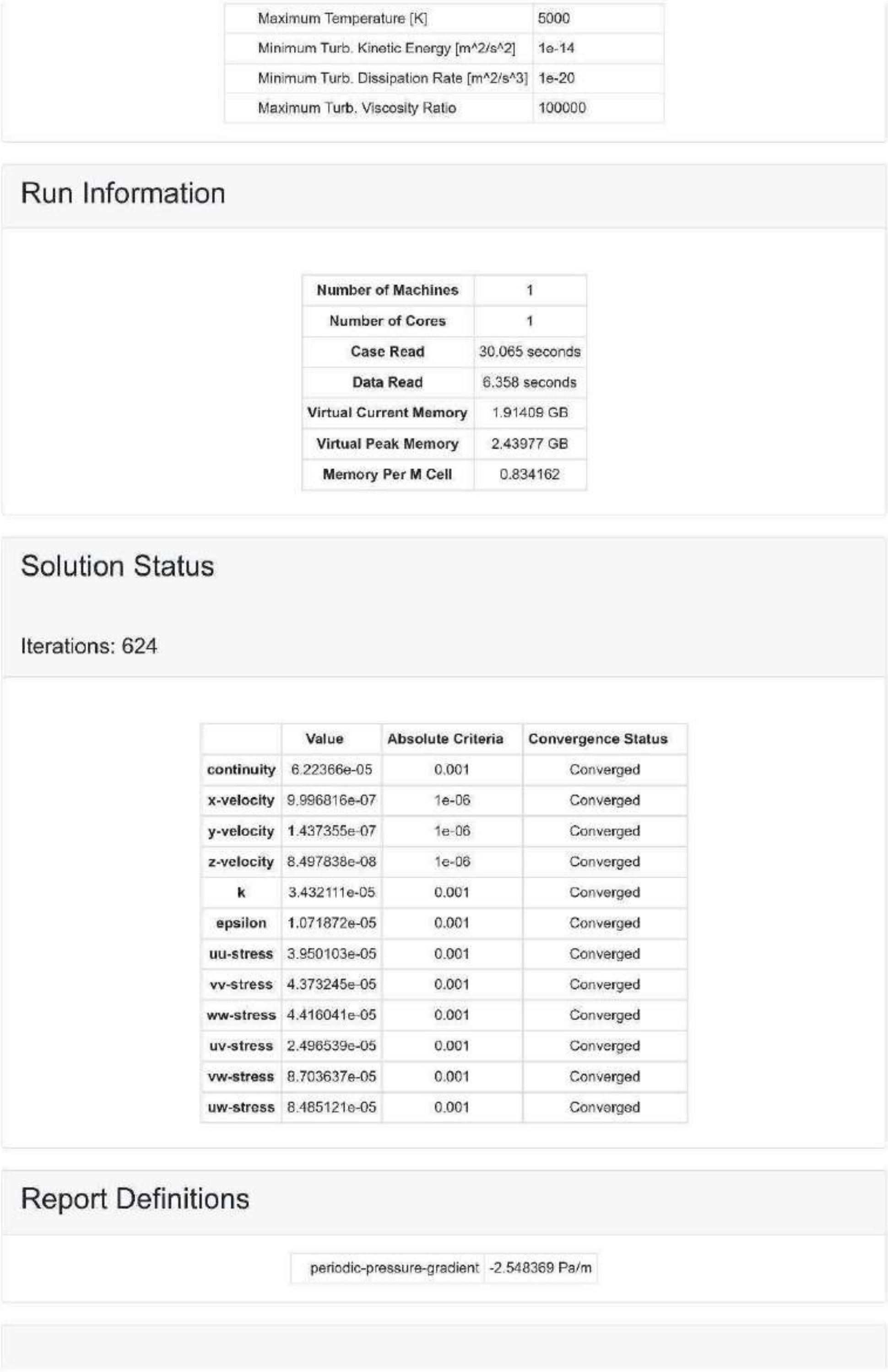
Rotationally Periodic?	no

Reference Values

Area	1 m^2
Density	1.225 kg/m^3
Enthalpy	0 J/kg
Length	1 cm
Pressure	0 Pa
Temperature	288.16 K
Velocity	0.2362586 m/s
Viscosity	1.7894e-05 kg/(m s)
Ratio of Specific Heats	1.4
Yplus for Heat Tran. Coef.	300
Reference Zone	fluid

Solver Settings

− Equations	
Flow	True
Turbulence	True
Reynolds Stresses	True
− Numerics	
Absolute Velocity Formulation	True
− Under-Relaxation Factors	
Pressure	0.1
Density	1
Body Forces	1
Momentum	0.5
Turbulent Kinetic Energy	0.5
Turbulent Dissipation Rate	0.5
Turbulent Viscosity	1
Reynolds Stresses	0.5
− Pressure-Velocity Coupling	
Type	SIMPLE
− Discretization Scheme	
Pressure	Standard
Momentum	First Order Upwind
Turbulent Kinetic Energy	First Order Upwind
Turbulent Dissipation Rate	First Order Upwind
Reynolds Stresses	First Order Upwind
− Solution Limits	
Minimum Absolute Pressure [Pa]	1
Maximum Absolute Pressure [Pa]	5e+10
Minimum Temperature [K]	1



Maximum Temperature [K]	5000
Minimum Turb. Kinetic Energy [m^2/s^2]	1e-14
Minimum Turb. Dissipation Rate [m^2/s^3]	1e-20
Maximum Turb. Viscosity Ratio	100000

Run Information

Number of Machines	1
Number of Cores	1
Case Read	30.065 seconds
Data Read	6.358 seconds
Virtual Current Memory	1.91409 GB
Virtual Peak Memory	2.43977 GB
Memory Per M Cell	0.834162

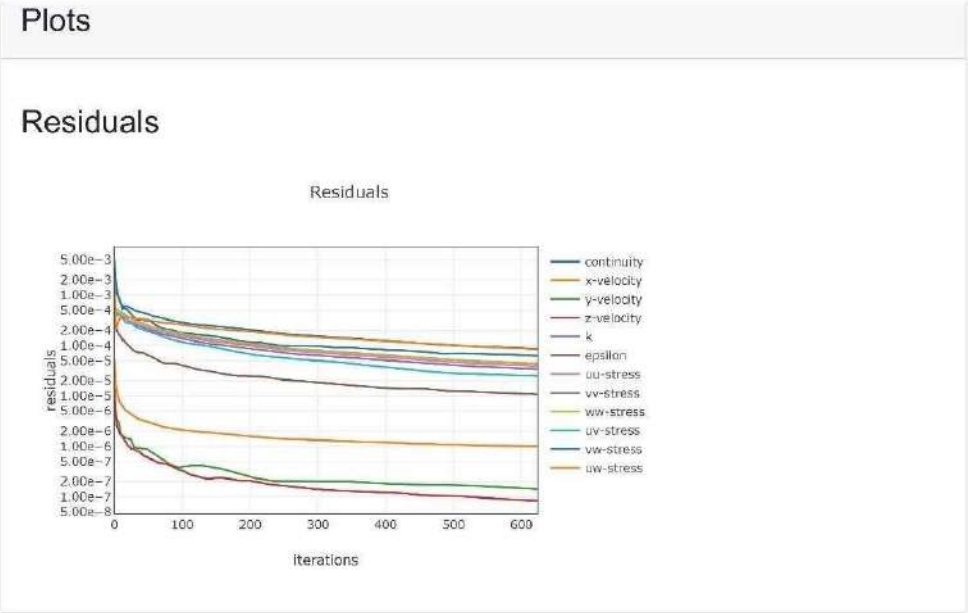
Solution Status

Iterations: 624

	Value	Absolute Criteria	Convergence Status
continuity	6.22366e-05	0.001	Converged
x-velocity	9.996816e-07	1e-06	Converged
y-velocity	1.437355e-07	1e-06	Converged
z-velocity	8.497838e-08	1e-06	Converged
k	3.432111e-05	0.001	Converged
epsilon	1.071872e-05	0.001	Converged
uu-stress	3.950103e-05	0.001	Converged
vv-stress	4.373245e-05	0.001	Converged
ww-stress	4.416041e-05	0.001	Converged
uv-stress	2.496539e-05	0.001	Converged
vw-stress	8.703637e-05	0.001	Converged
uw-stress	8.485121e-05	0.001	Converged

Report Definitions

periodic-pressure-gradient	-2.548369 Pa/m



4.1 Vertical Velocity Distribution

To investigate the vertical velocity distribution of flow within the CFD channel, three distinct positions were considered. The first reference position (P1) was situated between the first and second patches of FVIs. The second position (P2) was situated behind the central cylinder within the second FVIs patch. Additionally, a third position (P3) was situated within the unobstructed region i.e., located just above the second FVI patch, as illustrated in Figure 3.5. These reference positions were considered to facilitate a comparative analysis of the stream-wise velocity "u", the transverse velocity "v", and the depth-wise velocity "w" for all three CFD cases.

4.2 Stream-wise velocity "u"

The investigation started by examining the u-velocity profiles at position P1 for each of the cases (referred to as Figure 4.1 (i-a)). For Case 1 at P1, the u-velocity significantly increased up to 350% within the GR as compared to the CR. The height of the canopy is represented by the horizontal dotted line. In Case 2, the u-velocity decreased up to 62% in CR, whereas the GR u-velocity showed similar trends as in Case 1 and increased up to 325% as compared to CR. Whereas in Case 3, u-velocity decreased up to 16% in CR, whereas in the GR, an increasing trend was observed up to 22% as compared to the initial velocity. Overall, the u-velocity increased up to 20% in GR as compared to CR. The results showed that the most substantial velocity reduction within the vegetation zone occurred in Case 1, whereas Case 3 exhibited the least reduction in velocity.

At position P2, the stream-wise velocities exhibited an upward trend within the GR and increased up to 2000% as compared to the CR (as shown in Figure 4.1 (i-b)). However, within the CR, the uvelocity patterns showed a scattering effect. Notably in Case 1 and Case 2, the trends of velocity within the CR demonstrated similarities, with minor discrepancies because there was a minor difference of gap between the vegetation cylinders in Case 1, and 2 due to which the u-velocities in both cases are similar. In both of these cases, it was observed that the u-velocity significantly increased up to 2500% as compared to the CR. Conversely, in Case 3, the u-velocity in the GR is about 36.84% higher than in the CR, because of sparsity in Case 3 the GR and CR u-velocities are not disturbed significantly. From the results at positions P1 and P2, it is observed that a significant difference in velocities between CR and GR will form a mixing layer at the boundary or interface where the flow transitions from the GR to the CR. This mixing layer facilitates the momentum exchange phenomena between the slower-moving fluid from the CR and the high-velocity fluid from the GR.

During the analysis of u-velocity profiles at position P3, it was observed that there is a negligible difference of 4-5% in stream-wise velocity profiles of Case 1, Case 2, and Case 3 as compared to the inlet velocity (as shown in Figure 4.1 (i-c)). The reason behind the observed phenomenon is that position P3 was situated in the alternate FR.

It was observed that the most significant effects of FVIs were observed on P2 because it was situated inside the center of the second patch where the impact of FVIs on flow was maximum. While on the P1 position, it was observed that u-velocity experienced effects of FVIs but were not as significant as on P2 because it was created in between the first and second patches of FVIs where the u-velocity mainly showed the shedding behavior of flow in CR. Minimal changes in u-velocity were observed on the P3 position because it was situated in alternate FR, which demonstrated that the flow dynamics in FR were almost consistent. Moreover, due to the significant difference between the velocity of flow in CR and GR, S-shape velocity profiles were observed at P1 and P2. While logarithmic velocity profiles were observed at P3 because of minor fluctuations of flow in the alternate FR of P3. Furthermore, it was also observed that the velocity structure around FVIs remains almost similar around the density of (Case 1 and Case 2), whereas it changes in Case 3 density. The observation suggests that flow dynamics remain undisturbed until the density reaches approximately 0.005 cylinders/cm^2. However, beyond this density threshold, significant changes in flow dynamic patterns become apparent. It appears that this density represents a critical limit for the formation of a notable mixing layer and substantial momentum exchange.

4.3 Transverse velocity "v"

Noteworthy observations emerged for the simulated transverse velocity "v" at position P1 (Figure 4.1 (ii-a)). In Cases 1 and 3, an obvious rise in the v-velocity occurred within the CR, as compared to the GR. Conversely, Case 2 exhibited a different trend, wherein the v-velocity experienced a decline within the CR as compared to GR.

The fluctuations within the canopy zone at P2 were apparent across all three cases, with cases 2 and 3 displaying the most pronounced fluctuations (as shown in Figure 4.1 (ii-b)). It was observed that at P2 Case 2 expressed minor fluctuations in v-velocity as compared to Case 1 because of less density of FVIs while Case 3 showed maximum fluctuation because of sparse FVIs which allows the flow to move in the perpendicular direction and also causes vortex formations.

At position P3, the trends in v-velocity remained relatively uniform across cases 1, 2, and 3 (as shown in Figure 4.1 (ii-c)). The v-velocity value remained consistent with no fluctuations because P3 is located in an alternate FR where there are no FVIs which leads to uniform v-velocity across the lateral direction of flow.

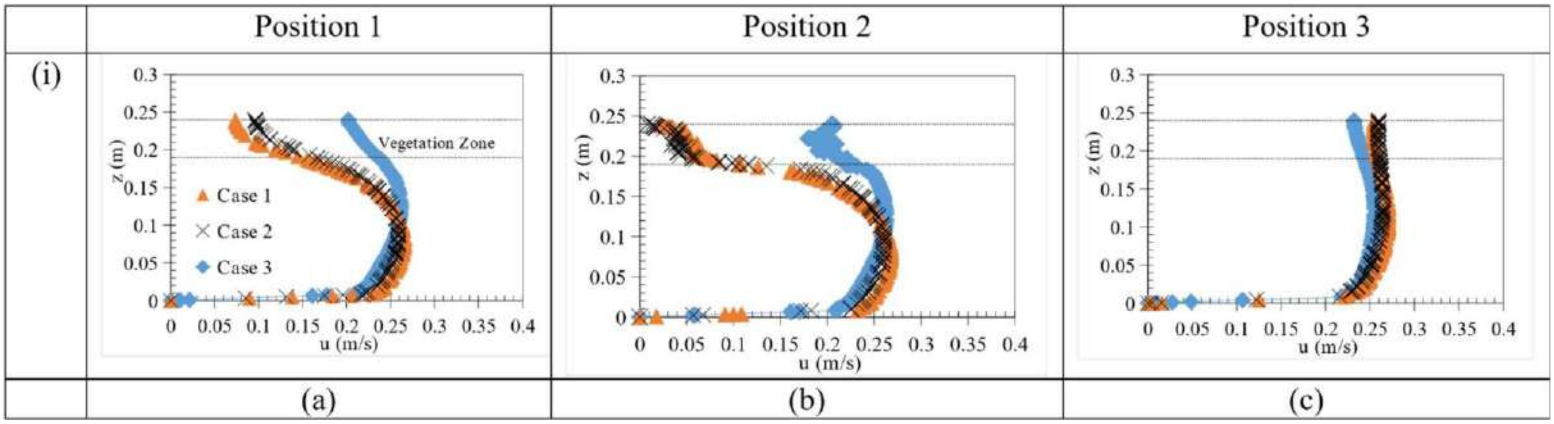
4.4 Depth-wise velocity "w"

During the analysis of the simulated depth-wise velocity "w" profiles at position P1, the w-velocity in Case 1 showed fluctuations and decreased in the CR as compared to the GR (as shown in Figure 4.1 (iii-a)). In cases 2 and 3, the w-velocity displayed an upward trend in the GR, while the wvelocity decreased in CR.

Moving to position 2, the w-velocity remained relatively stable within the FR across all three cases (as shown in Figure 4.1 (iii-b)). Within the CRs of cases 1 and 2, similar fluctuations were observed. However, in Case 3, the w-velocity exhibited more pronounced fluctuations, ranging from a maximum of 0.014 m/s to a minimum of -0.004 m/s.

Overall, the w-velocity showed a disturbed trend within the CR. While at position 3, the w-velocity displayed a nearly uniform distribution both in the FR and CR. The w-velocity values at position P3 were fluctuating within the range of (0-0.001) m/s (as shown in Figure 4.1 (iii-c)).

The decline and fluctuations in w-velocity within the CR at position P1 suggest the presence of FVI-induced turbulence, leading to irregular vertical flow components. Furthermore, the fluctuations in w-velocity suggest the existence of velocity gradients within the CR. Fluctuations of w-velocity within the CR highlight the complex vortex shedding and wake dynamics induced by FVIs. It was observed that at P1 the w-velocity displayed fluctuations within both the GR and CR while at P2 it was almost stable within the GR but showed fluctuations in CR, comparatively w-velocity at P3 showed a stable trend. These unique trends of w-velocity suggest that the vertical flow patterns are highly disturbed In Case1, and 2 due to the presence of dense FVIs and create the most favorable condition for turbulence within the CR and mixing layer at the boundary of CR and FR. Whereas in Case 3, w-velocity remained almost uniform because of the sparsity of FVIs which suggests that Case 3 conditions are not suitable for nutrient removal.



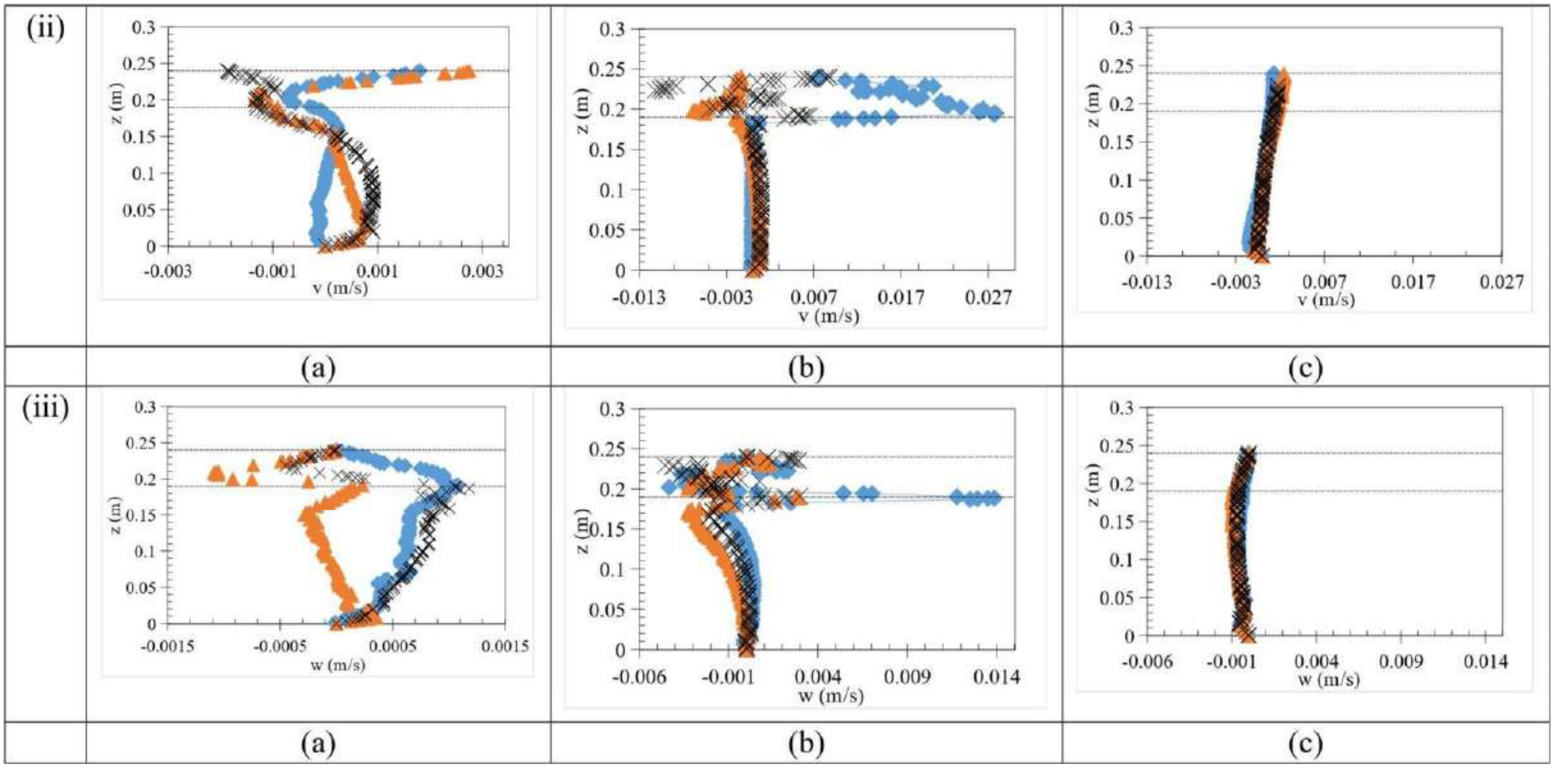


Figure 4.1:Vertical velocity distribution of (i) stream-wise velocity "u," (ii) simulated transverse velocity "v," and (iii) simulated depth-wise velocity "w," where (a), (b), and (c) represents positions P1, P2, and P3 respectively.

4.5 Depth averaged velocities in canopy region and free region

In Case 1, it was observed that the depth-averaged velocity in the GR is 73% greater than the depth averaged velocity within the CR, due to turbulence caused by FVIs (as shown in Figure 4.2). Inside the CR, the velocity was 0.15 m/s before encountering the FVI patches. After passing through each patch, the velocity decreased by 100% within the patch region, and on average the depth-averaged velocity within the CR in 68% as compared to the GR.

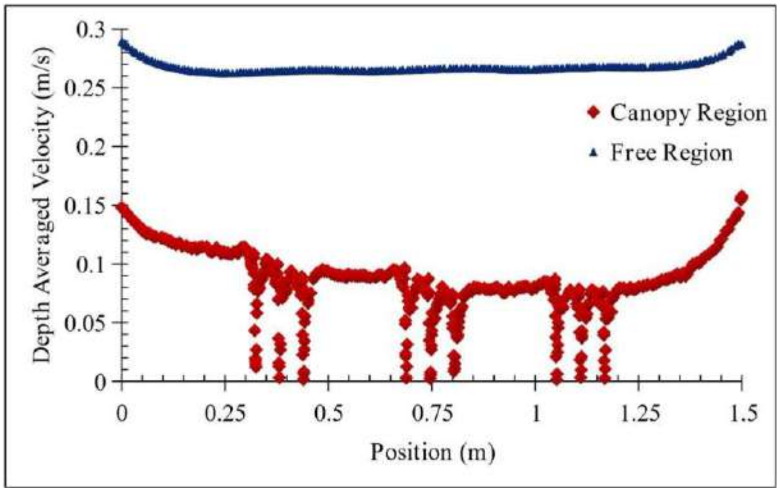


Figure 4.2: Depth averaged horizontal velocity in free region and canopy region for Case 1

For Case 2, the depth-averaged velocity in the GR reached its highest value of 0.28 m/s, which is 66% significant as compared to the depth-averaged velocity within the CR, but the depth-averaged velocity decreased up to 4% below the CR due to canopy-induced turbulence (as shown in Figure 4.3). While inside the CR, the velocity was initially 0.13 m/s before entering the vegetation zone, which is 50% decreased as compared to the depth-averaged velocity within the GR. As it traversed through the vegetation patches, the velocity fluctuated and decreased up to 60% as compared to the GR after passing through the first patch. After crossing the second patch, the velocity was further reduced by 55%, and it was further reduced by 40% while passing through the third patch. While inside the patch region, the velocity was reduced up to 100% as compared to alternate FR.

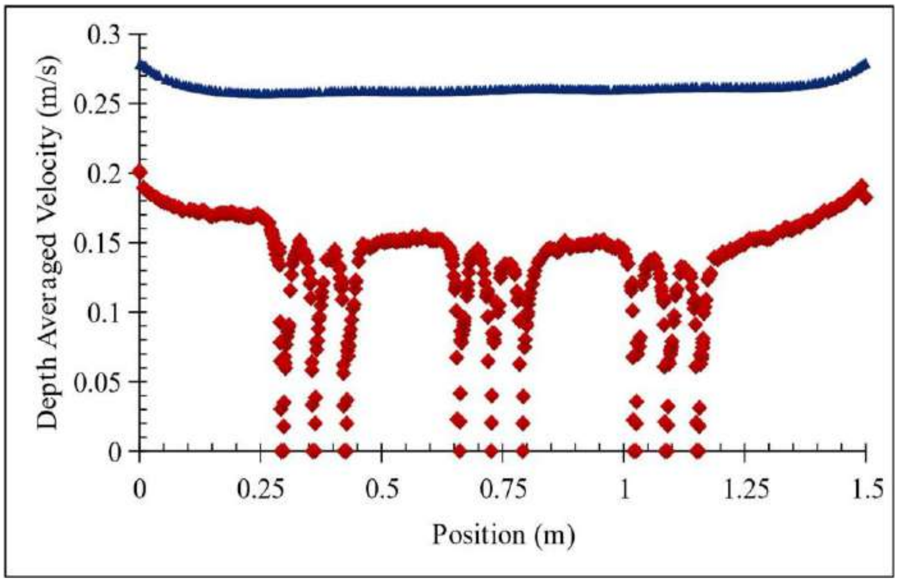


Figure 4.3: Depth averaged horizontal velocity in free region and canopy region for Case 2

In contrast, Case 3 displayed a stable depth-averaged velocity of 0.26 m/s in the GR, which is 20% greater as compared to the CR. It remained undisturbed under the CR due to the minimal turbulence caused by the low-density FVI patches (as shown in Figure 4.4). In the CR, the flow initially maintained a velocity of 0.21m/s, while approaching the first patch the velocity was reduced by 30% as compared to the GR. After passing through the first patch, the velocity decreased and displayed similar fluctuation patterns within the second and third patches. Case 3 exhibited low resistance to flow, resulting in nearly undisturbed flow conditions.

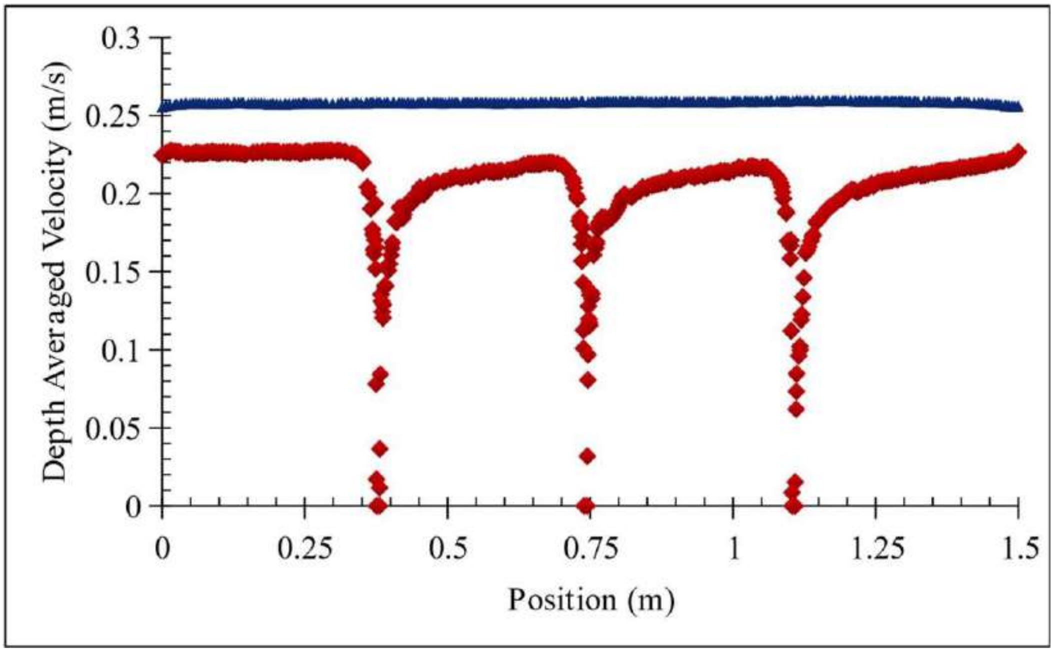


Figure 4.4: Depth averaged horizontal velocity in free region and canopy region for Case 3

The observed variations in depth-averaged velocity among the three cases showed the significant role of FVI density in shaping flow dynamics. In Case 1, the reduction in velocity within the CR and the subsequent decrease after passing through each FVI patch is due to the substantial turbulence generated by the dense FVI arrangement. The significant flow obstruction and turbulence within the canopy zone led to a successive reduction in velocity, highlighting the flowretarding effects of higher FVI density in cases 1, and 2. Similarly in Case 3 stable velocity profiles suggest a lower FVI density resulting in less flow resistance and turbulence by sparse FVIs. This demonstrated that the minimal resistance within the CR allows for relatively undisturbed flow. It shows that the FVIs induced resistance to the flow within CR and decreased the depth-averaged velocity but conversely induced high pressure on alternate FR and GR due to which the depthaveraged velocity increased in the alternate FR and GR. These findings are consistent with the research studies of Mavrommatis and Christodoulou (2022).

4.6 Overall Discharge

To assess the relative discharge percentages between open and vegetated regions, average discharge values were computed within the CR and the FR beneath the CR for all CFD cases (as demonstrated in Figure 4.5). In the first case, the analysis revealed a discharge percentage of 74% in the FR and 23% within the CR on average. In the second case, the flow discharge within the FR was 75%, contrasting with 26% within the CR. The third case exhibited discharge percentages of 63% in the FR and 45% in the CR.

It became evident that Case 1 exhibited higher flow discharge within the GR due to the greater vegetation density, which led to increased pressure within the CR, resulting in reduced discharge values. In the second case, with slightly lower vegetation density than the first case, the average discharge percentage within the CR exceeded that of the first case. However, in the third case, where vegetation density was comparably lower, discharge percentages between the canopy and open regions displayed minimal variation. It was observed that increasing the FVI density decreased the velocity within the CR which ultimately reduced the discharge percentage. By increasing the patch density by 3 times the discharge percentage by reduced by ~40%. It shows that as the density of FVIs was decreasing the discharge percentage in CR was increasing while it was decreasing in FR, which is consistent with the findings of Huai et al. (2014).

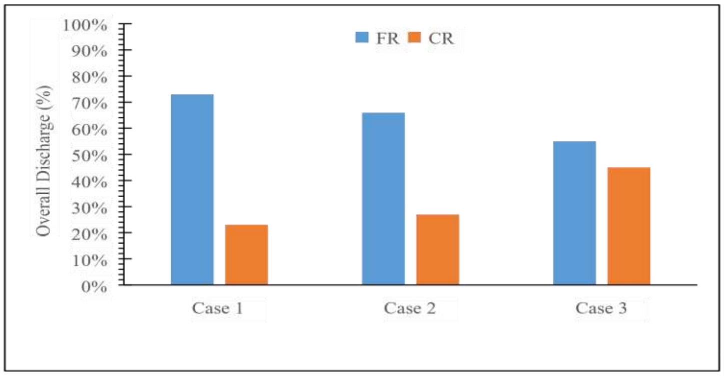


Figure 4.5: Comparison of overall discharge percentage of case 1, 2, and 3 in free region (FR) and canopy region (CR)

4.7 Contour Plots of Velocity Distributions

4.7.1 Contour Plots of Velocity Distributions on xy Plane

By conducting an analysis of the velocity contours of mean velocity "U" on the xy-plane (top surface) in Case 1, it was observed that the flow velocity was reduced by 38% as compared to the inlet velocity before entering the CR (as shown in Figure 4.6). While passing through the first patch of vegetation, the velocity further decreased by 35% as compared to the initial velocity. Subsequently, as the flow crossed the second patch of vegetation, the velocity was further reduced by 60%. Upon reaching the third patch of FVIs, the flow velocity experienced an additional decrease, reaching a minimum value of 0 m/s. While in the alternate FR around the FVI patches, the velocity of flow increased by 20-30%. However, after passing the third patch, the velocity gradually stabilized due to the periodic boundary conditions of the flow within the CFD model's inlet and outlet. Additionally, the shedding behavior of flow continued from 1 patch to the third patch. Shedding behavior was highest in the region between the first and second patches and after the third patch.

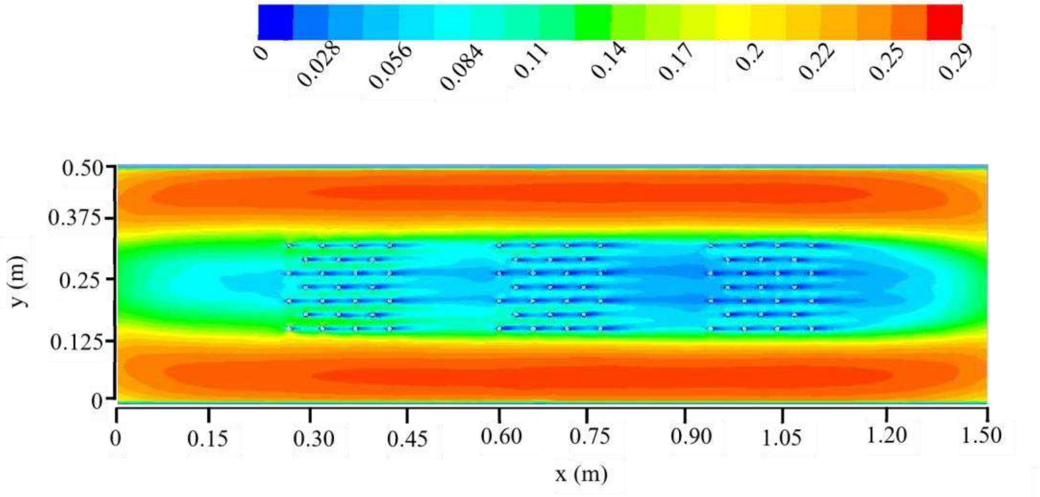


Figure 4.6: Velocity contours of mean velocity "u" along the horizontal top surface for case 1

Upon analyzing the velocity contours of Case 2, it was evident that the presence of medium-density FVI patches resulted in a reduction in flow velocity, although not as significant as observed in Case 1 (as shown in Figure 4.7). While passing through the first FVI patch, the flow velocity was decreased by 50% as compared to the inlet velocity of flow. Subsequently, as the flow passed through the second and third FVI patches, the velocity was further reduced up to 51% as compared to the velocity of flow after the first patch, and a minimum velocity of around 0 m/s was observed after some cylinders of the second and third patch. After traversing the third patch, the flow velocity was further reduced by 100% as compared to the velocity of flow after the second patch. It was noted that the second and third FVI patches had a more pronounced impact on reducing flow velocity compared to the first patch.

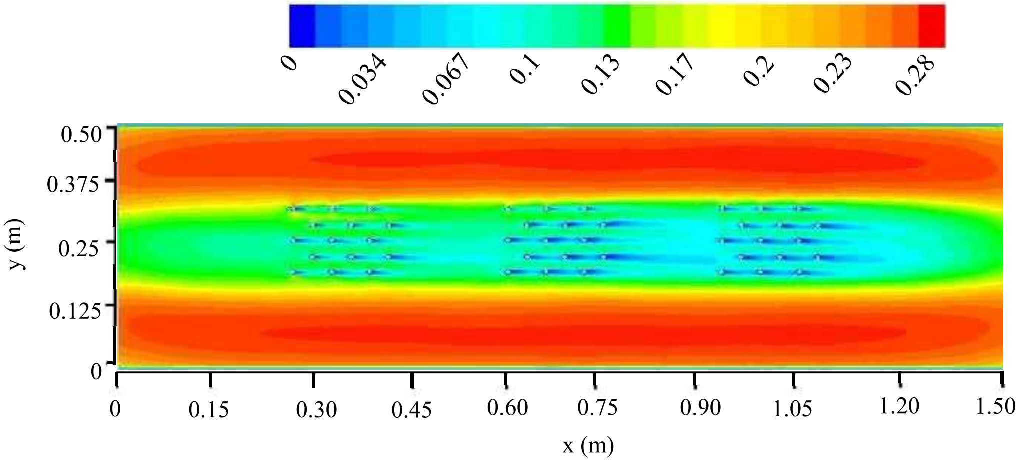


Figure 4.7: Velocity contours of mean velocity "u" along the horizontal top surface for case 2

Comparatively, the velocity contours of mean velocity U in Case 3 demonstrated that sparse FVI patches contributed to relatively stable flow dynamics as compared to cases 1 and 2 (as shown in Figure 4.8). Notably, the flow velocity reduced to 100% immediately behind the vegetation cylinder. However, at the shedding behavior of the FVIs, the flow velocity was observed to be decreased by 37%, while in the FR around the CR, the flow velocity remained undisturbed with a difference as compared to the inlet velocity of flow. The CFD channel walls consistently exhibited a flow velocity of 0 m/s across all three cases. It was observed that in highly dense FVIs Case 1 it was observed that shedding behavior was traveling from patch to patch, while in Case 2 the density was reduced by 40% therefore the shedding was observed just behind the cylinders. In Case 3, there was no shedding behavior observed after the cylinders or patches.

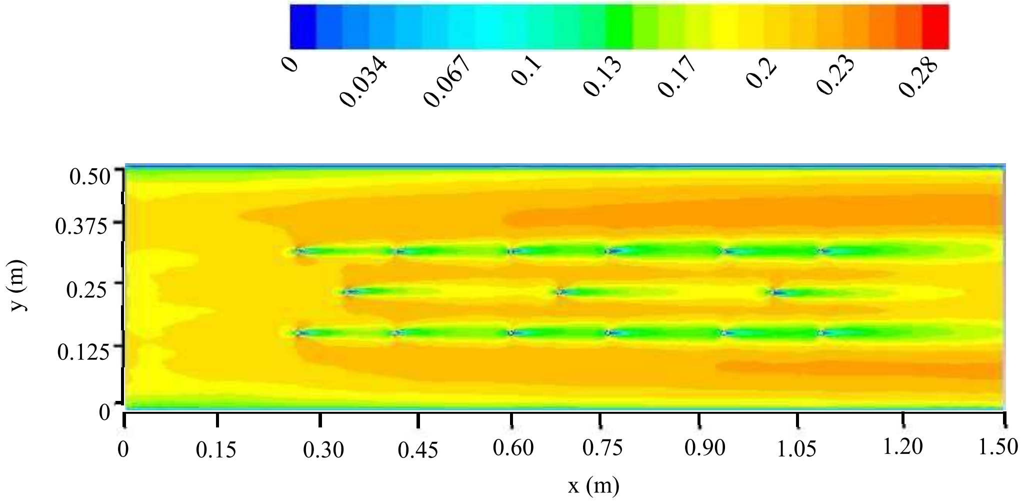


Figure 4.8: Velocity contours of mean velocity "u" along the horizontal top surface for case 3

Instability in flow occurred at the boundary of low-velocity CR and high-velocity FR, resulting in the development of a shear layer. This layer exhibits gradually increasing flow velocity as the flow transverses from the CR to the alternate FR. Consequently, momentum exchange between these two regions occurs due to interfacial instability. These findings suggested that the highest shedding was observed in Case 1 which causes the major differences between the FR and CR velocities which is the most suitable condition for Kelvin-Helmholtz instabilities, which ultimately causes more momentum exchange at the root of canopies, and the shedding of vortices and wakes facilitates contact between nutrient-rich water and vegetation surfaces, elevating the ecosystem's nutrient removal capacity. which is also investigated by the previous researchers (Borne and Fassman 2011; Yao et al. 2011).

4.7.2 Velocity Distribution on xz velocity contours

The analysis of velocity contours on the xz (vertical) plane in Case 1 revealed a relatively higher density of vegetation compared to Case 2 and Case 3, resulting in increased resistance to the flow due to high turbulence. As a consequence, the velocity within the CR decreased by 100% as compared to the inlet velocity, while the highest velocity of 0.29 m/s was observed in the depthaveraged free zone, which is 20% increased as compared to the initial velocity (as shown in Figure 4.9).

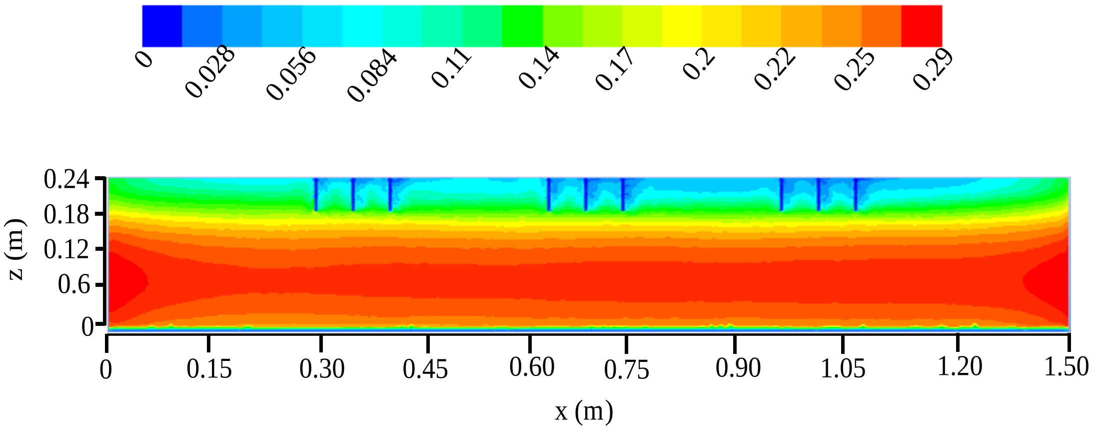


Figure 4.9: Velocity contours of stream-wise velocity alongthe longitudinal section (A) for case 1

In Case 2, the lower density of FVI patches caused a minor reduction in velocity, leading to minimal flow disturbance primarily observed around the cylinders (as shown in Figure 4.10). The results are supported by findings of depth-averaged velocities in GR and CR.

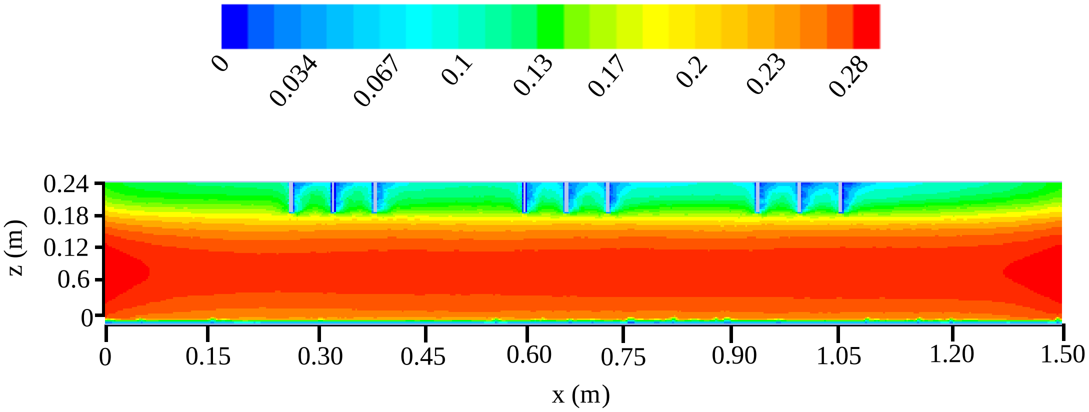


Figure 4.10: Velocity contours of stream-wise velocity along longitudinal section (A) for case 2

In contrast, Case 3 showed a velocity decrease due to minimal resistance caused by the FVIs, which instantly stabilized after crossing the CR (as shown in Figure 4.11). The sparse density of FVIs resulted in minimal flow disturbance. Below the vegetation zone, a layer-by-layer increase in velocity was observed, with a maximum increase of 15-20% velocity observed for cases 2 and 3 in the depthaveraged free zone, as compared to the inlet velocity. Notably, the minimum velocity was observed within the CR. The findings on the xz plane confirmed and complemented the observations of depth-averaged velocity, providing valuable insights into the influence of FVI density on flow dynamics in open channel systems with emerged vegetation patches, and the findings are consistent

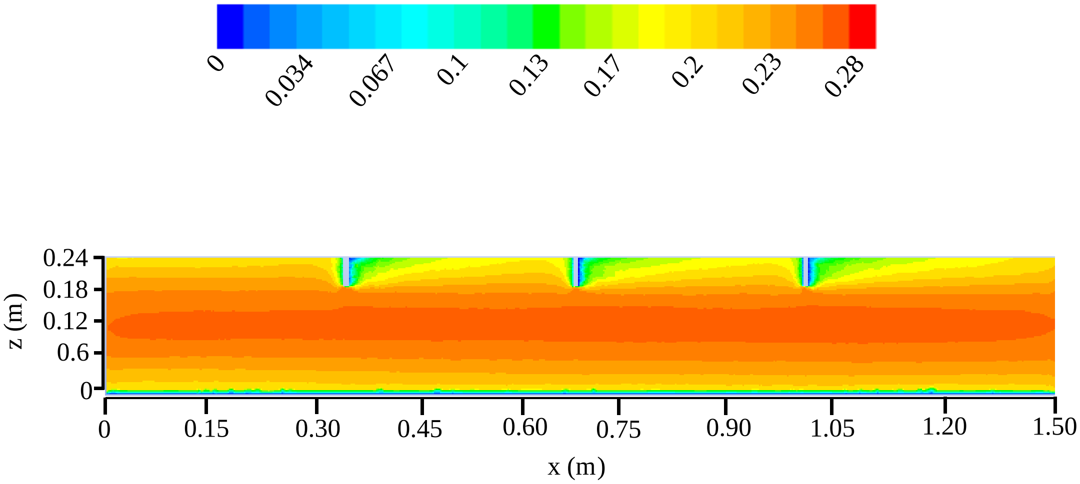


Figure 4.11: Velocity contours of stream-wise velocity along longitudinal section (A) for case 3

4.7.3 Velocity Distribution on yz velocity contours

While investigating the velocity contours in the yz (cross-section) plane, Case 1 showed that the velocity within the vegetation patches decreased by 100%, while in the FR surrounding the vegetation zone, it decreased by 40%. Moving away from the vegetation zone, the velocity exhibited an incremental increase, forming distinct layers, with the highest velocity observed in the FRs surrounding the vegetation zone (as shown in Figure 4.12).

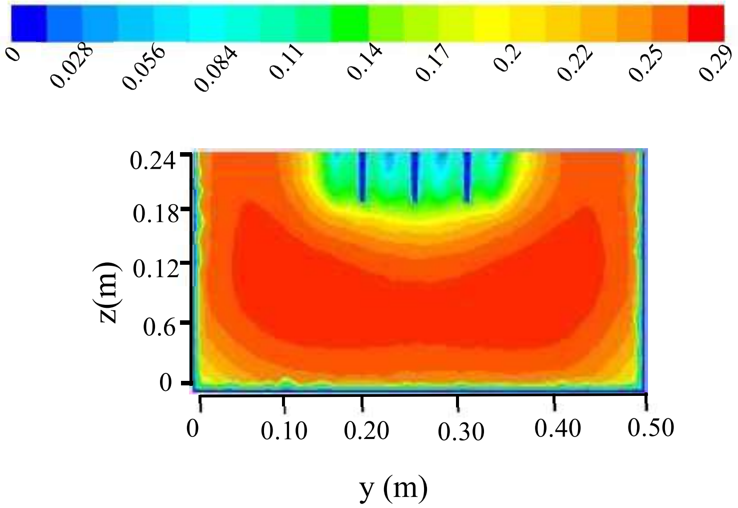


Figure 4.12: Velocity contours along lateral section (B) for case 1

Similarly, when observing the yz velocity contours in Case 2, it was verified that the vegetation zone had a minimal impact on reducing flow velocity due to its low density (as shown in Figure 4.13).

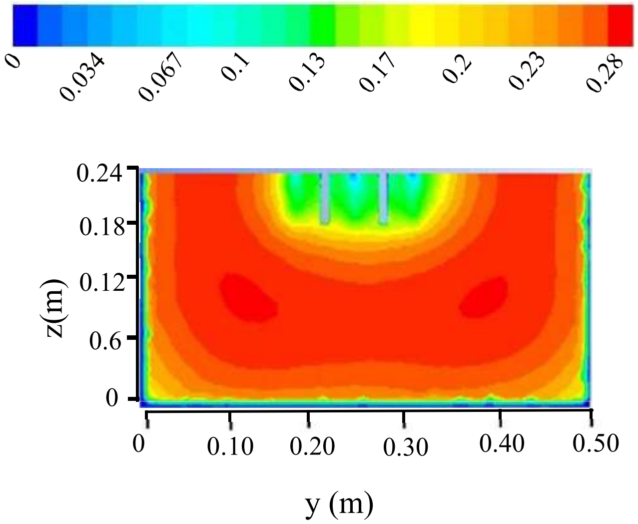


Figure 4.13: Velocity contours along lateral section (B) for case 2

In Case 3, the vegetation zone caused a slight reduction in flow velocity, which was even lower than observed in Cases 1 and 2 (as shown in Figure 4.14). The flow velocity experienced slight disturbances in this case, with the highest velocity observed in the free regions surrounding the vegetation zone.

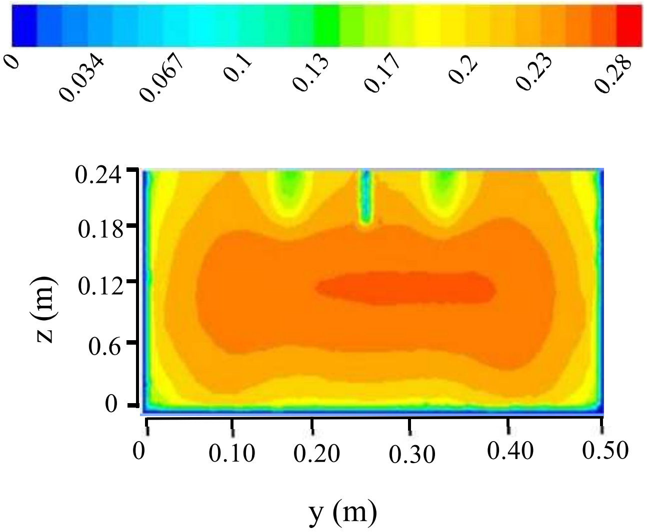


Figure 4.14: Velocity contours along lateral section (B) for case 3

The flow velocity experienced slight disturbances in this case, with the highest velocity observed in the FRs surrounding the vegetation zone. These findings underscore the varying influence of vegetation density on flow velocity and the complex spatial patterns of flow dynamics around the vegetation zone. The minimal velocity reduction in Cases 2 and 3 highlights the importance of considering vegetation characteristics and density when studying flow behaviors in open channel systems with emerged vegetation patches. It was observed that by increasing the density the pressure exerted by the FVIs increased significantly and increased the velocity in the alternate FR. These findings are similar to those investigated by Zhao and Huai (2016).

These velocity contours further verified that Case 1 is best suitable for maximum momentum exchange at the root of canopies because of distinct differences between the CR and GR velocities which will be more suitable conditions for nutrient removal. But, as there is more shedding behavior after the patches, it will disturb the open channel management by increasing the rate of sedimentation. Considering all the conditions, Case 2 is recommended for maximum momentum exchange and nutrient removal along with the stable flow structure. Whereas, Case 1 conditions are more suitable for shedding behavior.

4.7.4 Depth averaged Turbulence Kinetic Energy (TKE) Distribution

To examine the TKE distribution across the CFD channel, the average TKE values were assessed within both the CR and the FR (Figure 4.15). In the context of Case 1, notable findings were observed. The average TKE values within CR increased by 168% as compared to the FR. Specifically, the TKE value increased by 25 times within the first patch of FVIs. Subsequently, the second patch exhibited the highest TKE similar to that in the first patch, followed by the third patch in which the TKE values were increased by 3 times the value of TKE in the second patch.

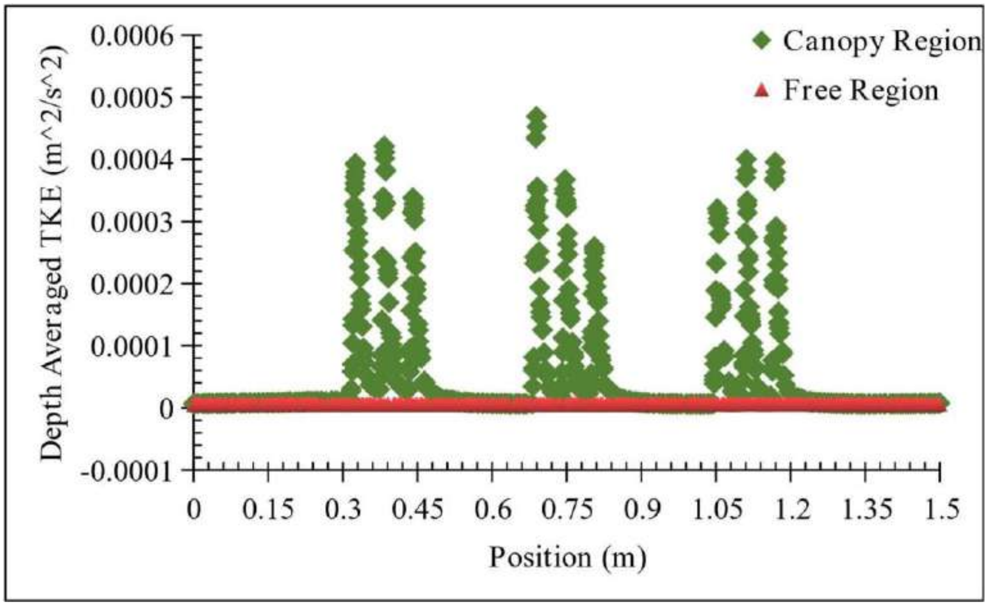


Figure 4.15: Turbulence Kinetic Energy (TKE) in free region and canopy region for case 1

In the context of case 2, distinct patterns of TKE were observed. The average TKE value within the CR amounted to 4.18 × 10^{-5} m^2/s^2, while the FR demonstrated a significant decrease of 97% of the average TKE value in CR (Figure 4.16). The TKE value remained constant within the FR, whereas within the CR, a peal TKE value of was observed before CR entry which is 43% less than the average TKE throughout the channel. This behavior demonstrates a substantial increase in TKE values within the intensely turbulent CR, while conversely there is a marked reduction in TKE values in the comparatively less turbulent FR.

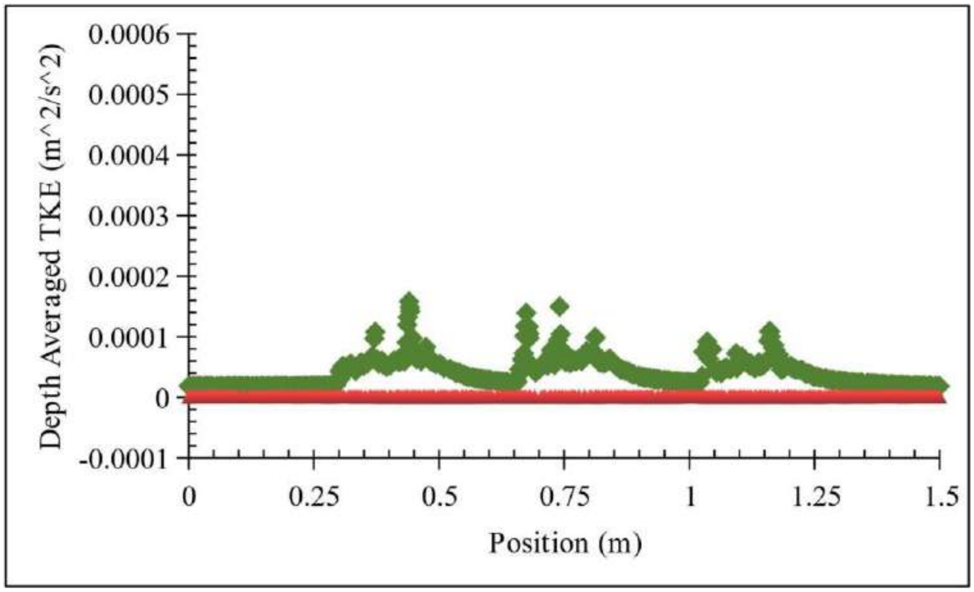


Figure 4.16: Turbulence Kinetic Energy (TKE) in free region and canopy region for case 2

Similarly, in Case 3, notable findings were observed in the distribution of TKE. The lowest TKE values were identified in both the FR and the CR as compared to cases 1 and 2, which is primarily attributed to the sparse arrangement of FVIs across all patches (referred to as Figure 4.17). Specifically, within the CR, the average TKE value was determined to be 45% higher as compared to the alternate FR, whereas the corresponding average TKE value in the FR was 60% lower than the TKE value in CR.

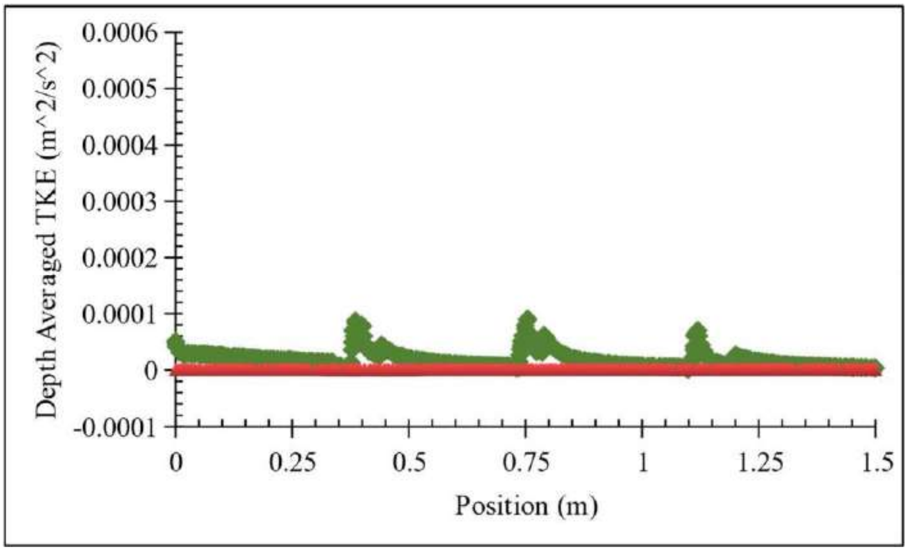


Figure 4.17: Turbulence Kinetic Energy (TKE) in free region and canopy region for case 3

An interesting trend emerged where TKE values exhibited an increment in instances marked by turbulence, a phenomenon linked to the presence of sparsely distributed FVIs in the CR. Notably, the highest TKE value was recorded in the 1st and 2nd patches, reaching a peak of 7.9×10^{-5} m^2/s^2 which is almost 77% higher than the Case 3. Conversely, Case 2 CR demonstrated a comparatively 40% lower TKE value than the overall average TKE Value in Case 1. The lowest TKE was observed in Case 3 in which there was a negligible difference between the TKE in CR and FR.

The TKE distribution across the CFD channel provides insight into the turbulence dynamics intricately influenced by the presence of FVIs with varying densities. In Case 1, the transition from the FR to the CR showed a substantial increase in average TKE, due to the significant turbulence within the CR. The notable peaks of TKE within each FVI patch signify the direct correlation between FVI presence and intensified turbulence, it is due to the inherent turbulence-rich nature of the CR. Case 2 reveals a similar pattern of increasing TKE upon entering the CR, demonstrating the dynamic turbulence interactions within the CR. This suggests that the disparity in density between Case 1 and Case 2 is not sufficiently substantial to exert a pronounced impact on the TKE values. In Case 3, the sparse distribution of FVIs causes lower average TKE values across both regions because there was no hindrance to flow.

4.8 Depth averaged Turbulence Intensity (TI) Distribution

To comprehensively examine the turbulence intensity (TI) distribution across the CFD channel in all cases, the mean TI was computed within both the CR and FR. In Case 1, the TI value in CR is ~6900% significant as compared to FR (as shown in Figure 4.18). Remarkably, the TI values within the FR exhibited a consistent profile across the channel because there was no turbulence observed in the FR. The behavior of TI closely matched the patterns observed in the TKE distribution. Increased turbulence in CR is closely related to the increased TI values, while a reduced trend in TI was observed within the FR between the FVIs patches and beneath the CR characterized by undisturbed flow conditions. The heightened TI values observed within the CR can be attributed to the substantial turbulence generated within this specific region.

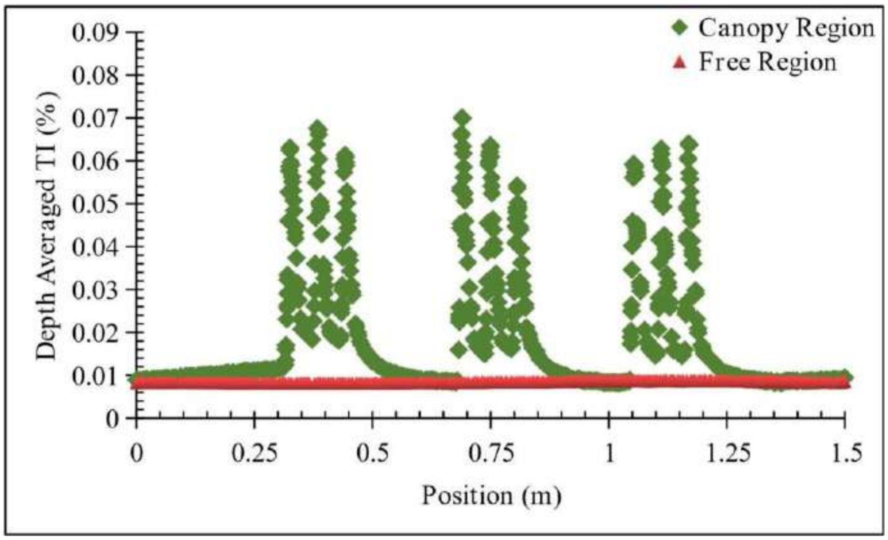


Figure 4.18: Turbulence intensity (TI) in free region and canopy region for case 1

In Case 2, the average TI within the CR was measured to be 185% higher than the FR (referred to as Figure 4.19). Meanwhile, the FR demonstrated a stable TI value throughout the channel, which is 20% lower than the lowest value of TI in CR. Fluctuations in TI was significant within the CR. Traversing through the CR of the first patch the TI increased up to 30-40% as compared to the average TI. Notably, the first two patches exhibited comparable TI profiles, featuring a decline in TI within the FR interposed between the patches. The calculated average TI value in FR between the patches was 70% higher than the TI in CR. In Case 2, the TI exhibited a notably lower magnitude compared to the CR of Case 1. Furthermore, within the FR of Case 2, there was a substantial reduction in TI, approximately by 50%, relative to that observed in Case 1.

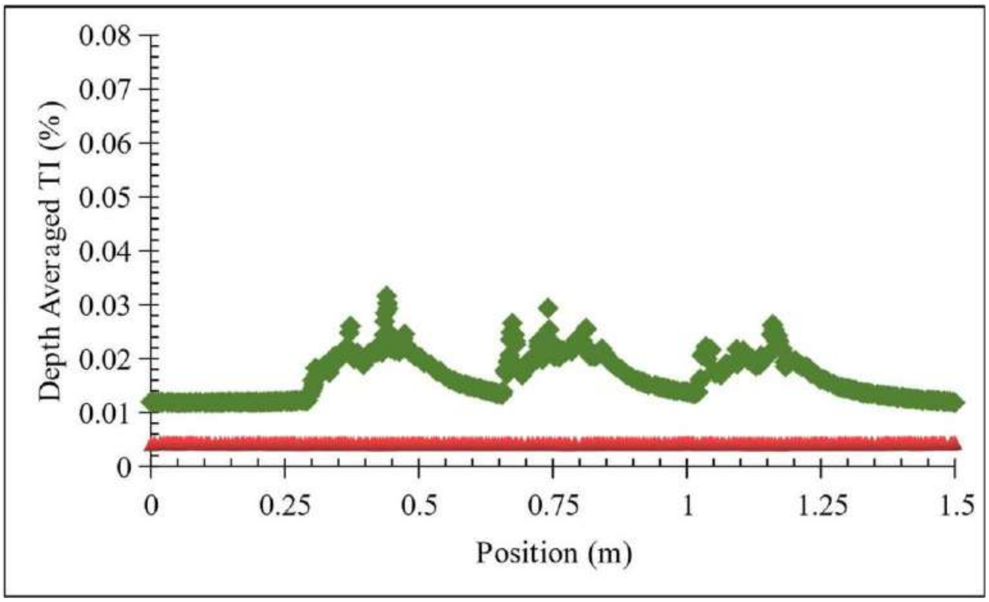


Figure 4.19: Turbulence intensity (TI) in free region and canopy region for case 2

In Case 3, a relatively low TI was observed as compared to cases 1 and 2. Inside the CR, the average TI value was 62% higher than the TI in FR (as shown in Figure 4.20). The minimal difference in the average TI values between the CR and FR is attributed to the sparse vegetation density in Case 3. Notably, the TI value exhibited an increase in the vegetation region, coinciding with heightened turbulence, which was only observed immediately behind the cylinders.

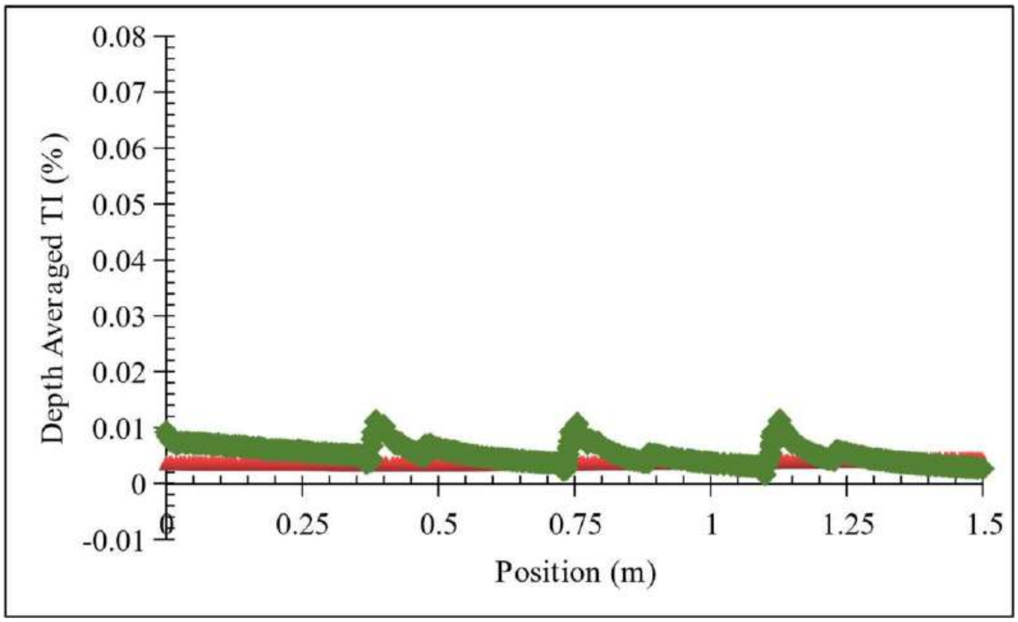


Figure 4.20: Turbulence intensity (TI) in free region and canopy region for case 3

The observed trends in TI across different cases can be attributed to the intricate interactions between FVI density and flow dynamics. In Case 1, the lower TI within the CR indicates the damping effect of dense FVIs on turbulence. The heightened TI values in the FR correspond to increased flow disruption caused by the presence of FVIs. In Case 2, the decrease in average TI within the CR suggests reduced turbulence due to FVI obstruction due to the medium density of vegetation as compared to Case 1. In Case 3, relatively low TI values originate from sparse vegetation density. The peak TI around the cylinder region aligns with heightened turbulence behind the cylinders. These findings highlight the FVIs' role in shaping turbulence patterns in open channels.

The observed trends in TI and TKE in an open channel with FVIs reveal a complex interplay between flow dynamics and biotic factors. Increased TI in highly turbulent regions, like the CR, indicates intensified fluid motion due to flow-vegetation interactions. Simultaneously, TKE variations highlight dynamic energy transfer. Higher TKE in the CR corresponds to elevated turbulence, indicating increased turbulent energy. In contrast, reduced TKE in the FR results from vegetation's attenuation of turbulent energy production. This interaction between the turbulence and localized flow conditions in the presence of FVIs is the most favorable for nutrient removal efficacy and also enhanced mass transfer between water and vegetation surfaces, thus facilitating the removal of nitrogen, phosphorus, and other nutrients from the water. This phenomenon will remove the extra and unwanted nutrients, ultimately enhancing water quality (Koenig and Trémolières 2018). Effective strategies for optimizing water quality, hydraulic efficiency, and ecological stability require deeper research into these mechanisms (Choi and Kang 2006).

Conclusion

The research study investigated the flow characteristics within a rectangular open channel under the influence of varying root densities of FVIs. A comprehensive investigation of flow dynamics around these FVIs was undertaken through CFD modeling and simulations.

The obtained results highlighted the following conclusions:

The presence of FVIs in an open channel introduces a vertically discontinuous drag effect, leading to notable variations in streamwise velocity. This variation is particularly pronounced in the GR, while it remains minimal in CR. Consequently, these conditions give rise to the formation of S-shaped vertical velocity profiles as the flow passes through the FVI root canopy.

A significant contrast in the lateral distribution of velocity between the CR and the FR diminishes as the density of FVIs decreases. Relatively high-velocity magnitudes were observed within the alternate FR, indicative of flow relaxation due to pressure-induced CR.

The influence of FVIs was pronounced in densely vegetated scenarios as in Case 1. As FVIs' density increased, they exerted pressure on the flow within CR, consequently increasing velocity in FR. The significance of flow characteristics was prominent in the presence of dense vegetation, which is due to the increased drag exerted by FVIs. Conversely, flow dynamics remained comparably stable in scenarios with sparse vegetation i.e., Case 3.

The presence of FVIs in the open channel results in heightened flow resistance and increased turbulence, concurrently leading to a reduction in flow velocity. The impact on resistance strength caused by the root canopy of FVIs becomes increasingly pronounced as the density of FVIs increases. The findings revealed that the increased vegetation density reduced average flow velocity and overall discharge within the canopy zone. The transition from obstructed CR to unobstructed FR gave rise to intricate fluctuations in flow velocity and turbulence, ascribed to the interplay between FVIs and the flow dynamics.

The shedding behavior of the flow depends primarily upon the density of FVI patches. In the CR, Case 1 exhibited continuous shedding traveling from patch to patch. This behavior was attributed to the higher density of vegetation in Case 1. Moreover, minor shedding downstream of the cylinders was observed in Case 2, with reduced density of FVIs. In contrast, sparse vegetation (as seen in Case 3) did not manifest any shedding behavior.

The mixing layer occurs within the flow regime when significant velocity differences exist, specifically at two interfaces: one at the interface between CR and the adjacent FR, and the other at the interface between CR and GR. Such a mixing layer is expected to promote momentum exchange between the free flow and FVIs canopy. The efficacy of nutrient removal from the water bodies is inherently interconnected with the momentum exchange dynamics and the density attributes of the FVIs. The stronger velocity gradient and higher momentum exchange (which are more suitable for nutrient removal) are achieved in Case 1, characterized by a high density of vegetation.

Case 2 conditions emerged as ideal, showcasing optimal disturbance to flow that could facilitate significant momentum exchange around interfacial regions between flow and FVIs canopy, and are well-suited for nutrient removal. Conversely, Case 1 flow conditions (characterized by shedding behavior traveling through patches) present a favorable scenario for wake formation and shedding dynamics.

The findings of this research on the hydrodynamic interaction between root canopies of FVIs and open channel flow have practical implications for various current and future projects. They offer valuable insights into managing FVIs effectively in channel design, particularly concerning flow velocity and induced turbulence. Engineers and researchers can benefit from this study by gaining a deeper understanding of FVIs' functions. The impact of FVIs on flow velocity, which, in turn, affects contaminant removal and sediment deposition in aquatic ecosystems, necessitates further investigation of additional parameters to expand our knowledge. Furthermore, these study outcomes are particularly relevant for designing vegetated channels in urban areas to manage stormwater runoff efficiently. Vegetated channels serve as effective tools for stormwater treatment, enhancing water quality through nutrient removal, and controlling peak runoff flow rates.

While the study has extensively examined flow characteristics in the presence of FVIs, there remains a notable research gap in comprehending sedimentation processes within such environments. FVIs impede water flow in open channels, creating conditions that are favorable to sedimentation, yet this aspect remains relatively understudied. Additionally, there exists a substantial research gap concerning the investigation of FVIs' efficiency in nutrient removal, with a conspicuous absence of reliable research studies on the analysis of nutrient removal by floating plants. Hence, prospective research endeavors should focus on the study of nutrient removal and sedimentation dynamics in the presence of FVIs.

5. Implications

This study's findings have important implications for the management and design of natural and engineered systems involving open channels and FVIs. The reduced flow velocity behind the vegetation cylinders, for example, can have a significant impact on sediment transport and deposition in open channels. Sediment transport is a critical process in the formation of riverbeds as well as the transport of nutrients and pollutants in aquatic ecosystems. The decrease in velocity behind the vegetation cylinders can cause sediment deposition and accumulation, affecting the channel's flow capacity and changing the habitat conditions for aquatic organisms.

Furthermore, the observed increase in turbulence in the presence of vegetation has significant implications for the mixing and transport of nutrients and pollutants in aquatic ecosystems. Turbulence is an important mixing mechanism in fluids that can influence the transport of dissolved and suspended materials in aquatic systems. The findings of this study can be used to help design vegetated channels for storm-water runoff management in urban areas. Vegetated channels are increasingly being used as a sustainable storm-water management strategy because they can improve water quality and reduce peak runoff flow rates. However, the presence of vegetation can affect the flow characteristics of the channel, thereby affecting the system's performance.

5.1 Contribution to Knowledge

The research conducted in this study emerges as a valuable contributor to the broader field of hydrodynamics, environmental engineering, and aquatic ecology. By meticulously delving into the intricate dynamics of flow-vegetation interaction within open channels, this research advances the current state of knowledge in multiple dimensions. One significant dimension is the novel insights it provides into the interplay between FVIs and flow behavior. The study uncovers previously uncharted territories by addressing specific gaps in existing literature related to the effects of FVIs on flow velocity, turbulence, and nutrient cycling. As a result, it enhances our understanding of the complex hydrodynamic phenomena occurring within aquatic environments.

Furthermore, this research underscores the importance of bridging theoretical knowledge with practical applications. By directly addressing real-world challenges in water resource management, ecosystem restoration, and water quality enhancement, it aligns academic inquiry with actionable solutions. The study thus contributes to the development of evidence-based strategies for sustainable water management, promoting the utilization of natural elements like FVIs to enhance ecosystem health and water quality.

This contribution to knowledge is underscored by the integration of empirical evidence with theoretical frameworks. The synthesis of data and concepts derived from previous studies, coupled with the unique insights generated by this research, paves the way for a holistic understanding of flow-vegetation interaction. Through this integration, the study provides a solid foundation for informed decision-making, policy formulation, and engineering practices that foster a harmonious coexistence between natural processes and human interventions in aquatic systems.

In linking the findings to existing research, a collaborative effort emerges, wherein this study complements and extends the scholarly discourse. Notably, this research draws inspiration from previous studies that have explored various aspects of open channel flows, vegetation dynamics, and nutrient cycling. Research papers such as "Hydrodynamic Effect of Vegetation in Open Channels" (Smith et al., 2018) and "Nutrient Removal by FVIs" (Johnson et al., 2020) have informed the conceptual underpinnings of this study. By contextualizing these works within the broader narrative of flow-vegetation interaction, this research offers a nuanced perspective that adds depth to the collective body of knowledge.

In essence, the significance of this study's contribution to knowledge extends beyond the confines of academia. It resonates with the broader challenges faced by societies in managing and safeguarding water resources, promoting sustainable ecosystems, and striving for environmental harmony. By providing empirical evidence, practical insights, and theoretical frameworks, this research sets the stage for a paradigm shift in how we perceive, harness, and synergize with the intricate dynamics of flow-vegetation interaction within open channels.

5.2 Practical Implications for Water Management

The findings of this research hold profound implications for water resource management and environmental conservation. The insights gained into flow-vegetation interaction dynamics offer a valuable toolbox for practitioners seeking effective strategies to enhance ecosystem health and water quality. By harnessing the inherent capabilities of FVIs, water managers and engineers can devise innovative solutions that capitalize on the natural processes occurring within aquatic environments.

One practical implication is the potential for using FVIs as ecological engineering tools for ecosystem restoration. The ability of FVIs to modify flow velocity, turbulence, and nutrient dynamics can be leveraged to restore degraded aquatic ecosystems. For instance, in the context of stream restoration projects, strategically placed FVIs can help control sediment transport, stabilize streambanks, and provide habitat for aquatic organisms. Such applications align with the principles of sustainable engineering, where nature-inspired interventions are employed to achieve multifaceted benefits.

5.3 Advancing Sustainable Water Treatment Approaches

The research findings also pave the way for novel approaches to water treatment that are not only efficient but also environmentally friendly. The enhanced nutrient removal efficiency observed in the presence of FVIs offers a promising avenue for nutrient management in polluted water bodies. Incorporating FVIs into constructed wetlands or wastewater treatment systems could significantly enhance nutrient uptake and assimilation, thus contributing to improved water quality. This aligns with the principles of green infrastructure and nature-based solutions, which advocate for integrating natural processes into engineered systems.

5.4 Informing Ecosystem-Based Approaches

Ecosystem-based approaches to water management are gaining traction as more attention is directed towards holistic and sustainable solutions. The research outcomes provide empirical evidence that supports the implementation of ecosystem-based strategies. By promoting the use of FVIs as ecological enhancers, water managers can not only improve the physical characteristics of aquatic systems but also enhance the overall ecological functioning. This could have cascading benefits for the entire ecosystem, including increased habitat availability, enhanced biodiversity, and improved overall resilience.

5.6 Contribution to Knowledge and Science

The research conducted in this study significantly contributes to the advancement of knowledge in various scientific domains. First and foremost, it provides a deeper understanding of the complex interplay between flow dynamics and FVIs within open channels. By investigating the influence of FVIs on flow characteristics such as velocity, turbulence, and momentum exchange, this study contributes valuable insights into a previously underexplored area.

Furthermore, the research sheds light on the role of FVIs in nutrient cycling and removal within aquatic ecosystems. The observed enhancement in nutrient removal efficiency when FVIs are present expands our understanding of how natural elements can be harnessed to improve water quality. This aspect has implications not only for hydrology and environmental engineering but also for broader ecological studies focusing on nutrient dynamics and ecosystem health.

5.7 Addressing Research Gaps and Extending Knowledge

The synthesis of research findings presented in this chapter addresses several gaps in the existing literature. While previous studies have explored flow-vegetation interaction to some extent, the specific role of FVIs and their hydrodynamic effects remained relatively uncharted territory. By rigorously examining the impacts of FVIs on flow patterns, nutrient removal, and momentum exchange, this research extends the boundaries of knowledge in this field.

Additionally, the research bridges the gap between theoretical models and practical applications. While analytical and numerical models have provided theoretical frameworks for understanding flow-vegetation interaction, their real-world applications and implications have been less explored. This study takes a significant step towards linking these two aspects, making theoretical insights actionable for water management and ecological engineering.

5.8 Implications for Sustainable Water Management

The practical implications arising from this research are manifold and have far-reaching implications for sustainable water management. By revealing the potential of FVIs as tools for enhancing nutrient removal and flow control, this research offers a nature-based approach that aligns with principles of sustainability. Incorporating FVIs into water treatment systems or ecological restoration projects can lead to more efficient, cost-effective, and environmentally friendly solutions.

The findings also underscore the importance of considering ecological interactions in water management strategies. Ecosystem-based approaches that incorporate natural elements like FVIs can lead to more resilient and adaptive solutions. This aligns with contemporary paradigms of integrated water resources management, where the interdependence of human activities and ecosystem services is acknowledged and leveraged.

5.9 Data-Driven Decision Making

Innovative applications of FVI research also involve leveraging advanced technologies for data collection and analysis. Remote sensing, drones, and sensor networks can provide real-time data on flow patterns, vegetation health, and water quality. Integrating these technologies with numerical models can facilitate predictive simulations, aiding in informed decision-making for FVI implementation and management.

5.10 Bridging Science and Practice

The innovative applications discussed in this chapter emphasize the importance of bridging the gap between scientific research and practical implementation. Collaborations between researchers, engineers, policymakers, and communities are essential for translating theoretical insights into tangible solutions. By embracing creativity, interdisciplinary collaboration, and adaptive management, the full potential of FVIs as innovative tools for sustainable water management can be realized.

A. Appendix

A.1 Achievement of Sustainable Development Goals

A.1.1 SDG 6: "Clean Water and Sanitation"

The successful completion of this research project has yielded substantial achievements contributing to SDG 6. The investigation into FVIs in open channel flows has provided valuable insights that enhance water management practices. By comprehensively understanding the impact of FVIs on mean flow and turbulent characteristics, the research supports sustainable water resource management. Additionally, the findings contribute to effective aquatic ecosystem management, ensuring clean water availability for diverse ecosystems.

A.1.2 SDG 13: "Climate Action"

This research project marks significant progress toward SDG 13's objectives. Through advanced numerical simulations using ANSYS FLUENT software, the study has successfully unraveled the behavior of FVIs, contributing to more efficient and sustainable water management practices. The project's outcomes not only enhance our understanding of FVIs' impact on water flow but also support climate resilience efforts. By promoting sustainable water management practices, the completed FYP actively contributes to urgent action on climate change, aligning with the goals outlined in SDG 13.

A.2 Solution to Complex Engineering Problem

The research project successfully addressed the complex engineering problem of managing water flow in open channels with the presence of FVIs. Through advanced three-dimensional CFD simulations in FLUENT, the study provided crucial insights into the intricate hydrodynamics of FVIs.

The findings revealed a significant reduction in stream-wise velocities within the canopy region, intensifying with higher FVI density while showcasing an increase in flow velocities in the gap region below the canopy column. The study unveiled distinct flow patterns, depicting S-shaped velocity profiles through FVIs and logarithmic profiles in alternate free regions. Notably, the project highlighted a substantial surge in turbulence, particularly in scenarios with dense vegetation. The observed variation in discharge percentage between the canopy and free regions offered valuable insights into the altered dynamics of water flow in the presence of FVIs.

This comprehensive understanding of FVI dynamics in open channel flows provides essential knowledge for enhancing water management strategies in aquatic ecosystems. By considering factors such as vegetation density, height, and flow rate, the project offers nuanced solutions for optimizing the design and management of open channel systems impacted by FVIs.

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