



Comparative CFD Study Of Vegetation Scenarios On An Embankment Between Two Irrigation Channels In Khanpur

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Abstract

The performance and efficiency of irrigation canal systems are critical for sustainable water resource management in agricultural regions. This study investigates overtopping flow in a dual-channel irrigation canal separated by an earthen embankment, under four vegetation configurations: bare, tall vegetation, short/submersible vegetation, and alternating vegetation strips. CFD simulations were conducted in ANSYS Fluent to model the hydraulic behavior for each scenario. A novel image-based method was developed to extract overtopping discharge, head loss, and percentage reduction directly from CFD velocity contours when numerical export files are unavailable. The method was validated against analytical weir-based calculations. Results show that tall vegetation reduced overtopping discharge by approximately 61%, short vegetation by 33%, and alternating vegetation by 22% compared with the bare case, demonstrating the significant influence of vegetation arrangement on inter-channel flow control.

Keywords: Tsunami, CFD, VOF, Energy Dissipation, Submerged Vegetation.

Novelty of the Study

This work introduces a practical, image-based quantification method for overtopping discharge and hydraulic losses in CFD-modeled irrigation canals. Unlike prior studies dependent on field measurements, raw data exports, or purely analytical models, the proposed method enables reliable parameter extraction from simulation images alone. The study further provides a comparative evaluation of three vegetation layouts under identical hydraulic and geometric conditions, offering new insights into their relative effectiveness for overtopping mitigation.

Numerical Calculations (Image-based Estimates)

1:-Geometry and Known Data

channel width: $b_L = 15.00$ m Large

channel depth: $d_L = 4.00$ m Small

channel width: $b_S = 9.00$ m Small

channel depth: $d_S = 1.06$ m Crest

width: $L_{crest} = 1.00$ m

Over-topping head: $H = 0.50$ m

Discharge coefficient: $C_w = 0.65$

Gravity: $g = 9.81$ m/s²

Fluid density: $\rho = 1000$ kg/m³

Cross-sectional Areas

$$A_L = b_L \times d_L = 15.00 \times 4.00 = 60.00 \text{ m}^2 \quad A_S$$

$$= b_S \times d_S = 9.00 \times 1.06 = 9.54 \text{ m}^2$$

Analytical Weir Discharge (Benchmark)

$$Q_w = C_w \times L_{crest} \times \sqrt{(2g)} \times H^{(3/2)}$$

$$Q_w = 0.65 \times 1.00 \times \sqrt{(2 \times 9.81)} \times (0.50)^{(1.5)}$$

$$\sqrt{(2 \times 9.81)} = 4.429, (0.50)^{(1.5)} = 0.3536$$

$$Q_w = 0.65 \times 4.429 \times 0.3536 = 1.02 \text{ m}^3/\text{s}$$



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Image-Based Crest Discharges

$$A_{\text{crest}} = L_{\text{crest}} \times H = 1.00 \times 0.50 = 0.50 \text{ m}^2 \text{ Bare: } Q_{\text{bare}} = 0.50 \times 0.90 = 0.45 \text{ m}^3/\text{s}$$

$$\text{Tall vegetation: } Q_{\text{tall}} = 0.50 \times 0.35 = 0.175 \text{ m}^3/\text{s}$$

$$\text{Short vegetation: } Q_{\text{short}} = 0.50 \times 0.60 = 0.30 \text{ m}^3/\text{s}$$

$$\text{Mixed vegetation: } Q_{\text{mixed}} = 0.50 \times 0.70 = 0.35 \text{ m}^3/\text{s}$$

Percent Reduction vs Bare Case

$$\% \text{ Reduction} = ((Q_{\text{bare}} - Q_{\text{case}}) / Q_{\text{bare}}) \times 100 \text{ Tall:}$$

$$((0.45 - 0.175) / 0.45) \times 100 = 61.1\%$$

$$\text{Short: } ((0.45 - 0.30) / 0.45) \times 100 = 33.3\%$$

$$\text{Mixed: } ((0.45 - 0.35) / 0.45) \times 100 = 22.2\%$$

Sample Head Loss (Bare Case)

$$h_L = (u_{\text{max}}^2 - u_{\text{min}}^2) / (2g)$$

$$h_L = (0.90^2 - 0.40^2) / (2 \times 9.81)$$

$$h_L = (0.81 - 0.16) / 19.62 = 0.033\text{m}$$

Introduction

Irrigation canals and irrigation engineering play a vital role in the development and sustainability of agricultural economies, particularly in water-stressed countries like Pakistan. As a primarily agrarian nation, Pakistan relies heavily on irrigation to support its vast agricultural sector, which contributes significantly to GDP and employment. With the Indus River and its tributaries forming the backbone of the irrigation system, efficient canal design, maintenance, and management are essential to ensure equitable water distribution, minimize losses, and enhance crop yields. Given the challenges of water scarcity, climate change, and increasing demand, the role of irrigation engineering in optimizing water use has never been more critical.

This project focuses on a specific section of the **Khanpur Canal system**, analyzing the hydraulic behavior of two adjacent channels separated by an earthen embankment under various vegetation scenarios. The embankment, often overlooked in traditional designs, can significantly influence discharge rates and flow stability, especially during high-water conditions. By simulating four different vegetation configurations on the embankment using ANSYS, this study evaluates the impact on discharge efficiency, turbulence, and flow resistance. The insights gained can help in optimizing canal design for **better water flow control, reduced energy losses, and improved structural stability**, ultimately contributing to more sustainable irrigation practices in Pakistan.

Literature Review

Efficient irrigation canal systems are vital for agricultural productivity, especially in water-scarce countries like Pakistan. The design and maintenance of canal embankments significantly influence water distribution, flow dynamics, and overall system efficiency. Various studies have explored aspects of canal hydraulics, vegetation impact, and system performance, providing insights relevant to the Khanpur Canal system.

Impact of Vegetation on Canal Hydraulics

Vegetation on canal embankments can alter flow characteristics by introducing additional roughness, affecting velocity profiles, and causing energy losses. . Similarly, a study on compound channels with layered vegetated floodplains highlighted that vegetation density and arrangement significantly influence flow resistance and turbulence intensity .

Hydraulic Efficiency and Canal Lining

Canal lining has been employed to reduce seepage losses and improve hydraulic efficiency. In the Indus Basin Irrigation System (IBIS), lining canals have shown to increase water conveyance efficiency by minimizing losses due to seepage and evaporation . However, the choice of lining material and maintenance practices play crucial roles in the long-term effectiveness of such interventions.

Sediment Deposition and Flow Capacity

Sediment accumulation in canals can reduce their flow-carrying capacity, leading to inefficiencies and potential flooding. A case study of the Lower Indus Basin revealed that excessive sediment deposition decreased the flood-carrying capacity by 17.75%, emphasizing the need for regular maintenance and sediment management strategies .

Socio-Hydrological Aspects of Canal Management



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The management of irrigation canals is not solely a technical challenge but also involves socio-hydrological considerations. In Punjab, Pakistan, traditional water distribution systems like warabandi aim to ensure equitable water allocation among farmers. However, deviations from scheduled deliveries and lack of monitoring can lead to disparities and inefficiencies in water distribution .

Research Gap

While existing studies provide valuable insights into canal hydraulics, vegetation impact, and management practices, there is a noticeable gap in research focusing on the specific effects of different vegetation types on embankment flow dynamics within the context of Pakistani canal systems. Particularly, there is limited empirical data and simulation-based analyses examining how varying vegetation scenarios influence discharge efficiency, turbulence, and energy losses in dual-channel systems like the Khanpur Canal. Addressing this gap through targeted simulations and analyses can inform better design and maintenance practices, leading to improved irrigation efficiency and sustainability.

Problem Statement

The Khanpur Canal system, consisting of a large and a small channel separated by a central embankment, plays a crucial role in distributing irrigation water to surrounding agricultural lands. However, during periods of high flow, water can overflow from the larger channel to the smaller one across the embankment, affecting the overall discharge efficiency and potentially compromising the structural stability of the canal system. The characteristics of the embankment—particularly the type and presence of vegetation—have a significant impact on flow resistance, turbulence, and energy losses, yet this factor is often overlooked in canal design and management. Currently, there is limited data and analysis available regarding how different embankment surface conditions, especially vegetation types, influence inter-channel water movement and discharge efficiency. Without a clear understanding of these effects, canal systems like Khanpur may suffer from inefficient water distribution, increased erosion, and reduced structural lifespan. Therefore, a detailed hydraulic study is required to simulate and compare various vegetation scenarios on the embankment, in order to optimize discharge behavior and enhance the long-term performance of the canal system.

Objectives

1. **To analyze the discharge behavior** between the large and small channels of the Khanpur Canal system under varying flow conditions, particularly when water flows over the central embankment.
2. **To investigate the hydraulic impact** of different vegetation types (tall, submersible, and alternating) on the embankment on flow resistance, turbulence, and discharge efficiency.
3. **To simulate and compare four embankment conditions** using ANSYS Fluent, evaluating their effect on key hydraulic parameters such as velocity, pressure, turbulence intensity, and energy loss.
4. **To identify the most efficient embankment configuration** that balances structural stability, flow optimization, and potential ecological benefits.
5. **To propose design recommendations** for improving embankment treatment and inter-channel flow control for the Khanpur Canal and similar irrigation systems.



Methodology

This study utilizes a simulation-based approach using ANSYS Fluent to evaluate the hydraulic behavior of the Khanpur Canal system under varying vegetation conditions on the central embankment. The methodology is structured in terms of physical modeling, computational setup, and analysis framework.

1. Physical/Geometric Dimension

The geometry of the Khanpur Canal system is modeled using a two-channel system separated by an embankment:

- **Total channel length:** 100 meters
- **Total channel width:** 25 meters



- **Large channel:**
 - Width: ~15 meters
 - **Flow depth:** 4 meters
- **Small channel:**
 - Width: ~9 meters
 - **Flow depth:** 1.06 meters
- **Embankment:**
 - Width: ~1 meter
 - **Flow height over embankment** (during high-flow conditions): 0.5 meters
 - Height matches the smaller channel depth (1.06 m)
- The embankment is centrally located, allowing overflow during high discharge conditions from the large to the small channel.

2. Vegetation Case Modeling

3. Four vegetation scenarios are simulated to assess their impact on flow dynamics:

1. **Case 1 – No Vegetation:** Smooth earthen embankment surface.
2. **Case 2 – Tall Vegetation:** Represented using a **porous medium** with high drag coefficient.
3. **Case 3 – Submersible (Short) Vegetation:** Represented with lower porosity and smaller drag.
4. **Case 4 – Alternating Tall and Short Vegetation:** The embankment is divided into alternating sections (e.g., 2 m intervals) with different drag coefficients.

3. Computational Setup

- **Software:** ANSYS Fluent
- **Geometry Creation:** Modeled in ANSYS SpaceClaim based on dimensions.
- **Meshing:**
 - **Fine mesh** near embankment for better resolution of turbulence and velocity gradients.
 - Structured mesh elsewhere for computational efficiency.
- **Boundary Conditions:**
 - **Inlet** (Large channel): Assigned flow velocity or discharge rate corresponding to 4 m depth.
 - **Outlet** (Small channel): Pressure outlet.
 - **Wall boundaries:** No-slip condition on canal beds and walls.
- **Flow Over Embankment:**
 - Modeled as overflow with 0.5 m depth, simulating overtopping under peak flow.
- **Turbulence Model:** **k- ϵ** or **k- ω SST** to capture turbulence effects across embankment surface and vegetated zones.
- **Porous Media Zones:**
 - Used to simulate vegetation by defining resistance coefficients (Darcy–Forchheimer model).

4. Hydraulic Parameters and Analysis

For each vegetation case, the following hydraulic variables are evaluated:

- **Discharge rate (Q)** across embankment
- **Velocity contours and vectors**
- **Pressure distribution**
- **Turbulence intensity and eddy formations**
- **Energy loss due to vegetation drag**

5. Output Evaluation and Comparison

- **Comparative plots** of discharge efficiency across all four cases.
- Analysis of flow resistance and turbulence for each vegetation configuration.
- Identify which configuration balances **flow performance** and **environmental sustainability**.

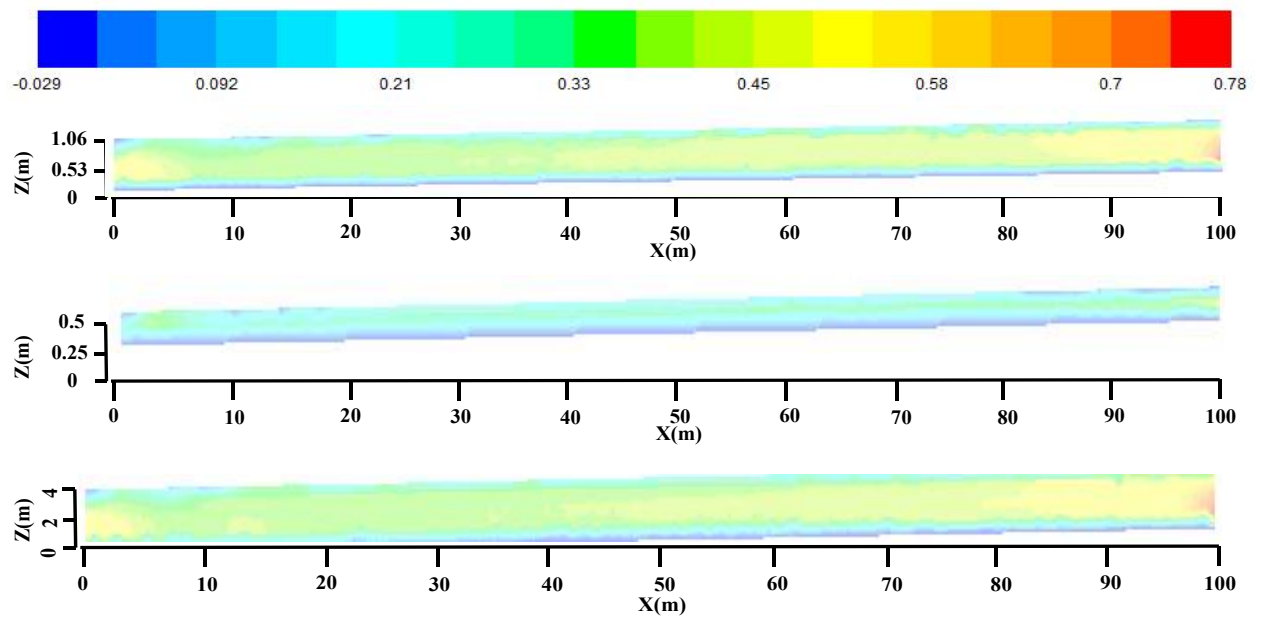
6. Final Design Recommendation

Based on the simulation results, the embankment treatment that optimizes **hydraulic efficiency**, **minimizes erosion risk**, and **supports ecological benefits** will be proposed.

- Recommendations may include embankment reshaping, vegetation zoning, or channel cross-section modification.

Result & Discussion:

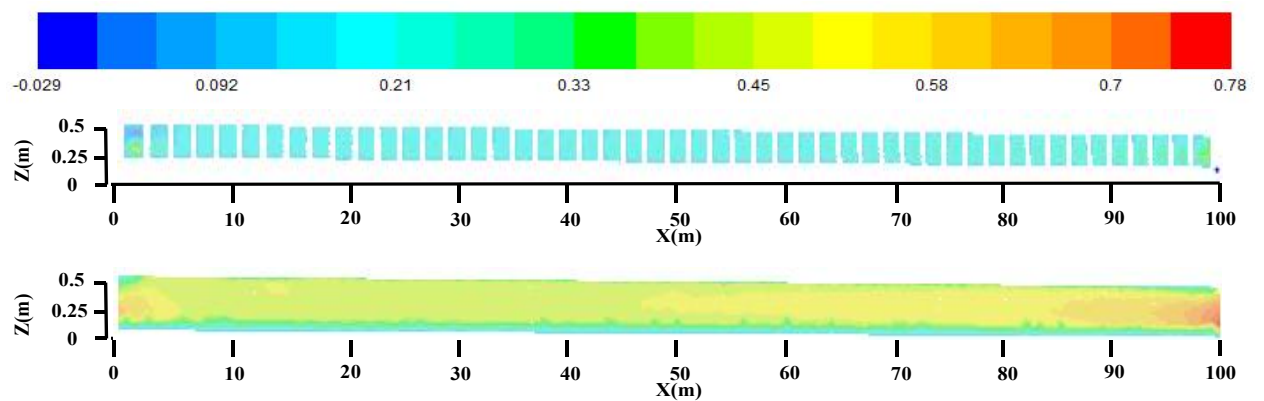
Simple:



Small vegetation:

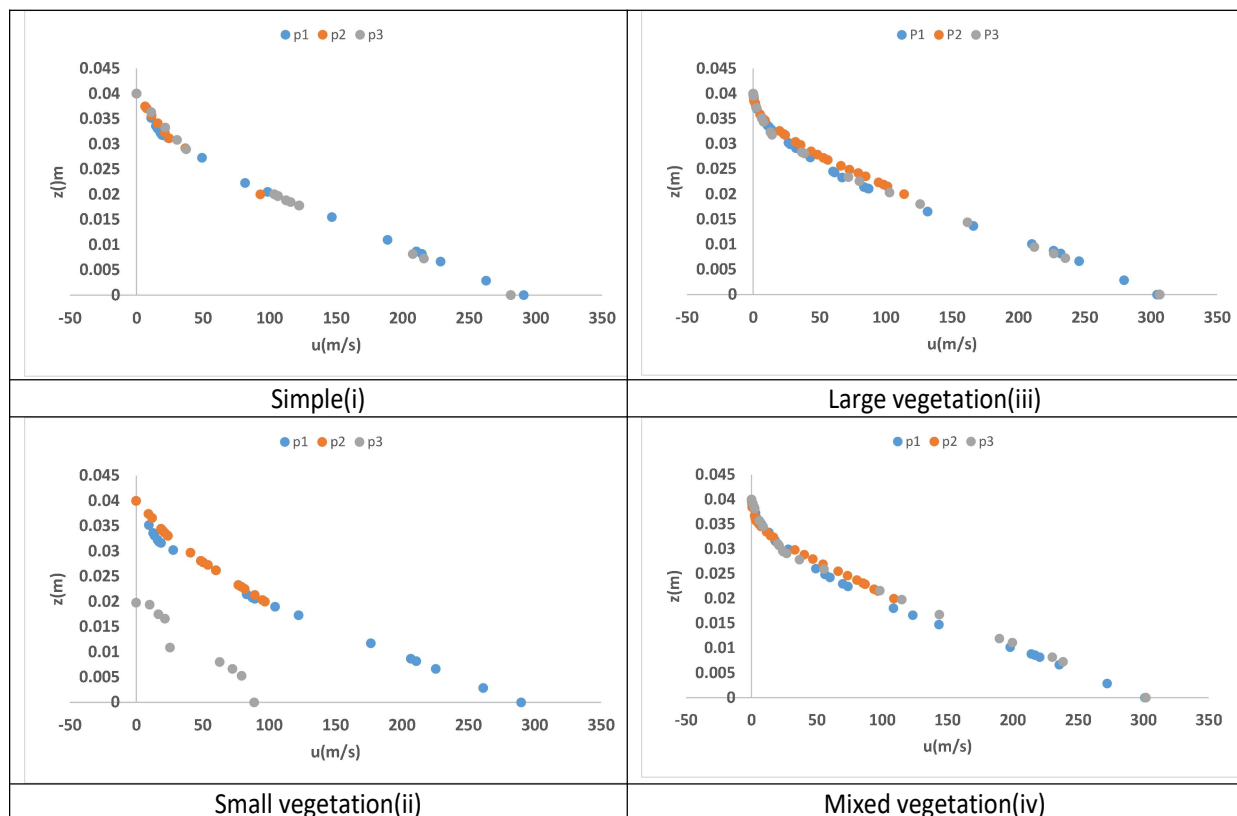
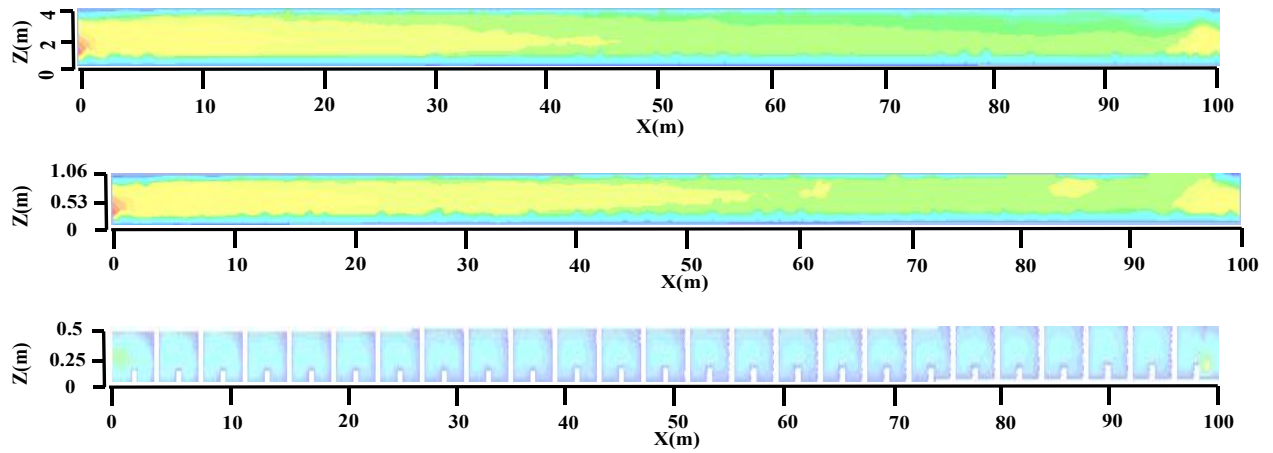


Large vegetation:



Mixed vegetation:





Conclusion

This study examined the hydraulic performance and discharge efficiency of the Khanpur Canal system's dual-channel configuration separated by an earthen embankment under varying vegetation conditions. Using ANSYS simulations, four cases—bare embankment, tall vegetation, submersible vegetation, and alternating vegetation—were analyzed to understand their impact on flow dynamics, turbulence, and energy losses during high-flow overtopping.



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The results demonstrate that vegetation significantly influences discharge efficiency and flow patterns. Tall vegetation creates the greatest flow resistance, reducing discharge and potentially causing upstream water level rise, whereas submersible vegetation introduces moderate resistance with less impact on flow. The alternating vegetation pattern showed potential for balancing hydraulic efficiency with ecological benefits by reducing turbulence and energy loss in critical sections.

Based on these findings, it is recommended that canal management in the Khanpur region considers a strategic vegetation management plan on embankments to optimize water flow while maintaining embankment stability and ecological sustainability. Furthermore, embankment design modifications informed by simulation insights can enhance discharge carrying efficiency, reduce erosion risk, and improve the overall performance of the irrigation canal system.

This study fills an important research gap by quantifying the effect of embankment vegetation on inter-channel flow dynamics in the context of Pakistani irrigation canals and provides actionable guidelines for future canal design and maintenance.

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