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INVESTIGATION OF FLOW DYNAMICS AND VELOCITY DISTRIBUTION IN WATER INTAKE STRUCTURES

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Abstract

This study investigates the flow dynamics and velocity distribution within the water intake structure of the Dekhqonobod Pumping Station, located at Station 864+64 in the Kuva district of the Fergana region, Uzbekistan. Commissioned in 1975, the station is currently operating three Model 24 double-suction centrifugal pumps. The primary objective of the research is to analyze the velocity distribution of inflowing water at three characteristic cross-sections within the intake structure using the SonTek RS5 Doppler flow meter. The analysis incorporates the technical specifications of the pumping system, including a pressurized pipeline with a length of 840 meters, a diameter of 600 mm, a pumping head of 14 meters, and a flow rate of 1,25 m³/s. The study aims to optimize the hydraulic performance of the intake structure by characterizing flow behavior and managing the incoming velocity profile. This information is critical for enhancing energy efficiency, reducing hydraulic losses, and ensuring uniform inflow to the pump impellers, thereby extending equipment lifespan and operational stability.

Keywords: Water intake structures, flow dynamics, velocity distribution, pump station efficiency, sediment accumulation, irrigation water management.

1. Introduction

The increasing demand for efficient agricultural water management, particularly in arid and semi-arid regions, has elevated the strategic importance of optimizing pump station performance within irrigation and water supply systems. In Uzbekistan's Fergana Valley, where agricultural production heavily relies on engineered water infrastructure, the operational efficiency of rural pumping stations has become a critical factor in ensuring consistent and equitable water distribution[1],[2],[3]. The performance evaluation of the Great Fergana Canal – Sokh Shohimardonsoy-1 and Great Fergana Canal – Sokh pumping stations in Kuva district holds significant importance in the context of irrigation systems and water supply infrastructure. This study analyzes the operational efficiency of these stations with specific focus on water flow distribution, energy consumption, and the impact of water quality on system performance. The research aims to identify technical and economic challenges in agricultural water management and to propose viable engineering solutions[4]. Efficient utilization and equitable distribution of water resources remain critical for agricultural sustainability, particularly in arid regions like the Fergana Valley, Uzbekistan. Pumping station performance directly affects the reliability and efficiency of irrigation networks[5]. Given the increasing demand for optimized water infrastructure in the region, this analysis serves as a foundation for systemic improvements. Key technical indicators—such as hydraulic performance, pressure losses, and specific energy consumption—are examined alongside field-based water quality assessments. Previous studies have introduced innovative approaches to reduce energy consumption and improve the hydraulic efficiency of pumping units [6][7] Further, the role of water quality monitoring and real-time control systems in enhancing the performance of intake structures has been underscored by researchers[7],[8]. Recent contributions also emphasize the significance of analyzing velocity distribution within intake zones to improve hydraulic regime stability. Recent studies have emphasized the significance of numerical

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simulations and turbulence modeling in optimizing intake structures and improving flow distribution[9]. Furthermore, the use of vortex energy analysis and two-phase flow models has proven effective in enhancing hydraulic efficiency in forebay structures[10]

2. Materials and Methods

2.1 Study Area and Hydraulic Configuration

This study was conducted at the Dekhqonobod Pumping Station, located at Station 864+64 (PK-864+64) in the Kuva district of the Fergana region, Uzbekistan—an area characterized by high agricultural water demand and a critical reliance on irrigation infrastructure for rural water management. The research focused on analyzing the flow dynamics and spatial velocity distribution within the station's water intake structure, a component that significantly affects both pump efficiency and sediment transport behavior[3].

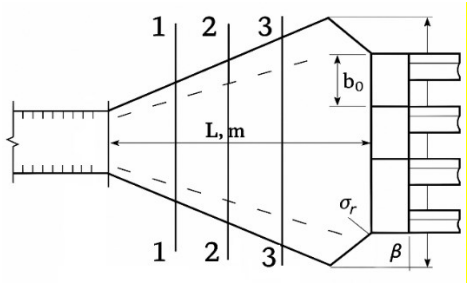


Figure 1. Structure of the water intake facility.

The intake structure features a curvilinear channel with a central alignment angle of approximately 42° and a total length of 15 meters. To capture the internal hydraulic behavior, three characteristic cross-sections—designated as Stvor 1–1, 2–2, and 3–3—were selected for detailed velocity measurements. These sections were spaced at 3-meter intervals and strategically positioned to encompass hydraulic variability, including sediment-prone zones and regions exhibiting turbulence during high-discharge conditions fig 1.

The measured flow widths at these cross-sections were as follows:

- Stvor 1–1: 5.8 meters
- Stvor 2–2: 10.2 meters
- Stvor 3–3: 13 meters

These geometric parameters were essential for defining hydraulic control volumes and served as the foundation for generating velocity contour plots and estimating cross-sectional discharge. Flow velocity data were collected using the SonTek RS5 Doppler Current Profiler, a state-of-the-art fifth-generation acoustic Doppler velocimeter optimized for shallow open-channel flow environments. The device utilizes Smart Pulse+™ signal processing, which combines pulse-coherent and broadband Doppler techniques to achieve sub-centimeter resolution in flow velocity estimation across both longitudinal and lateral axes [11].

The RS5 unit was deployed at each stvor along multiple vertical sampling lines across the channel width. Integrated real-time kinematic (RTK) GPS and bottom-tracking sensors guided positioning, which ensured accurate spatial dereferencing of every velocity data point. Measurements were carried out under steady-state pumping conditions, and external disturbances such as pump cycling and wind-induced surface waves were minimized to ensure data integrity.

2.2 Data Collection Protocol and Processing

Data acquisition was performed during the March to August irrigation season, capturing a range of hydraulic conditions from low to moderate flow regimes. Velocity data were logged at consistent time intervals and exported in real-time via the River Surveyor Live software suite. The software enabled immediate visualization of depth-averaged velocities, vertical profiles, and signal return strength, allowing researchers to identify anomalies during acquisition and adjust deployment strategies if necessary.

Each velocity transect was processed to construct high-resolution transverse velocity distribution profiles, which were used to assess:

1. **Flow asymmetry**

Asymmetric distribution of velocity magnitudes and directions across the channel width potentially induced by intake geometry, approach angle, or local boundary conditions, leading to non-uniform transport dynamics.

2. **Development of near-wall stagnation regions**

Localized zones of significantly reduced or near-zero flow velocity adjacent to channel boundaries, often caused by adverse pressure gradients or boundary layer separation, which may act as initiation points for sediment accumulation.

3. **Formation of recirculating eddies**

Occurrence of closed-loop secondary flows or vortices within the main flow domain, particularly in regions with abrupt geometric transitions or obstructions, contributing to energy dissipation and complex flow structures.

4. **Velocity gradients conducive to sediment deposition**

Spatial variation in flow velocity, especially abrupt deceleration zones, which reduce the flow's sediment transport capacity and promote settling of suspended particles under gravity. All cross-sections were analyzed independently and then compared

across stores to identify longitudinal trends and establish a velocity decay model within the intake geometry[6] .

2.3 Flow Instability and Sediment Deposition Assessment

One of the core objectives of the velocity profiling campaign was to identify zones of hydraulic inefficiency within the intake structure. Observations indicated a substantial drop in flow velocity near the left and right sidewalls of the channel. These low-velocity regions are prone to sediment deposition, which can degrade hydraulic performance, increase maintenance costs, and negatively impact pump impeller operation.



Figure 2. Erosion of pump impellers due to the impact of river sediments**.**



Figure 3. SonTek RS5 used for measuring inlet velocity distribution at 3 station.



Figure 4. Flow monitoring at Dekhqonobod pump station using SonTek RS5 Doppler sensor.



Figure 5. Field survey with RS5 Doppler device at 2 station water intake facility.

This image illustrates the wear and damage that occur on pump impellers when exposed to abrasive river sediments over time. Such degradation is often caused by flow instabilities that transport high concentrations of suspended particles into the pumps. To better understand and characterize these instabilities, the cross-sectional measurement design using the SonTek RS5 Doppler profiler was optimized for detailed hydraulic assessment. Field investigations at the Dekhqonobod pumping stations (Figures 3–5) employed this modern instrument, enabling high-resolution spatial mapping of flow velocities within the intake channels.

This methodological framework provided the necessary basis for accurate hydraulic characterization, with the resulting measurements and analyses presented in the following sections.

3. Result

Field measurements revealed a significant reduction in flow velocity along the sidewalls (right and left banks) of the intake structures. This deceleration is attributed to hydraulic dead zones, which promote the accumulation of riverine sediments. As part of the hydrodynamic assessment at the third monitoring cross-section (Stvor-1) of the Dekhqonobod pumping station, comprehensive velocity profiling was carried out to characterize the flow regime.

The visual evidence and velocity measurements indicate that the velocity distribution within the intake basin is uneven, leading to:

1. Reduced hydraulic performance of the intake system,
2. Increased maintenance frequency and operational costs, and

Greater wear and malfunction risks for pump aggregates.

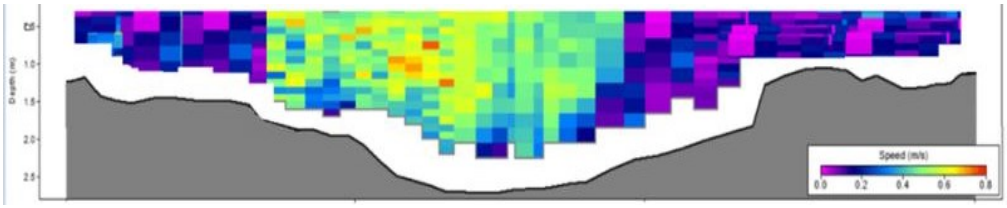


Figure 6. Data obtained from field investigations at the first cross-section (Stvor-1) of the Dekhqonobod pumping station.

At **Section-1**, the surface width of the flow was L_1 =5.8 m, and the average flow depth—from the free surface to the channel bed—was h_1=0.40 m. The corresponding cross-sectional area was ω_1=2.00 m². The maximum inflow velocity at the entrance was 0.77 m/s, decreasing to 0.25 m/s near the left bank and 0.43 m/s near the right bank. These results indicate that the main flow was concentrated along the right side of the intake (Figure 7), with the velocity distribution described by:

$y = -0.0505x^2 - 0.0038x + 0.6671$ and $R^2 = 0.9258$

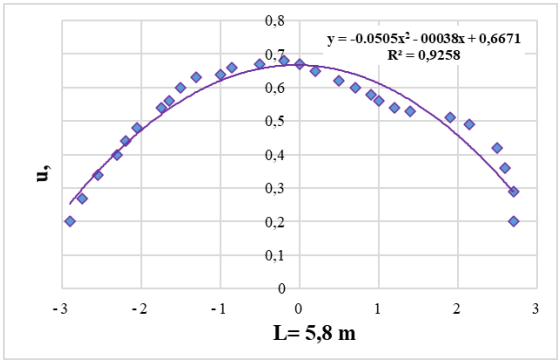


Figure 7. Velocity distribution at the first cross-section (Stvor-1) of the Dekhqonobod pumping station.

At **Section-2**, the measured average discharge was 1.80 m³/s, with an average velocity of 0.47 m/s, a surface width of L_2=10.2 , a flow depth of 1.12 m, and a cross-sectional area of 3.83 m² (Figure 8).

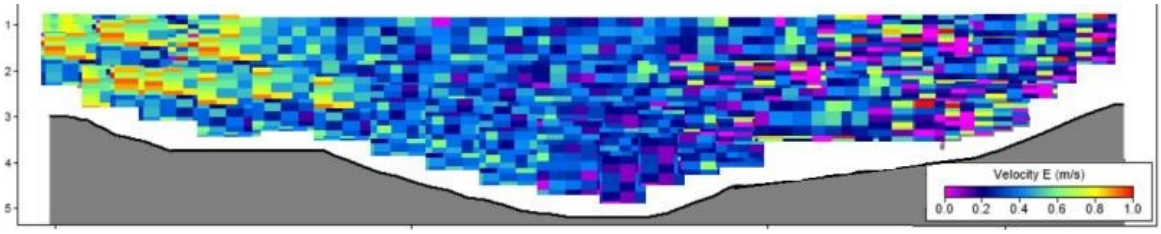


Figure 8. Data obtained from field investigations at the second cross-section (Stvor-2) of the Dekhqonobod pumping station.

The velocity at the centerline reached 0.74 m/s, while near the left bank it decreased to 0.24 m/s. A vortical (swirling) flow was observed approximately 4.3 m 4 to the right of the centerline. The velocity distribution was modeled by:

y=-0,0138x2+0,0025x+0,5616, R^2 = 0,9406 (Figure 9).

At **Section-3**, the average discharge was 1.20 m³/s, with an average velocity of 0.45 m/s, a surface width of L_3=13.0 m, a depth of 0.86 m, and a cross-sectional area of 2.66 m² (Figure 10).

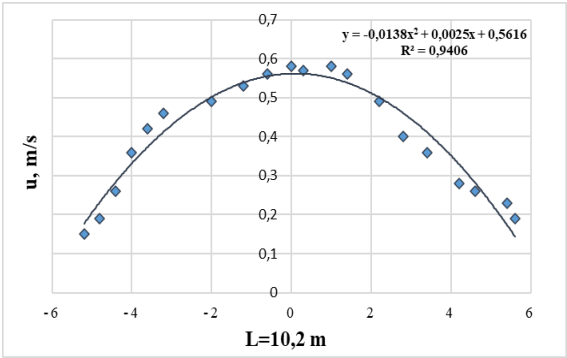


Figure 9. Velocity distribution at the second cross-section (Stvor-2) of the Dekhqonobod pumping station.

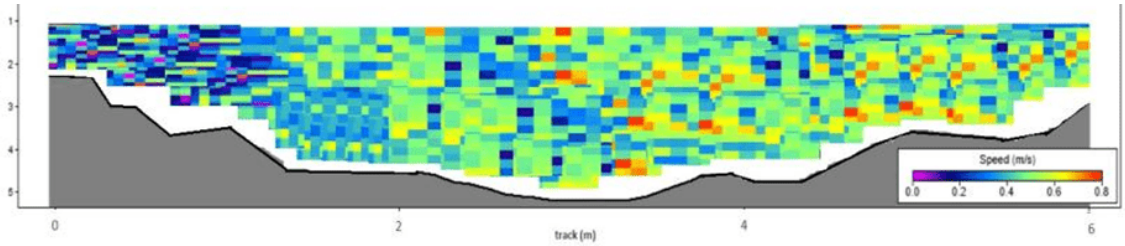


Figure 10. Data obtained from field investigations at the third cross-section (Stvor-3) of the Dekhqonobod pumping station.

The velocity at the centerline was 0.61 m/s, increasing to 0.59 m/s between 4–6 m to the right. On the left side, between 1.3–3.5 m from the centerline, the velocity remained relatively stable. The velocity distribution followed:

$y = -0.0102x2 + 0.0024x + 0.5081$, $R^2 = 0.9211$ (Figure 11).

Summary of Observations. Across all three cross-sections, the velocity distribution was asymmetric, with the main flow tending to concentrate along the right side of the intake structure. This asymmetry, coupled with observed dead zones along the banks, is a key contributor to localized sediment deposition. The parabolic regression models for each section showed high coefficients of determination (R^2>0.92), indicating a strong fit between measured velocities and the mathematical profiles. These results provide a quantitative basis for future optimization of intake geometry to improve hydraulic efficiency and reduce sediment-related maintenance.

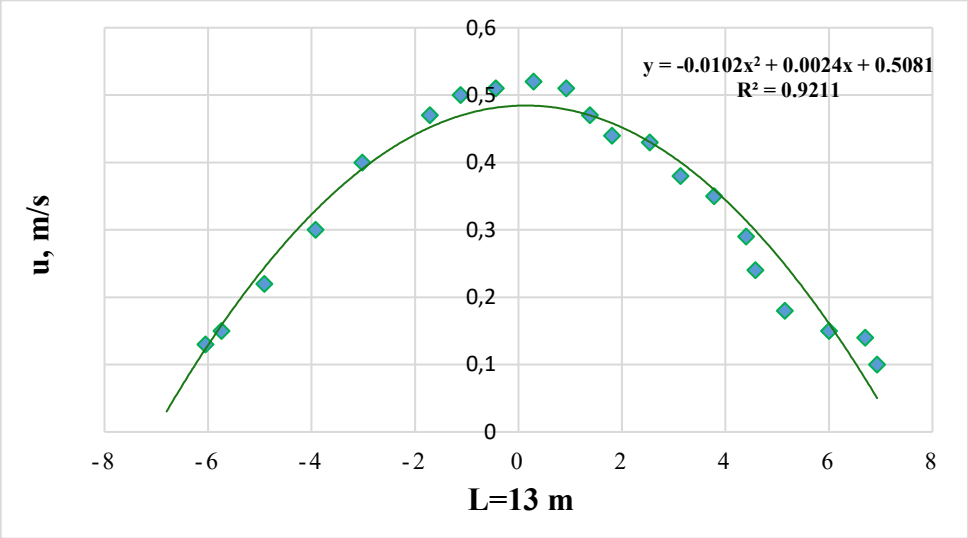


Figure 11. Velocity distribution at the third cross-section (Stvor-3) of the Dekhqonobod pumping station

4. Discussion.

The findings obtained during the study confirm that uneven flow velocity distribution in water intake structures represents a significant hydraulic challenge. In particular, the observed discrepancies in velocity across different cross-sections (stvor lines) indicate that flow velocities are not uniformly distributed. Notably, in areas near the intake structure walls, a substantial reduction in flow velocity was detected. This reduction may lead to the deposition of suspended sediments, commonly known as sedimentation or siltation, which in turn can negatively affect the operational efficiency of pumping units.

These observations align directly with the research conducted by, who have extensively studied the performance of hydraulic intake facilities. Emphasized that uneven flow distribution within pumping stations results in reduced energy efficiency and increases the frequency and cost of maintenance. Their 2022 study established a strong correlation between flow velocity and water quality, showing that zones with reduced velocity are prone to the accumulation of sediments, which adversely affects the physico-chemical composition of the water. This study not only reinforces these prior findings from a practical standpoint but also extends them by identifying spatial variations in velocity distribution using Doppler-based precision measurements. These measurements enable the detection of hydraulically weak zones within the intake structure.

In their 2023 work, the authors demonstrated that appropriate flow guidance can reduce the inflow of suspended solids into intake structures. The collected data provide a foundation for developing structural optimization strategies aimed at maintaining flow stability, improving energy efficiency, and reducing sediment deposition. In this context, the activation of stagnant zones through hydraulic interventions is considered essential. Proposed solutions include the installation of flow-stabilizing devices such as baffle plates and flow deflectors as well as the elimination of near-wall stagnant flow regions.

Such approaches are also consistent with international best practices, which have been successfully implemented in improving pumping station performance in several developing countries. Furthermore, this study highlights the potential for applying mathematical modeling of flow dynamics to predict future performance and assess possible system behavior over its operational lifecycle. This capability is critical for planning long-term maintenance and

ensuring sustained operational stability of hydraulic structures.

5. Conclusion.

This study carried out a detailed hydraulic investigation of the Dekhqonobod pumping station intake structure using high-resolution field measurements with the SonTek RS5 Doppler profiler. The results revealed pronounced spatial non-uniformity of inflow velocity, with significant reductions along the intake sidewalls leading to hydraulic dead zones. These stagnation regions directly contribute to sediment accumulation, accelerated erosion of pump impellers, and an overall reduction in system efficiency. The findings not only corroborate earlier studies on intake hydraulics but also provide field-based evidence for the mechanisms linking flow asymmetry, sedimentation, and energy losses.

The scientific contribution of this work lies in its ability to move beyond generalized assumptions by quantifying velocity gradients across three representative cross-sections under real operating conditions. The regression models ($R^2 > 0.92$) provide a robust diagnostic framework for intake efficiency assessment and serve as a benchmark for validating computational simulations. By identifying hydraulically weak zones, this research establishes a foundation for practical engineering interventions such as optimized intake geometries, baffle installations, and vortex suppression devices, all of which are necessary to improve flow uniformity and reduce maintenance costs.

From an applied perspective, the results demonstrate that Doppler-based profiling can play a central role in predictive management of pumping facilities. Integration of field diagnostics with CFD modeling is recommended to further generalize the methodology and design sustainable modernization strategies. Such approaches are crucial for irrigation-dependent regions like Uzbekistan, where pumping station performance directly determines agricultural water security.

In conclusion, the study confirms that systematic velocity profiling is not merely a monitoring tool but a decision-support mechanism for hydraulic infrastructure management. Its application can significantly extend equipment lifespan, optimize energy consumption, and ensure reliable water delivery. These outcomes underscore the broader potential of combining field-based diagnostics with engineering design to modernize pumping stations and strengthen water management systems across arid and semi-arid regions.

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