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Experimental Investigation of Lateral Intake–Induced Hydrodynamic Alterations in the Vertical Velocity Structure of Open-Channel Flow

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ABSTRACT: *Lateral intakes are widely used in open-channel systems for irrigation and water diversion, where their hydraulic performance strongly influences flow stability and efficiency. This study experimentally investigates the effect of lateral withdrawal on the vertical distribution of flow velocity in a trapezoidal main open channel under steady subcritical conditions. Experiments were conducted in a laboratory flume with a right-angle lateral intake, where lateral intake flow ratios ranged from 5% to 25% and main channel discharges varied between 27 and 39 L/s. A total of 528 velocity profiles were measured using a three-dimensional acoustic Doppler velocimeter at multiple upstream locations and across three transverse zones. The flow depth was divided into bottom, middle, and upper layers to assess depth-dependent velocity variations. Results indicate that lateral withdrawal significantly affect the vertical velocity structure, with the bottom flow layer exhibiting the highest sensitivity, followed by the middle and upper layers. The magnitude and spatial extent of velocity deviation increase with the lateral intake discharge ratio (Q_r), and vary across the channel width. Near the intake, the maximum impact occurs close to the intake in the near-side zone, while it shifts farther upstream in the mid-channel and far-side zones due to momentum redistribution and bed friction effects.. These findings highlight the importance of taking in consideration the vertical velocity structure in the hydraulic design and operation of lateral intakes.*

KEY WORDS: Open-channel flow; Velocity distribution; Lateral intake; Lateral intake ratios (Q_r); Flow velocity layer; Velocity profiles; Irrigation channels

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I. INTRODUCTION

Lateral intakes constitute a key hydraulic element in open-channel systems, where they are used to divert a portion of the main flow toward secondary channels serving irrigation networks and hydropower facilities. The design and operation of such structures require careful hydraulic consideration to ensure flow stability, efficiency, and safety. Despite their widespread application, the flow behavior at channel divisions remains a challenging topic in water resources engineering, owing to the complex interaction between flow dynamics and channel geometry [1]. In lateral intake, the diverted flow is influenced by multiple interdependent factors, and the interaction of lateral intake effects and inertial forces redirects the main flow gradually, causing water to enter the intake at a certain angle [2], [3]. This generates complex three-dimensional hydrodynamics at the intake, including secondary flows such as helical recirculation and vortices, thereby affecting the vertical velocity distribution and promoting non-uniform velocity profiles [4]. The hydrodynamic characteristics of lateral withdrawal are related to the withdrawal conditions, and water intake structure parameters, including the intake width-to-depth ratio, withdrawal angle, intake type, and water diversion ratio [5], [6].

1.1 influence of lateral intakes on the vertical velocity distribution

The vertical velocity distribution upstream of the lateral intake deviates from uniform flow patterns, showing higher velocities near the bed due to the intake's influence on flow resistance and roughness [7], [8] (4). The branching discharge is governed by several interrelated parameters. Specifically, it increases as the main channel flow velocity and the Froude number upstream the lateral intake decreases. Additionally, the branching discharge rises with an increase in the (Y_b / Y_u) branch water depth to U.S main channel water depth ratio [9].

1.2 influence of lateral intakes on water surface profiles

The approaching flow conditions in open channels with bottom intake structures, such as racks, strongly affect upstream water surface profiles by modifying free surface elevations depending on channel slope and rack void ratio [10]. As the upstream Froude number increases, water surface profiles transition from a rising pattern under subcritical flow to a lowering pattern under supercritical flow, thereby altering the hydraulic gradient near the intake [11]. Moreover, lateral intake processes induce additional variations in the upstream water surface profile, including drawdown effects that lead to a localized reduction in surface elevation near the intake entrance [12].

1.3 influence of the lateral intake angle

A comparison between experimental observations and numerical simulations demonstrated that the Volume of Fluid (VOF) method is effective in simulating flow patterns in curved open-channel bends [13], [14]. In addition, the VOF-based numerical approach, coupled with a high-resolution interface-capturing scheme, has been widely employed for accurate free-surface tracking [15]. Furthermore, the selection of appropriate turbulence models plays a crucial role in reliably simulating hydrodynamic characteristics and capturing complex flow behaviors [16]. Several studies have examined the influence of branching angle on the maximum discharge conveyed into branch channels, experimental investigations reported that the highest diversion discharge was achieved at a branching angle of 45°, followed by 60°, whereas the lowest discharge occurred at 90° [9], [17]. Similarly, the optimal diversion angle is 60° when compared with 30°, 60°, and 90° that provides the maximum diversion flow [18], [19].

Based on flow patterns and separation characteristics, the lateral intakes with a 45° configuration demonstrates a superior flow pattern compared to the 90° configuration, indicating reduced disturbance to the overall velocity distribution and potentially less pronounced impacts on upstream water surface profiles [9], [20]. Additionally, the inclined banks of the branch channel significantly influence the flow pattern by causing the bottom stream-tube width to exceed that at the free surface [21]. Furthermore, incorporating a slope ratio at the intake has been shown to improve overall flow patterns and reduce the width of recirculation zones. While increasing the slope ratio enhances the control of recirculation, it may simultaneously intensify surface vortex formation, which can contribute to variations in vertical velocity distribution and increased upstream water surface drawdown due to stronger secondary flow structures [22].

The location of the separation zone within the branch channel is strongly dependent on the branching angle, forming along the downstream wall at a 30° diversion angle, whereas it shifts to the upstream wall at a 90° angle [1]. Furthermore, the separation zone sizes across a range of diversion angles (45°, 56°, 67°, 79°, and 90°) indicated that an angle of approximately 55° represents the optimal diversion configuration, as it minimizes the extent of the separation zone within the intake channel [23], [13], [24].

1.4 influence of the lateral intake on sediment transport

Regarding the morphological alterations induced by lateral intakes, construction of a branch channel to divert part of the main flow significantly modifies the hydraulic conditions and river bed mechanics of the main channel, leading to changes in bed forms, particularly within the junction zone [25]. Such morphological adjustments may give rise to several issues, including variations in the main channel slope resulting from localized erosion and sediment deposition. Moreover, lateral water withdrawal in open channels reduces sediment transport capacity, promoting local sediment accumulation near the side overflow and indirectly affecting upstream flow dynamics [26]. Formation of a pronounced scour hole at the downstream edge of the branch channel entrance for right-angle diversion flow over a movable sand bed [27]. Additionally, the branch channel with a 45° bend resulted in the minimum diverted sediment load when compared with diversion angles of 45°, 60°, and 75° [19].

1.5 Problem statements

Lateral intakes are widely used in open-channel systems; however, their influence on the vertical velocity distribution in the main channel is not yet fully understood. Previous studies have largely focused on discharge division, water surface profiles, or sediment transport, while detailed investigations of layer-wise velocity behavior upstream of lateral intakes remain limited. Moreover, the spatial extent of intake influence across the channel width and upstream distance, particularly under subcritical flow conditions, has not been systematically quantified. This study addresses these gaps through controlled laboratory experiments that examine the effects of varying lateral intake ratios (Q_r) on vertical velocity layers across different transverse zones, aiming to support improved hydraulic analysis and design of lateral intake structures.

II. MATERIAL AND METHODS

2.1 Experimental Arrangement

Experiments were conducted in the irrigation and hydraulics laboratory of channel maintenance research institute (CMRI) at national water research center (NWRC), Egypt. The laboratory channel consisted of two parts, the main channel, and a branch channel. The main channel was concrete-lined trapezoidal channel with 16.22 m long, 60 cm wide and 42 cm in depth with side slopes of 1:1. The division corner to the branch channel was sharp edged and located 11.0 m downstream of the main channel inlet. The branch channel was a 4-inch diameter side pipe on the right-hand side, with its invert aligned with the bed of the main channel to accurately represent the operating conditions of branch canal intake gates in open channels.

Figure 1: The flume laboratory at the Channel Maintenance Research Institute

The water flow was supplied from an underground source, and a stilling basin was installed at the entrance of the main channel to promote uniform flow expansion and minimize turbulence. The main channel discharge was regulated using a control valve located at the flume inlet, while the lateral discharge was controlled via a separate valve at the intake. Discharges in both the main and branch channels were measured using ultrasonic flow meters mounted on the outside of the pipes. A schematic layout of the experimental channel is shown in (Fig.2). This setup enabled precise regulation and accurate achievement of the target lateral intake ratios throughout the experimental study.

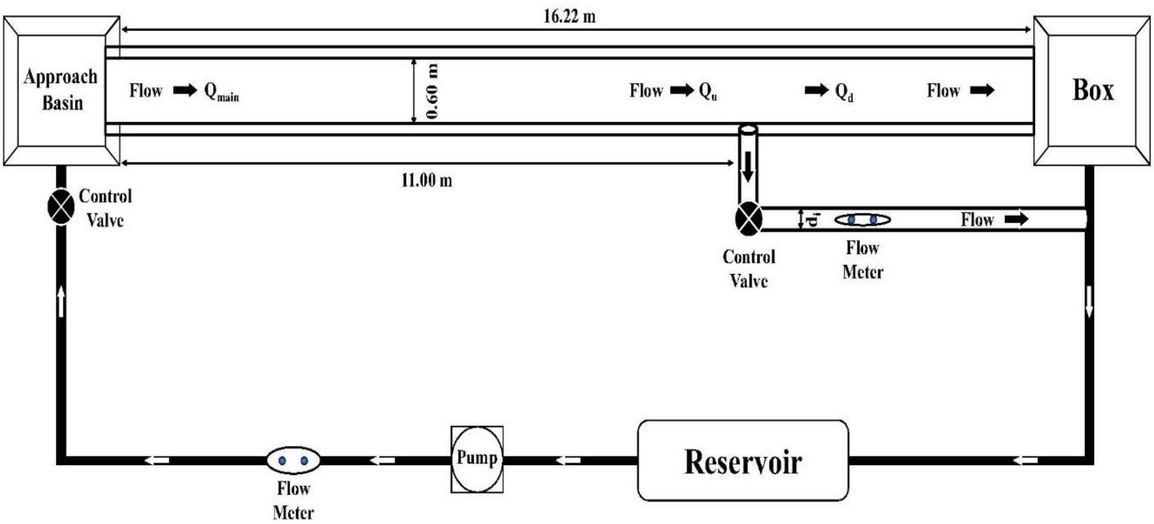


Figure 2: A schematic layout of the experimental Arrangement

2.2 Experimental Measurement Equipment

Since experimental measurements are inherently sensitive to instrument precision, the validity of the results is directly affected by the quality of the measuring devices. Thereby, Water depths were recorded using a calibrated mobile point gauge with an accuracy of ±1 mm, providing sufficient resolution to detect minor fluctuations in free-surface elevation and to accurately characterize spatial variations in the water surface profile. Similarly, the mean flow velocities were measured using a VECTRINO acoustic velocimeter. The VECTRINO is a high-resolution 3D acoustic Doppler velocimeter with an accuracy of ±0.5% of the measured value plus ±1 mm/s, enabling precise characterization of both mean and turbulent flow structures. The flow control and measurement devices to accurately capture and regulate hydraulic behavior are shown in (Fig.2).

(a) (b) (c)

(d) (e) (f)

Figure 2: Flow control and measurement devices in the physical model (a): the flow meter device, (b) the inlet control valve, (c) flow sensor at the main pipe, and lateral intake pipe (d) a mobile point gauge, (e) the Victorino velocity device, and (f) the lateral intake pipe.

2.3 Experimental Methodology

This study investigates the hydrodynamic effects of lateral intakes on the vertical distribution of velocity layers within the main channel. For each experimental run, the procedure starts with the smoothing case in which the lateral intake was fully closed to establish an undisturbed reference flow. The storage feeding tank was subsequently filled, and the inlet valve of the supply pipeline was gradually opened to achieve the target discharge by adjusting both the valve opening and the corresponding flowmeter readings.

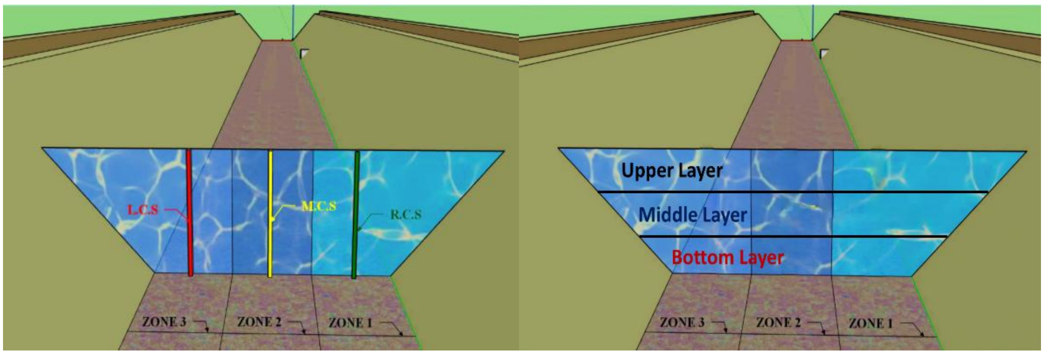
A downstream tailgate was employed to regulate the flow depth, which was maintained at 30 cm. This depth was selected in accordance with hydraulic similarity principles, particularly Froude similarity. Such considerations are essential for accurately reproducing gravity-dominated flow behavior in open-channel systems. All experiments were conducted under steady-flow conditions to ensure repeatability and consistency of the measured hydraulic parameters

The lateral discharge changed five times, 5%, 10%, 15%, 20% and 25 %, respectively. For each lateral discharge ($Q_{int.}$), five different discharges were tested in the experiment for the main channel (Q_{main}), 27 L/s, 30 L/s, 33 L/s, 36 L/s, and 39 L/s respectively. Froude number in the main channel upstream of the lateral intake varied from 0.055 to 0.075.

The main channel cross section was segmented into three equal bed width transverse zones {R.C.S - zone 1: (the near – intake), M.C.S - zone 2: (mid - channel), and L.C.S - zone 3: (far - from-intake zones)} as shown in Fig. (3). Successive vertical layers of uniform 2 cm thickness were defined within each transverse zone to ensure precise hydraulic measurements. Each transverse zone was discretized into three flow layers {bottom flow layer, middle flow layer, and upper flow layer}.

This approach allows for a detailed assessment of the velocity field and associated non-uniformities in cross-sectional vertical velocity distributions layers upstream the lateral intake. The present study seeks to address the following research objectives: -

- Examine the variation of velocity profiles across different vertical water layers, including: the lower layer (near-bed region), the middle layer, and the upper layer (near free surface); for each tested withdrawal ratio.
- Investigate the interaction between lateral withdrawal and vertical momentum exchange, and its effect on flow stratification and shear distribution.
- Support the optimization of lateral intake design and operation, aiming to improve hydraulic efficiency, flow uniformity, and operational reliability in irrigation, water supply, and river diversion systems.



(a) **(b)**

Figure 3: The flume {(a) systematically divided into three equal transverse zones, (b) systematically divided into three equal vertical zones}

A comprehensive experimental program was carried out to examine the hydrodynamic influence of lateral intakes on velocity distributions layers in the main channel, with the measurement setup and parameters detailed in (Table 1).

***Table I.* Experimental Conditions and Runs**

Main Flow (Q_{main})	Froude Number	Flume Width (B)	Water Depth (Y)	Lateral Intake Angle	Lateral Intake Ratio (Q_r)
(L/s)	(Fr)	(m)	(m)	(°)	(%)
27	0.055	0.60	0.30	90	0, 5, 10, 15, 20, 25

30	0.060
33	0.065
36	0.070
39	0.075

Total number of measured velocity profile sections = 528

A total of 528 velocity profiles were collected in the present study. These profiles, corresponding to lateral withdrawal conditions, were classified according to the transverse measurement zones. Specifically, 169 velocity profiles were recorded in Zone (1) – Right Cross Section (R.C.S) – [near - intake], 191 profiles in Zone (2) – Middle Cross Section (M.C.S) – [mid – channel], and 168 profiles in Zone (3) – Left Cross Section (L.C.S) – [far - from-intake]. This comprehensive experimental dataset enables a systematic evaluation of the effects of lateral intakes, under varying lateral intake ratios (Q_r), on the velocity distribution within the main channel.

The layer-averaged flow velocities ($V_{avg.}$) for the bottom, middle, and upper layer of the flow were derived from detailed vertical velocity profiles measured at multiple cross-sections [C.S.1, C.S.2, C.S3., and C.S.4] located just upstream, and at distances of 1.0 m, 3.0 m, and 5.0 m upstream of the lateral intake respectively, as shown in Fig. 4. To rigorously evaluate the influence of lateral withdrawal on the vertical distribution layers of velocities within the main channel, the absolute differences in average velocity (ΔV_{avg}), and their corresponding percentages (ΔV_{avg} %) were systematically computed for each flow layer at the selected cross-sections. These analyses provide a detailed assessment of how lateral withdrawal alters the flow velocity distribution within the main channel across the investigated cross-sections.

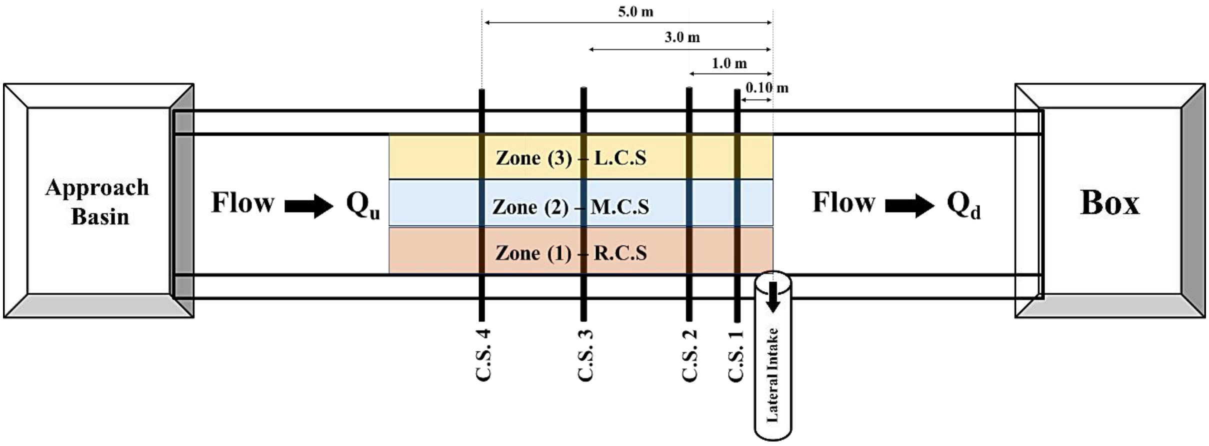


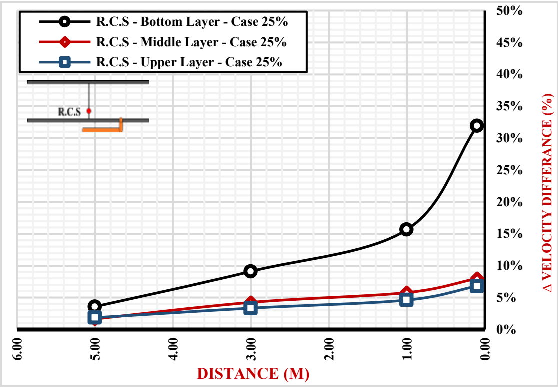
Figure 4: A schematic layout of the measuring cross section, and transverse zones

III. RESULTS AND DISCUSSIONS

A detailed analysis of the absolute deviations in layer-averaged velocity (Δ_{Vavg}), and the associated percentage (ΔV_{avg} %) was systematically conducted across three hydraulically transverse zones of the main channel. These zones comprised Zone (1), represented by the Right Cross Section (R.C.S) located near the lateral intake; Zone (2), corresponding to the Middle Cross Section (M.C.S) positioned at mid - channel; and Zone (3), represented by the Left Cross Section (L.C.S) situated far - the intake. In parallel, the same analyses were conducted for the three vertical flow layers namely, the bottom, middle, and upper layers. These analyses provide a detailed assessment of how lateral withdrawal affect the flow velocity distribution within the main channel across the investigated cross-sections.

3.1 the Influence of Lateral Withdrawal on {Zone (1) - (R.C.S) - near intake}

The effect of lateral withdrawal on the velocity distribution within the three vertical flow layers, the bottom, middle, and upper layers—at Zone (1), located near the lateral intake, is illustrated in Fig. 5.



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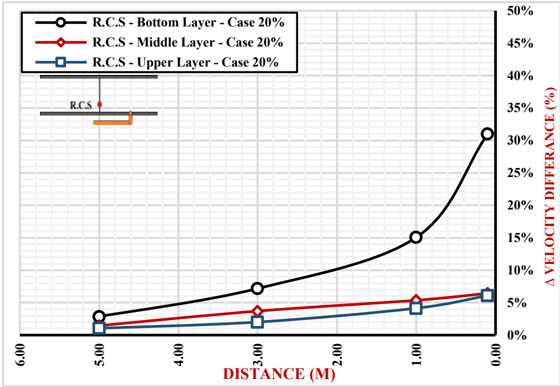

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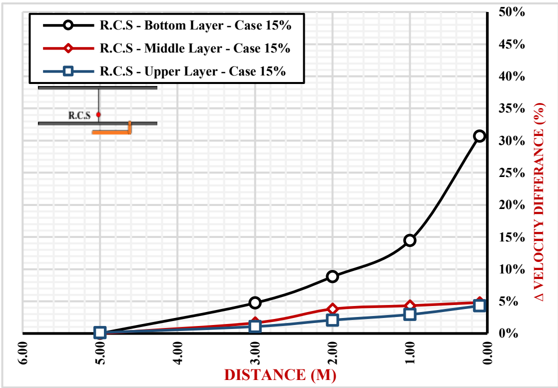

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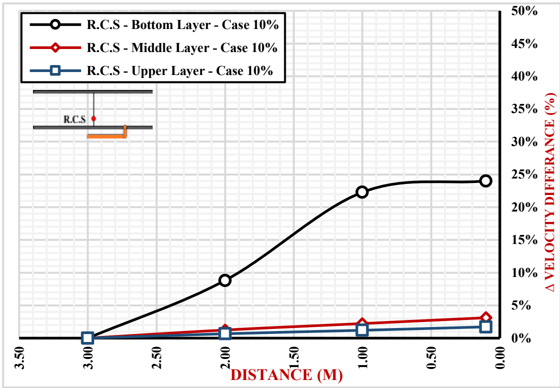

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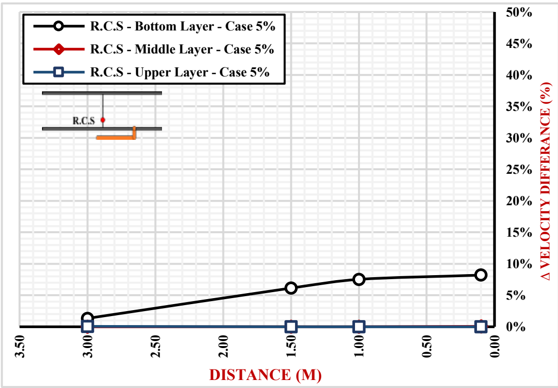


(e)

Fig. 5: Typical longitudinal velocity distribution profile at (R.C.S – Zone 1) for flow rate = 33 l/s, and the lateral intake ratio (Q_r) {(a): 25 %,(b) 20 %,(c) 15 %,(d) 10 %,and (e) 5 %} U.S the lateral intake.

The analysis of the velocity distribution charts presented in Fig. (5) indicates that the maximum impact on the velocity difference percentage (ΔV_{avg} %) occurs within the bottom flow layer. The absolute differences in average velocity (ΔV_{avg} %) are observed to vary as a function of both the lateral intake ratio (Q_r) and the upstream distance of the measuring cross-section (C.S.) relative to the lateral intake.

a. For Bottom Flow Layer

The influence of lateral withdrawal on the bottom flow layer exhibits two distinct behaviors depending on the magnitude of the lateral intake ratio (Q_r). For high lateral intake ratios (Q_r =15% – 25%), the bottom layer shows a consistent response pattern, with the rate of change in (ΔV_{avg} %) modulated by both lateral intake ratios (Q_r), and the upstream cross-section location. The maximum impact is recorded at C.S. 1 – just upstream of the intake. A notable reduction of approximately 50% in (ΔV_{avg} %) is observed at C.S. 2, followed by a gradual decline at C.S. 3 and C.S. 4 as the measurement distance upstream increases.

For low lateral intake ratios (Q_r =5% – 10%), the behavior differs markedly from that observed at higher lateral intake ratios (Q_r). While the maximum impact (ΔV_{avg} %) is at C.S. 1, the influence percentage remains high through C.S. 2 before gradually diminishing at C.S. 3 and C.S. 4. This indicates that at lower withdrawal rates, the lateral intake effect (ΔV_{avg} %) persists farther upstream in the bottom layer compared to high-intake scenarios.

b. For Middle, and Upper Flow Layer

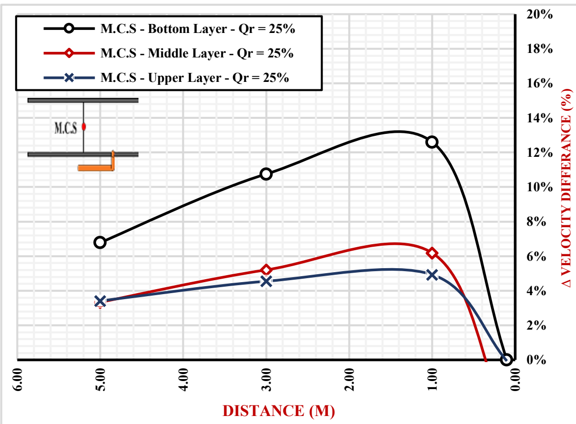
In contrast, the middle and upper flow layers exhibit a similar pattern, characterized by significantly lower (ΔV_{avg} %) compared to the bottom layer. For these layers, the peak influence (ΔV_{avg} %) occurs at C.S. 1 and decreases progressively with increasing upstream distance. At the minimal lateral intake ratio (Q_r =5%), the effect on both middle and upper layers is negligible.

The percentage influence on velocity distribution (ΔV_{avg} %) varies with both the lateral intake ratio (Q_r), and the cross-section location. For the bottom layer, (ΔV_{avg} %) ranges from 31.91% at C.S. 1 to 1.34% at C.S. 3 for Q_r = 25%, and 5%, respectively. In the middle layer, the influence spans 8.0% at C.S. 1 to 1.66% at C.S. 4 for Q_r = 25%, while for Q_r = 10% it ranges from 3.12% at C.S. 1 to negligible at C.S. 3. Similarly, for the upper layer, (ΔV_{avg} %) varies between 6.81% at C.S. 1 and 1.86% at C.S. 4 for Q_r = 25%, and between 1.72% at C.S. 1 to negligible at C.S. 3 for Q_r=10%.

These findings demonstrate a clear depth-dependent response of the flow to lateral withdrawal, with the bottom layer exhibiting the greatest sensitivity, while the middle- and upper-layers experience progressively attenuated effects. The magnitude and spatial extent of the influence are strongly dependent on both the lateral intake ratio and the upstream distance of measuring location.

3.2 the Influence of Lateral Withdrawal on {Zone (2) - (M.C.S) – mid channel}

The effect of lateral withdrawal on the velocity distribution within the three vertical flow layers - namely, the bottom, middle, and upper layers—at Zone (2), located at mid-channel, is illustrated in Fig. 6.



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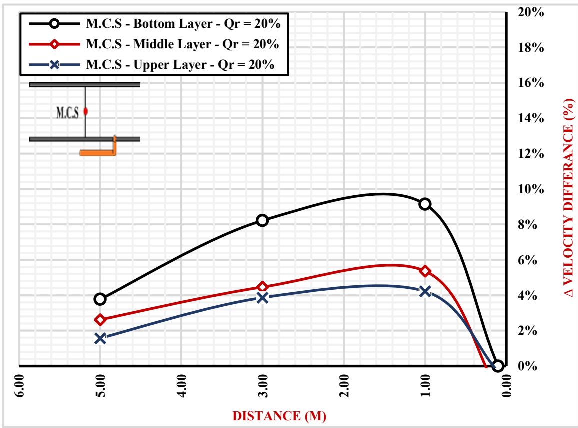

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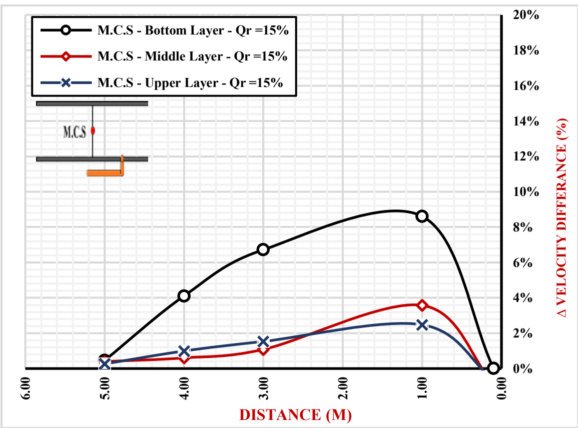

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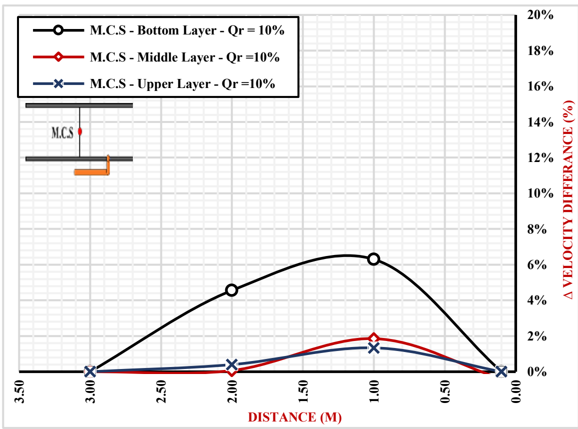

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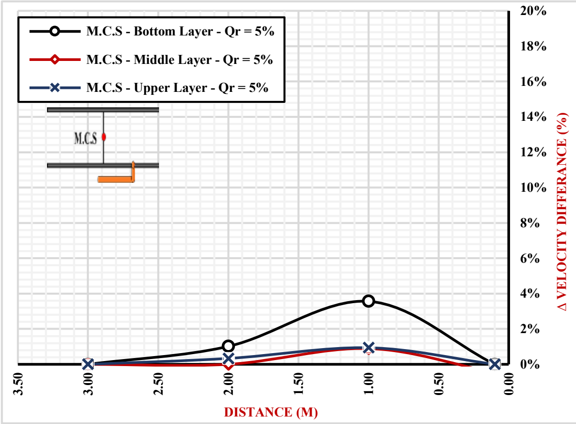


(e)

Fig. 6: Typical longitudinal velocity distribution profile at (M.C.S – Zone 2) for flow rate = 33 l/s, and the lateral intake ratio (Q_r) {(a): 25 %,(b) 20 %,(c) 15 %,(d) 10 %,and (e) 5 %} U.S the lateral intake.

The analysis of the velocity distribution profiles illustrated in Fig. (6) reveals that the influence percentage (ΔV_{avg} %) behavior is the same for the flow layers (bottom, middle, upper layer). Furthermore, the most pronounced influence on the percentage variation in mean velocity (ΔV_{avg} %) is concentrated within the bottom flow layer of the main channel. Furthermore, the magnitude of the absolute differences in mean velocity percentages (ΔV_{avg} %) does not remain uniform along the flow domain; rather, it exhibits a clear dependency on both the lateral diversion ratio (Q_r) and the upstream distance of measuring cross-section relative to the lateral intake. This behavior highlights the sensitivity of the flow behavior in open channels to lateral withdrawal, particularly near the bed layer, where momentum redistribution and flow distortion are intensified due to the interaction between the main channel flow and the lateral intake.

a. For Bottom Flow Layer

As the flow approaches the lateral intake, a transverse pressure gradient develops due to the extraction of discharge toward the lateral intake. This induces a lateral acceleration of fluid particles and initiates a gradual redistribution of momentum across the channel width and depth. The peak effect of the percentage influence on velocity distribution (ΔV_{avg} %) due to lateral withdrawal in zone (2) – M.C.S – mid channel in flow layers (bottom, middle, and upper layer) doesn't occur at C.S. 1 – just upstream the intake as in zone (1) – R.C.S - near intake. Rather, it manifests at C.S.2; where the combined effects of flow acceleration and relatively undisturbed continuity are maximized

At C.S.1 – just upstream the intake, a portion of the flow is extracted laterally, and the resulting increase in turbulence, generation of secondary currents, and associated energy dissipation act to reduce the streamwise velocity within the main channel.

b. For Middle, and Upper Flow Layer

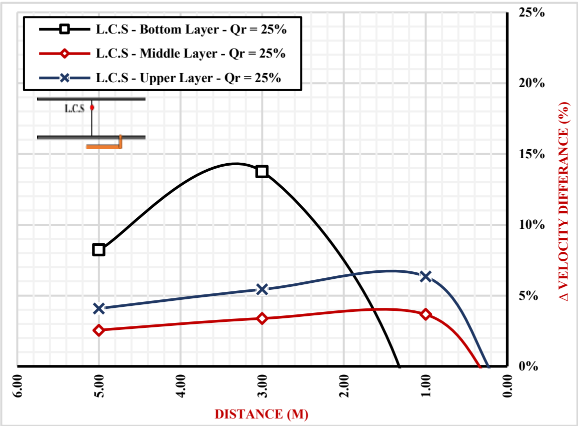
In the mid-channel zone, the influence of lateral withdrawal on the velocity distribution within the middle and upper flow layers exhibits a nonuniform and transitional behavior. For high lateral intake ratio (Q_r = 20-25%). at C.S 2; the effect of lateral withdrawal is more pronounced in the middle layer than in the upper layer. The main flow begins to respond to the forthcoming discharge extraction. The middle layer experiences a higher influence than the upper layer because it is closer to the core of the flow momentum. This layer carries a significant portion of the channel's discharge and is more directly affected by the initial lateral pressure gradients and the development of secondary currents induced by the lateral withdrawal. The upper layer, in contrast, is less constrained and more influenced by free-surface continuity, so the immediate effect is smaller.

For low lateral intake ratios (Q_r = 5-15%), as the distance upstream increases at C.S. 3, and C.S.4. The flow has sufficient space to allow momentum redistribution and gradual adjustment to the expected discharge extraction. The middle layer begins transferring part of its momentum to the upper layer through vertical shear and turbulence. This reduces the relative influence in the middle layer, while the upper layer's influence becomes more noticeable as vertical mixing and secondary circulation propagate the effect upward.

For bottom, middle, upper layer in zone (2) – M.C.S; the peak influence occurs at C.S. 2 and decreases gradually with increasing upstream distance. **For the bottom layer**, the peak influence (ΔV_{avg} %) ranges from 12.60% to 3.56% at C.S. 2 for Q_r = 25%, and 5%, respectively. **In the middle layer**, the peak influence (ΔV_{avg} %) spans from 6.19% to 0.89% at C.S. 2 for Q_r = 25%, and 5%, respectively. Similarly, **for the upper layer**, the peak influence (ΔV_{avg} %) varies between 4.93% to 0.94% at C.S. 2 for Q_r = 25%, and 5%, respectively.

3.3 the Influence of Lateral Withdrawal on {Zone (3) - (L.C.S) – far from intake}

The influence of lateral withdrawal on the velocity distribution across the three vertical flow layers—namely, the bottom, middle, and upper layers—within Zone (3) – L.C.S, corresponding to the far-from intake zone, is presented in Fig. 7.



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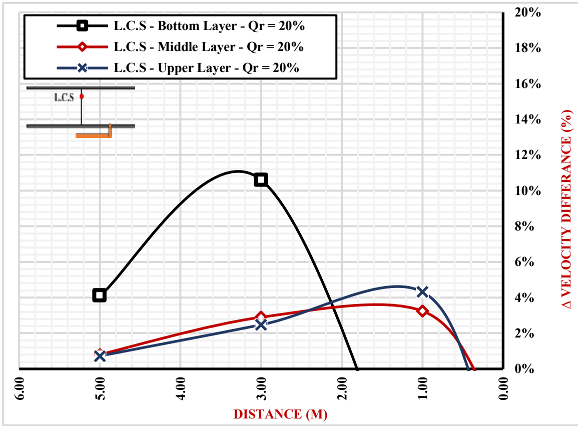

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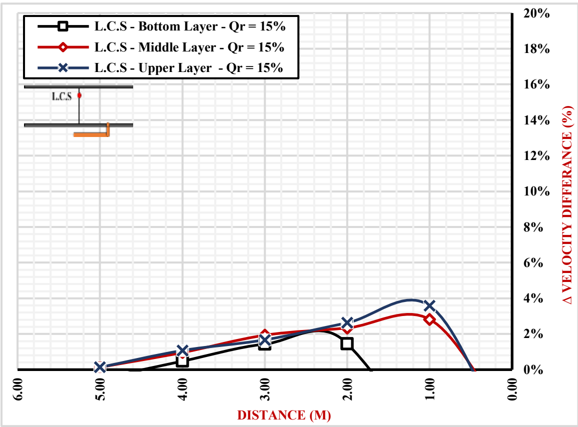

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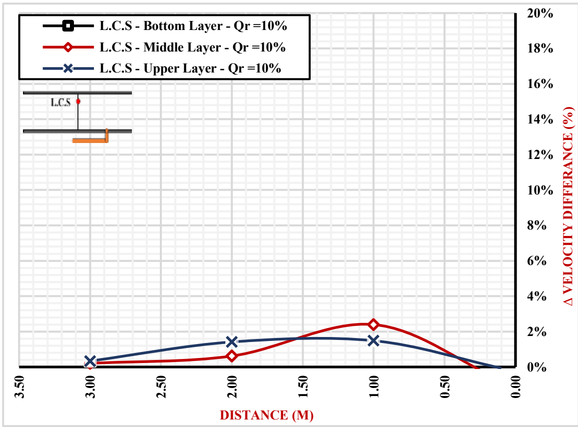

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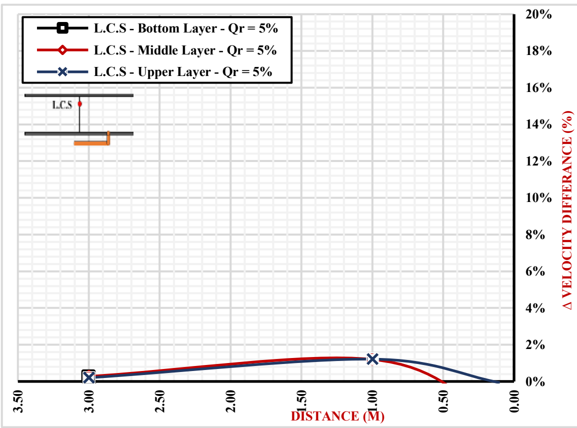

(e)

Fig. 7: Typical longitudinal velocity distribution profile at (L.C.S – Zone 3) for flow rate = 33 l/s, and the lateral intake ratio (Q_r) {(a): 25 %,(b) 20 %,(c) 15 %,(d) 10 %,and (e) 5 %} U.S the lateral intake.

The behavior of lateral withdrawal influence on the bottom, middle, and upper flow layers—within Zone (3) – L.C.S reflects the non-uniform and depth-dependent adjustment of open-channel flow to lateral withdrawal. The upper and middle layers respond over shorter adjustment lengths due to lower frictional resistance, whereas the bottom layer requires a longer distance for the effects of momentum extraction to become fully developed.

a. For High Lateral Intake Ratios (15-25%)

For bottom flow layer: In the bottom flow layer, the maximum influence of lateral withdrawal is not observed at C.S. 1, 2 located just, and at distance 1m upstream of the intake, but rather at C.S. 3, situated approximately 3 m upstream of the intake. This behavior is primarily governed by the dominant effects of bed shear stress and near-bed friction, which substantially attenuate the immediate response of the bottom flow layer to lateral discharge extraction. In the near-intake region, the flow field is characterized by intense turbulence, localized lateral redirection of streamlines toward the intake, and higher energy dissipation. These processes act to counterbalance the streamwise momentum deficit induced by the withdrawal, thereby mitigating its direct manifestation within the bottom layer and, in some cases, leading to a localized reduction in longitudinal velocity.

With increasing upstream distance from the intake, the influence of lateral withdrawal becomes progressively more apparent in the bottom layer as vertical momentum transfer and turbulent mixing redistribute the effects of discharge extraction from the upper and middle layers toward the near-bed region. At C.S.3 at distance 3 m upstream, the flow is subjected to sufficient hydrodynamic adjustment to the imposed disturbance, allowing the withdrawal-induced momentum imbalance to be more clearly reflected in the bottom-layer velocity field. Beyond this location, the magnitude of the influence gradually diminishes as turbulence intensity decays and the flow reaches a quasi-equilibrium condition, explaining the reduced impact observed at C.S.4.

For Middle, and Upper flow layer: In contrast, the middle and upper flow layers demonstrate their greatest sensitivity to lateral withdrawal at C.S.2, located 1 m upstream of the intake. These layers experience reduced frictional constraints compared to the bottom layer, allowing them to respond more rapidly to the lateral pressure gradients induced by the withdrawal. As the flow approaches the intake, a portion of the streamwise momentum is diverted laterally, producing significant modifications in the velocity distribution across these layers.

At C.S.1, just upstream the intake, the influence percentage of lateral withdrawal (ΔV_{avg} %) is minimal or even negative. This behavior is primarily due to the presence of strong secondary currents, heightened turbulence, and localized flow separation, all of which diminish the longitudinal velocity component in these regions. With increasing upstream distance, the intensity of lateral pressure gradients decreases, secondary flows reduce, and the effect of lateral withdrawal on velocity distribution progressively diminishes in both layers.

Although both the middle and upper layers exhibit similar behaviors, the magnitude of the impact is consistently greater in the middle layer. This is resulting from its intermediate position within the flow depth, where it functions as a transitional zone facilitating vertical momentum exchange between the upper free-surface region and the bottom flow layer. Whereas, the upper layer is influenced by free-surface constraints, which tend to moderate velocity variations and reduce the apparent effect of lateral withdrawal.

b. For Low Lateral Intake Ratios (5-10%)

For bottom flow layer; the influence percentage of lateral withdrawal (ΔV_{avg} %) is negligible or even negative across all measurement sections. This behavior is primarily related to the control of bed friction and near-bed shear stress, which strongly mitigate any immediate response of the bottom layer to small lateral extractions. At low withdrawal ratios, the fraction of streamwise momentum removed from the main channel is insufficient to overcome the stabilizing effects of bed shear and near-bed turbulence. Consequently, the longitudinal velocity in the bottom layer exhibits minimal or slightly reduced response throughout the upstream measurement sections.

For Middle, and Upper flow layer; the effect of lateral withdrawal is amplified due to reduced bed friction and intensified sensitivity to lateral pressure gradients. The maximum impact (ΔV_{avg} %) occurs at C.S.2 (1 m upstream of the intake), with the middle layer subjected to a stronger response than the upper layer for lateral intake ratio (Q_r), reflecting its central role in vertical momentum exchange and its contribution to overall channel discharge. At C.S. 3 (3 m upstream the intake), the influence percentage in the upper layer exceeds that in the middle layer, highlighting upward propagation of withdrawal-

(ΔV_{avg} %) induced perturbations through turbulence and vertical mixing. By C.S.4 (5 m upstream the intake), the effect on both layers becomes insignificant, as the flow gradually approaches a quasi-equilibrium state and the perturbation from lateral extraction reduces.

At a low lateral intake ratio ($Q_r = 5\%$), the influence pattern changes slightly. The maximum influence percentage (ΔV_{avg} %) remains at C.S.2, but the impact is nearly identical in the middle and upper flow layers, indicating that vertical momentum redistribution is less differentiated at very low extraction discharge rates. the effect diminishes gradually toward C.S. 3, and becomes minimal, while at C.S. 1, just upstream the intake, exhibits a negative influence in both layers (middle, upper flow layer). This reversal is expected caused by secondary currents and localized flow separation, which locally reduce the longitudinal velocity.

The percentage influence on velocity distribution (ΔV_{avg} %) varies with both the lateral intake ratio (Q_r), and the cross-section location. **For the bottom layer**, (ΔV_{avg} %) ranges from 13.75% at C.S. 3 to negligible for $Q_r = 25\%$, and 5%, respectively. **In the middle layer**, the influence percentage (ΔV_{avg} %) extends 3.24% at C.S. 2 to 0.17% at C.S. 4 for $Q_r = 25\%$, and 5%, respectively. while for $Q_r = 5\%$ it ranges from 1.20% at C.S. 2 to 0.28% at C.S. 3. Similarly, **for the upper layer**, (ΔV_{avg} %) varies between 6.34% at C.S. 2 and 4.08% at C.S. 4 for $Q_r = 25\%$, and between 1.48% at C.S. 2 to 0.34% at C.S. 3 for $Q_r =5\%$.

This vertical and longitudinal variability in velocity distribution highlights the importance of considering both measurement location and flow depth when assessing the hydraulic impact of lateral withdrawal on velocity distribution in open-channel flows.

IV. CONCLUSIONS AND RECOMMENDATIONS

This experimental study investigated the hydrodynamic influence of lateral intakes on the vertical velocity distribution in an open-channel flow under steady subcritical conditions. A comprehensive analysis was conducted on the measured velocity profiles obtained across multiple transverse zones, vertical flow layers, lateral intake ratios, and upstream measurement locations. Based on these observations, the following key conclusions are drawn:

- The impact of lateral intake on flow velocity is strongly depth-dependent. The bottom flow layer exhibits the highest sensitivity to lateral withdrawal, followed by the middle layer, while the upper layer is least affected. This behavior is attributed to the combined effects of bed shear stress, vertical momentum exchange, and turbulence intensity.
- Increasing the lateral intake ratio significantly amplifies the deviation in layer-averaged velocities. High intake ratios (15–25%) cause pronounced disturbances in velocity distribution, especially in zone (1) – R.C.S - near the intake and within the bottom flow layer, whereas low intake ratios (5–10%) result in limited and rapidly attenuating effects upstream.
- The hydraulic response to lateral withdrawal varies markedly across the channel width: in the near-intake zone 1- (R.C.S), the maximum velocity deviation (ΔV_{avg} %) occurs at C.S.1 just upstream of the intake, particularly in the bottom layer. In the mid-channel zone 2 - (M.C.S), peak influence (ΔV_{avg} %) shifts upstream to C.S.2 (1 m from the intake) due to momentum redistribution and flow acceleration. In the far-from-intake zone (L.C.S), the response is delayed, with the bottom layer reaching maximum influence (ΔV_{avg} %) farther upstream at C.S.3 (3 m upstream the intake), reflecting the damping role of bed friction and gradual vertical momentum transfer.
- The middle flow layer plays a critical transitional role in transferring withdrawal-induced disturbances between the upper and bottom layers. This vertical interaction governs the redistribution of momentum and explains the observed shift of maximum influence across layers and zones.
- In several cases, especially at low intake ratios and very close to the intake, negative velocity deviations were observed. These are attributed to intensified turbulence, secondary currents, and localized flow separation that reduce streamwise velocity near the intake entrance.

Based on the findings of this study, the following recommendations are proposed for engineering practice and future research:

- Lateral intake designs should explicitly account for the strong sensitivity of the bottom flow layer, particularly under high withdrawal ratios, to minimize adverse effects such as excessive bed shear, sediment deposition, or local scour.
- Intake operation with moderate withdrawal ratios is recommended where flow stability and uniform velocity distribution are critical.
- Extend the experimental program to investigate the combined effects of intake angle, intake geometry, and bed mobility on vertical velocity distribution.

- Integrate experimental results with advanced CFD simulations to provide a unified physical and numerical framework for lateral intake design.

ABBREVIATIONS

The following abbreviations are used in this manuscript:

$Q_{main} = Q_m$	Main channel discharge
$Q_{int.}$	Lateral intake discharge
Y_u	Upstream water depth in main channel
Y_b	Water depth in branch channel
VOF	Volume of fluid
Y	Flow water depth
B	Channel bed width
Q_u	Flow discharge upstream lateral intake
Q_d	Flow discharge downstream lateral intake
Q_r	Discharge ratio between the lateral intake and the main channel
R.C.S	Right cross section of velocity (Zone 1)
M.C.S	Middle cross section of velocity (Zone 2)
L.C.S	Left cross section of velocity (Zone 3)
U.S	Upstream lateral intake
$V_{avg.}$	Flow average velocity
$\Delta V_{avg.}$	The absolute differance in average velocity
$\Delta V_{avg.}\%$	The influence percentage on the average velocity
F_r	Froude Number
C.S	Cross section

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