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# Numerical investigation of the effect of the wall side slope of the tributary canal on the flow dynamics at river confluences

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**A B S T R A C T**

The study explores the intricate dynamics of flow at river confluences, focusing on the impact of changing the side slope of the tributary canal wall on the flow patterns. Using the Flow-3D model, the research investigates the influence of the side slope angle (*Z*), discharge ratio ($Q_r=Q_2/Q_3$), and Froude number ($F_r$) on the flow dynamics at river confluences. To achieve this, the study considers various angles for the side slope, different discharge ratios, and Froude numbers in a confluence with a 90-degree angle. The findings reveal that altering the lateral slope of the tributary canal wall significantly affects the flow pattern, leading to changes in the length and relative width of the separated flow zones. The augmentation of the lateral angle resulted in a proportional escalation in the length of the separation zone contiguous to the water surface. Nevertheless, the comparative width of the separation zone and the relative water level at the inclinations of 60 and 75 degrees surpassed those at 45 and 90 degrees. Moreover, the incline of the walls at 60 and 75 degrees resulted in a 32% increase in the water level upstream of the confluence, as compared to the downstream.


Keywords:
Flow dynamics
River confluence
Side Slope
Separation Zone
Flow-3D

## 1. Introduction

The analysis of flow in intersecting channels is complicated due to the significant role played by numerous parameters. Flow dynamics at river confluences involve six distinct zones: the stagnation zone, flow deflection zone, separation zone, maximum velocity zone, flow recovery zone, and shear layer zone (Best, 1987). Over the past three decades, studies in the field and laboratory have revealed the complex characteristics of flow at river confluences (Shafaei Bejestan & Hemmati, 2008). Experimental and theoretical investigations have provided insights into the confluence of channels at different angles and under various conditions (Taylor, 1944). Ghobadian (2005) explored the intricate patterns of flow, erosion, and sedimentation at river confluences through the use of a physical model. The findings of his research revealed that an increase in discharge ratio and connection angle resulted in the expansion of both width and length of the separation zone. Conversely, an increase in the Froude number downstream and width ratio led to a reduction in the dimensions of the separation zone. These results shed light on the complex dynamics governing river confluences, offering valuable insights for further research in this field. Wang and Yan (2007) conducted a study which highlighted the significance of the ratio of branch discharge to total discharge in discordance confluences. They emphasized that this ratio serves as a crucial control factor influencing the dimensions of the flow separation zone. Furthermore, their findings indicated that in cases of unequal bed levels, the separation zone is notably absent near the bottom.

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The results study of Shafaei Bajestan and Hemmati (2008) revealed that when the discharge of the branch channel is less than 75% of the discharge of the main channel at the upstream of junction, an increase in the difference in the bed level of the two channels leads to a decrease in the depth of the scour. Conversely, when the discharge exceeds 75%, the amount of scour is found to increase with an increase in the bed level differences.

Ghobadian and Basiri (2015) conducted a study to examine the impact of the downstream curved edge of the confluence on scour at the river junction with concordance bed levels. They utilized the SSIIM model and observed that the scour depth in the mild curvature, as compared to the steep curvature, decreased by 51% and 28% for ratios of minor branch discharge to total discharge of 0.5 and 0.66, respectively.

Aghazadeh Soureh and Hemmati (2018a) investigated the three-dimensional effect of bed discordance and the discharge ratio on the dynamics of the flow at river junction using the Flow-3D numerical model. The results of their research showed that the change in bed discordance level changed the flow pattern, so that the flow separation zone near the bed was observed only for the concordance confluence and did not occur in the discordance state. In addition, Aghazadeh Soureh and Hemmati (2018b) reported that the junction angle plays an important role in the confluence of rivers, especially in the concordance confluences, so that with increasing the angle, the dimensions of the flow separation increased. Samir et al. (2023) evaluated the morphological and hydrodynamic parameters of the Nile River confluence and finally presented a dimensionless relationship for scour prediction. Yuan et al., (2024) investigated the prediction of flow hydrodynamics at the confluence of rivers using entropy model.

Seyedian et al. (2014) conducted a study to examine the impact of the lateral slope/angle of the main canal wall on the inlet flow pattern to the intake. Their findings revealed that an increase in the lateral angle of the wall resulted in a reduction in the width of the separated area at the bottom, while simultaneously causing an expansion of the separated zone in the flow surface. Furthermore, alterations to the lateral angle of the wall were found to decrease the cross-sectional area of the diversion flow. In a similar vein, Khosravinia et al. (2014) delved into the effects of a 45° lateral slope of the main channel on the distribution of velocity, water level, and dimensions of the flow separation zone in a confluence with a 90° angle, comparing it with the 90° lateral slope mode. Their research unveiled that in the 45° lateral slope scenario, the length and width of the separation zone were diminished at the bed level but expanded at the water surface compared to the 90° lateral slope configuration. Notably, in the 45° lateral slope setting, the narrow width of the separation zone near the bottom precluded the formation of an area with high acceleration downstream of the junction, consequently leading to a reduction in shear stress in this particular region. Parchami et al. (2021) conducted a numerical investigation to analyze the impact of main channel cross-sections (rectangular and trapezoidal) and confluence angle (45 and 90 degrees) on flow dynamics at concordance and discordance junctions. The study revealed that at the concordance confluence with a 90-degree angle, a flow separation zone forms near the bed in both cross-sections. However, in the trapezoidal section, the dimensions of the separation zone at the water surface are greater than in the rectangular section. At an equal bed level junction with a 45-degree angle, this phenomenon did not manifest in either cross-section. Conversely, for the unequal bed level case, a detachment zone formed only at the water surface in the trapezoidal section. Furthermore, at the unequal bed level confluence with a 90° angle, the flow separation zone did not form near the bed; rather, its dimensions at the water surface were greater in the trapezoidal section compared to the rectangular section. Additionally, backwater in main channel at the upstream the confluence was reduced in the trapezoidal section at a 45° connection angle.

In conclusion, while significant research has been conducted on flow dynamics at river confluences, there is still a need for further investigation into the effects of other factors, such as the wall side slope of tributary canal, on flow dynamics especially separation zone at confluences. The dimensions of the separation zone in the downstream corner of a confluence play a significant role in influencing the flow and sediment pattern. While several studies have been conducted in this field, there remains a gap in understanding the impact of the wall side slope of the tributary canal on the dimensions of the separation area. Therefore, the present research aims to address this gap by investigating the effect of the tributary canal's wall side slope on the dimensions of the separation area. This will contribute to a more comprehensive understanding of flow patterns and aid in the development of effective management strategies for river systems.

## 2. Materials and Methods

### 2.1. Flow 3D

Flow 3D proved to be a powerful computational tool for conducting mathematical simulations, particularly in the realm of fluid dynamics. Its capabilities extended to a diverse array of challenges related to fluid flow, making it a valuable resource for engineers and researchers alike (Hassan and Shabat, 2023). The current investigation involved utilizing the FLOW-3D software to conduct a numerical simulation of the effect of the side slope of a tributary canal wall on flow dynamics. The numerical model in this study corresponds to a physical model constructed at Shahid Chamran University of Ahvaz (Ghobadian, 2005). The software's flow governing equations consist of the continuity equation and the momentum equation.

**continuity equation:**

$$V_F \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u A_x) + R\frac{\partial}{\partial y}(\rho v A_y) + \frac{\partial}{\partial z}(\rho w A_z) + \xi \frac{\rho u A_x}{x} = R_{DIF} + R_{SOR} \quad (1)$$

where $V_F$ is the fractional volume open to flow, $\rho$ is the fluid density, $R_{DIF}$ is a turbulent diffusion term, and $R_{SOR}$ is a mass source. The velocity components (u, v, w) are in the coordinate directions (x, y, z). A is the fractional area open to flow in the x-direction, $A_y$ and $A_z$ are similar area fractions for flow in the y and z directions, respectively.

**Momentum Equations**

$$\frac{\partial u}{\partial t} + \frac{1}{V_F}\left\{uA_x\frac{\partial u}{\partial x} + vA_yR\frac{\partial u}{\partial y} + wA_z\frac{\partial u}{\partial z}\right\} - \xi\frac{A_y v^2}{xV_F} = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial x}\right) + G_x + f_x - b_x - \frac{R_{SOR}}{\rho V_F} \quad (2)$$

$$\frac{\partial v}{\partial t} + \frac{1}{V_F}\left\{uA_x\frac{\partial v}{\partial x} + vA_yR\frac{\partial v}{\partial y} + wA_z\frac{\partial v}{\partial z}\right\} + \xi\frac{A_y uv}{xV_F} = -\frac{1}{\rho}\left(R\frac{\partial \rho}{\partial y}\right) + G_y + f_y - b_y - \frac{R_{SOR}}{\rho V_F} \quad (3)$$

$$\frac{\partial w}{\partial t} + \frac{1}{V_F}\left\{uA_x\frac{\partial w}{\partial x} + vA_yR\frac{\partial w}{\partial y} + wA_z\frac{\partial w}{\partial z}\right\} = -\frac{1}{\rho}\left(R\frac{\partial \rho}{\partial y}\right) + G_z + f_z - b_z - \frac{R_{SOR}}{\rho V_F} \quad (4)$$

These formulas include ($G_x, G_y, G_z$) as body accelerations, ($f_x, f_y, f_z$) as viscous accelerations, and ($b_x, b_y, b_z$) as flow losses in porous media or across porous baffle plates. The last terms take into consideration the injection of mass at a specific source represented by a geometry component.

### 2.2. Metodes

The model, initially created in AutoCAD software in three dimensions, was then converted to a format compatible with FLOW-3D. The main canal has dimensions of 7.5 meters in length and 35 centimeters in width, while the tributary canal measures 3.5 meters in length and 25 centimeters in width. At the upstream intersection, the main branch has a length of 3.5 meters with a 90-degree angle. The right wall of the tributary canal features side angles of (45, 60, 75, 90) degrees (Figure 1). Model calibration and validation were based on experimental results from Ghobadian (2005) and numerical results from Aghazadeh Soureh and Hemmati (2018a). A mesh size of 1.5 centimeters and a Manning roughness coefficient of 0.0085 were established based on the research conducted by Aghazadeh Soureh and Hemmati (2018 a, b) and Parchami et al. (2021).

While Aghazadeh Soureh and Hemmati (2018a) recommended the k-ε (RNG) turbulence model, this study opted for the LES turbulence model based on research by Parchami et al. (2021) and multiple numerical model runs. The illustration in Figure 2 displays the specific locations of the cross-sections utilized for extracting flow patterns. The table (1) provides a comprehensive overview of the parameters and their respective ranges of variation.

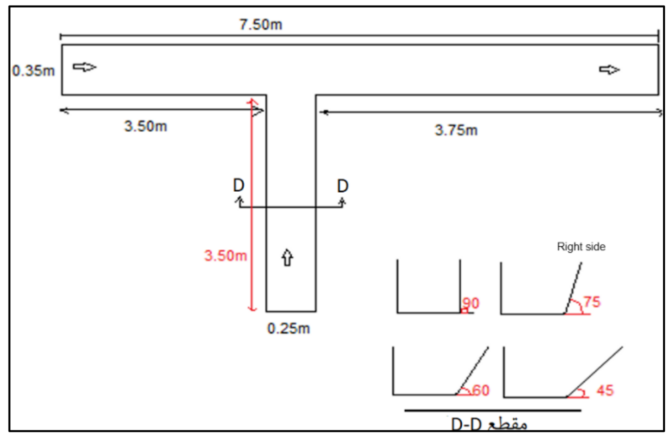



Figure 1. A view of the lateral slope of the tributary canal wall and the confluence plan of the two canals

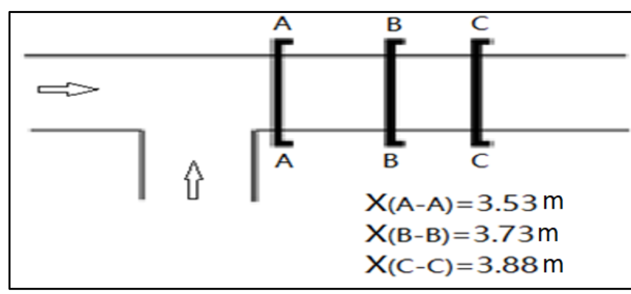



Figure 2.Different cross-sections to extract the flow pattern

Table1.The range of potential variations in parameters within different scenarios

| Parameters | Variation ranges |
|---|---|
| $Z$ (degree) | 45, 60, 75, 90 |
| $\theta$ (degree) | 90 |
| $F_r$ | 0.15, 0.26, 0.45 |
| $Q_r$ | 0.2, 0.5, 0.67 |

## 3. Results and discussion

### 3.1. Effect of the wall side slope of tributary canal on flow patterns at confluence

The study investigated the impact of the side slope of the tributary canal wall on flow dynamics at the confluence of two canals. The flow dynamics were analyzed at two different levels: near the bed (Fig. 3) and near the water surface (Fig. 4). The results revealed significant differences in flow dynamics between these two levels. Specifically, it was observed that the presence of a side slope in the right wall of the tributary canal prevented the occurrence of flow separation near the bed, with the flow separation area being reduced as a result. In line with the research conducted by Aghazadeh Soureh and Hemmati (2018a), it has been noted that there is a noticeable absence of a separation zone in the vicinity of the bed at bed discordance junctions. Furthermore, the study found that increasing the side slope of the canal wall led to an increase in the size of the maximum velocity near the bed. This increase in maximum velocity could have implications for erosion and sediment patterns within the canals. Notably, at a slope of 90 degrees, the formation of a flow separation zone in the downstream corner of the confluence in the main channel resulted in a decrease in the cross-sectional area of the flow and an increase in flow velocity.

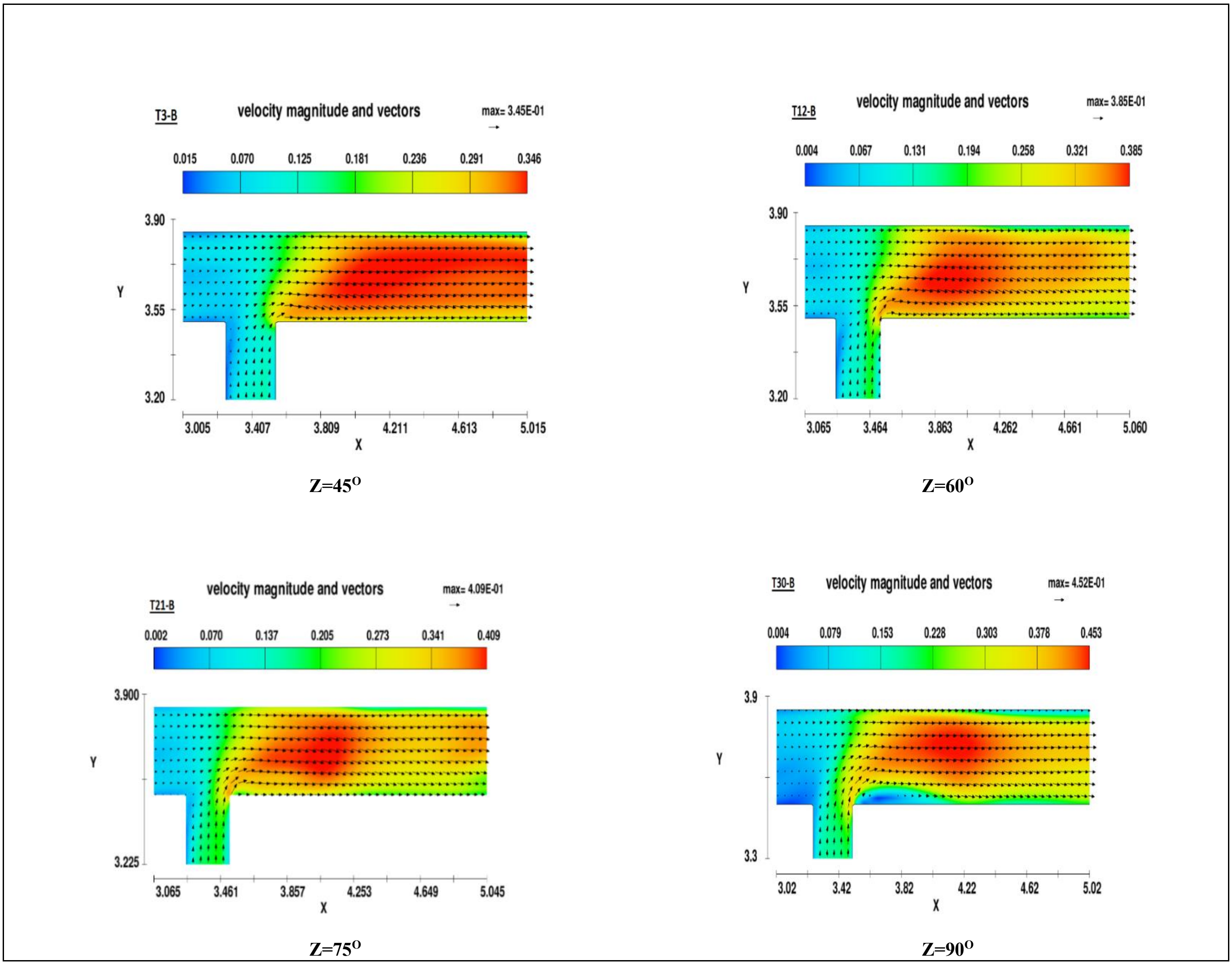



Figure 3: The effect of wall side slope of the tributary canal on flow dynamics near the bed ($F_r$=0.15, $Q_r$=0.67)

The flow dynamics at the confluence of two canals near the water surface exhibit significant variations. It is apparent that reducing the wall side slope results in a drastic reduction in the dimensions of the flow separation zone, almost eliminating its presence at a slope of Z=45°. The largest dimensions of the flow separation zone are observed in the wall with a vertical slope of Z=90°, and the flow recovery zone is formed at a considerable distance from the junction downstream. Moreover, the wall side slope impacts the velocity distribution at the confluence site. The maximum velocity values at slopes of 45, 60, 75, and 90 degrees near the water level are 0.36, 0.38, 0.42, and 0.47 m/s, respectively. Notably, the width of the flow separation zone at slopes of 60 and 75 degrees exceeds that of other cases, resulting in a greater flow separation at the water surface towards the opposite wall of the main channel. In summary, alterations in the slope of the lateral channel wall have a discernible impact on the flow dynamics at the confluence, influencing the dimensions of the flow separation zone and velocity distribution.

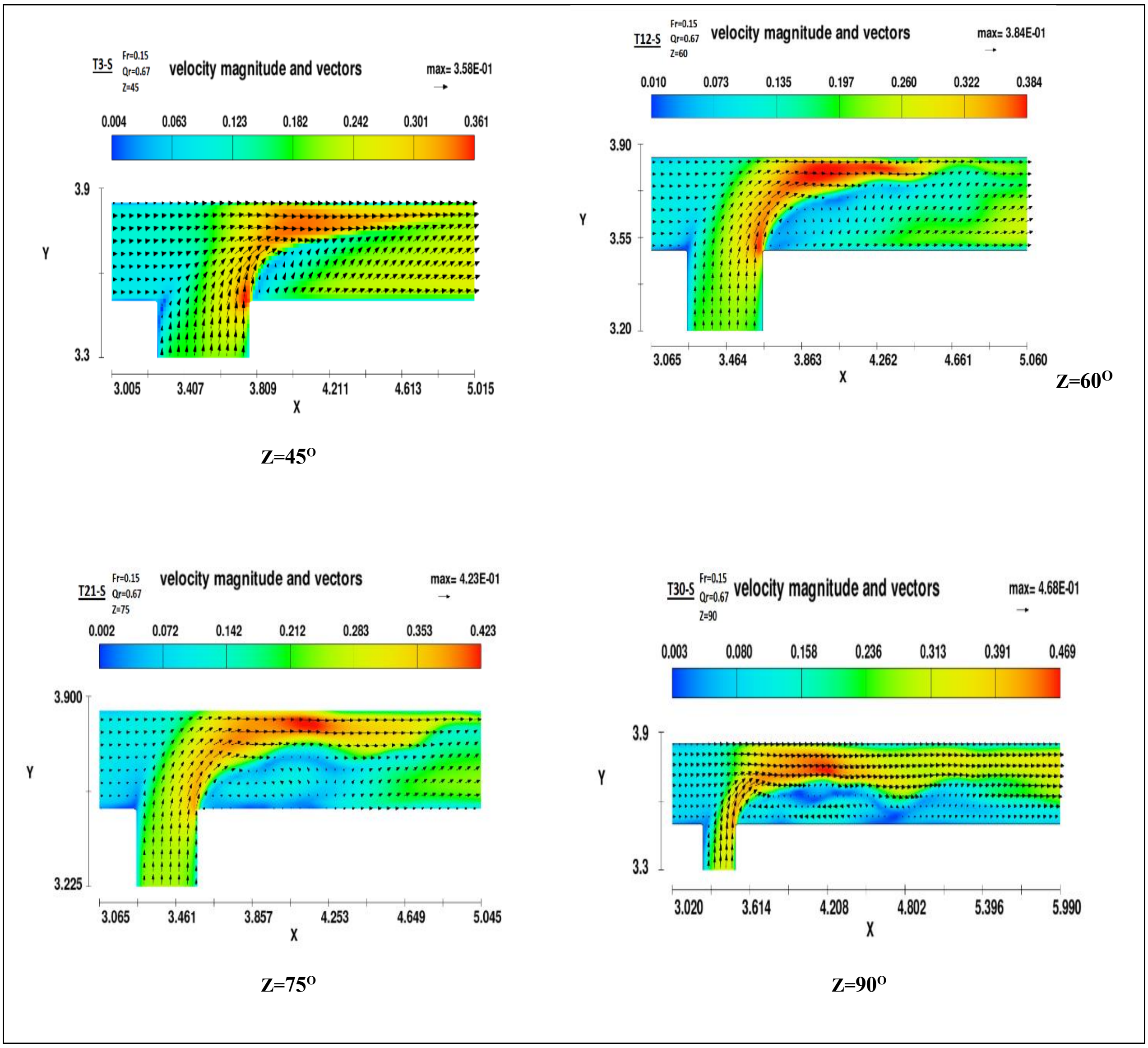



Figure 4: The effect of wall side slope of the tributary canal on flow dynamics near the water surface ($F_r$=0.15, $Q_r$=0.67

The results from Tecplot 360 software, as shown in Figure (5), provide valuable insights into the flow patterns near the water surface at the confluence. It is observed that the flow separation zone near the water surface exhibits distinct patterns across different side slopes/angles. At a 45° angle, just at the downstream edge of the junction towards the center of the main canal, a smaller dimension separation zone is evident. For a 60° angle, two types of rotating cells are observed, one rotating clockwise and the other counterclockwise. This pattern is also observed at a smaller scale for a 45° slope. Furthermore, at a 75° angle, the separation zone displays two different cores, with the separation zone shifting from the center of the main canal to the right wall of the main canal as the wall side slope increases. Notably, at a 90° angle, the dimensions of the separation zone, particularly its length, are significantly larger, covering a substantial area of the main canal.

The findings of the flow pattern in various cross-sections downstream of the intersection with different wall side slopes are illustrated in Figures 6 to 8. In section A-A, located at a distance of X=3.53 m from the source, the separation zone is not observed for slopes of 45, 60, and 75 degrees, whereas it is visible throughout the water column for a 90-degree angle. Moving to section B-B at X=3.73 m from the source, the separation zone is not observed at a 45° angle. The dimensions of the flow separation zone increase with depth as the angle and flow ratio increase, leading to obstruction of the main channel's flow path (Figures 6 and 7). Furthermore, the width of the flow separation zone is more pronounced at 60 and 75-degree angles compared to other cases, particularly evident in section C-C. At angles of 45, 60, and 75 degrees in section C-C, the separation zone forms near the water surface, extending towards the bed at a 90-degree angle. Figures 6 to 8 indicate that as the angle and discharge ratio increase at the same Froude number, the separation zone begins to form at the downstream edge of the junction, particularly noticeable at a 90-degree angle. The right wall's lateral angle of the secondary channel at 45, 60, and 75 degrees allows for further flow penetration from the tributary canal to the main canal, preventing the formation of a separation zone. In summary, a lateral wall angle of 45 degrees is deemed most suitable for preventing the formation of a flow separation zone with larger dimensions.

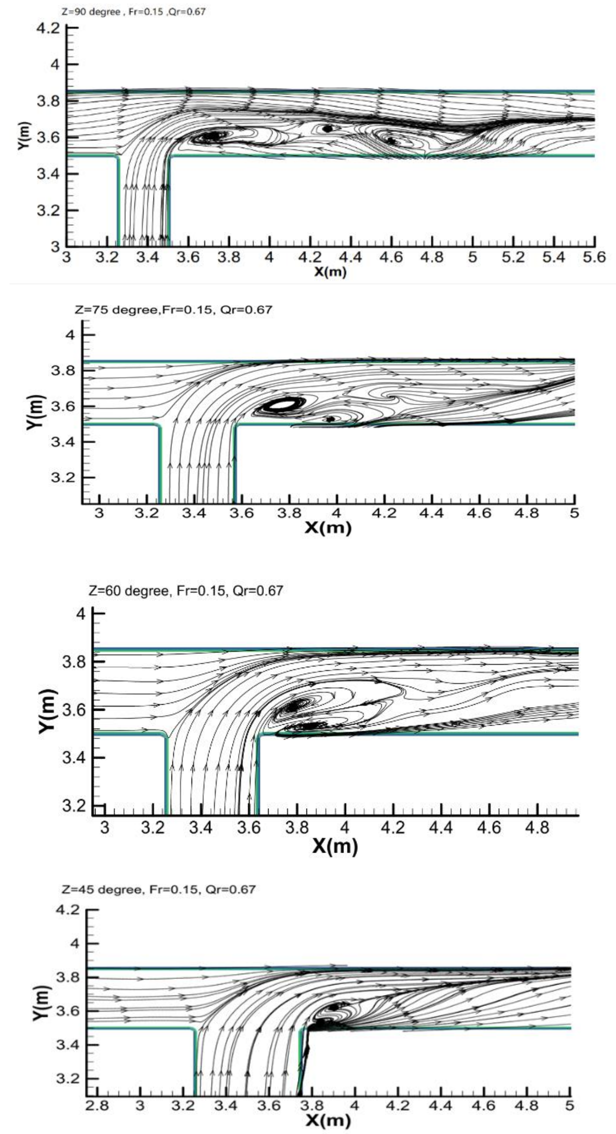



Figure 5. Stream lines at the junction with different wall side slopes of the tributary canal near the water surface (Fr=0.15, Qr=0.67)

### 3.2. Effect of the wall side slope of tributary canal on backwater at the upstream of the confluence in the main canal

Figure 9 illustrates that the ratio of water level upstream of the junction to its level downstream of the confluence is higher at angles of 60 and 75 degrees compared to 45 and 90 degrees, especially evident in higher discharge ratio ($Q_r$=0.67). This is attributed to the increased dimensions of the separation zone and subsequent obstruction of the flow path in the main channel, leading to a greater occurrence of water return upstream of the confluence. At low Froude numbers (0.15 and 0.26), the wall side slope does not significantly impact backwater upstream of the junction. However, at high Froude number (0.45) and high discharge ratio ($Q_r$=0.67), the water level upstream of the confluence increases by approximately 32% compared to the downstream water level for 60-and 75-degree side slopes, whereas this increase is less than 7% for other Froude numbers (0.26 and 0.15). For lower discharge ratios, the water level ratio upstream of the confluence is less than 5%. Jin et al. (2023) noted a decrease in the upstream-to-downstream water depth ratios as the downstream main branch were widened.

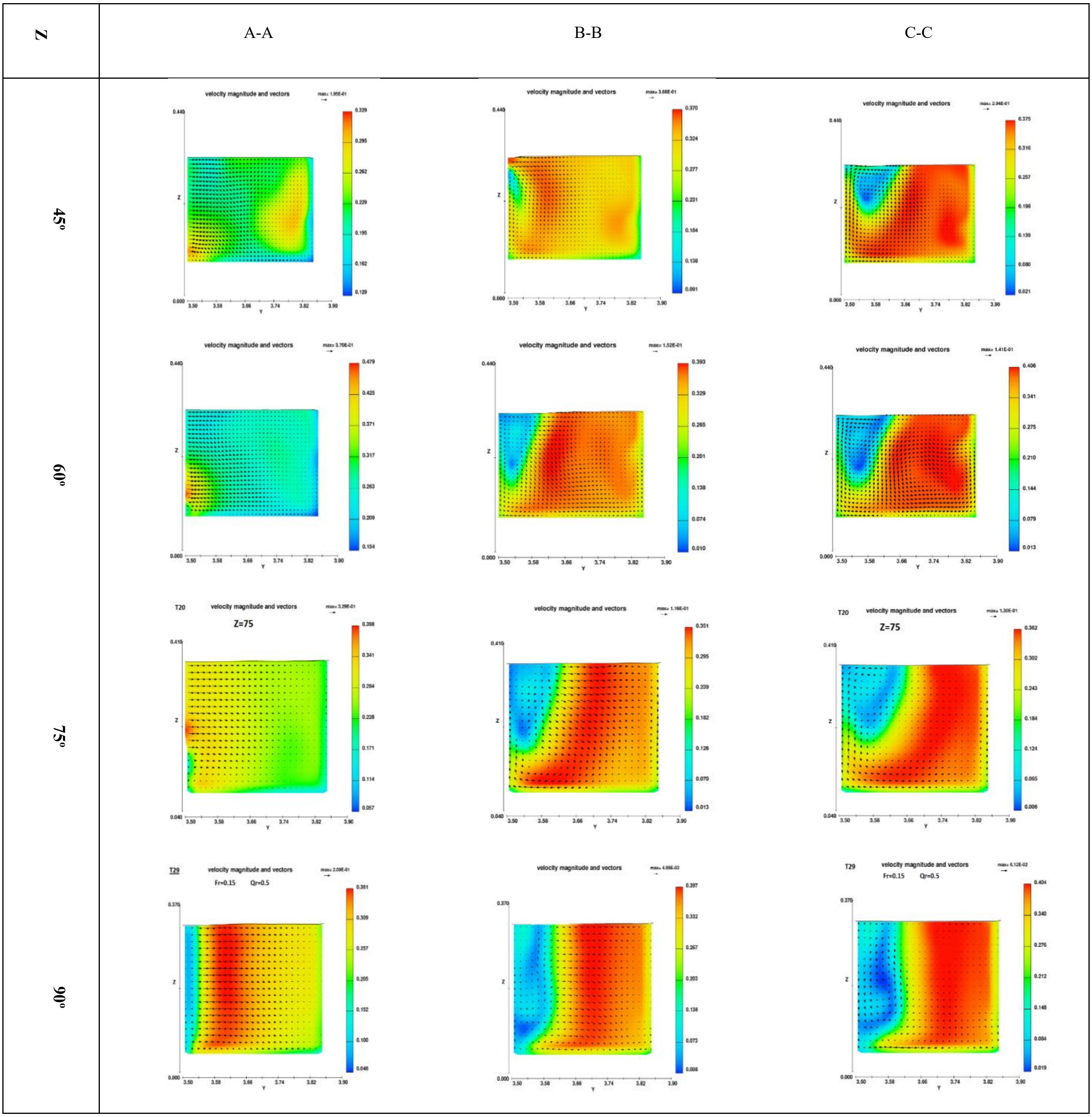



Figure 6 - Flow dynamics in different cross-sections ($F_r$=0.15, $Q_r$=0.5)

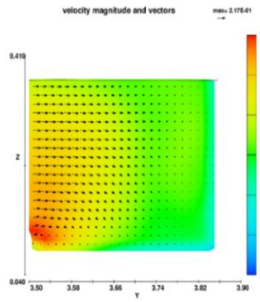
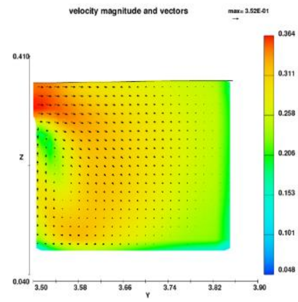
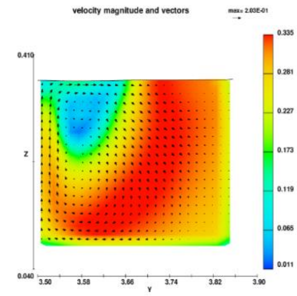
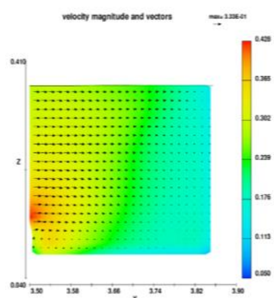
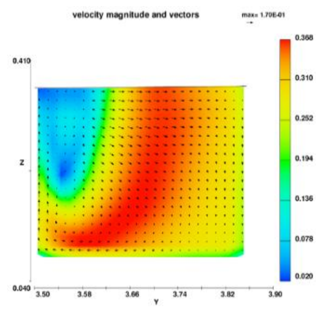
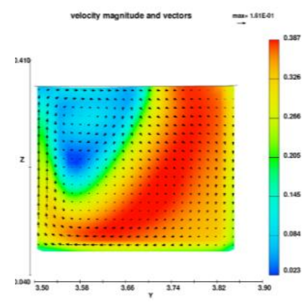
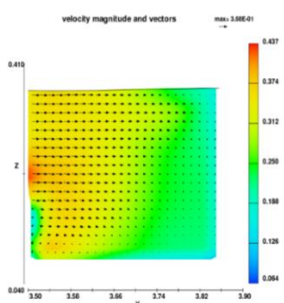
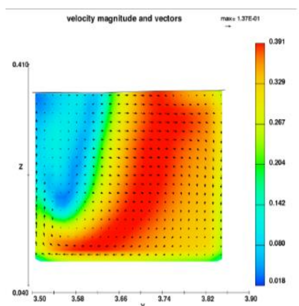
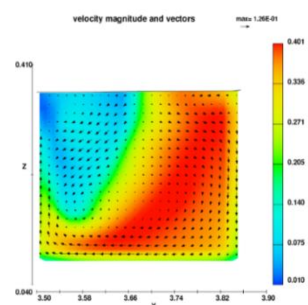
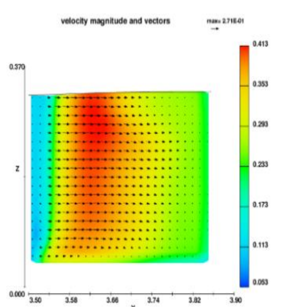
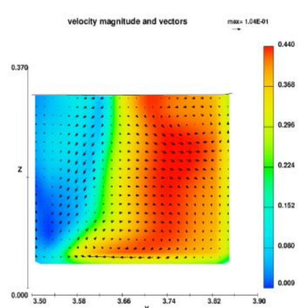
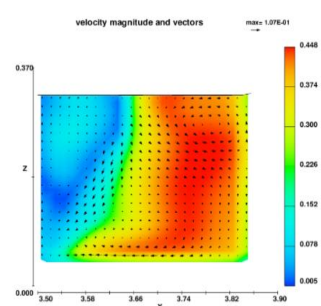
| Z | A-A | B-B | C-C |
|---|---|---|---|
| 45° |  |  |  |
| 60° |  |  |  |
| 75° |  |  |  |
| 90° |  |  |  |

Figure 7 - Flow dynamics in different cross-sections ($F_r$=0.15, $Q_r$=0.67)

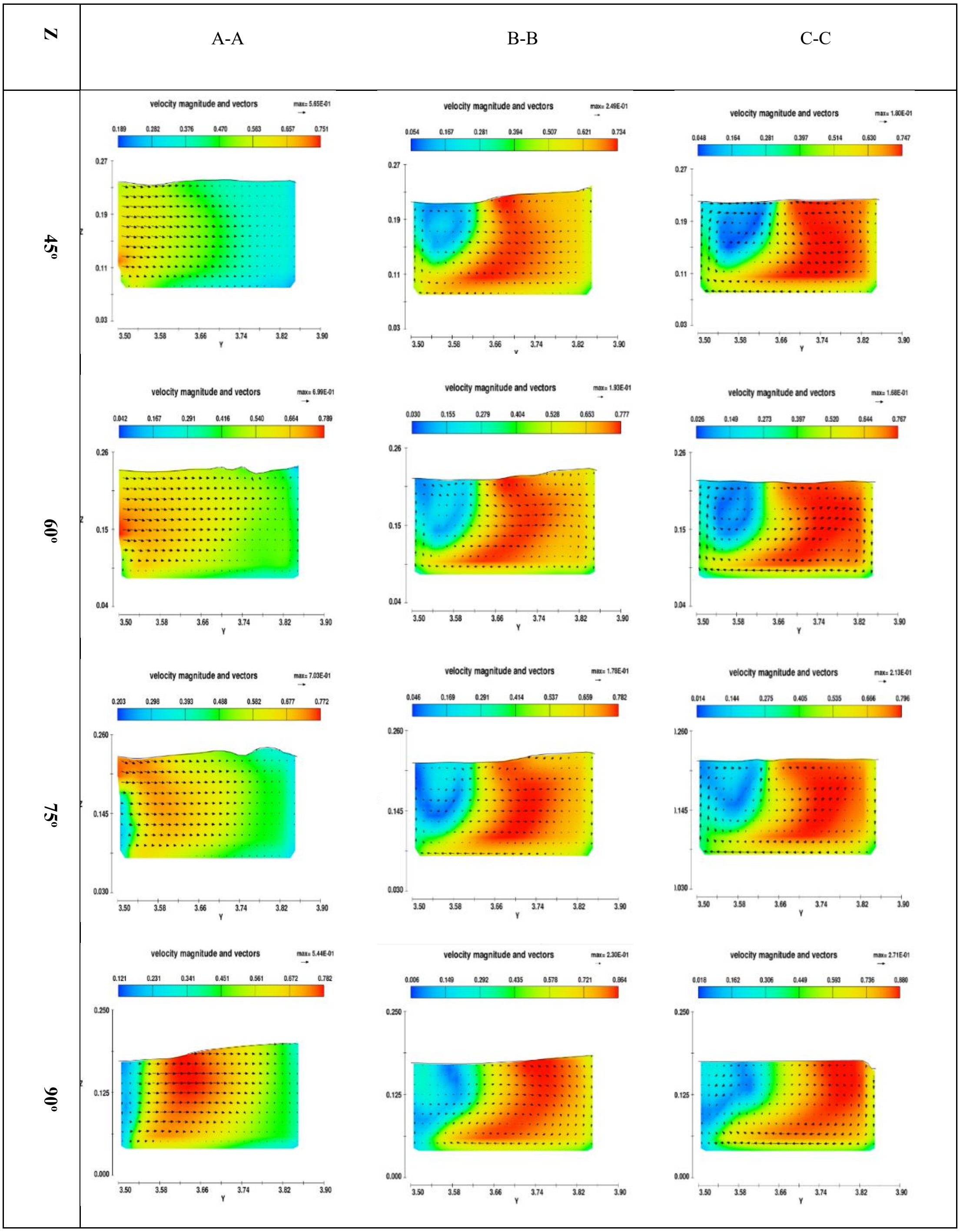



Figure 8 - Flow dynamics in different cross-sections ($F_r$=0.45, $Q_r$=0.67)

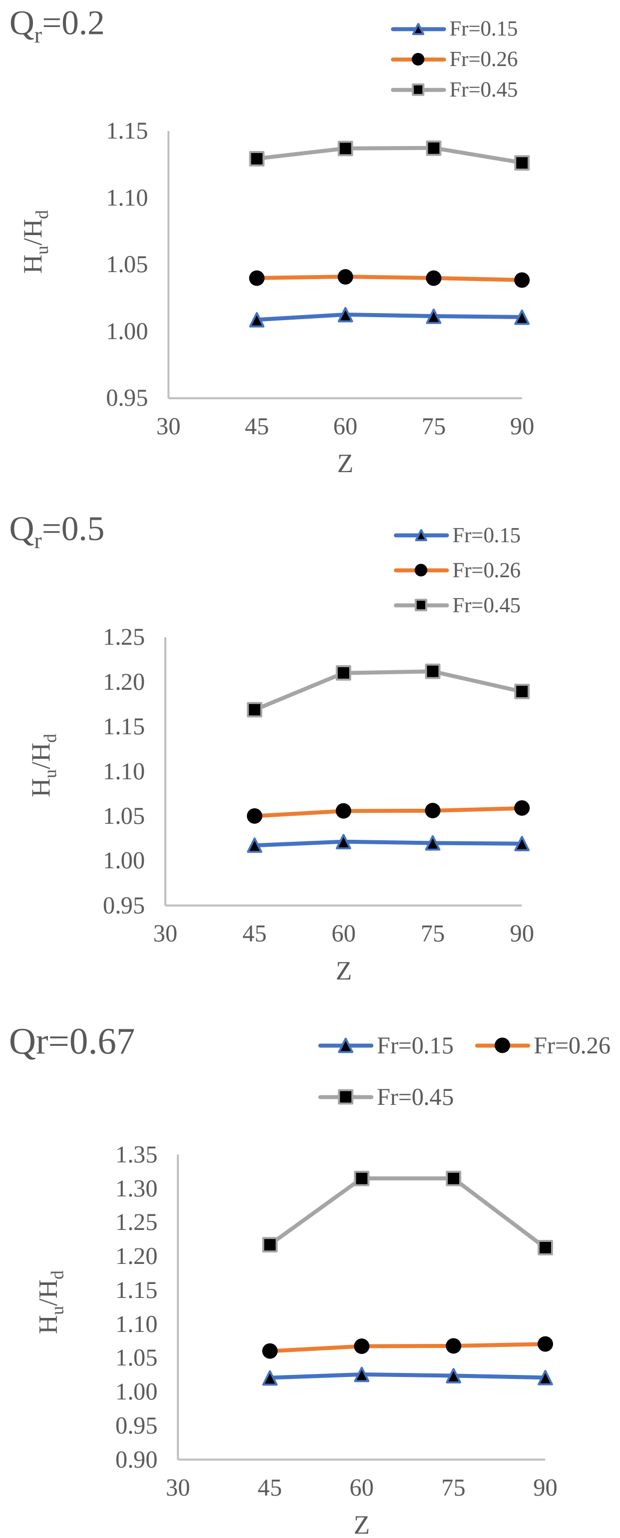



Figure 3. The effect of the wall side slope on the backwater upstream of the confluence in the main channel

## 4. Conclusions

In the current research, the Flow-3D numerical model was utilized to examine the impact of different wall side slopes, Froude numbers, and discharge ratios on flow dynamics at the junction of two canals. The results revealed that the impact of the wall side slope on the size of the flow separation area varies depending on its proximity to the bed and the water surface. Different side slopes resulted in varying effects on the formation of flow separation zones, with noticeable differences between 45, 60, 75, and 90-degree slopes. Furthermore, changing the wall side slope from oblique to vertical position led to an increase in the length of the separation zone near the water surface, reaching its maximum at a 90-degree angle. The length of the flow separation zone was observed to be lowest at a 45° angle and highest at a 90° angle. Additionally, the widest area of flow separation was observed at 60 and 75-degree angles, while the narrowest occurred at a 45-degree angle. This suggests that a wall side slope of 45 degrees is the most suitable in preventing the formation of a flow separation zone with larger dimensions. Moreover, the difference in water levels upstream and downstream of a confluence was found to be greater at 60 and 75-degree angles compared to 45 and 90-degree angles. This difference is attributed to the widening of the flow separation zone, causing obstruction in the main channel and increased backwater upstream of the confluence. Overall, these findings highlight the significant influence of wall side slopes, Froude numbers, and discharge ratios on flow dynamics at canal junctions, providing valuable insights for hydraulic engineering and river management.

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