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Behaviour of Hydraulic Parameters in Multiple Off-takes Branching Channels

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Abstract: River bifurcation is essential for flood control, irrigation and water management, where stable flow conditions are crucial. Sibu is a town in Sarawak that is prone to flooding and has a river bifurcation at a 90° off-take downstream of Sungai Rajang. The influence of off-take angles on hydraulic parameters, such as velocity, flow depth, and Froude number, in bifurcating rivers remains insufficiently understood, and this may be a reason for the continuous flooding. This study uses three-dimensional computational fluid dynamics (CFD) simulation through FLOW-3D to investigate the hydraulics behaviour in multiple off-takes branching channels. A trapezoidal channel with off-take angles ranging from 15° to 90° was modelled to analyse the effects on velocity, Froude number and flow depth. The model was validated with experimental data; the initial conditions such as water elevation and hydrostatic pressure were applied. The results revealed that smaller off-takes (15° to 45°) produced more uniform and subcritical flow with wider separation zones and greater flow depth in the branch channel. In contrast, larger angles (60° to 90°) led to higher velocity, increased Froude number and reduced flow depth. These findings highlight the sensitivity of hydraulics parameters to geometric changes and provide valuable insights for the design and optimization of river diversion projects and bifurcation systems.

Keywords: branching channel; off-takes angles; hydraulics parameter; FLOW-3D; CFD

1. Introduction

River bifurcation, where a single channel divides into two or more downstream channels are fundamental morphological features in both natural and engineered waterways. They occur in diverse environment such as delta and braided rivers to irrigation intakes and flood diversion structures. The hydraulic behaviour of a bifurcation is governed by complex interactions involving separation zones, secondary currents, turbulence, and energy loss, as shown in Figure 1. These complex interactions control how discharge, sediment, and momentum are partitioned at the downstream branches which may influence the channel's stability, sediment pattern and flood conveyance efficiency. Sibu is located in low-lying areas of Sungai Rajang and the river bifurcates into Sg. Igan and Sungai Rajang at 90° off-take downstream, flowing to the South China Sea. It is prone to flooding mostly due to high river flow and tidal effects. Recent work by Isia et al. (2023) highlighted that Sibu, Kuching, Bintulu and Miri had the highest physical exposure due to frequent flood events.

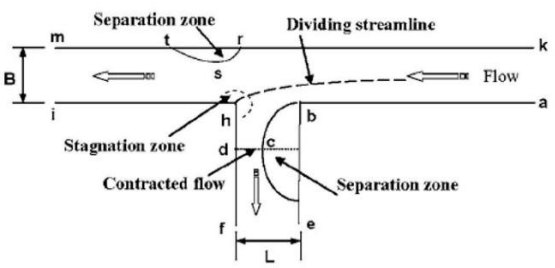

Fig. 1 – Hydraulic behaviour in a branching channel (Alomari et al., 2016)

There are studies on river branching on the discharge ratio and separation zones in the main and branch channels. River bifurcation is a complex process as it involves various parameters such as off-take angles, Froude number, cross-sectional area, water level and velocity. Previous studies have shown that the correlation between these parameters governs

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the efficiency of the discharge ratio and the development of recirculation zones.

In one of the most influential works, Hsu et al. (2002) established a theoretical framework for subcritical 90° dividing flow. They found the relationship between the discharge ratio, depth ratio (Y_w/Y_d) and downstream Froude number. Masjedi & Foroushani (2012) found that increasing the main channel flow depth consistently enhances the discharge ratio into the lateral intake in the river bend. This is because the Froude number decreases with increasing depth at a constant discharge. Thus, lower Froude number conditions are more favourable for diversion efficiency. Similarly, Sayed (2019) observed that the branch discharge ratio decreased with higher upstream velocity and Froude number, while greater upstream depth increases the discharge into the branch. This study also found that the depth within the branch channel was consistently lower than the flow depth in the upstream main channel.

Momplot et al. (2017) showed that the occurrence of a recirculation pattern in the branch can be predicted using upstream Froude number and channel aspect ratio, where the aspect ratio is directly dependent on flow depth. Higher flow depth leads to a lower Froude number, resulting in shallower and more stable separation zone. Extending the understanding, Montaseri et al. (2019) demonstrated that the dividing stream-surface varies vertically, where the dividing lines widen near the free surface and become narrow when they are close to the bed surface. This highlights that discharge ratio is depth-dependent across the vertical profile.

Recent research has shown that channel cross-sectional geometry also plays a critical role. Harmizi et al. (2023) developed simplified polynomial formulations comparing rectangular and trapezoidal channels, demonstrating that rectangular channels result in increasing flow depth at higher discharge ratios and Froude numbers. Complementing this, Zawawi et al. (2019) derived a mathematical model based on continuity and momentum conservation to predict river flowrates under various bifurcation angles. Their findings indicated that a 90° off-take angle could effectively reduce downstream flowrate, suggesting a solution for flood mitigation. In computational modelling, 3D simulations have enabled detailed visualization of bifurcation. Zakaria et al. (2023) used FLOW-3D to analyse a 90° off-take branching channel, confirming that separation length decreases as discharge ratio increases. Further works for multiple off-take angles (15° to 90°) found that moderate angle (30° to 45°) maximises discharge efficiency and separation width, while large angle (>75°) reduces intake and large turbulence (Zakaria et al., 2025). Importantly, both studies revealed that separation width exerts a stronger influence on discharge ratio than separation length, which provides new insights into geometric controls on bifurcation studies.

This study aims to discuss the effect of varying off-take angle in a trapezoidal branching channel on velocity, Froude number and flow depth distribution in the upstream, downstream and branch channel.

2. Methodology

This present study focuses on variations of hydraulic parameters in multiple off-take branching channels. The simulation setup consists of mesh configuration, initial and boundary conditions, and selecting a suitable turbulence model. The model was validated by comparing the simulation with experimental results to ensure its accuracy. Furthermore, a mesh convergence study was conducted to assess the numerical stability and reliability.

2.1 Study Area

Figure 2 shows the Rajang-Igan river bifurcation in Sibu. The Rajang River bifurcates into two nearly at 90° off-take angles and the amount of flow for the main and branch channels needs to be quantified. In addition, Sibu is located at the estuary of the Rajang River and is influenced by the tide. This study examines the effect of varying off-take angles, simplified by a straight channel and non-dimensionalised using Froude number, and validated using previous experimental results with a free flow outlet boundary condition using FLOW-3D.

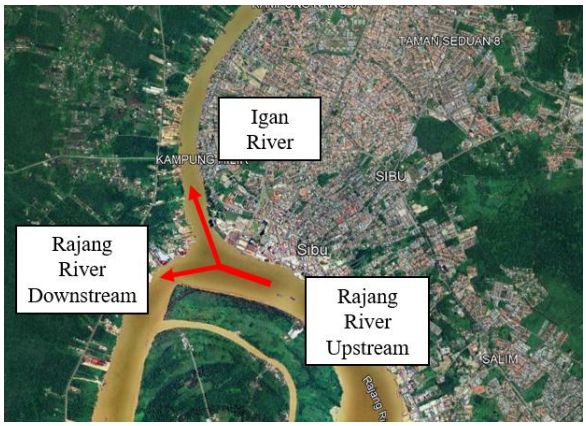

Fig. 2 – Location of the Rajang-Igan bifurcation in Sibu

2.2 Simulation Setting Up

Figure 3 shows the layout of the branching channels. The layout consists of a main channel upstream and downstream with a bifurcated channel. The Q_u represent the upstream discharge, whereas Q_b and Q_d is the branch and downstream discharge, respectively. The channel is a trapezoidal cross-section with a bottom width of 2.86 m, a side slope of 60° and a maximum water level of 1.8 m. The discharge diverts to the branch channel with multiple off-take angles, θ varying from 15° to 90°. The upstream discharge, Q_u was 10 m^3/s.

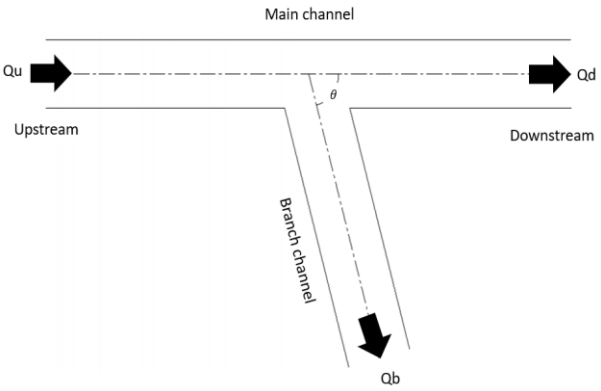

Fig. 3 – Simulation layout of bifurcation channels

2.3 Physics Options in FLOW-3D

Two main physics settings were applied: gravity and turbulence. Gravity was set in the vertical (z) direction at -9.81 m/s^2. The RNG turbulence model was applied with fluid properties based on 20℃. The wall shear boundary condition was automatically set to a no-slip condition when viscous flow was selected.

2.4 Initial and Boundary Conditions

The initial condition includes the water elevation and hydrostatic pressure. The discharge at the inlet boundary was increased gradually to the required discharge to lessen the effect of the immediate change of velocity, which results in a more stable simulation and shorter time to reach steady state. Figure 4 shows the setup in FLOW-3D with selected boundary conditions.

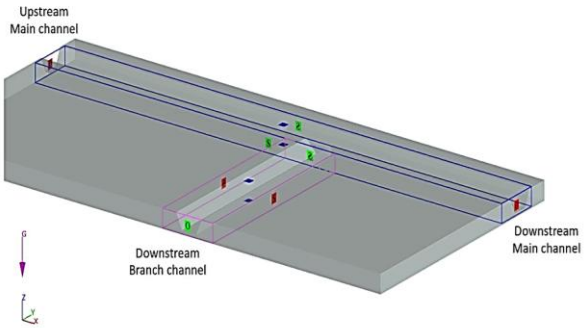

Fig. 4 – Selected boundary conditions

The boundary conditions used in the simulation are summarised in Table 1. The main channel inlet was assigned as a volumetric flowrate (Q) boundary to prescribe the constant discharge of 10 m^3/s. The downstream end of the main channel and downstream of the branch channel were both set as outflow (O) boundaries, allowing water to exit freely without backwater. These downstream end boundary conditions assumptions were made to offer simplified cases and to be validated with previous experimental works. The top of the channel was defined as a pressure (P) boundary to represent the free surface open to atmospheric pressure, while the channel bed was kept as a symmetry (S) boundary, following the default setting to represent no shear or penetration through the bed.

Table 1 – Boundary conditions applied in the simulation

Boundary Location	Boundary Condition
Main channel upstream (inlet)	Volumetric Flowrate (Q)
Main channel downstream (outlet)	Outflow (O)
Branch channel downstream (outlet)	Outflow (O)
Top of channel	Pressure (P)
Bottom of channel	Symmetry (S)

2.5 Model Validation

The model was validated with laboratory experiment data from Sayed (2019). The effect of varying upstream discharge on the discharge ratio (Q_d/ (Q_u) was observed in FLOW-3D simulation to ensure the simulation is reliable for further analysis.

A 90° branching channel configuration with 8.0 m of main channel and 3.0 m of branch channel length was set up. Both channels had the same depth and width of 0.2 m. The downstream of the main and branch channels was free from any hydraulic structure such as weirs.

Figure 5 shows the result of model validation. Fives upstream discharges, Q_u of 1.19, 1.78, 2.47, 3.37, and 4.00 L/s were simulated. From the result, Q_u increased with decreasing Q_r. The results of FLOW-3D simulation and experimental data differ in values but show good agreement in terms of overall trend. This validates that the simulation can recreate the 90° off-take branching channel

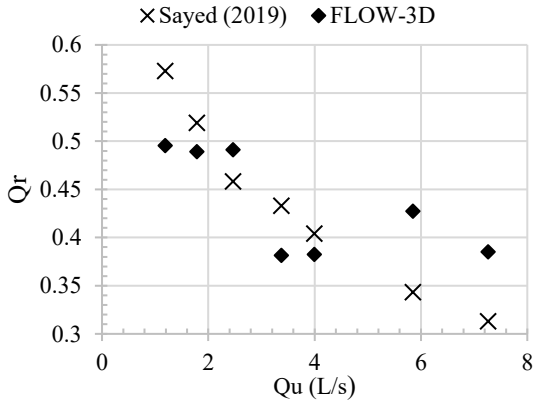

Fig. 5 – Model validation results

2.6 Mesh Convergence Study

To ensure numerical reliability, a mesh convergence study was conducted in continuation of the work by Zakaria et al. (2025). Three mesh sizes, namely Mesh 1 (0.2 × 0.2 × 0.2 m), Mesh 2 (0.1 × 0.1 × 0.1 m), and Mesh 3 (0.08 × 0.08 × 0.08 m) were evaluated. The mesh convergence demonstrated an average error of 4.77% between Mesh 1 & Mesh 2, and 6.58% between Mesh 1 and Mesh 3. across all off-take angles. The average error for Mesh 1 and Mesh 2 remained below 5%, validating the use of the coarser mesh for simulating a multiple off-take branching channel is sufficient.

2.7 Vertical Confinement

In addition, vertical confinement analysis was undertaken to assess the flow structure across the depth. Both 90° and multiple off-take angles revealed that velocity distribution and separation zones were nearly identical across vertical slices resulting in separation zones that are vertically homogeneous (Zakaria et al., 2023, 2025). This result indicates that a surface can adequately represent three-dimensional separation dynamics, thus simplifying analysis and simulations.

3. Results and Discussion

In this section, the correlation between the variations of hydraulics parameter and discharge ratio is discussed.

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3.1 Velocity distribution at various off-take angles

Table 2 presents the variation of velocity in the upstream (V_u), downstream main channel (V_d), and branch channel (V_b), for bifurcation angles ranging from 15° to 90°. These results highlight the influence of off-take angles on flow diversion and velocity distribution across the channels.

From the result, when the off-take angle is between 15° and 45°, V_u remained nearly constant, varying from 1.52 to 1.53 m/s, while V_d was slightly lower, ranging from 1.36 to 1.39 m/s. V_b were the lowest (0.10 – 0.12 m/s), indicating only small fraction of flow was diverted into the branch channel at lower off-take angles.

At off-take angle 60° to 75°, V_u increased to between 1.68 and 1.78 m/s, indicating that the flow constriction at the junction becomes less. V_d showed a similar increase to between 1.32 and 1.52 m/s, while V_b increased to between 0.16 and 0.25 m/s, reflecting greater discharge diversion into the branch.

At 90°, a significant change was observed. V_u reached its maximum velocity (1.99 m/s) while downstream velocity dropped to 1.20 m/s. V_b increased to 0.71 m/s, indicating that 90° off-take angle strongly influences the discharge into the branch, but results in higher energy loss and velocity reduction in the main channel.

Table 2 – Upstream, downstream and branch velocity

θ	V_u (m/s)	V_d (m/s)	V_b (m/s)
15°	1.52	1.36	0.12
30°	1.53	1.39	0.10
45°	1.52	1.36	0.10
60°	1.78	1.52	0.16
75°	1.68	1.32	0.25
90°	1.99	1.20	0.71

3.2 Froude Number distribution at various off-take angles

Table 3 shows the variation of upstream Froude number ($Fr_{u)}$, downstream main channel Froude number (Fr_d) and branch channel Froude number (Fr_b) for off-take angles from 15° to 90°. These values provide insights into relative flow regime transitions and energy distribution across the bifurcation systems.

At off-take angles between 15° and 45°, Fr_u remained nearly consistent at 0.38, while downstream Fr_d ranged from 0.346 to 0.364. Fr_b is the smallest (0.032 to 0.035), reflecting subcritical and relatively weak flow entering the branch.

When the off-take angle is from 60° to 75°, both Fr_u and Fr_d increased to 0.472 and 0.434 upstream, and 0.410 and 0.35 downstream, respectively. The branch Froude number also increases slightly from 0.054 to 0.077, indicating the increased of branch conveyance as the off-take angle increased.

At 90°, the upstream flow accelerated further with the highest Fr_u at 0.549. In contrast, the Fr_d decreased to 0.313 while Fr_b increased to 0.196. This behaviour reflects the strong diversion of flow and energy into the branch channel at greater off-take angle, consistent with the observed velocity distribution, but also highlights increased head loss and inefficiency in the main channel.

Overall, the results demonstrate that a larger off-take angle enhances branch channel flow and energy but reduces efficiency in the main channel, with the most significant contrast occurring at 90°. These findings align with previous bifurcation studies, where higher angles are associated with stronger separation zones and more pronounced redistribution of momentum. For Sibu, it is expected that the upstream water levels will rise and conveyance will decrease at the Rajang-Igan bifurcation, intensifying flood risk during high flow and tidal events.

Table 3 –Froude Number in each channel

θ	Fr_u	Fr_d	Fr_b
15°	0.380	0.346	0.035
30°	0.382	0.364	0.032
45°	0.377	0.348	0.034
60°	0.472	0.410	0.054
75°	0.434	0.350	0.077
90°	0.549	0.313	0.196

3.3 Changes in Flow Depth with Various Off-Take Angles

Table 4 presents the variation of upstream flow depth upstream (Y_u), downstream flow depth (Y_d) and branch channel flow depth (Y_b) with various off-take angles ranging from 15° to 90°. These values illustrated how flow depth responds to the change in junction geometries.

At off-take angles from 15° to 45°, the flow depths were relatively uniform across all channels, between 1.72 m and 1.79 m. Y_u and Y_d were nearly identical while the branch channel exhibited slightly higher depth, 1.74 m to 1.79 m, reflecting minimal disturbance in water surface profiles at lower off-take angles.

As for the off-take angles of 60° and 75°, a more noticeable variation was observed. Y_u decreased to 1.52 and 1.60 m, respectively, while Y_d increased slightly to 1.55 and 1.64 m, respectively. Y_b remained comparable between 1.55 m and 1.61 m. This indicates a redistribution of energy and water levels, where the branch diversion increased but without a significant drawdown in the main channel.

At 90° off-take angle, the most significant changes occurred. Y_u dropped to 1.40 m while Y_d and Y_b decreased to 1.49 m and 1.36 m, respectively. This reduction reflects the strong hydraulic losses associated with 90° off-take angles, where the flow separation and turbulence caused the significant water level changes.

Table 4 – Changes in flow depth in various off-take angles

θ	Y_u (m)	Y_d (m)	Y_b (m)
15°	1.729	1.732	1.791
30°	1.722	1.724	1.740
45°	1.734	1.743	1.751
60°	1.528	1.555	1.548
75°	1.600	1.639	1.612
90°	1.397	1.493	1.363

3.4 Discharge Ratio and Hydraulics Parameter Correlations

Figure 6 showed the variation of discharge ratio (Q_r) with off-take angles. The discharge ratio is the ratio of downstream (Q_d) to upstream discharge (Q_u). The results indicate that Q_r decreased with increasing off-take angles from 15° to 90°. When the off-take angles increased from 15° to 45°, Q_r results to more than 0.85, before gradually decreasing from angles of 60° to 90°. The lowest Q_r observed is at the 90° diversion. This trend highlights the decrease in

the efficiency of flow diversion into the branch channel as the off-take angle increases.

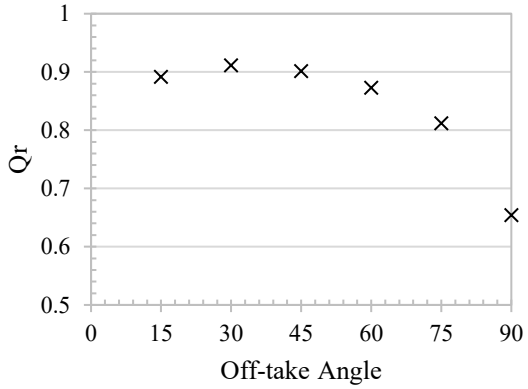

Fig. 6 – Discharge ratio with various off-take angles

The discharge ratio behaviour correlates closely with the observed velocity, Froude number and flow depth variations. At lower angles (15° to 45°), Q_r results in balance velocities between the main and branch channels and uniform flow depths. The branch Froude number is very small, reflecting weak inertial energy despite the greater discharge ratio flowing into the downstream channel. This is because the separation width is greater at lower off-take angles, while the separation length decreases (Zakaria et al., 2025).

As the off-take angle increased from 60° and 75°, Q_r slightly decreased. This reduction aligns with an increase in upstream velocity and Froude number, and a slight drawdown in flow depth. These indicate that flow separation and turbulence began to influence the junction, reducing the discharge ratio into the branch even as branch velocities and Froude number increased moderately.

At 90° off-take angle, Q_r decreased significantly to 0.65, consistent with the strong flow separation observed at the 90° junction (Zakaria et al., 2025). The upstream velocity is the highest at 1.99 m/s while flow depth dropped to the lowest value of 1.40 m, resulting in the highest Froude number. In the branch, both velocity and Froude number increased significantly, indicating a smaller separation and greater discharge flows into the branch. The overall reduction in Q_r at 90° angle reflects inefficiency, causing turbulence and energy loss at the junction.

These findings confirm the correlation of discharge ratio, velocity, Froude number and flow depth. A lower off-take angle enhances a higher discharge ratio with stable subcritical flow. While at greater off-take angles enhances branch flow energy but reduces the efficiency, resulting in greater hydraulic losses in the main channel.

4. Conclusion

This study aims to study the variation of velocity, flow depth and Froude number with different off-take angles. At off-take angles between 15° and 45°, the main and branch channels maintained balanced velocities and uniform depth. while the branch Froude number remained small, reflecting stable subcritical flow with minimal turbulence. For off-take angles of 60° and 75°, the discharge ratio decreased slightly as upstream velocity and Froude number increased. The flow depth decreased. As for 90° off-take angle, a significant change was observed. The upstream velocity reached its maximum velocity while the downstream velocity decreased. The velocity at the branch increased. This indicates that the 90° off-take angle strongly influences the discharge into the branch, but results in higher energy loss and velocity reduction in the main channel. These results provide a clear hydraulic explanation for recurrent flooding. The sharp angle enhances turbulence, separation and energy loss, which reduces downstream conveyance capacity and elevates upstream water level during high flows. Thus, lower and moderate off-take angles support efficient and balanced flow diversion.

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