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SIMULATING CHANNEL BIFURCATION FLOWS WITH WEIRS FOR FLOOD RISK REDUCTION

NG K.J.[1], TAN C.Y.[1*], SELVARAJOO A.[1], HANIFFAH M.R.M.[2], KASIMAN E.H.[2], LAI S.H.[3], YUAN D.[4], TEO F.Y.[1]

[1] Faculty of Science and Engineering, University of Nottingham Malaysia, 43500 Semenyih, Selangor, Malaysia
[2] School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[3] Department of Civil Engineering, Universiti Malaya, Kuala Lumpur, 50603, Malaysia
[4] Department of Mechanics, Tianjin University, Tianjin 300072, China

[(*)] *keey5tcy@nottingham.edu.my*

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ABSTRACT

Weir is widely used for controlling the flow discharges and water levels of a bifurcated river for flood risk reduction. The effects of weir on the bifurcation flow properties and hydrodynamic processes were not systematically studied by previous research, some of these have limitations and only showed that the discharge ratios were varied by the changes of weir height. Thus, there is a need to further explore on the effect of overall weir geometry and weir location on flow properties. In this study, an one-dimensional (1D) numerical model of Hydrological Engineering Centre - River Analysis System (HEC-RAS) has been applied to simulate an idealised channel with the applications of a variety of weir geometries at various locations. The model has been set to simulate a U-shaped main channel with two identical U-shaped bifurcated channels. Simulations have been undertaken for the weirs with cross-sectional shapes of rectangular, Cipolletti (trapezoidal), and V-notch (triangular). Comparisons of velocity profiles and water elevations with different Froude numbers have been undertaken. The results present the relationships of the outlet discharge ratio and velocity ratio to weir height, crest length, and crest angle ratio with different cross-sectional shapes and locations of weir. The findings show that flood risks could be potentially reduced by understanding the flow behaviours of channel bifurcation with presence of weirs as controlled structure.

Keywords: Bifurcation channel, flood risk, HEC-RAS, numerical model, Froude number

INTRODUCTION

River bifurcation is an integral process that involves elements of alluvial fans, braided rivers, fluvial lowland plains, and deltas. It determines the partitioning of water flow and sediments along the downstream branches (Kleinhans et al., 2012; Bertoldi, 2004). Out of many geomorphological systems, the understanding for river bifurcations is critical but inadequate (Kleinhans et al., 2012). Suggested by Schielen and Blom (2018), river bifurcations are normally existing in braided rivers, alluvial fans, anabranching rivers, cut-off channels, diversions for flood control or water intakes, and in constructed side channels as part of the river restoration schemes. The study on bifurcation is a major piece of puzzle in engineer's design of flow bifurcating hydraulic structure for flood control, irrigation river navigation, and other applications in floodplains (Caddis et al., 2012; Cheah et al., 2019; Shah et al., 2020). Schielen and Blom (2018) predicts the changes in bed elevation and bed surface gravel content in two bifurcated channels. This study suggested that the stability of the two open downstream branches is determined by the partitioning of the sediment load over the bifurcates. Some of the early research studies on one-dimensional (1D) model described the development of bifurcation towards the equilibrium states for different bed materials. These include sand-bed rivers by Wang et al. (1995) gravel-bed rivers by Bolla Pittaluga et al. (2003) and suspended bed-material load by Slingerland and Smith (1998). Among these studies, Wang et al. (1995) have carried out the first bifurcation research that introduce nodal point relation to describe the partitioning of the sediment and discharge.

Schielen and Blom (2018), have stated that river bifurcations can only found in alluvial fans, braided rivers, anabranching rivers, deltas, cut-off channels, diversions for flood control or water intake, and in constructed side channels that are part of river restoration schemes. Bolla Pittaluga et al. (2003) also stated that bifurcations are unit processes that are important for development of braided river networks. Particularly, weak variations of the geometry of a bifurcation may strongly affect water and sediment partition into the downstream branches. The morphology and development of a bifurcation is largely affected by the dominant sediment transport mechanism which eventually determines the partitioning of sediment discharge into the two downstream branches. Other study by Hoey (1992), highlighted the sensitive dependence of braided rivers on conditions at bifurcations. A first attempt to describe river bifurcations with movable bed has been done by Wang et al. (1995). The authors have introduced an empirical nodal point condition for a simple geometry sketch of bifurcation which relates water and sediment discharges into the downstream branches. They proposed the following nodal point conditions for: water discharge balance, sediment discharge balance, and constancy of water level. Bolla Pittaluga et al. (2003), have formulated an alternative based on a quasi-two-dimensional approach to overcome this difficulty.

Other than that, several previous studies have investigated the effect of branching angles on the river flow rates. As mentioned by Sayed (2019), this study aims to investigate the percentage of discharge diverted to the branch channels. Studies on branching channel flow have focused on the flow characteristics, such as branching flow discharge and regimes. Sayed's study showed that highest discharge rates were achieved when the angle of branching was equal to 45˚ and then an angle of 60˚, whereas at an angle of 90˚, lowest discharge rates were obtained. This is related to the way that the branch channel and the main channel are connected, which causes the disturbance in the flow and loss of energy in the branch region. Branching channel flow was considered a very complicated flow as it is depending on many factors. For example, controlling structures at the end of the main and branch channel may change the flow rates of the stream. Furthermore, based on a study by Mohd Zawawi et al. (2019), on the effects of bifurcation angles in river flow rates, they found that the right-angled bifurcation at one of the branches would be efficient to reduce the amount of flow rates in Channel 1 greatly. Thus, this study showed that appropriate angles of bifurcation can help to reduce the flow rates after bifurcated junction so that it is below the critical flow rates. The implementation of right-angled bifurcation can be a way to mitigate flood events. However, the actual locations for flood mitigation purposes were not clearly stated.

Bifurcations play a fundamental role in determining the downstream partitioning of fluid and momentum (Miori et al., 2012). The study of channel junctions and control structure is a crucial topic in river engineering. The design of a channel bifurcation and control structure requires an accurate analysis of the flow field, e.g., water surface elevation and discharge subdivision in the branches (Zanichelli et al., 2004). In general, the flow carrying capacity of a flood control structure is determined based on a design flood for a specific return period. The weir is considered as one of the oldest hydraulic control structures used to measure the flow of water in open channels. Weirs are used for flood risk reductions and applications in open channel flows. They commonly act as a flood control and flow regulator devices.

Based on Thomas et al. (2011), water surface was controlled, and systematically varied using the application of weir in each distributary. The downstream water surface gradients within the distributaries were systematically altered from equality by lowering or elevating the exit control weirs. The results from the study showed that when two exit control weirs were of equal elevation, the water surface gradients in the distributaries were also equal, the discharge partitioning was, as would be expected in a symmetrical bifurcation, also equal. When the weirs had different angles, the distributaries with the lowest weir conveyed the largest discharge and vice versa. Discharge partitioning for the experimental set was found to be a function of the inverse weir height ratio. Study on the weir cross-sectional shape and its location are still poorly characterised. Also, none of the above work analyses river bifurcation in U-shape channel.

The capability of the control structure to restrain certain amount of flow is very important in flood mitigation. Thus, in this study, different geometries of the weir will be investigated to find out the most appropriate geometry of the weir to control flood. The application of a numerical model allows an alternative approach to understand the hydrodynamics of an idealised U-shape bifurcation channel. One-dimensional (1D) numerical model of Hydrological Engineering Centre - River Analysis System (HEC-

RAS) will be selected to simulate steady and gradually-varied flow model in this study. This open source software solves the 1D energy equation by using standard step method (Brunner, 2010). This model will be simulated for different parameters of weir geometry and various locations of weir. The main objective of this study is to investigate the hydrodynamic flow behaviours of the bifurcation channel. The model will be applied for the weirs with cross-sectional shapes of rectangular, Cipolletti (trapezoidal), and V-notch (triangular). Velocity and water profiles will be recorded with proper validation procedures.

METHODOLOGY

In this study, the numerical model setup is necessary to determine the inputs that are suitable and logical for simulation of a bifurcation system. The geometry setup of this study was based on Thomas et al. (2011), a 0.5m-wide inlet main channel followed by a symmetrical bifurcation with 0.25m-wide equal-width outlet distributary channels. In the model setup, the width of the outlet distributary channels would be set to half of the inlet main channel and equal-width for both distributary channels. The depth of the channel of present study would be same as the width of the outlet distributary channel.

Choice of the bifurcation angle, δ was based on the work by Federici and Paola (2003) which stated that stable bifurcations occur when $60^\circ < \delta < 90^\circ$. As suggested by Hardy et al. (2011), particularly large bifurcation angles will cause instability as they increase the flow velocity along the inner bank. In branching flow study, the highest discharge rate was achieved when the branching angle was 45˚ whereas, lowest discharge rate was obtained when branching angle is 90˚. This condition may be due to increase in difficulty in diverting the water caused by phenomenon of continuity when the branching angle increases (Sayed, 2019). Thus, the bifurcation angle in the present study would be chosen so that it is close to the mid-range which was reported by Sayed (2019) and is still controlled within the range suggested by Hardy et al. (2011).

Different kinds of weirs were classified based on cross-sectional shape, plan view or the crest length (Bijankhan and Ferro, 2017). Rectangular, triangular, Cipolletti and circular are some of the important and common cross-sectional shapes of weirs (Kumar et al., 2012). Bijankhan and Ferro (2017) have studied regarding the flow over triangular, labyrinth, parabolic, elliptical and W-weirs. In the present study, however, three different cross-sectional shapes of the weir which are commonly adopted by the others would be considered. They are rectangular, Cipolletti (trapezoidal) and V-notch (triangular). Refer to Table 1, weir crest shapes can be classified into four categories based on the ratio of upstream water depth, h to weir width, W ratio (h/W ratio) (Hager and Schwalt, 1994).

Table 1: Classification of weir based on weir crest shapes

Long-crested weir	**0 < h/W ≤ 0.1**
Broad-crested weir	0.1 < h/W ≤ 0.4
Short-crested weir	0.4 < h/W ≤ 2
Sharp- crested weir	h/W > 2

Other than typical shape of weir, compound shaped weir could be implemented in the study of bifurcation flow. However, Kulkarni and Hinge (2021) mentioned according to previous studies, manufacturing compound shaped weir for accurate discharge measurement was a challenge work. This may have significant impact on the bifurcation flow when compound shaped weir is implemented in the study. Therefore, more study can be conducted for further understanding the effect of compound shaped weir on the flow properties of bifurcation flow.

In this study, further analysis would be based on the work that carried out by Joseph (1978) on a trapezoidal shaped broad crested weir. One characteristic that is important to be taken into consideration is the side slope of the trapezoidal weir. The sides of the Cipolletti weir inclined outwardly at a slope of 1 horizontal : 4 vertical (USBR, 2001). V-notch weir might manage the discharges of normal range at a structure easily. But sometimes, this kind of weir is not capable to sustain larger flows. This is due to the relatively greater head required for a small flow compared to other weirs. Although sharp-crested rectangular and Cipolletti weirs were sometimes used for measuring small flow, V-notch weir was more sensitive and accurate in measuring small flows. Thus, it was recommended to use V-notch when such flow measurement is required (USBR, 2001).

Based on this theory suggested by USBR (2001), it could be concluded that V-notch weir carried less flow than trapezoidal and rectangular weir. So, in the present study, the inlet discharge for V-notch weir would set to be smaller than trapezoidal and rectangular weir. Hydrological Engineering Centre - River Analysis System (HEC-RAS) was used to simulate the river model. An idealised channel would be considered. Some of the conditions of the real river will be idealised to simplify this investigation. Surface roughness of the channel would be idealised by setting the value of Manning's roughness coefficient, n in the software to be 0.015 and 0.035 for channel and riverbanks respectively. These values would be adopted for the whole stretch of the channel under this study, which is not the case for a real river. Another assumption is that, in the software, the water used was clear water with no presence of sediments. Thus, making sure that the water is of constant density and viscosity along the channel.

Furthermore, another assumption is that no water is going in or out of the channel to achieve conservation of mass ($Q_{in} = Q_{out}$). Thus, infiltration would not present along the channel and the riverbed was considered as non-porous which was untrue in a real scenario. In addition, in an idealised channel, precipitation of rainwater and evaporation of river water was neglected. Also, the ground water table of the riverbank would not affect the water in the channel under study. Next, the channel would have a uniform geometry and shape of cross section along the river. The channel cross sections were considered irregular section from semi-circle U-shape channel for the upstream channel to semi-ellipse U-shape channel for the downstream channels respectively. The two symmetrical outlet distributary channels have identical characteristics in term of channel length, width, and angle of the channel from the centreline.

Firstly, river reaches were created in geometric data for the river geometry. These reaches would be drawn from upstream to downstream. Length of each reach was 20m. Reaches A, B and C indicated mainstream and two bifurcated streams respectively. Reach A would meet at Junction 1 and bifurcated to form Reach B and Reach C which were symmetrical. Each bifurcated stream was branched at 30˚ which formed 60˚ bifurcation angle (called tributary angle in HEC-RAS) at Junction 1. The junction lengths would be set to be 10m. Steady flow computation mode with momentum equation would be selected as the modelling approach for this junction. This was because the energy equation did not consider the angle of the tributary entering or exiting, while momentum equation did. It was more appropriate to use momentum equation if the tributary angle would cause significant energy loses (HEC-RAS 5.0 Users Manual).

Figure 1 shows the overall layout of the reaches. Reach A as upstream channel was divided into two downstream branches named Reaches B and C. This simulated the Y-shaped symmetrical fluvial bifurcation. The upstream channel cross section was a semi-circle U-shape channel with 2.5m depth and 5.0m width whereas downstream channel was a semi-ellipse U-shape channel with 2.5m depth and 5.0m width. This study focused on the channel flow, the cross section was set without left overbank and right overbank. Manning’s n value was set 0.035 for the channel. Contraction and expansion coefficients were set as 0.1 and 0.3.

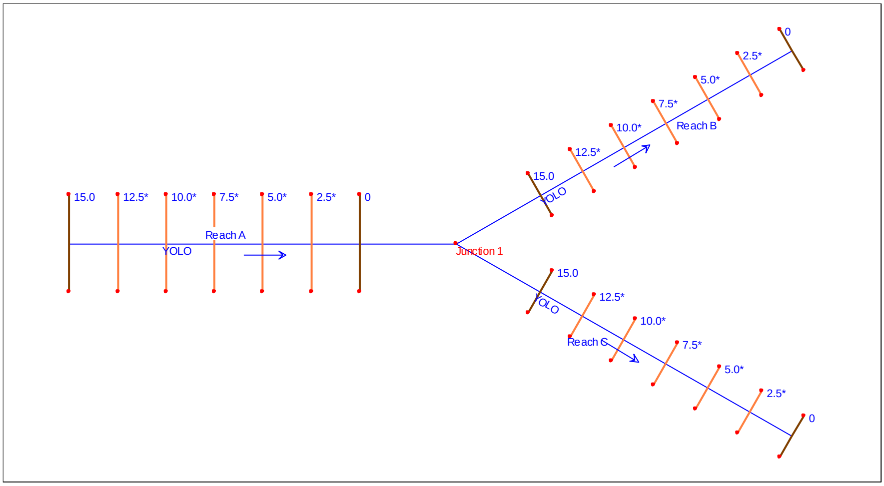
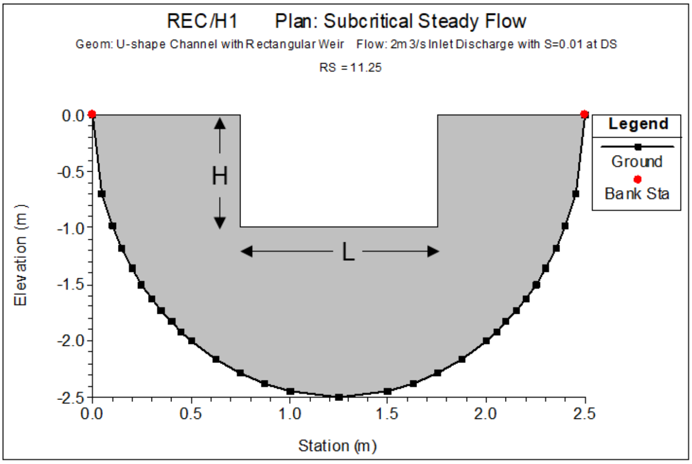
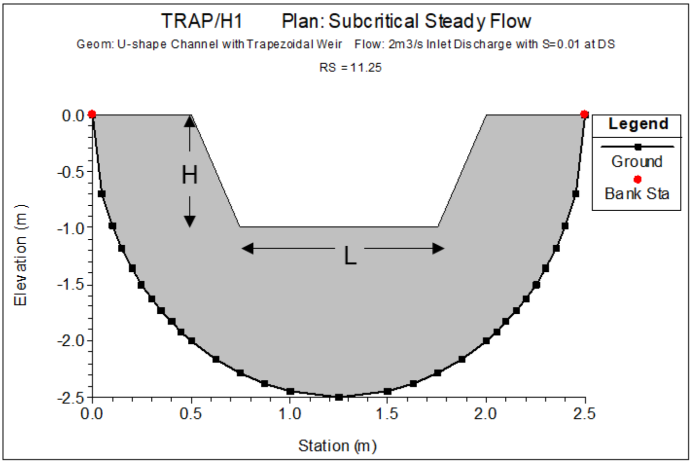


Figure 1: Overall layout of the reaches in HEC-RAS setup

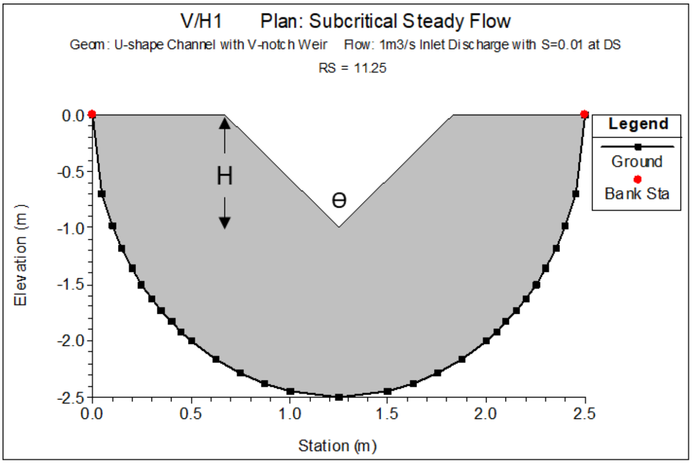
In the present study, weirs of different cross-sectional shapes, heights, crest lengths and crest angles were the main study focus. Weir cross-sectional shapes under the study scope were rectangular, trapezoidal and V-notch. Figure 2 shows the cross section view of trapezoidal and V-notch weir respectively. The side slope of the trapezoidal weir was 1:4 (horizontal: vertical) resembled that of a Cipolletti weir. Weirs would be located at River Sta. 11.25, which is between River Sta. 10.0 and River Sta. 12.5 as shown in Figure 3.



Cross section a



Cross section b



Cross section c

Figure 2: Typical cross section views of the (a) rectangular (REC), (b) trapezoidal (TRAP), and (c) V-notch (V) weirs in an idealised channel

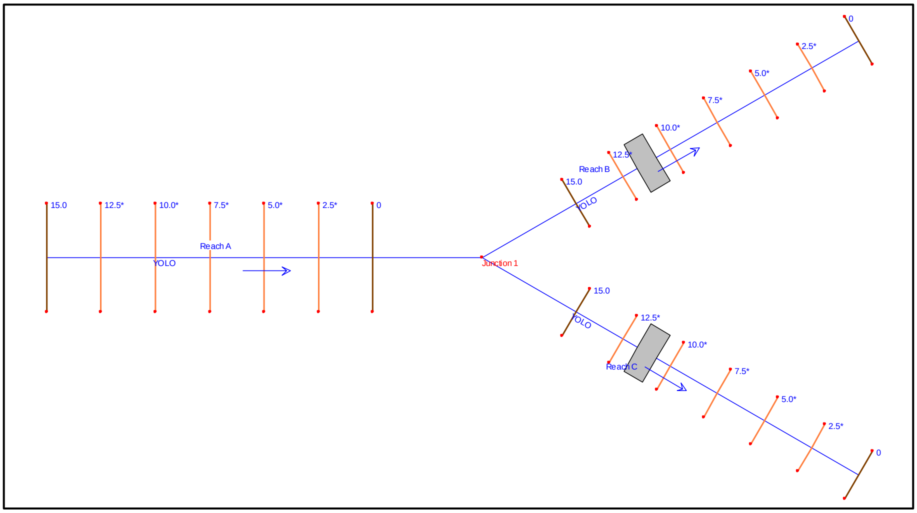


Figure 3: Overall layout with weirs of the reaches in HEC-RAS setup

Steady and subcritical flow was assumed for this study. Average slope of channel bottom at the downstream was set as 0.01 (1%). Connections to junction were considered internal boundary conditions and filled automatically based on how the river reaches were connected in geometric data editor established previously. Flow optimization was selected as it optimized the split flow at the stream junction (Junction 1). This allowed the programme to balance flow splitting from one reach into two until energy grade lines of the receiving streams were within specified tolerance (by default is 0.02ft). Flow optimization was performed by first computing the water surface profiles for all reaches, then compared with the computed energy grade lines for the cross sections just downstream of the junction. The flow went into each reach would be redistributed and the profiles would be recalculated if the energy in the split reaches was not within the tolerance. This iterative process would continue until a balance was obtained.

RESULTS AND DISCUSSIONS

The outlet discharge ratios for rectangular weirs, trapezoidal weirs and v-notch weirs against different weir height combinations are shown in Figure 4. Based on the graphical presentation, the relation of outlet discharge ratio and weir height ratio are found to be linear. These findings are capable to help in predicting the outlet discharge of the distributary channels. In vice versa, appropriate weir height which is suitable to achieve targeted outlet discharge for each reach can be predicted as well. Comparison of this relationship for different weir shapes can be observed in this study and this linear relationship was also proved by Thomas et al. (2011).

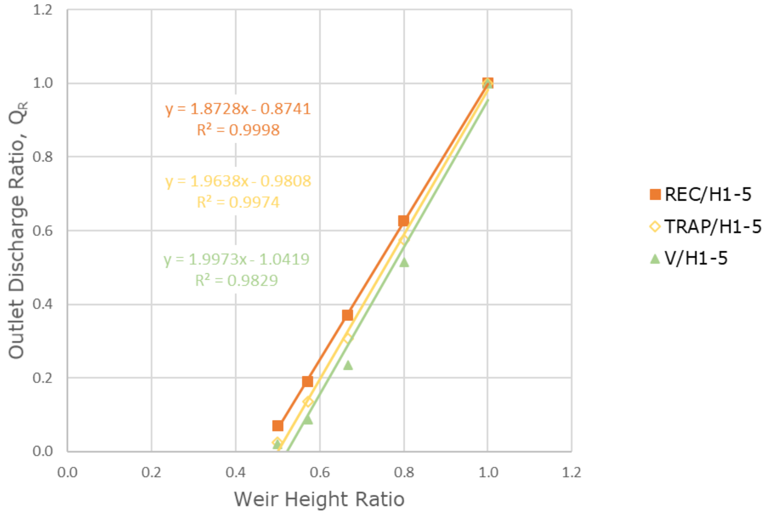


Figure 4: Outlet discharge ratio versus weir height ratio for different weir shapes

Based on the graphical presentation in Figure 5, the relation of outlet discharge ratio and crest length ratio are found to be almost linear and can be represented with linear equations. Alternatively, the results also show that the relation of outlet discharge ratio and crest angle ratio is linear. The findings showed that the appropriate crest length or angle which is suitable to achieve targeted outlet discharge for each reach can be predicted.

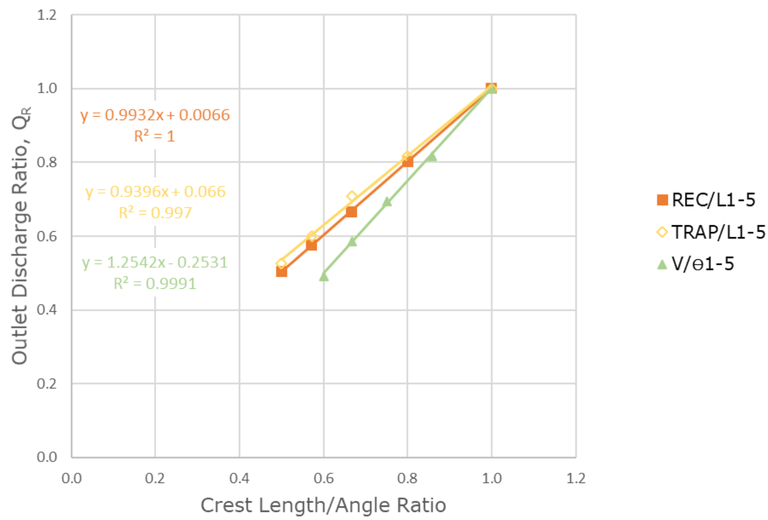


Figure 5: Outlet discharge ratio versus crest length or angle ratio for different weir shapes

Referring to the graphical presentation in Figure 6, the relation of outlet velocity ratio and weir height ratio are found to be almost quadratic and can be represented with quadratic equations as shown in the graphs.

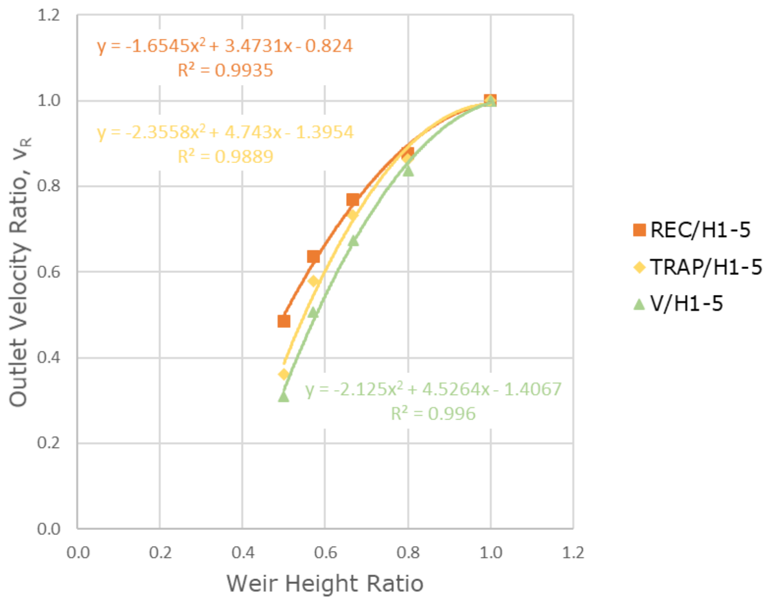


Figure 6: Outlet velocity ratio versus weir height ratio for different weir shapes

Based on the graphical presentation in Figure 7, the relation of outlet velocity ratio and crest length ratio are found to be quadratic and can be represented with quadratic equations as shown in the graphs.

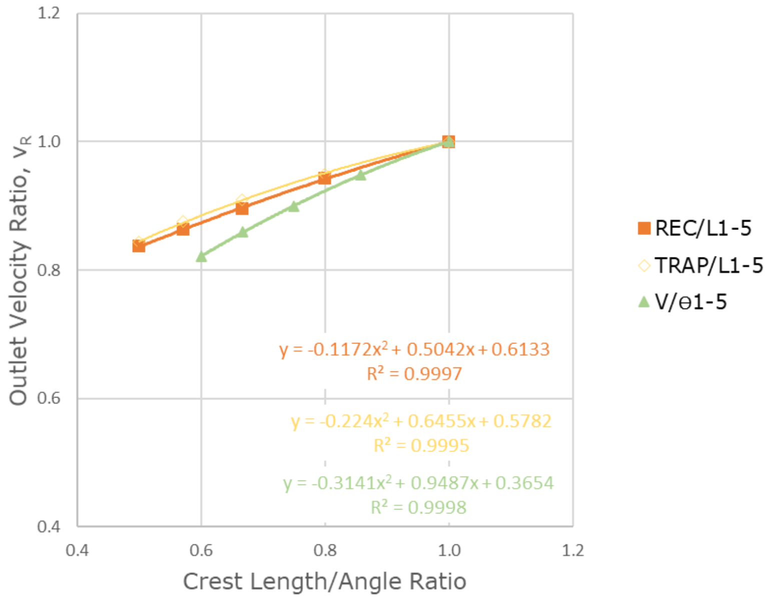


Figure 7: Outlet velocity ratio versus crest length or angle ratio for different weir shapes

It is expected in symmetrical bifurcation as the discharge partitioning is equal, which is also recorded by Thomas et al., 2011. There is a sudden surge in velocity when meeting the weir and then the velocity keeps on increasing within the study area. Figure 8 shows velocity profiles for rectangular weir with unequal weir height at Reaches B and C. The overall velocity for Reach B decreases while the overall velocity for Reach C increases compared to the equal weir height case. It concluded the value of weir height is higher when the overall velocity increases. Another highlight is that when there is significant difference between the weir height at Reaches B and C, the difference between the overall velocity for Reaches B and C at downstream becomes more significant. Similar trends are observed for trapezoidal weir and V-notch weir.

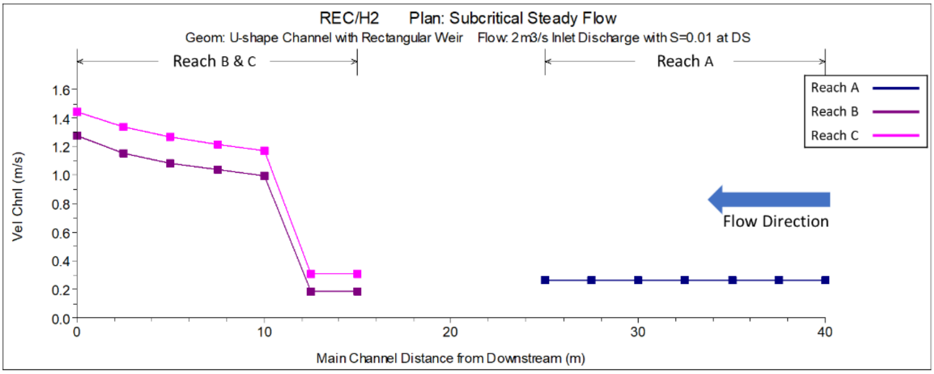


Figure 8: Velocity versus main channel distance for REC/H2

It is observed that the surface profiles for Reaches B and C are the same since the weir height is the same at both channels. This is expected in symmetrical bifurcation as the discharge partitioning is equal as also recorded by Thomas et al. (2011). The highest elevation recorded is 2.3m at the most upstream of Reaches B and C which means that the water surface is elevated for a small distance just before the bifurcation. The percentage of raise is calculated to be about 7% (0.15m raise). After passing the weir, the surface elevations drop drastically downstream of the bifurcation and the water surface does not recover to the initial water level within the study area. And the percentage of drop is more than 50%. Thomas et al. (2011) also observed similar observations in their paper but with slightly lower percentage of raise.

Figure 9 shows the surface elevation profiles for rectangular weir with unequal weir height at Reaches B and C. The highest elevation recorded at the most upstream of Reaches B and C is lower than the equal weir height case and it is getting lower when the weir height difference between weir at Reaches B and C increases. In conclude, the bigger the difference between the weir height at Reaches B and C, the lower the overall elevation. It is worth noticing that the surface elevations drop more for at the reach with smaller value of weir height (weir height in the present study is calculated from the top of the channel till the crest elevation of the weir). Thus, for unequal weir height cases, Reach B always has the lower surface elevations at downstream compared to Reach C. One more thing to highlight is that when the difference between the weir height at Reaches B and C increases, the difference between the drop in elevation for Reaches B and C at downstream becomes more significant. Similar trends are observed for trapezoidal and V-notch weirs.

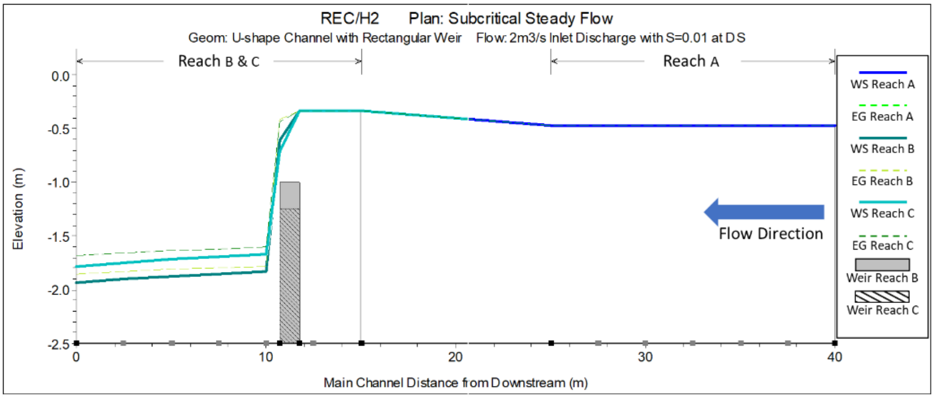


Figure 9: Water elevation versus main channel distance for REC/H2

It is observed that the Froude number profiles for Reaches B and C are the same since the weir height is the same at both channels. This is expected in symmetrical bifurcation as the discharge partitioning and velocity is equal for both downstream channels (Thomas et al., 2011). It is observed that there is a sudden surge in Froude number when meeting the weir and then the Froude number keeps on increasing within the study area. Figure 10 shows Froude number profiles for rectangular weir with unequal weir height at Reaches B and C. The overall Froude number for Reach B decreases while the overall Froude number for Reach C increases compared to the equal weir height case. This concludes that when the value of weir height is higher, the overall Froude number increases. Thus, for unequal weir height cases, Reach C has the higher overall Froude number than Reach B. One more thing to highlight is that when the difference between the weir height at Reaches B and C increases, the difference between the overall Froude number for Reaches B and C at downstream becomes more significant. The Froude numbers computed in all runs under this study are less than 1. This infers that the flow is subcritical for all the runs. It is worth noticing that the Froude number profile display the same trend as velocity profile. Similar trends are observed for trapezoidal weir and V-notch weir

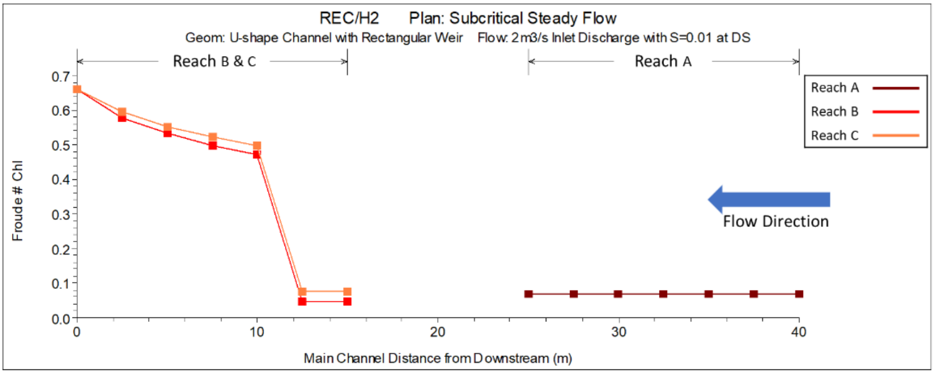


Figure 10: Froude number versus main channel distance for REC/H2

CONCLUSION

This study has presented results that are able to help to understand the flow characteristics of river bifurcation in an idealised channel with presence of weirs as controlled structure. The results have shown that the outlet discharge ratios are linear to the weir height and length ratios regardless of the cross-sectional shapes of the weir. The findings have proved that the bifurcated reach with higher weir height and longest crest length will cause dominant discharge. The most significant discharge happened when the difference between the weir height and crest length of the downstream reaches is the greatest. It is also shown that the bifurcated reach with weir of bigger crest angle will cause dominant discharge. The most significant discharge dominant happened when the difference between the crest angle of the downstream reaches is the greatest. However, the dominance behaviour is less sensitive by manipulating crest length or angle if compared to manipulating weir height. Thus, choosing between which weir geometry to be manipulated will depend on how significant the engineer wants the changes in discharge values to be. It may also depend on the restrictions at the real conditions onsite. On the other hand, the relationship of the outlet velocity ratio to weir height and crest length ratio is quadratic regardless of the cross-sectional shape of the weir. The findings shown that the bifurcated reach with higher weir height and longer crest length will cause higher velocity value. It is also worth remarking that the bifurcated reach with weir of bigger crest angle will cause higher velocity value. All of these findings provide important information for hydraulic engineers during designing a controlled structure to mitigate flood in rivers with bifurcation. It could be potentially contributed to reduce flood risks with the complement of this information for best practices of flood management.

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