PJSRR (2016) 2(2): 40-56
eISSN: 2462-2028 © Universiti Putra Malaysia Press

Pertanika Journal of Scholarly Research Reviews
http://www.pjsrr.upm.edu.my/

Flow in a Branching Open Channel: A Review

Nashwan K. Alomari,[a, b] Badronnisa YUSUF,[a*] Thamer Ahmed Mohammed Ali,[a] & Abdul Halim GHAZALI[a]
[a]Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
[b]Department of Dams and Water Resources, College of Engineering, Mosul University, Mosul, Iraq.
[*]nisa@upm.edu.my

Abstract – Branching channel flow refers to any side water withdrawals from rivers or main channels. Branching channels have wide application in many practical projects, such as irrigation and drainage network systems, water and waste water treatment plants, and many water resources projects. In the last decades, extensive theoretical and experimental investigations of the branching open channels have been carried out to understand the characteristics of this branching flow, varying from case studies to theoretical and experimental investigations. The objectives of this paper are to review and summarise the relevant literatures regarding branching channel flow. These literatures were reviewed based on flow characteristics, physical characteristics, and modeling of the branching flow. Investigations of the flow into branching channel show that the branching discharge depends on many interlinked parameters. It increases with the decreasing of the main channel flow velocity and Froude number at the upstream of the branch channel junction. Also it increases with the increasing of the branch channel bed slope. In subcritical flow, water depth in the branch channel is always lower than the main channel water depth. The flow diversion to the branch channel leads to an increase of water depth at the downstream of the main channel. From the review, it is important to highlight that most of the study concentrated on flow characteristics in a right angle branch channel with a rigid boundary. Investigations on different branching angles with movable bed have still to be explored.

Keywords: Branching channel, diversion discharge, numerical model, open channel, separation zone.

Introduction

Branching channel flow has been studied in recent decades and still garners the attention of water resources engineering researchers as it is commonly exists in many water engineering related projects, and due to the complexity of branching flow involving many interlink factors thus making the generalization of the phenomenon much difficult to achieve (Lama, Kuroki, & Hasegawa., 2002). Studying the flow in the diversion channel has a direct application in water supplying plants, water treatment plants, as well as irrigation and drainage network system design (Ramamurthy, Minh Tran, & Carballada, 1990). Constructing a branch channel to divert some part of the water from the main flow affects the main channel flow and river bed mechanics, changing the bed form, especially in the junction region (Yonesi, Omid, & Haghiabi, 2008). These changes lead to many problems, such as changes in the main channel slope due to erosion and sedimentation in the main channel as well as on the branch channel.

Earlier studies on branching channel flow were focused on the flow characteristics, such as branching flow discharge and regimes. For example, the earliest study conducted by Taylor (1944) investigated ways to estimate a flow discharge in the branch channel. Based on experimental results, he proposed a graphical trial and error procedure for free flow branching flow discharge. Grace and Priest (1958) studied branching flow with a different branch to main bed width ratio with free overflow and classified the flow into two regimes, without standing waves for relatively small Froude number flow and with local standing waves near the branch channel.

The research on the branching channel flow later advanced with the exploration of theoretical equations. Ramamurthy and Satish (1988), Ramamurthy et al. (1990), and Hsu, Tang, Lee, & Shieh (2002) derived a theoretical model for branching flow into a right angle and short branch channel. Based on energy, momentum, and mass conservation principles and on the assumption that there is no energy loss along the main channel. Hager (1987), Kesserwani et al. (2010) and Ghostine et al. (2013) derived their theoretical equations by treating the branching flow as a lateral flow over zero high side weir. Most of the branching channel flow studies have been done with rigid boundary and 90˚ branching angle, while only a few articles investigated different branching angles (e.g. Al Omari & Khaleel, 2012; Keshavarzi & Habibi, 2005; Khaleel, Taha, & Alomari, 2015) or with movable bed condition (e.g. Kerssens and Van Urk, 1986). Herrero et al. (2015), for example, investigated a right angle diversion flow with movable sand bed. He observed a scour hole constructed at the downstream edge of the branch channel entrance.

This review paper briefly describes many papers related to diversion flow for different cases of flow condition and channel geometry, highlights some of the phenomena that occur in the diversion flow system, and demonstrates physical and mathematical models which have been used to simulate this type of flow.

Flow Characteristics

Diversion discharge

In the branching channel flow, some of the total discharge diverts towards the branch channel. The discharge ratio (Q_r) is always used to describe a diversion flow in the branching channel and is equal to the percentage of the branch channel discharge (Q_b) relative to the main channel discharge (Q_u). Hager (1992) and Ingle and Mahankal (1990) recognised that (Q_r) is considered one of the most relevant parameters in the analysis of branching channel flow. This ratio depends on many factors, such as the Froude number upstream and downstream of the main channel and in the branch channel (F_u, F_d, and F_b, respectively), the water depths upstream and downstream in the main channel and in the branch channel (y_u, y_d, and y_b, respectively), the bed slope (S), the branching angle (θ), the bed width ratio, the branch channel to main channel bed width (B_r), the bed roughness, and, if there is a side weir, the shape of the crest and weir height. In general, there is a reverse relationship between (Q_r) and (y_b/y_u) (Al Omari & Khaleel, 2012), (F_u) (Bejestan, Moghaddam, Karami & Seyedian, 2013; Hager, 1987; Krishnappa & Seetharamiah, 1963) and (F_d). Figure 1 shows the relationship between (F_d) and (Q_r) developed by Hsu et al. (2002). Furthermore, (Q_r) decreases as (y_u) (Masjedi & Foroushani, 2012) and the branch channel bed slope (S_b) (Al Omari & Khaleel, 2012) decrease. In addition, there is a direct effect of the (Q_r) on the sediment ratio (S_r), that is, the divert sediment to total sediment, which increases as (Q_r) increases (Moghadam, Bajestan, Sedghi, & Seyedian, 2010).

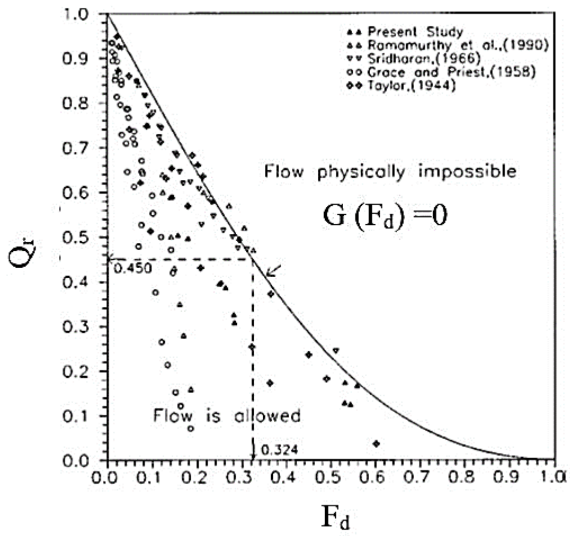

Figure 1: Relationship between (F_d) and (Q_r) (Hsu, Tang, Lee, & Shieh, 2002).

Many researchers have proposed equations to describe (Q_r) in the branching channel system:
Ramamurthy and Satish (1988) presented a theoretical model for dividing the flow into a right angle, subcritical flow, and short branch channel for the difference bed width ratio. They developed their model based on the momentum, energy, and continuity principles. By assuming that there is no energy loss between the upstream main channel and the branch channel and that the flow in the maximum contraction section of the branch channel is critical, the (Q_r) can be found from this relation:

$$Q_r = \frac{1}{3\sqrt{3}} C_c B_r F_u^2 \left(1+\frac{2}{F_u^2}\right)^{3/2} \qquad \text{……………….……(1)}$$

Where C_c is the contraction coefficient.
In addition, by considering momentum they related the downstream to upstream main channel water depth ratio (y_d/y_u) with (Q_r):

$$\left(\frac{y_d}{y_u}\right)^3 - \frac{1}{4}\left(1+\frac{y_d}{y_u}\right)^2 \frac{y_d}{y_u} Q_r - \left(2F_u^2+1\right)\left(1-Q_r\right)\frac{y_d}{y_u} + 2F_u^2\left(1-Q_r\right)^2 = 0 \qquad \text{…(2)}$$

Moreover, using the continuity equation:

$$F_d = F_u\left(1-Q_r\right)\left(\frac{y_u}{y_d}\right)^{3/2} \qquad \text{……..……………(3)}$$

This theoretical model was verified with experimental results for this and previous work for $B_r \leq 1$, $F_d < 0.7$, and $F_b > 0.35$, as shown in Figure 2.
In 1990, Ramamurthy et al. developed a theoretical model for (F_u) up to 0.75 to relate the discharge ratio with the upstream Froude number and the upstream to downstream water depth ratio (R_y) in the dividing flow at a right angle, rectangle, equal width, and horizontal open channel. This model has a wider application than the previous model (Ramamurthy & Satish 1988) because there is no restriction on the nature of the flow in the branch channel. This model was validated with experimental data from this and previous studies. Using the momentum equation, they found the discharge ratio and water depth:

$$\frac{Q_r}{40}F_u^4+\left(\frac{1}{6}+\frac{5}{6}(1-Q_r)-(1-Q_r)^2R_y\right)F_u^2+\frac{R_y^2-1}{2R_y^2}=0 \qquad \text{..........(4)}$$

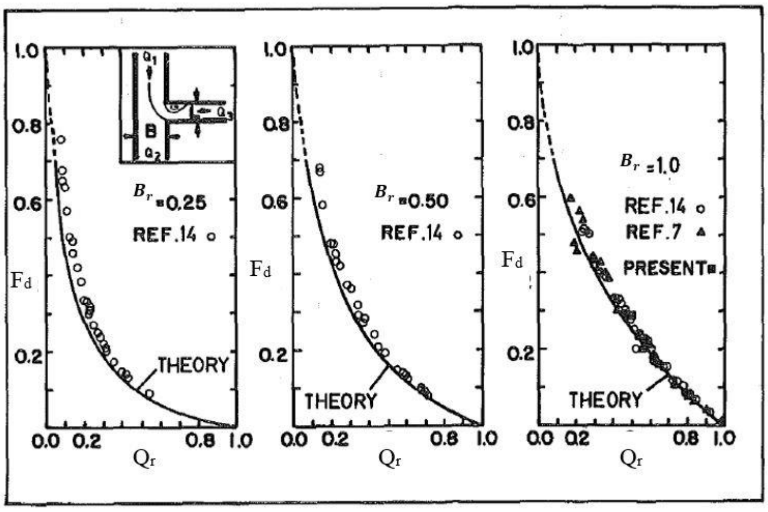

Figure 2: F_d with Q_r (Ramamurthy & Satish, 1988).

Using energy considerations, Hsu et al. (2002) found that the energy head in the main channel upstream (H_u) and downstream (H_d) of the branch channel are almost equal to each other. The energy equation can be applied to a one-dimensional (1D) dividing flow model to find the discharge ratio:

$$\left(\frac{y_u}{y_d}\right)^3-\left[1+\frac{1}{2}F_d^2\right]\left(\frac{y_u}{y_d}\right)^2+\frac{1}{2\left(1-Q_r\right)^2}F_d^2=0 \qquad \text{................(5)}$$

This equation states that for a 90˚ dividing flow, there is equal width, subcritical, and zero bed level flow.
An empirical equation for calculating the discharge ratio based on the branching angle, water depth in the branch channel to depth of water in the downstream main channel, branch channel slope and downstream main channel Froude number was observed by Al Omari and Khaleel (2012):

$$Q_r=27.98\left[\left(S_b^{0.029}.\mathrm{Sin}\theta^{0.053}\right)/\left(\frac{y_b}{y_d}^{0.384}.F_d^{0.409}\right)\right] \qquad \text{..........(6)}$$

Where S_b is the branch channel bed slope, and θ is the branch channel angle.
They took three branching angles (30˚, 60˚, and 90˚) and four branching channel bed slopes (0.001, 0.0015, 0.002, and 0.0025).

Moreover, there are many researchers who have considered a branching channel flow as a flow over a zero high side weir:

Hager (1987) described the flow intensity over a side weir as follows:

$$q=-\frac{3}{5}n^*c\sqrt{gH^3}\left(y-W\right)^{3/2}\left[\frac{1-W}{3-2y-W}\right]^{1/2}\left\{1-(\theta+S_o)\left[\frac{3(1-y)}{y-W}\right]^{1/2}\right\} \qquad \text{.........(7)}$$

In this equation, q is discharge intensity per unit width ($m^3/s/m$), n* is the amount of side outflow, c is the weir crest influence (1 for a sharp-crested weir, 8/7 for zero weir height), g is gravity acceleration (m/s^2), H is total energy (m), y is water depth over total energy, W is weir height over total energy, θ is the contraction angle, and S_o is the bottom slope. For zero weir height (W = 0, $(\theta + S_o) \cong 0$). This equation was verified with experimental data for $0.3 \leq F_u \leq 2$ and the height of the side weir (W) between 0 and 20 cm.

Following this study, Kesserwani et al. (2010) used Eq. (7) to cope with a two-dimensional (2D) branching channel flow pattern. Past experimental and theoretical data were used to validate this model for sub-, trans-, and supercritical diversion.

Water depths, water surface, and hydraulic jump

The main factors that have an effect on the water depths in the branch channel system are discharge ratio and the Froude number (Hsu et al., 2002). In the subcritical flow, the depth of water in the downstream main channel is more than the water depth in the upstream main channel and both are greater than the water depth in the branch channel (Barkdoll, Hagen, & Odgaard, 1998). In the main channel, the lowest level of water occurs in the first half of the junction region, in the branching side, and the highest water level occurs just downstream of the junction region near the downstream edge of the branch channel (Al Omari & Khaleel, 2012). Ramamurthy, Qu, & Vo, (2007) also noted that the water depth rose at the downstream edge of the branch channel (stagnation zone) and in the region just downstream of the junction region on the opposite side of the branch channel (about 2% higher than the water depth in the stagnation zone). In the branch channel, the water surface drops at the upstream corner at the entrance of the branch channel. The lowest water depth in the branch channel happens in the contraction zone and starts to increase as the separation zone decreases (towards the flow) (Ramamurthy et al., 2007). Figure 3 shows the water depths from the experimental data and numerical prediction with the three-dimensional (3D) volume of fluid (VOC) numerical turbulent model.

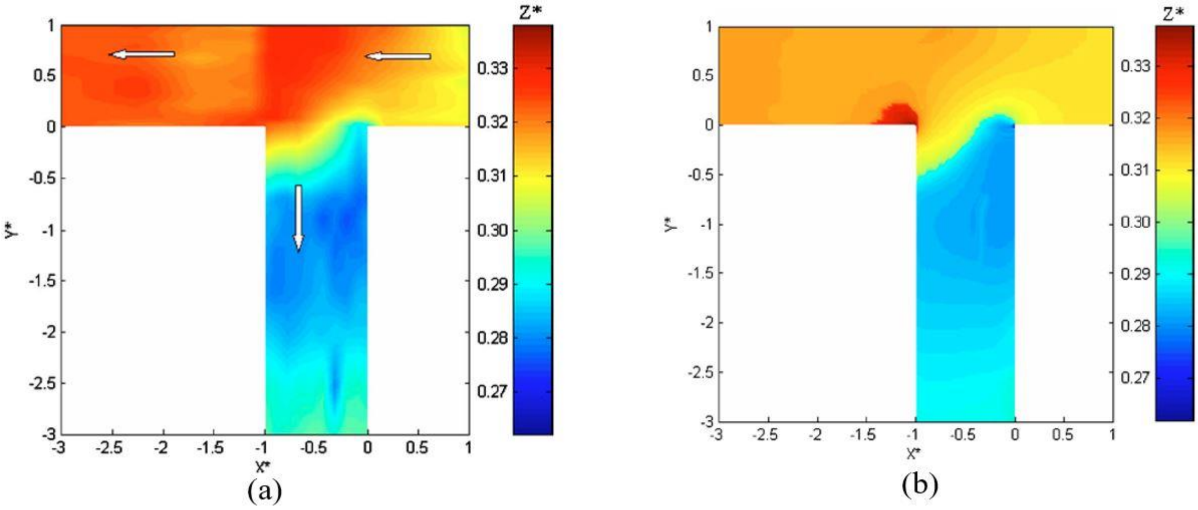

Figure 3: Water surface profiles for Q_r = 83.8%. (a) Experimental data, (b) Numerical model (Ramamurthy et al., 2007).

The depths of water upstream and downstream main channel are uniform and can be measured at 4 times of the channel bed width (B) before and after junction region, while the branch channel water depth can be measured at 6 to 10 of the channel bed width from the branch channel entrance (Hsu et al., 2002). The relationship between (y_u/y_d), (F_d), and (Q_d/Q_u) was plotted by Hsu et al. (2002) for their experimental and theoretical work and previous studies (Figure 4), in which they found that (y_u/y_d) increased as (Q_d/Q_u) increased and (F_d) decreased.

For subcritical flow, (y_u/ y_d) can be calculated from Eq. (2) (Ramamurthy & Satish, 1988), Eq. (4) (Ramamurthy et al., 1990), or Eq. (5) (Hsu et al., 2002).

El Kadi Abderrezzak et al. (2011) discovered that there are two hydraulic jumps, one in the main channel and another in the branch channel. They found that the hydraulic jump length in the branch channel gradually decreases as the height of the weir in the branch channel end increases, while the hydraulic jump in the main channel moved upstream towards the junction as the weir height in the main channel end increases.

Velocity distribution and streamlines
Many researchers have studied the distribution of velocity components in the branching channel system experimentally (e.g. Bagheri & Heidarpour, 2012; Ramamurthy et al., 2007) and numerically (e.g. Shamloo & Pirzadeh, 2007a, b). The velocity in the branching junction is 3D, towards the main flow (V_x), towards the branch flow (V_y), and normal to the flow (V_z) (Keshavarzi & Shamsaddini-Nejad, 2002).

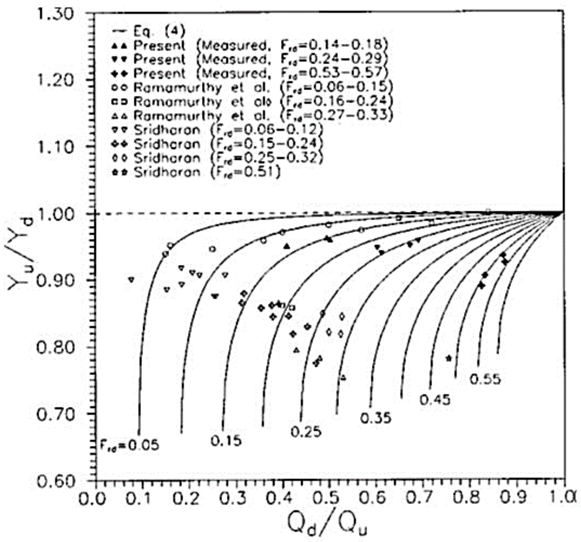

Figure 4: The relationship between (y_u/y_d), (F_d), and (Q_d/Q_u) (Hsu et al., 2002).

During their experimental work, Neary and Odgaard (1993) found that an increase of the main mean velocity (V_r) in the branch leads to a reduction in the size of the separation zone in the branch channel and extension of the dividing streamline farther into the main channel. In addition, the strength of the secondary circulation (δ) (velocity near the surface – velocity near the bed) near the upstream wall at the beginning of the branch channel increases as (V_r) increases. This secondary circulation starts to appear at a threshold velocity ratio of 0.03.

In 2007, Ramamurthy et al. composed a 3D velocity distribution in the junction region experimentally and numerically at a 90˚, sharp-edged angle. They found that the highest velocity component (V_y) occurred in the branch channel near the surface just downstream from the entrance at the maximum contraction of the flow, and that the highest velocity component (V_x) occurred at the upstream edge of the branch channel. In the beginning of the branch channel, the velocity component (V_y) starting from negative values, reversing the branch flow from the upstream wall, and increasing to assume positive values towards the downstream wall. These negative values indicated the flow separation in this region. The length of this negative value region increased upwards towards the surface and lead to a widening separation towards the surface. In the main channel, they observed negative values of the velocity component (V_x) in the opposite side of the branch channel downstream from the junction, indicating a zone of separation in this region.

Numerical investigation of the velocity component field and subsequent comparison with experimental results showed that the FLUENT software is an effective tool for simulating the flow velocity in the branching channels (Shamloo & Pirzadeh, 2007b). Furthermore, using the κ-ε model gives good agreement in simulating velocities in the branch channel; it has also been shown that the κ-ω model is better than κ-ε model (Omidbeigi, Ayyoubzadeh, & Safarzadeh, 2009).

Depending on the distribution of the velocity components, streamlines can be drawn. These streamlines help to discover the separation zone's size and location (Keshavarzi & Habibi, 2005). In the junction region, the flow is divided into two regions: towards the branch channel and towards the downstream main channel. The width of the dividing streamlines towards the branch channel at the bottom are more than their width at the surface (Lakshmana et al., 1968; Lama, Kudoh, & Kuroki, 2003), which leads to the diversion flow taking more discharge from the lower layers than the upper layers (Barkdoll, 2004). This difference between the widths in terms of diversion from a trapezoidal main channel is less than the diversion from a rectangular main channel (Moghadam et al., 2014). The reason for this non-homogenous diversion is that the velocity component towards the downstream end of the main channel in the upper layer is greater than the velocity in the lower layers. Thus, the high momentum in the upper layer forces the flow to continue towards the downstream end of the main channel (Neary & Odgaard, 1993; Omidbeigi et al., 2009). Figure 5 shows the streamlines pattern in the branching channel junction.

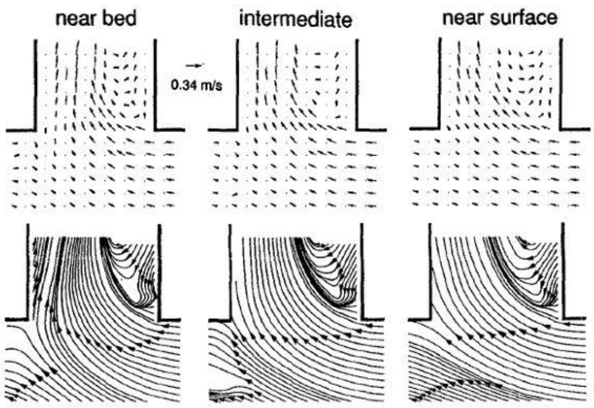

Figure 5: Streamline patterns in smooth branching channel junction bed (Neary & Odgaard, 1993).

Separations zones

Separation zones occur because of the low velocity of the flow and the recirculation of water in the same place (Neary et al., 1999). These zones envelop the recirculating flow (Ramamurthy et al., 2007). Because of the low velocity, a sedimentation area appears in these zones (Barkdoll et al., 1999; Shamloo & Pirzadah, 2007b) and privilege areas for fish and plant reproduction (Mignot et al., 2014). There are two main separation zones, as shown in Figure 6.

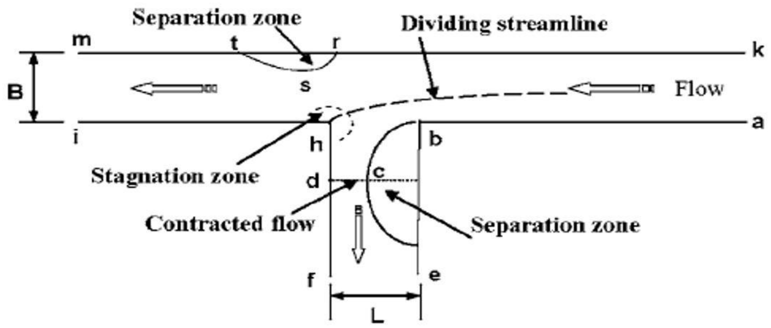

Figure 6: Zones of separation and stagnation point in the branching channel system (Ramamurthy et al., 2007).

A separation zone in the upstream branch channel wall near the entrance of the branch channel at a 90˚ branching angle (e.g. Hayes, Nandakumar, & Nasr-El-Din, 1989; Ramamurthy et al., 2007; Zhou & Zeng, 2009) and in the downstream wall at a 30˚ branching angle (Lama et al., 2002; Lama et al., 2003). In the laminar flow, the initiation of the recirculating of the flow in the branch channel depends on the branching channel ratio and the Reynolds number in the upstream main flow (Lee & Chiu, 1992). This zone appears because the flow entering the branch channel has a high momentum towards the downstream main channel flow (Neary & Odgaard, 1993). The location and size of this zone depends on the discharge ratio. An increasing discharge ratio leads to this zone decreasing (Goudarzizadeh, Hedayat, & Jahromi, 2010; Kasthuri & Pundarikanthan, 1987). In addition, it is smaller near the bottom than it is at the surface (Ramamurthy et al., 2007). Moreover, increasing the branching angle from 45˚ to 90˚ leads to this zone moving towards the downstream branch channel and the smallest separation zone occurs at a 55˚ branching angle (Keshavarzi & Habibi, 2005). Furthermore, using submerged vanes to control the sediment leads to the length of this zone increasing because vanes work on the distribution of velocity non-uniformity in the branch channel (Abdel Haleem, Helal, Ibrahim, & Sobeih, 2008).

A separation zone in the main channel just downstream of the junction on the opposite side of the branch channel (Satish, Ramarnurthy, & Narasiah, 1989). This regain does not happen all the time; it happens when the branch channel takes an important percentage of discharge from the total discharge, which leads to the streamlines curving towards the branch channel and after the junction region starts to expand (Shamloo & Pirzadah, 2007b). No threshold value of the discharge ratio was observed in the previous studies on the formation this zone of separation.

Stagnation point
A stagnation point is a point in the flow. At this point, the velocity of the flow is very small and the pressure and flow depth are highest in the flow system. In the branching channel system, there is one stagnation point located at the downstream edge of the branch flow entrance, as shown in Figure 6.

Contraction coefficient
Due to separation of flow at the beginning of the branch channel, the flow will be contracted, as shown in Figure 6. The contraction coefficient (C_c) is equal to the ratio of contraction width to branch channel width. This coefficient increases linearly as the discharge ratio increases and as the channel width ratio decreases (Ramamurthy et al., 1996). The contraction width at the bottom is wider than it is at the surface (Lama et al., 2002).

Energy head, energy loss coefficient, and power

The power and total energy are changing during the flow as a result of the friction loss and turbulence of the flow. In the branching flow system, increasing the branching flow leads to the energy loss increasing (Li & Zeng, 2009).

For the main channel, Cheong (1991), Hsu et al. (2002), and Peruginelli and Pagliara (1992) found that the energy head in the main channel upstream and downstream of the branch channel are almost equal each other. Ramamurthy et al. (1996) found the energy loss coefficient between the upstream and downstream main conduit (K_{12}) and branch conduit (K_{13}) from the following equations:

$$K_{12} = \frac{E_u - E_d}{V_u^2/2g} \qquad \text{..........................(8)}$$

$$K_{13} = \frac{E_u - E_b}{V_1^2/2g} \qquad \text{..........................(9)}$$

Where E_u, E_d, and E_b are the total energy at the upstream and downstream main conduit and the branch conduit, respectively. They also found (K_{13}) from their empirical approach as follows:

$$K_{13} = [Qr/(B_r)]\left[\frac{1}{C_c} - 1\right]^2 \qquad \text{.....(10)}$$

Both direct energy measurements and the empirical approach can be applied to find (K_{13}) for ($0 < Q_r < 1$, $0 < B_r < 1$).

In the diversion area, Hsu et al. (2002) calculated the energy loss coefficient across the flow division (K_e) for a subcritical, equal width, 90˚ dividing flow with a zero bed level as a function of (F_u), (Q_d/Q_u), and (y_r) from the following equation:

$$K_e = (1-(Q_d/Q_u))\left[1 - \frac{2y_r^3 + \left(1-(Q_d/Q_u)\right)^2 F_u^2}{y_r^2\left(2+F_u^2\right)}\right] \qquad \text{............(11)}$$

They noted that (K_e) increased as (Q_d/Q_u) and (F_u) increased, and decreased as (Q_b) increased. Assuming (H_u) ≈ (H_d) ≈ (y_d) and total energy in the branch channel (H_b) ≈ (y_b), (K_e) can be found from the following equation (Li & Zeng, 2009):

$$K_e = Q_r\left(1-y_r\right) \qquad \text{..............(12)}$$

Physical Characteristics

Branching angle

Another aspect that influences the branching channel system is the branching angle. Lama et al. (2002) noted that the separation zone in the branch channel occurs in the downstream wall of a 30˚ branching angle. On the other hand, it occurs in the upstream wall of a 90˚ branching angle (e.g. Herrero Casas, 2013; Ramamurthy et al., 2007). Keshavarzi and Habibi (2005) found from a laboratory study and by comparing separation zone sizes in different diversion angles (45˚, 56˚, 67˚, 79˚, and 90˚) that the optimum angle of the diversion is 55˚ according to separation zone size in the intake channel. Based on the maximum branch channel discharge, the best angle for the diversion channel is 60˚ from among 30˚, 60˚, and 90˚ (Al Omari & Khaleel, 2012). An experimental study of the diversion channel from a 180˚ bend main channel showed that a 45˚ branching channel angle gave maximum (Q_r), for (F_u) = 0.47 from among 45˚, 60˚, 75˚, and 90˚ (Masjedi & Taeedi, 2011). Furthermore, a 60˚ bend for the maximum diversion flow and 45˚ bend for other discharges gave a minimum amount of diverted sediment from among 45˚, 60˚, and 75˚ (Pirestani et al., 2011). In addition, Dehghani et al. (2009) recommended using an 115^o branching channel from the bend flow because the upstream scour length is shorter than it in 150^o.

Bed slope

There are a limited number of researchers who have studied the effect of the branch channel slope. Al Omari and Khaleel (2012) found that increasing the branch channel bed slope leads to the discharge ratio (Q_r) increasing. In addition, the maximum increasing of (Q_r) reached 12.13% when the branch channel bed slope was changed from 0.001 to 0.0025 with other variables fixed.

Bed roughness

The roughness of the bed affects many factors contributing to the flow behaviour in the branching channel system. Neary and Odgaard (1993) found that the velocity profile (across the depth) for a smooth bed is more uniform than a rough bed, as shown in Figure 7.

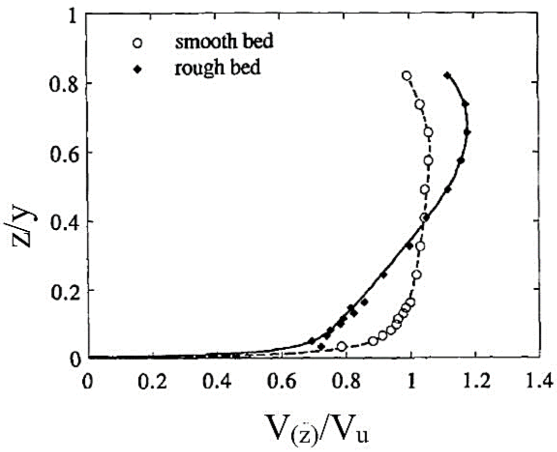

Figure 7: Velocity profiles in main channel (Neary & Odgaard, 1993)

In addition, the width of the dividing streamlines from the main channel wall (the diversion wall) 15.25 cm upstream of the diversion near the surface (S_d) is 0.46 from its width near the bed (B_d) for a rough bed and 0.60 B_d for a smooth bed. That means the difference between the width of the dividing streamlines at the surface and at the bed increases as the roughness increases.

During a numerical study using two types of branch channel bed, that is, with and without vegetation, Li and Zeng (2009) reported that increasing the vegetation density lead to an increase in overall energy loss, a decrease in (Qr), and a shortening of the recirculation zone. In the sediment transport concept, the diverted sediment in the branch channel decreases as the roughness coefficient increases (Raudkivi, 1993).

Modeling of the Branching Flow

Physical models

The physical models for branching flow differ in dimensions, flow, and boundary conditions from one work to another, depending on the purpose of the study. For example, most of the physical models took the branching channel angle as equal to 90˚ (e.g. Herrero Casas, 2013; Kubit & Ettema, 2001;

Neary & Odgaard, 1993). On the other hand, a limited number of the physical models assumed other angles (e.g. Al-Neelah & Khaleel, 2013; Lama et al., 2002; Riad, 1961) in order to study the effect of the branching angle on the flow or to investigate the effect of the other variables on the flow in different angles. As regards the bed width ratio, some researchers took a different bed width ratio according to the objective of the study. For example, Ramamurthy et al. (1996) studied the various energy loss coefficients and contraction coefficients for a range of discharge ratios and three conduit width ratios (0.22, 0.77, and 1). In addition, bed condition plays a significant role in the branching flow studies (rough or smooth, movable or rigid boundary).

To study the sediment transport in the branch channel, the physical models should be built as a movable bed. Kerssens and Van Urk (1986) used a sediment flume with a sand bed to study the effect of branching flow on the bed and water level in the main reaches up and downstream of the water intake. Kubit and Ettema (2001) fed floating debris into the water flow in order to simulate a solution to the control of ice and floating debris by using two types of booms.

Regarding practical applications and case studies of the branching channel flow, Ho et al. (2010), Michell et al. (2006), Nakato (1984), Nakato et al. (1990), and Nakato and Ogden (1998) provided physical hydraulic models to solve and reduce the sediment flow into the water intakes. These solutions included installation of submerging vanes in the main channel, in front of the intakes entrance.

Table 1 summarises typical physical model properties used to simulate branching channel flow.

Mathematical and numerical models

There are different types of mathematical and numerical models describing branching channel flow. In general, all these models depend on one or more of the following equations: 1) a continuity equation, 2) a momentum equation, and 3) an energy equation. In the past, solving these equations depended on a manual numerical solution, but in the last decade, as a result of the advances in computer technology, many programs have been invented to solve these equations.

Kerssens and Van Urk (1986) used a 1D mathematical model (RIVMOR) and verified it with experimental results to study the effect on the bed and water levels of water being withdrawn from the open channels. This mathematical model is based on the motion and continuity equations of both the water and sediment. The results showed that there was aggradation in the bed downstream the water withdrawal and degradation upstream the water withdrawal.

Depending on the momentum, energy and continuity principles, Ramamurthy and Satish (1988) presented a theoretical model for a 90˚ branching channel, subcritical flow for different bed width ratios, as shown in Eqs. (1) and (2). Thereafter, Ramamurthy et al. (1990) developed a theoretical model to find the discharge ratio and water depth ratio for same main and branch channels bed width, as shown in Eq. (4).

2D and 3D Reynolds-averaged Navier–Stokes (RANS) equations are used in the numerical model of the branching channel flow with one or more of these turbulent closure models. such as the κ-ω turbulence model (Omidbeigi et al., 2009), the κ-ε turbulence model (Goudarzizadeh et al., 2010; Issa & Oliveira, 1994; Seyedian, Bajestan, & Farasati, 2014; Xudong, Guangqing, Qing, Guojing, & Hua, 2011), the κ-ε along with Renormalization Group (RNG) methods (Moghadam et al., 2014), the Boussinesq model (Vasquez, 2005), the Reynolds stress model (RSM) (Mirzaei, Ayyoubzadeh, & Firoozfar, 2014), or any other turbulence model, such as the Spalart–Allmaras (SA) model (Mignot et al., 2013).

Table 1: Typical physical model properties used to simulate branching channel flow.

Authors	**Main channel**					**Branch channel**					**Branch channel angle and location**	**Total discharge L/S**	**Type of upstream flow**
	C.S[I]	**L[II] m**	**W[III] m**	**d[IV] m**	**S[V] x10^{-3}**	**C.S**	**L m**	**W m**	**d m**	**S x10^{-3}**			
Al Omari and Khaleel, 2012	R[VI]	10.0	0.3	0.45	0.25	R	2.0	0.15	0.3	1-2.5	30° °, 60°, 90° , at 4.5	13 to 17.25	subcritical
Barkdoll et. al., 1999	R	24.0	1.5			R	2.44	0.61			90°, at 15.5	104	subcritical
El kadi Abderrezzak et al., 2011	R	4.91	0.3		0	R	2.61	0.3		0	90°, at 2.0	4 to 12	
Herrero Casas, 2013	R	9.0	0.2	0.35		R	2.5	0.2	0.35		90°, at 6.0	3.5 to 6.0	subcritical
Hsu et.al., 2002	R	12.0	0.147		0	R	4.0	0.147		0	90°, at 5.35	3.02 to 5.37	subcritical
Keshavarzi and Habibi, 2005	R	15.8	0.5	0.4	3	R					45°, 56°, 67°, 79°, 90°		subcritical
Kubit and Ettema, 2001	R	24.0	1.5			R	2.44	0.61			90°, at 15.5		subcritical
Lama et al. 2002	R	8	0.78		0	R	2	0.045		0	30°, at 3.0	5.1 to 9.4	subcritical
Maghadam et.al., 2010; Karami-Moghaddam et.al., 2011; Bejestan et.al., 2013	T[VII]	8	0.225	0.7		R	5	0.2	0.7		30°, at 5.5	5 to 35.2	subcritical
Mignot et al., 2014	R	4.9	0.3	0.2	0	R	2.6	0.3	0.2	0	90° , at 2.0	4.0	subcritical
Neary and Odgaard, 1993	R	18.3	1.2	0.61		R	1.2	0.61	0.61		90°, at 13.1	Qr=0.50	subcritical
Omidbeigi et. al., 2009	R	18	1.0	0.9		R	2	0.4	0.4		90°, at 11.43	58	subcritical
Ramamurthy et. al., 2007	R	6.198	0.61	0.305		R	2.794	0.61	0.305		90°, at 2.794	46 to 47	subcritical
Ramamurthy and Satish, 1988	R	5.454	0.254	0.432	0	R	2.6	0.254	0.432	0	90°, at 2.6		subcritical
Riad, 1961	R	19.9	0.8			R	10	0.5			45°, at 8.2	30.1 to 111.3	subcritical
Yonesi et al., 2008	R	30	1.5		5	R	2.7	0.6		0	60°, at 23	45 to 90	subcritical

Where: [I] = cross section; [II], [III] and [IV] = length, width, depth in meter, [V] = bed slope, [VI] and [VII] = rectangular and trapezoidal cross section.

Simulation of the laminar branching flow has been reported using an incompressible steady form of the 2D Navier–Stokes equations (Hayes et al., 1989) and 3D Navier–Stokes equations (Neary & Sotiropoulos, 1996).

Shettar and Murthy (1996) obtained a good agreement by comparing the measured discharge ratio, water surface profiles, separation zone parameters, and loss in energy at a 90˚ diversion flow and a 2D numerical model. This 2D numerical model was based on the depth-averaged forms of continuity and momentum equations associated with the κ-ε turbulence model. Using a triangular grid element mesh, Vasquez (2005) simulated the branching channel flow of both a 30˚ and 90˚ branching angle using the River2D program. This program use Shallow Water equations (SWE) with the Boussinesq closure model. Shamloo and Pirzadeh (2007a, b) used the fluent software to solve RANS equations, the κ-ε model to predict the velocity, and the RSM turbulent model to predict the dimensions of the separation zone. Omidbeigi et al. (2009) investigated velocity, bed shear stresses, and turbulence in the branching flow and showed that using an RSM turbulence model was more accurate than using other models and that using the κ-ω model was better than using the κ-ε model. Each model had advantages over the other and there was no universal model for solving all branching flow problems.

Li and Zeng (2009) implemented a 3D RANS model to simulate the branching channel flow in vegetated and non-vegetated branch channel bed. Good results were found for simulating the velocity profiles and flow pattern of a 90˚ branching flow using a 3D hybrid model that was developed in 2009 by Zhou and Zeng. This model is a combination of a Large Eddy Simulation (LES) model for the junction region, and a RANS model for the rest of the channel.

2D models provide accurate results, at least for predicting discharge ratio and water surface profiles for subcritical branching flow, even when compared with 3D models, (El Kadi Abderrezzak & Paquier, 2009). Miller (2004) used three mathematical models (HEC-6, TABC, and CH3D-SED) in order to simulate the effect of connecting the Mississippi River with the wetlands from the west bay of the Mississippi River and determine the best location for the branch channel basing on branching sediment amount. In 2007, Ramamurthy et al. developed a 3D numerical free surface turbulence model to predict flow characteristics in the channel junction region using the VOF scheme and compared the outcome of the free surface with experimental data.

An unsteady mathematical model to predict dividing flow at a 90˚ diversion angle was presented by Kesserwani et al. (2010). They assumed the branch channel as a side weir with zero height, used the numerical solution to the modified St. Venant equations for the side weir model to deal with the 2D flow pattern, and employed an upwind implicit numerical solver to compute the new governing equations. They validated this model for sub-, trans-, and supercritical flow. To simulate the intake of a water treatment plant from the river, Khan (2012) used a 3D computational fluid dynamics model (CFD) for this job.

Ghostine et al. (2013) compared 1D and 2D mathematical models for simulating 90˚ lateral super-, trans-, and subcritical flow, then validated the results with the previous experimental data. For the 1D model, they considered that the lateral flow was a flow over a zero height side weir, while for the 2D model they used 2D St. Venant equations. They performed a numerical approximation of the two approaches with a second-order Runge–Kutta discontinuous Galerkin (RKDG) scheme. The results showed that the 2D approach gave results similar to the experimental data for all types of flow and the 1D approach was satisfactory for the subcritical flow and became increasingly significant for the trans- and supercritical flow.

Conclusions

Branching channel flow is considered a very complex flow, as this flow depends on many factors such as controlling gates at the end of the main and branch channel, velocity, Froude number and momentum in both of the main and branch channels, and the geometry of the branching channel system. This review paper highlighted the flow and physical characteristics of the branching flow. In addition, it reviewed many of the diversion flow physical and mathematical models properties.

Regarding flow characteristics, the branching discharge decreases as velocity, Froude number and momentum in the upstream main channel flow increases. Moreover, it increases by increasing the upstream main channel water depth and branch channel bed slope. In subcritical flow, water depth in the main channel rises downstream diversion area. On the other hand it decreases in its depth in the branch channel. There is a stagnation point that occurs in the downstream corner of the branch channel entrance. Two separate zones form in the branching channel system: one in the downstream main channel, in front of the branching junction, which occurs when a branch channel takes an important amount of water, and another at the beginning of the branch channel.

Lastly, from this review, it is important to study the effect of the different branching channel geometries, such as branching angle, and movable bed on the branching water and sediment flow and bed morphology.

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