Comparison of Flow Characteristics at Rectangular and Trapezoidal Channel Junctions

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Abstract. The channel junctions are an integral part of any channel network used in practice. There are several examples of such flows in channels such as water conveyance systems in hydropower plants, canals, natural and manmade waterways, sewers and drains etc. The water levels in different channels before and after a junction need to be monitored effectively to avoid problems such as overflow and skewed flow distribution. This paper analytically investigates the complex flow features of combining and dividing flows at rectangular and trapezoidal channel junctions. Furthermore, parametric investigations have also been carried out to establish dependence of depth ratio on various parameters for rectangular and trapezoidal channel sections.

1. Introduction
Junctions in open channels are major elements of natural and manmade waterways, and their systematic hydraulic treatment is currently rarely accounted for. This is mainly due to the relatively large number of parameters involved, and the complex flow features associated with junctions. The efficiency of any hydraulic network depends on its discharge carrying capacity through the different elements of the system. It is therefore of primary importance to know the quantity of fluid passing through various elements of the system. In the design of an efficient channel network, junctions are most critical element and therefore analysis of flow characteristics at channel junction is very important. Channel junctions can be of either a combining type or of a dividing type. In combining type of junction the two channel branches combine into one and in the dividing type of junction a main channel divides into two branches. The available information refers either to particular junction structures or to simplified junction geometries. This paper is aimed at generalisation of present knowledge by taking combining and dividing type of flow at junctions. Furthermore, the present study analyses comparative flow features at rectangular and trapezoidal channel junctions.

1.1. Previous studies on rectangular / trapezoidal channel junctions
Taylor (1944) analysed simple dividing flow for right angled junction and combining flow for junction angles of 45° and 135°, for rectangular junctions. For the prediction of channel junction parameters another study used (Milne-Thomson, 1949) conformal transformation technique. In this study flow depth has been assumed to be same in all the channels, which is not a general case. A similar type assumption was made by Law (1965) in his analysis of dividing flow. Webber and Greated (1966) and Gurram (1994) proposed theoretical approaches, based on conservation of mass and momentum, to evaluate for the upstream to downstream depth ratio. Equality of the upstream depth in branch...
channels was assumed. In another study presented by Hsu et al (1998) overall mass momentum and energy conservation were used to calculate energy loss coefficient as well as the depth ratio. It is pertinent to mention that all of these studies were performed for equal width of channels.

Other works in this area are by Ramamurthy et al (1987, 1990). They studied dividing flow in short channels. Pandey and Mishra (1999, 2000) have developed a correlation using momentum balance for different hydraulic parameters for rectangular and trapezoidal channel sections. They however have not examined comparative flow characteristics in rectangular and trapezoidal channel sections at channel junction. The main aim of this paper is to carry out a comparative study on flow characteristics at a channel junction as the shape of the channels change from rectangular to trapezoidal.

2. Development of a Model for Channel Junction

The proposed model (Figure 1 and 2), involves a main channel that is a straight prismatic channel, to which two lateral branches of junction angle \( \theta_1 \) & \( \theta_2 \) are connected. Also all the channels are of unequal widths. The details of the model can be found in detail in [10]. For the sake of completeness model is presented here in brief. Effects of bottom slope and boundary roughness are of minor influence on the near flow field of a junction; hence only two to three times of channel widths has been considered in both upstream and downstream directions. Furthermore a horizontal smooth junction is assumed.

2.1. Combining Flow

When two channels combine in a single channel, the depth just downstream of the junction will be fixed by the back water characteristics of that channel and the magnitude of combined rate of flow. The unknown in this problem is to predict depth in main and branch channels. One of the factors involved is the ratio of incoming flow and outgoing flow. In the model for the combining channels, this ratio has been taken as of the independent variable.

A theoretical model has been developed by considering three channels (1), (2) & (3) of the trapezoidal shape and having base widths \( b_1 \), \( b_2 \) and \( b_3 \) respectively. The combining flow from two branch channels to a main channel may be determined with the aid of momentum principle and mass continuity with the following assumptions:

1. The flow is taking place from channels (1) and (2) to channel (3).
2. Direction of channels (1) & (2) with respect to the axis of channel (3) are \( \theta_1 \) & \( \theta_2 \) respectively and also \( \theta_1 \leq \theta_2 \).
3. The flow is parallel to channel walls and the velocity is uniformly distributed immediately above and below the junction.
4. The wall friction is neglected as compared to other forces.
5. The depth of flow in the channel (1) & (2) are equal just upstream of junction.

Taking the control volume as shown with ‘dotted lines’ in the Fig. 1, the sections have been positioned at a distance of two times the width of branch channel on the upstream of the junction in the branch channels and three times the width of main channel on the downstream of the junction in the main channel.

From continuity equation we can write,
\[
Q_1 + Q_2 = Q_3
\]
where \( Q_1 = A_1 V_1 \), \( Q_2 = A_2 V_2 \) and \( Q_3 = A_3 V_3 \)

Where \( Q_1 \), \( Q_2 \), and \( Q_3 \) are discharges, \( A_1 \), \( A_2 \) and \( A_3 \) are cross-sectional areas of control sections and \( V_1 \), \( V_2 \) and \( V_3 \) are velocities in channels (1), (2) and (3) respectively.

Now, hydrostatic force at any section will be,
\[
P = \gamma . A. \vec{y}, \quad \text{ where } A = (b + zy) \]

and
\[ y = \frac{(\frac{1}{2}zy + \frac{y}{3})}{(b + zy)} \cdot 2 + (by + \frac{y}{2}) \cdot (b + zy) = \frac{(b + \frac{z}{3})y^2}{(b + zy)} \]

Hence,

\[ P = \gamma \cdot (b + zy) \cdot y \cdot \left(\frac{b}{2} + \frac{zy}{3}\right) \]

\[ P = \gamma \left(\frac{b}{2} + \frac{zy}{3}\right) y^2 \]  

(1)

Now, applying the momentum principle,

\[ P_1 \cos \theta_1 + P_2 \cos \theta_2 - P_3 - U + W \sin \alpha = P_f + \Delta P = \frac{y}{g} (Q_3 V_3 - Q_1 V_1 \cos \theta_1 - Q_2 V_2 \cos \theta_2) \]  

(2)

Where \( P_1, P_2, \) and \( P_3 \) are pressure forces in the channels (1), (2) and (3) respectively. \( U \) is the component of the reaction force exerted by the walls of the branch channels to the main channel. This is also known as momentum transfer from the branch channels to the main channel. \( W \) is the weight of the water in control volume, where \( \alpha \) is the bed slope of the channels and \( P_f \) is frictional force due to channel walls. In this equation putting \( W \sin \alpha = P_f = 0 \) and \( U = P_2 \cos \theta_2 \), then equation (2) reduces to:

\[ P_1 \cos \theta_1 - P_3 + \Delta P = \frac{y}{g} (Q_3 V_3 - Q_1 V_1 \cos \theta_1 - Q_2 V_2 \cos \theta_2) \]  

(3)

Taking L.H.S. of equation (3) \( P_1 \cos \theta_1 - P_3 + \Delta P = \)

\[ \gamma \left[ \left(\frac{b_1}{2} + \frac{zy_1}{3}\right) y_1^2 \cos \theta_1 - \left(\frac{b_2}{2} + \frac{zy_2}{3}\right) y_2^2 - \left(\frac{b_3}{2} + \frac{zy_3}{3}\right) \cos \theta_1 \right] y_1^2 \]

\[ = \gamma \left(\frac{b_1}{2} y_1 - y_2 - \frac{b_3}{3} \right) \left(y_1^2 - y_2 \right) \]  

(4)

Now taking R.H.S. of equation (3)

\[ \frac{y}{g} \left[ \left(\frac{Q_3}{A_3} - Q_1 \frac{Q_1}{A_1} \cos \theta_1 - Q_2 \frac{Q_2}{A_2} \cos \theta_2 \right) \right] = \frac{y Q_1^2}{g A_3} \left[ 1 - \frac{(1-q_1)^2 \cos \theta_1}{A_1/A_3} + \frac{q_2 \cos \theta_2}{A_2/A_3} \right] \]  

(5)

(where \( Q_2/Q_3 = q_r \))

Noting that \( b_1/b_3 = Br_1, b_2/b_3 = Br_2, y_1/y_3 = y_r\) and \( zy_3/b_3 = k_3 \)

We get,

\[ A_1/A_3 = \frac{(b_1 + zy_1) y_1}{(b_3 + zy_3) y_3} = \frac{(Br_1 + k_3 y_r) y_r}{(1 + k_3)} \]

Similarly,

\[ A_2/A_3 = \frac{(Br_2 + k_3 y_r) y_r}{(1 + k_3)} \]

Also,

\[ \frac{Q_1^2}{g A_3} = \frac{Q_2^2}{g A_3} \cdot \frac{A_1^2}{A_3} = \frac{P_1^2 A_1^2}{A_3} = \frac{P_2^2 (b_3 + zy_3)^2 y_3^2}{(b_3 + zy_3) y_3} = \frac{b_3 y_3 (1 + k_3)^2}{(1 + 2k_3) P_3^2} \]

Putting the values in equation (5), we get:
\( \frac{\gamma q^2 z}{g A_3} \left[ 1 - \frac{(1-q_1)^2 \cos \theta_1}{A_1/A_3} - \frac{q_2^2 \cos \theta_2}{A_2/A_3} \right] = y_1 b_1 y_3(1+k_3)^2 \frac{F_2^3}{(1+2k_3)} \left[ 1 - \frac{(1-q_1)^2 \cos \theta_1}{(B_1+k_3 y_3) y_3} + \frac{q_2^2 \cos \theta_2}{(B_2+k_3 y_3) y_3} \right] \) \quad (6)

Now equation (3) reduces to,

\( y \left( \frac{1}{2} b_3 (y_1^2 - y_3^2) - \frac{z}{3} (y_1^3 - y_3^3) \right) = y_1 b_3 y_3(1+k_3)^2 \frac{F_2^3}{(1+2k_3)} \left[ 1 - \frac{(1-q_1)^2 \cos \theta_1}{(B_1+k_3 y_3) y_3} + \frac{q_2^2 \cos \theta_2}{(B_2+k_3 y_3) y_3} \right] \) \quad (7)

Or \( \frac{(1+2k_3)}{b_3 y_3} \left[ \frac{1}{2} b_3 (y_1^2 - y_3^2) - \frac{z}{3} (y_1^3 - y_3^3) \right] = F_2^3 (1+k_3)^2 \left[ 1 - \frac{(1+q_1)^2 \cos \theta_1}{(B_1+k_3 y_3) y_3} + \frac{q_2^2 \cos \theta_2}{(B_2+k_3 y_3) y_3} \right] \) \quad (8)

Finally after simplification, equation (8) would be,

\[ (1+2k_3) \frac{1}{2} (y_1^2 - 1) + \frac{k_3}{3} (y_3^3 - 1) = F_2^3 (1+k_3)^2 \left[ 1 - \frac{(1+q_1)^2 \cos \theta_1}{(B_1+k_3 y_3) y_3} + \frac{q_2^2 \cos \theta_2}{(B_2+k_3 y_3) y_3} \right] \) \quad (9)

Equation (9) is the general equation of combining flow at trapezoidal or rectangular (by putting \( k_3 = 0 \)) channel junction.

### 2.2. Dividing Flow

In dividing flow a main channel branches into two branch channels. The division of flow will depend upon the back water characteristic of two branch channels and the dynamic conditions existing at the junction. In this case also the similar assumptions as in case of combining flow are considered. This case however is slightly different from the combining type of junction flows. One of the important parameters to be ascertained beforehand in modelling the dividing channel junction is momentum transfer from main to the branch channels. Pandey A. K. (2000) has evaluated the momentum transfer coefficient for the two branch channels at the junction connected at an angle \( \theta_1 \) & \( \theta_2 \) as \( \rho Q_1 V_3^2 C \) and \( \rho Q_2 V_3^2 C \), where \( C = \left[ \frac{5}{6} - \frac{F_2^3}{40} - \frac{k_3}{12} \frac{(1+2k_3)}{(1+k_3)^2} \right] \) for a trapezoidal channel junction. These coefficients can be used for rectangular channel as well by putting \( k_3 = 0 \).

Taking the control volume as shown by the dotted lines in the Figure 2, the section has been positioned at a distance of two times the width of the channel at upstream and three times the width of the channel at downstream of the junction.

Now applying continuity equation and momentum principle in the flow direction of the main channel (3) we get,

\[ P_3 - P_1 \cos \theta_1 - P_2 \cos \theta_2 - U_1 - U_2 - \Delta P = \frac{\gamma}{g} (Q_1 V_1 \cos \theta_1 + Q_2 V_2 \cos \theta_2 - Q_3 V_3) \) \quad (10)

Here terms carry their usual meanings and \( U_1 \) and \( U_2 \) are the momentum transfer from the main channel to the branch channels and are given by \( U_1 = \rho Q_1 V_3 C \sin \theta_1 \) and \( U_2 = \rho Q_2 V_3 C \sin \theta_2 \).

Now, substituting momentum transfer terms, expressions for pressures and using continuity equation, the final equation relating all the hydraulic parameters can be written as:

\[ (1+2k_3) \left[ \frac{1}{2} (y_1^2 - 1 + y_3^2 B r_2 \cos \theta_2) + \frac{k_3}{3} (y_3^2 (1 + \cos \theta_2) - 1) \right] \]
\[ F_r^2 (1 + k_3)^2 \left[ 1 - C \left( (1 - q_r) \sin \theta_1 + q_r \sin \theta_2 \right) - \frac{(1 + k_3)^2 \cos \theta_1}{y_r} \left( \frac{(1 - q_r)^2 \cos \theta_1}{y_r} + \frac{q_r^2 \cos \theta_2}{y_r} \right) \right] \]  

Equation (11) is the general equation of dividing flow at a trapezoidal or rectangular (by putting \( k_3 = 0 \)) channel junction.

### 3. Experimental Validation

To validate the predicted flow characteristics from the developed model, experiments were also conducted in the hydraulics laboratory of MN NIT Allahabad, India. The geometrical details of the channel junction are given in Table 1. It can be seen from Table 1 that the width of all the channels both in case of combining and dividing junction has been kept different. Further, the branching angle of branch channel (1) and branch channel (2) has been kept 30° and 90° respectively to the axis of main channel (3). The experiments were conducted over a wide variety of flow situations. The complete details of the experimental set up can be found elsewhere (Pandey, A. K. 2000).

The effects of various parameters such as combining or dividing angles \( \theta_1 \) & \( \theta_2 \), Froude number in the main channel (3) width of the channels and discharges in the channels have been discussed in detail for rectangular and trapezoidal channel junctions separately and can be found elsewhere (Pandey et al, 1999), (Pandey, A. K. 2000) and (Mishra and Pandey, 2000).

#### 3.1 Parametric Investigation: comparative flow characteristics

Table 3 shows comparative prediction of flow depth from the model, in similar flow conditions for rectangular and trapezoidal channel junctions. For a given depth, to pass the same discharge/flood through the main channel, two common cases have been illustrated e.g. (i) channels having equal bottom width and (ii) channels utilising equal flow area. Comparative impact of the shape of the channel cross section i.e. rectangular or trapezoidal on the flow depth has been analysed and shown in the Table 3.

To understand interdependence of some of the hydraulic parameters, parametric investigations have been carried out. Figure 3 shows dependence of depth ratio on various parameters for a combining channel junction. It is shown in Figure 3 (a) and Figure 3 (b) that depth ratio increases with the increase in discharge ratio for both rectangular and trapezoidal channel junctions. Further, the same is also validated by the experimental observations. It is depicted by Figure 3 (c) that to pass the same discharge/flood with the same bottom width and same depth of flow through the main channel; there would be considerable increase in depth ratio for rectangular channel as compared to trapezoidal channel. Figure 3 (d) shows that to pass the same discharge/flood with the same flow area and same depth of flow through the main channel; there would be decrease in depth ratio for rectangular channel as compared to the trapezoidal channel. The above mentioned results validate the fact that to carry the same discharge, the channels having more bottom width will have lesser impact on increase in depth ratio at junctions.

Figure 4 shows dependence of depth ratio on various parameters for a dividing channel junction. It is shown in Figure 4 (a) and Figure 4 (b) that depth ratio increases with the increase in discharge ratio for both rectangular and trapezoidal channel junctions. The similar behaviour was noticed during the experiments conducted. It is depicted by Figure 4 (c) that to pass the same discharge/flood with the same bottom width and same depth of flow through the main channel; there would be increase in depth ratio for rectangular channel as compared to trapezoidal channel. Figure 4 (d) shows that to pass the same discharge/flood with the same flow area and same depth of flow through the main channel; there would be decrease in depth ratio for rectangular channel as compared to trapezoidal channel.

All the results obtained from the parametric investigations are in line with the established conclusions, indicating that the developed model maps the flow phenomenon for rectangular and trapezoidal channels very well.
4. Conclusions
A theoretical model for prediction of depth of water at sub-critical channel junctions is developed for both combining and dividing type of flows at channel junctions using the principle of momentum balance. The effects of various parameters such as combining or dividing angles $\theta_1$ & $\theta_2$, width of the channels and discharges in the channels on flow depths have been established. All the terms required in the momentum balance have been developed from the interpretation of flow field at the sub-critical combining and dividing channel junction. The predicted depths match very well with the experimental data. Parametric investigations also indicate that the model developed predicts effect of shape of channel cross section on flow depths very well. Furthermore, the results shows that to pass the equal discharge, increase in depth ratio at rectangular channel junction are more as compared to trapezoidal channel junction having same bottom width. Furthermore, to pass the equal discharge with same flow area; there would be comparatively smaller increase in depth ratio for rectangular channel as compared to trapezoidal channel. The developed model can be used to find out the maximum depth of flow at the junction which can be used for designing the structure or sides of the channels to avoid danger of overflowing under flood conditions.

Table 1. Geometric details of the channel used in experiment.

| Type of Channel | Channel No. | Bottom Width (m) | Side Slope H : V | Combining / Dividing angle from the direction of flow in main channel |
|-----------------|-------------|------------------|------------------|---------------------------------------------------------------|
| Rectangular     | 1           | 0.350            | NA               | 30°                                                          |
|                 | 2           | 0.250            | NA               | 90°                                                          |
|                 | 3           | 0.450            | NA               | NA                                                           |
| Trapezoidal     | 1           | 0.172            | 1: 1.732         | 30°                                                          |
|                 | 2           | 0.072            | 1: 1.732         | 90°                                                          |
|                 | 3           | 0.272            | 1: 1.732         | NA                                                           |

Table 2. Experimental validation - predicted flow depths and measured flow depths.

| Type of Flow | Type of Channel | Measured Depth $y_1$ (m) | $y_3$ (m) | $K_s$ | $q_e$ | $F_3$ | Predicted Depth $y_1$ (m) | Error (%age) |
|--------------|----------------|--------------------------|-----------|-------|-------|------|--------------------------|--------------|
| Combining    | Rectangular    | 0.1075                   | 0.1143    | 0.000 | 0.805 | 0.251 | 0.1138                   | 0.42         |
|              |                | 0.0727                   | 0.0832    | 0.000 | 0.795 | 0.401 | 0.0832                   | 0.05         |
|              |                | 0.1081                   | 0.1302    | 0.000 | 0.405 | 0.610 | 0.1326                   | -1.82        |
| Dividing     | Rectangular    | 0.0911                   | 0.0945    | 0.193 | 0.439 | 0.202 | 0.0930                   | 1.56         |
|              | Trapezoidal    | 0.0801                   | 0.0838    | 0.170 | 0.500 | 0.278 | 0.0838                   | 0.01         |
|              |                | 0.0926                   | 0.1053    | 0.197 | 0.875 | 0.365 | 0.1024                   | 2.83         |
|               | Rectangular    | 0.1097                   | 0.1107    | 0.000 | 0.380 | 0.238 | 0.1096                   | 1.01         |
Table 3. Rectangular vs Trapezoidal –comparative analysis of predicted flow depths for similar flow features.

| Junction Features | Flow Features | Predicted y₁ | Change in y₁ |
|-------------------|---------------|--------------|--------------|
|                   | Type of Flow  | Q₃ (m³/s)   | y₃ (m)       | b₃ (m) | A₃ (m²) | qᵣ | Rect. y₁ | Trap. y₁ | Rect. - Trap. (%) |
| Br₁ = Br₂ = 0.8,  | 4.0  -----    | 0.2 3.2942  | 2.8395       | 16.02  |        |     |          |          |                |
| θ₁ = 0°, θ₂ = 90°,| 0.4 3.8004   | 3.0506       | 24.58        |        |        |     |          |          |                |
| Rect. Z = 0,      | 0.6 4.0542   | 3.1691       | 27.93        |        |        |     |          |          |                |
| Trap. Z = 1.732   | 0.8 4.1852   | 3.2326       | 29.47        |        |        |     |          |          |                |
| Combining         | 0.2 3.2942  | 3.2193       | -9.03        |        |        |     |          |          |                |
| ----- 12.0        | 0.4 3.2861  | 3.5313       | -6.94        |        |        |     |          |          |                |
| Br₁ = Br₂ = 0.8,  | 0.6 3.4775  | 3.6920       | -5.81        |        |        |     |          |          |                |
| θ₁ = 0°, θ₂ = 90°,| 0.8 3.5550  | 3.7752       | -5.83        |        |        |     |          |          |                |
| Rect. Z = 0,      | 50.0 2.60   |             |              |        |        |     |          |          |                |
| Trap. Z = 1.732   |             |            |              |        |        |     |          |          |                |
| Dividing          | 0.2 2.7885  | 2.7162       | 2.66         |        |        |     |          |          |                |
| ----- 12.0        | 0.4 3.1910  | 2.8324       | 12.66        |        |        |     |          |          |                |
| Br₁ = Br₂ = 0.8,  | 0.6 3.2685  | 2.8642       | 14.12        |        |        |     |          |          |                |
| θ₁ = 0°, θ₂ = 90°,| 0.8 3.1928  | 2.8358       | 12.59        |        |        |     |          |          |                |
| Rect. Z = 0,      |              |              |              |        |        |     |          |          |                |
| Trap. Z = 1.732   |              |              |              |        |        |     |          |          |                |

Br₁ = Br₂ = 0.8,
θ₁ = 0°, θ₂ = 90°,
Fig. 1: Schematic layout of combining flow type Junction

Fig. 2: Schematic layout of dividing flow type Junction
Figure 3. Combining flow at channel junction.

(a) Rectangular channel-experimental validation

(b) Trapezoidal channel-experimental validation

(c) Rectangular vs Trapezoidal for same discharge, flow depth & bottom width of main channel

(d) Rectangular vs Trapezoidal for same discharge, flow depth & flow area of main channel
Figure 4. Dividing flow at channel junction.
Nomenclature

A   =  C/S area of the channel
C  =  Constant
F  =  Froude number
\textbf{g}  =  Gravitational acceleration
k  =  Side slope x flow depth to bottom width ratio
P  =  Pressure force
P_f  =  Frictional force due to walls of the channel
Q  =  Discharge
q_r  =  Discharge ratio
b  =  Bottom width of the channel
Br  =  Width ratio
T  =  Top width of the channel
U  =  Momentum transfer from main to the branch channel
V  =  Flow velocity
W  =  Weight of the control volume section
y  =  Flow depth
y_r  =  Flow depth ratio
\rho  =  Specific gravity
\gamma  =  Specific weight
\alpha  =  Bed slope of the channel
\theta  =  Combining or dividing angle of the branch channel to the axis of main channel

Subscripts

1  =  Branch channel 1
2  =  Branch channel 2
3  =  Main channel 3
r  =  Ratio

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