Review of Flow Hydrodynamics and Sediment Transport at Open Channel Confluences

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Abstract

Confluences are common occurrences along the natural rivers as well as artificial open channels. A confluence is characterized by the presence of a stagnation zone, a separation zone, a mixing layer and the recovered flow in the downstream. The bed erosion occurs because of turbulence at the confluence. The eroded soil at the confluence poses problems by deposition in the downstream locations such as check dams, barrages, and reservoirs if not controlled, resulting in reduction of water storage capacity as well as water quality. Recently, the number of studies on the confluences have increased, however, link between flow hydrodynamics and sediment transport, bed morphology at the confluence is still incompletely understood. In this paper, earlier studies on open channel confluences are discussed to summarize flow hydrodynamics and sediment transport phenomenon.

Keywords: River confluence; Hydrodynamics; Shear layer; Bed erosion; Sediment transport

Introduction

A confluence is a place where two flows with different flow and sediment characteristics merge together. Confluences are common occurrences along the natural rivers as well as artificial open channels. In general, a lateral flow confluences into a main flow at various angles. The confluence angle influences the flow and sediment transport at the confluence region. The bed erosion occurs because of turbulence at the confluence. Sometimes, the bank opposite to the direction of lateral flow fails due to the increase in lateral momentum. In addition, the main flow width in the downstream of the confluence increases due to increase of discharge. A confluence is characterized by the presence of a stagnation zone, a separation zone, a mixing layer and the recovered flow in the downstream. A secondary circulation (helicoidal flow cells) induced by the centrifugal action of the lateral flow when merging with the main flow leads to formation of a scour-hole along the central portion of the confluence. The eroded soil from the confluence poses problems by deposition in the downstream locations such as check dams, barrages and reservoirs resulting in reduction of water storage capacity as well as water quality. Hence, this necessitates studies on control of bed erosion at the confluence.

In this paper, earlier studies on open channel confluences are discussed to summarize flow hydrodynamics and sediment transport phenomenon. The efforts to understand the fluvial processes at confluence were made in different disciplines including hydraulics [1-4], sedimentology [5-7], ecology [8,9]. The early studies on open channel confluences were conducted on rigid bed models to understand various flow characteristics such as flow depths, separation zone, and velocity patterns. The studies on river confluences were carried out in laboratory experiments by Taylor [10], Ramamurthy et al. [1], Best and Roy [11], Escauriaza et al. [12], and field studies at river confluence are conducted by Best [6], Rhoads [13], Biron et al. [14], Lane et al. [15], etc. Later, studies were conducted to study sediment transport and scour phenomenon at river confluence on mobile bed models. The hydrodynamics and sediment transport at river confluences are explained in the present paper.

Flow Hydrodynamics at Confluences

Flow depths and separation zone

An open channel confluence is characterized by presence of a stagnation zone, detached flow at the downstream corner called separation zone, flow constriction opposite to separation zone and fully recovered flow beyond separation zone (Figure 1). The prediction of afflux on the upstream of confluence helps in determining the flood level and also for provision of freeboard in case of artificial canals. This section discusses variation of flow depth in the main, lateral and downstream channels at the confluence due to merging of flows and the factors affecting the flow depth at the upstream of the confluence.
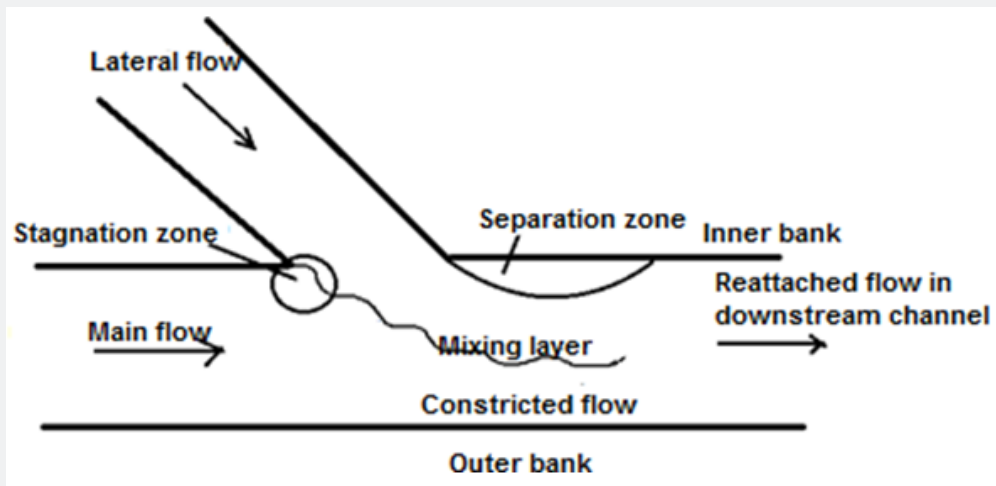
Figure 1: Different flow zones identified at a open-channel confluence.

The lateral flow transfers momentum while merging with the main flow at the confluence. The momentum from lateral flow depends on discharge and flow velocity of the lateral flow. The deceleration of flow at the upstream sections of confluence due to the momentum transfer leads to conversion of velocity head to hydraulic head which causes rise in flow depth in the upstream [1,10,16-19]. The depth ratio (ratio of main and downstream flow depths) depends on discharge ratio (=ratio of discharge in lateral flow to that of main flow) and also on the junction angle [17,20]. Reverse flow along the lateral channel was also observed due to partial diversion of flow from main channel to the lateral channel in case of low discharge ratios [21]. The depth ratio is more in subcritical flow than transitional flow because of low velocity and high flow depth associated with subcritical flow [22]. As the discharge ratio increases, the momentum of lateral flow increases and pushes the main flow towards outer bank and acts as an obstruction to the incoming flow in the main channel. This causes rise in flow depth at outer bank in the downstream channel.

Figure 2: Mixing layer along the confluence (source: from field visit).

Separation zone is a common characteristic observed at river confluences. When the lateral flow merges with the main flow at the confluence, the momentum transfer occurs from lateral to the main flow and hence the flow in the main channel is pushed towards outer bank. This creates a recirculation zone with low velocities called Separation zone near the inner bank of the confluence. This separation zone extends up to certain distance downstream of the confluence leading to constriction of flow in the downstream channel at the separation zone and the flow then recovers to full width of channel. At the separation zone, the flow depth decreases as the flow gets deflected from the inner bank which leads to flow concentration towards the outer bank [6,23]. The water level at the separation zone decreases upto 15% less than that of main flow depth and the difference in water levels at inner bank and outer bank at the separation zone is upto 5% [24]. The minimum depth of flow in the separation zone occurs for the minimum discharge ratio [25]. The separation zone is characterized by presence of a sediment bar along the inner bank of the confluence [26-30]. Sorting of sediments and also deposition occurs at the separation zone which leads to form discordant beds [31] (Figure 2).

As the momentum transfer increases with increase of discharge ratio, the shape index of separation zone, α (ratio of width to length of separation zone) increases [5,17,23]. The separation zone index is affected by the junction angle [17,25]. Since the momentum transfer occurs in more or less same direction as that of the main flow, at small junction angles, the discharge ratio does not affect the separation zone [25]. Hence, the flow constriction increases with an increase of junction angle at the separation zone. The coefficient of contraction which is the ratio of width of flow at separation zone and the downstream channel width, increases with increasing junction angle. The discharge ratio has less impact on size of separation zone in transitional flows because of formation of hydraulic jump at the confluence [25]. The size of separation zone in subcritical flow is higher than that of transitional flow [22]. Separation zone is may not be observed in case of confluences with discordant beds because of turbulence created by bed difference [32].

Velocity distribution and mixing

Flow velocities at the confluence vary from ambient flows due to merging of two different flows. The near bed velocities at the separation zone are similar to that of ambient flow. Whereas, at the separation zone, surface flow has less velocities compared to velocities at the bed level and also has recirculating velocities. The near bed velocities at the confluence increase with discharge ratio which causes soil erosion and sediment transport [5]. Also, the flow constriction at the separation zone has direct impact on the flow velocities which increase away from the separation zone [18,25]. Hence, the velocities along the inner bank are lesser than the outer bank [33-35]. In addition, modification of downstream channel geometry also affects the flow conditions at the confluence [36].

The interaction of the two merging flows depends on the lateral flow momentum [15,34,37-39]. The lateral advection of momentum results in acceleration of fluid in the central portion of the combining flows and the two velocities will be gradually merged in to a single velocity along the mixing layer [15,37,40,41]. Mixing layer with distinct flow and sediment characteristics of merging flows along a natural confluence is shown in Figure 2. The shear layer or mixing layer extends upto three to four times the channel width in the downstream of the confluence which occupies a partial portion of the flow cross-sectional area at the confluence. The shear layer moves from one side of the confluence to the other with change in discharge ratio [37,42,39]. High flow turbulence intensity and high shear stresses are observed within the shear layer with Turbulence Kinetic Energy (TKE) within this layer being two to three times higher than usual flow [43]. In addition, coherent rotating vortices form within the shear layer [44,41].

A hydraulic jump was forms at the confluence under certain flow conditions. The formation and position of hydraulic jump at the confluence depends on the geometry of the channels as well as the inflow Froude numbers [45]. However, a hydraulic jump may not form at the junction all the times [46]. The hydraulic jump forms in the downstream channel only when the discharge ratio exceeds 0.127 [47,48]. This indicates a lower bound for lateral flow discharge to form a jump. For a given main flow Froude number, the jump forms only for higher discharge ratios at smaller confluence angles. Beyond discharge ratio of 0.37, hydraulic jump does not form at the confluence. The discharge ratio, Froude number, width ratio and confluence angle control the formation of hydraulic jump at the confluence [48].

Sediment Transport

Erosion and deposition are the processes of removal and transport of sediment till settle down at low velocity regions. The flow velocity at which sediment particles start moving is called entrainment velocity. Each size of grains has a particular entrainment velocity. Hence, the flow should attain the entrainment velocity in order to erode the soil. The bed erosion occurs if the movement of water exerts the shear stress more than critical shear stress required for the movement of particles. The eroded particles at a location may lead to deposition at some other location in the downstream due to decrease in velocity. This cyclic process of erosion and deposition occurs throughout the length of the river. The amount and size of sediment moving in a river are determined by three factors viz., entrainment velocity, flow capacity and sediment supply. The other sources for bed erosion are flow in culverts and around bridge piers. The enormous amount of sediment being carried in the flow causes decreasing storage capacity of a reservoir.

The convergence of flows at a confluence often leads to erosion of the riverbed and formation of a deep scour at the confluence [49]. A secondary circulation (helicoidal flow cells) induced by the centrifugal action of the lateral flow when

merging with the main flow leads to formation of a scour-hole along the central portion of the confluence [26,29,44,40,49,50]. Increased velocities and turbulence along the central region of the confluence cause bed erosion. Best and Ashworth reported a scour-hole as large as 400m x 2000m at the Ganges–Brahmaputra River confluence in Bangladesh, which migrated 3.5km downstream in only 28 months. The scour at the confluence affects the downstream flow velocity which results in formation of vortices due to change in hydraulic conditions [11,44,51]. The maximum scour depth at the confluence could be four to five times the average flow depth of the incoming flows [52-54]. The confluence scour changes from elliptical to more circular with an increase of confluence angle and it also depends on the symmetry of the confluence angle [49]. Thus, with an increase of confluence angle, the scour depth increases because of increase in momentum [28,55]. In addition, the scour depth increases with an increase of discharge ratio [28,34,29]. The scour depth at the confluence is maximum when the confluence is symmetrical and both main and lateral discharges are equal. The scour-hole is observed along the central portion of the confluence, bisecting the confluence angle, if the discharge in both the incoming flows is equal, otherwise, the scour-hole tends to be parallel to the dominant flow direction [49]. The position of the scour-hole depends on the flow momentum ratio between the two confluent rivers [15,28,38,49,52]. Further, the size and location of scour-hole are studied in natural confluences by Rhoads and Sukhodolov [37], Riley and Rhoads [56], Riley et al. [57], and experimental studies are conducted by Best [58], Boyer et al. [42], etc.

In alluvial rivers, channel morphology and sediment transport processes are inevitably linked [59]. It is observed that generally, the difference between the flow and sediment characteristics of two merging flows such as discharge, flow depth and sediment concentration impact the mixing process at the confluence. Mixing of flows at the water surface level along the confluence depends on the hydrological seasons and the yearly hydrological regime. The highest mixing of flows occurs during peak discharge seasons and lowest during rising discharge seasons [60]. Edward et al. estimated the complete mixing time and distance at Solimos and Negro confluence were around 30 hours and 100km, respectively. Highest mixture of sediments occurs at the bed level because of change in velocities and hence, high-density flows are observed near bed zones [61,62]. The sediment distributions across the main and lateral flows influence the distribution of suspended sediment at the confluence. The increased turbulence levels at the confluence lead to an increase of the sediment transport capacity along shear layer of the confluence [29]. The stagnation point at the upstream corner causes an asymmetric distribution of the flow and sediment transport. Hence, the greatest sediment transport occurs around the edges of the scour-hole which is generally observed at the downstream corner of the confluence [63]. The lateral flow characteristics play a key role in controlling the grain size and sorting of bed material in the downstream direction of the confluence [13, 64-69].

Discussion of Previous Literature

The discussion of previous literature is presented in two sections,

(i)   Experimental studies and

(ii)   Numerical studies.

Experimental studies

Taylor [10] was the first to report the study on open channel junction flows. This study was analytical work based on momentum principle applied to simple open channel junction geometry. By assuming simple channel geometry and boundary conditions, he derived a non-dimensional expression for rise in upstream flow depth for 45° junction angle. He also provided a graphical solution for rise in upstream flow depth. His study was restricted only to subcritical flows. The analytical work of Taylor [10] was extended by Webber & Greated [70] experimentally in predicting the flow depth rise at the junction with momentum principle. They defined a theoretical flow pattern at the junction region using a conformal mapping method. Experiments were conducted with junction angles of 30°, 60° and 90° with subcritical flows. The observations were agreeable with that of Taylor [10] at small junction angles and discharge ratios but differ at higher junction angles and discharge ratios.

Later, a non-dimensional relationship for rise in flow depth was developed by Ramamurthy et al. [1] using discharge ratio and main flow Froude number for subcritical flows. This relation was obtained based on the experimental results on right angled rectangular channel junctions of equal width with varying discharge ratios. A 1D approach was presented by Hsu et al. [17] for determining the upstream depth of right angled junction of rectangular channels with transitional flows. Afflux because of merging flow was observed using water surface mapping by Weber et al. (2001). The separation zone was identified using different experiments by Bryan and Kuhn [27], Liu et al. [34], Birjukova et al. [35], etc.

The velocity pattern at the confluence was studied by Joy and Townsend [36], Weber et al. [24], etc. Experiments were conducted by Weber et al. [24] to obtain velocity patterns and shear stress distribution. They presented 3D flow velocities for right angled rectangular channel junction for varying discharge ratios. The separation zone was also identified using the velocity mappings. The scour phenomenon at river confluences was studied experimentally by Mosley [44], Ghobadian & Bajestan [71], Bejestan &Hemmati [72] , Borghei & Sahebari [28], Ribeiro et al. [29,43] , Giglou et al. [55], etc. The studies were conducted on mobile bed confluence models with rigid side walls and discussed about the maximum scour depth and scour-hole. The above mentioned studies investigated the influence of discharge ratio, flow widths, particle grain size and confluence angle

experimentally. Many studies including Webber and Greated [70], Best [6], Hager [25], Ramamurthy et al. [1], Gurram et al. [20], Hsu et al. [17], Shakibainia et al. [73], Mignot et al. [39,74], Schindfessel et al. [23] have identified discharge ratio as an important parameter influencing flow and sediment transport at the confluence. Vanes and circular piles have been shown to reduce the flow velocities and secondary circulation along the mixing layer and as a result reduced bed erosion was reported by Wuppukondur and Chandra [75,76].

Numerical studies

Bradbrook et al. [77,78] used κ – ε model to study flow features such as the separation zone and secondary circulation at confluence. They reported that momentum ratio is a key parameter in controlling separation zone. In this steady flow model, secondary circulation increases due to bed discordance at the confluence. Large Eddy Simulation (LES) was used by Bradbrook et al. [79] to study unsteady flow conditions at the confluence. Huang et al. used κ – ω model to simulate flow in a right angled open channel junction and the simulation results were in good agreement with experimental results. Frizzell et al. [80] used a 2D depth averaged, κ – ε model to study the flow phenomenon at confluence. The model over predicted the length of separation zone compared to experiments but was accurate in predicting the width of separation zone. The results of a 1D model developed by Ghostine et al. [81] were compared with 2D model solving Saint Venant equations. They reported that 1D model performed well only for small confluence angles and discharge ratios. Whereas, for higher confluence angles and discharge ratios, performance of 2D model was compared with experimental results and found that 2D model predictions were better when compared with 1D model. A 3D numerical model was used by Yang and Chen [82] to study separation zone and secondary circulation at confluence. They assumed fully turbulent flow in the 3D model, but the flow is transition from laminar to turbulent in the experimental study. They found that the simulated results were under predicting compared with experimental results due to this flow transition.

The mixing process at confluence with concordant and discordant beds was studied using a 3D model and field measurements by Biron et al. [32]. The 3D model simulation results showed that the influence of discordant bed on the mixing process at the confluence was found to be less compared to field measurements. However, a wide range of confluence angles and discharge ratios were considered in an experimental study by Shaekibaenia et al. and used a 3D numerical model to compare the flow phenomenon at the confluence.

A multilayer functional link neural network (MFLN) method was used by Yang &Chen [82] to investigate flow velocities at the confluence and observed good match between simulated and measured results. Two ANNs namely Multi-layer Perception (MLP) and Radial basis function (RBF) were used by Balouchi et al. to predict maximum scour depth and compared with experimental results. The MLP model predicted accurate results for low discharge ratios and RBF predicted better results for high discharge ratios. Further, the flow characteristics at river confluence was studied numerically by Shakibainia et al. [73,83], Shi-he and Bing [84], Baranya et al. [85], and Lyubimova et al. [61]. It shows that the earlier numerical studies on confluence have emphasized more on studying the flow phenomenon with only a few studies on sediment transport.

Conclusion

Recently, the number of studies on the confluences have increased, however, link between flow hydrodynamics and sediment transport, bed morphology at the confluence is still incompletely understood. Most of the previous studies were performed to understand the hydrodynamics at the confluence using rigid bed models [2,16,32,35,40,48]. These studies provided clear implications of bed erosion and sediment transport. A few studies on sediment transport highlighting scour phenomenon and deposition processes at river confluence were performed using mobile bed physical models in the laboratory [28,44,55,58]. The eroded soil at the confluence poses problems by deposition in the downstream locations such as check dams, barrages, and reservoirs if not controlled, resulting in reduction of water storage capacity as well as water quality. Kothyari [86] reported that by 2020, 30 major reservoirs and by 2050, 80% of the existing reservoirs in India will lose half of their original capacity. It is reported that reservoirs all over the world are losing storage capacity by as much as 5% every year. In addition, the flow at the confluence concentrates more towards the outer bank causing bank erosion due to flow separation. This results in river bank failure and inundation in the adjacent areas along the river bank. Hence, this necessitates studies on control of bed erosion and controlling the flow movement towards outer bank at the confluence.

Acknowledgement

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