Review of Flow Hydrodynamics and Sediment Transport at Open Channel Confluences

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Submission: April 26, 2018; Published: June 14, 2018

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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.
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.
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 up to 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, $a$ (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 subcritical flow than that of transitional flow [22]. Separation zone index 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, 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 up to 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 Solimoes 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], Ghabadian & 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...
实验性地。许多研究包括 Webber 和 Greatest [70], Best [6], Hager [25], Ramamurthy 等 [1], Gurram 等 [20], Hsu 等 [17], Shakibainia 等 [73], Mignot 等 [39,74], Schindfessel 等 [23] 识别了流程比率作为影响参数，流量和沉积物输送。Van 和圆形桩已经显示减少流量流速和次级循环沿混合层和作为结果，冲刷在 Wuppukondur 和 Chandra [75,76]。

**Numerical studies**

Bradbrook 等 [77,78] 使用 $\kappa-\varepsilon$ 模型来研究流速特性，如分离区和次级循环区。他们报告说，为保持分离的参数是一个关键的控制参数。在稳定流程模型中，次级循环增加到床离散度的影响。Large Eddy Simulation (LES) 被 Bradbrook 等 [79] 用于研究不steady流程条件的影响。Huang 等使用 $\kappa-\omega$ 模型来模拟流量在右角度联管通道和模拟结果的流速在良好一致的实验结果。Frizzell 等 [80] 使用 2D 深度平均，$\kappa-\varepsilon$ 模型来研究流速现象。模型描述了距离实验结果的距离相比实验是准确的。他们报告说，1D 模型工作良好，对于较小的厚度和运输率。然而，对于更高的运输率和沉积物，2D 模型被比较与实验结果，并发现 2D 模型预测更好。当与 1D 模型比较时，3D 数值模型被使用 Yang 和 Chen [82] 来研究分离区和次级循环。他们在过渡流在 3D 模型中，但流动是来自 laminar 到湍流的实验研究。他们发现，模拟结果是在预测相比与实验结果由于此流程转变。

混合过程在合流处与具有相同或不同床的床体被使用 3D 模型和领域测量的 Biron 等 [32]。3D 流动模拟结果显示，影响的分离床在流程过程中在合流处被发现与实验比较。然而，范围的厚度和运输率在实验研究中被考虑在实验性研究中由 Shakibainia 等和使用 3D 数值模型来比较的流程现象。

一个由 Yang &Chen [82] 使用的多层功能链接网络 (MFLN) 方法，使用了由 Balouchi et al. 获得最大冲刷深度和与实验结果比较。MLP 模型提供了与实验结果的准确结果。MLP 模型使用多层神经网络和 RBF 预测的 responding 结果。进一步，流程的特性在合流处被研究数值性地由 Shakibainia 等 [73,83], Shi-he and Bing [84], Baranya 等 [85], 和 Lyubimova 等 [61]。它显示了早期的数值性研究在合流处已经强调更多再研究流程现象与只有少数研究在合流处的实验研究。

**Conclusion**

最近，对合流处的流动的研究已经增加，然而，用影响流量水动力学和沉积物运行，床体形态在合流处仍然没有完全理解。大多数的早期研究被用作来理解水动力学的影响。这合流处使用 rigid 床模型 [2,16,32,35,40,48]。这些研究提供了沉积物冲刷和床体冲刷的明显影响。在低运输率和 RBF 预测更好的结果。进一步，流程的特性在河流中被研究数值性地由 Shakibainia 等 [73,83], Shi-he and Bing [84], Baranya 等 [85], 和 Lyubimova 等 [61]。它显示了早期的数值性研究在合流处已经强调更多再研究流程现象与只有少数研究在合流处的实验研究。

**Acknowledgement**

作者会感谢 Dr. Venu Chandra, Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Madras, India 为帮助编写 manuscript。

**References**


Civil Engineering Research Journal

Series B, St Anthony Falls Laboratory, Univ. of Minnesota, Minneapolis, Minn.


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DOI: 10.19080/CERJ.2018.05.555664

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