Impact of Navigation on Flow and Sediment Transport at River Confluences: An Experimental Study

Submitted to

Ministry of Shipping

Government of India

under

National Technology Centre for Ports, Waterways and Coasts (NTCPWC)

by

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1. Introduction

Confluences are common occurrences along natural rivers as well as artificial channels. From an environmental standpoint, confluences are considered hot spots within the fluvial network. They enhance the river eco-system by providing ecological connectivity and heterogeneity in flow, water quality and bed substrate. The confluence is characterized by the presence of a stagnation zone, a separation zone, a mixing layer and the recovered flow in the downstream (Best and Reid 1984). The convergence of main and lateral flowsat the confluence often leads to erosion of the bed and form a deep scour at the confluence. 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 (Mosley 1976). Increased velocities and turbulence along the central region of the confluence cause the bed erosion. The scour depth increases with an increase of confluence angle because of increase in momentum (Giglou et al. 2016). The position of the scour-hole depends on the flow momentum ratio between the two confluent flows (Lane et al. 2008). Discharge ratio (ratio between main and lateral flow discharges) has been identified as a key parameter which influences the separation zone as well as the processes at the confluence by various studies.

Similarly, flow and sediment transport phenomena at river bends are complex than straight channels. River bends also experience erosion due to change in flow at the bend location. Pressure gradients and centrifugal force produce secondary circulation which changes the flow pattern and sediment transport at the bends (Kassem and Chaudhry 2002; Khosronejad et al. 2007). The increased velocities and turbulence at the outer bank result in scouring at the bends which leads to river bank failures (Roca et al. 2009).

The recent increase in the number of studies on river confluences and river bends has yielded a better, still incomplete understanding of the link between flow dynamics, sediment transport and bed morphology. The convergence of the flows at the confluence results in deceleration at the upstream sections of confluence which leads to conversion of velocity head to hydraulic head (Pinto 2015). The afflux generated at the confluence creates problems of inundation in the upstream areas. Also, the eroded soil from the confluences and river bends poses problems of 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 (1996) 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 major reservoirs all over the world are losing storage capacity by as much as 5% every year (Wisser et al. 2013). In addition, the flow at the confluence and bends concentrates more towards the outer bank causing bank erosion due to flow separation (Suresh et al. 2013). This results in river bank failure and inundation in the adjacent areas along the river bank. It is reported in the literature that bank erosion is a significant source of sediment load in rivers which has adverse environmental impact. The bank erosion also widens the river which results in reduced sediment transport capacity. Hence, this necessitates studies on river confluences and bends to understand the flow and sediment transport phenomenon in detail to benefit bank protection, navigation, flood control, irrigation and other water resources projects.

Generally, vanes and piles are flow training structures designed to modify the near-bed flow pattern and redistribute flow and sediment transport (Odgaard and Kennedy 1983). Submerged vanes are conventionally used to control sedimentation in the intake canals (Wuppukondur et al. 2016). Vanes (or piles) create a horizontal vortex along the flow which eliminates secondary circulation in lateral direction which generally occurs at confluences, bends, and at the entrance of intake canals. The horizontal vortex strength depends on angle of attack, vane spacing and vane arrangement i.e., single row or multiple rows (Allahyoneri et al. 2008). Similarly, spur dykes are bank protection structures constructed transverse to the flow, extending from the bank to mitigate bank erosion and to deepen navigation channels (Zhang and Nakagawa 2008). The spurs perform by reducing the concentration of flow at the bends and redistributing the flow. Hence, these structures can be used at confluences and bends to effectively control bed and bank erosions. However, there is a need to check feasibility of installing vanes or piles if navigation is taking place in the rivers. Therefore, the present study aims to investigate the impact of ship waves created by navigation on flow, sediment erosion and deposition at the confluence.

2. Literature review

The overview of previous studies on the present topic is presented in two sections, (i) International studies and (ii) National studies corresponding to international arena and Indian arena, respectively.

2.1 International studies:

Taylor (1944) 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 45^0 junction angle. The analytical work of Taylor (1944) was extended by Webber and Greated (1966) experimentally in predicting the flow depth rise at the junction with momentum principle. Experiments were conducted with junction angles of 30^0, 60^0 and 90^0 with subcritical flows. The observations were agreeable with that of Taylor (1944) 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. (1988) 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. (1998) for determining the upstream depth of right angled junction of rectangular channels with transitional flows. The afflux because of merging flow was observed using water surface mapping by Weber et al.(2001).

The velocity pattern at the confluence was studied by Joy and Townsend (1981), Weber et al. (2001), etc. Experiments were conducted by Weber et al. (2001) to obtain velocity patterns and shear stress distribution. They presented 3D flow velocities for right angled rectangular channel junction for varying discharge ratios. The scour phenomenon at river confluences was studied experimentally by Mosley (1976), Ghobadian and Bajestan (2007), Bejestan and Hemmati (2008), Borghei and Sahebari (2010), Ribeiro et al. (2012), Giglou et al. (2016), 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.

2.2 National studies:

Only a few studies are reported from India on river confluences to the author's knowledge. Biswal et al. (2010) and Biswal(2012) studied the flow phenomenon in a compound channel junction. The variation of water surface elevations, bed shear stress and turbulence with discharge ratio was studied experimentally. Both subcritical and transcritical flow regimes were compared in this study. Later, Wuppukondur and Chandra (2017) studied performance of vane and circular pile models as bed erosion mitigation structures at the confluence. Experiments were conducted in a distorted mobile bed model with two different confluence angles under different flow discharges. The experimental results showed that piles have better performance over vanes in controlling bed erosion at the confluence.

3. Objectives of the proposed study:

From the above review of literature, it can be noticed that the studies on erosion at confluences and bends with mobile boundaries are still incomplete. The bed erosion mitigation structures proposed by Wuppukondur and Chandra (2017) are applicable only to very wide open channels since the obstruction created by the vanes or piles at the confluence adversely impacts the navigation capacity of both the merging channels. Vessels (or ships) in the navigation channels generate surface waves (ship waves) which result in severe wave-wash damage to the river banks (Dam et al. 2008). The ship waves also alter the sediment transport in navigation channels (Nyugen et al. 2012; Shengcheng et al. 2014a). However, the wave characteristics and its impacts on banks in navigation channels are not yet fully investigated (Shengcheng et al. 2014b). Hence, it is required to extensively study the ship waves at the confluence for both channel design and operational safety of vessels in navigational channels. Therefore, the objectives of the proposed research are:

1. To study wave heights and wave velocities with a vessel in main (or lateral) channel and also with two vessels at the confluence region.
2. To study the impact of ship waves on sediment mixing, bed topography and bank erosion with a vessel in main (or lateral) channel and also with two vessels at the confluence region.
3. To study flow hydrodynamics and sediment mixing in detail at the confluence region with vanes or piles and to improve the vane installation guidelinesin case of navigation channels.

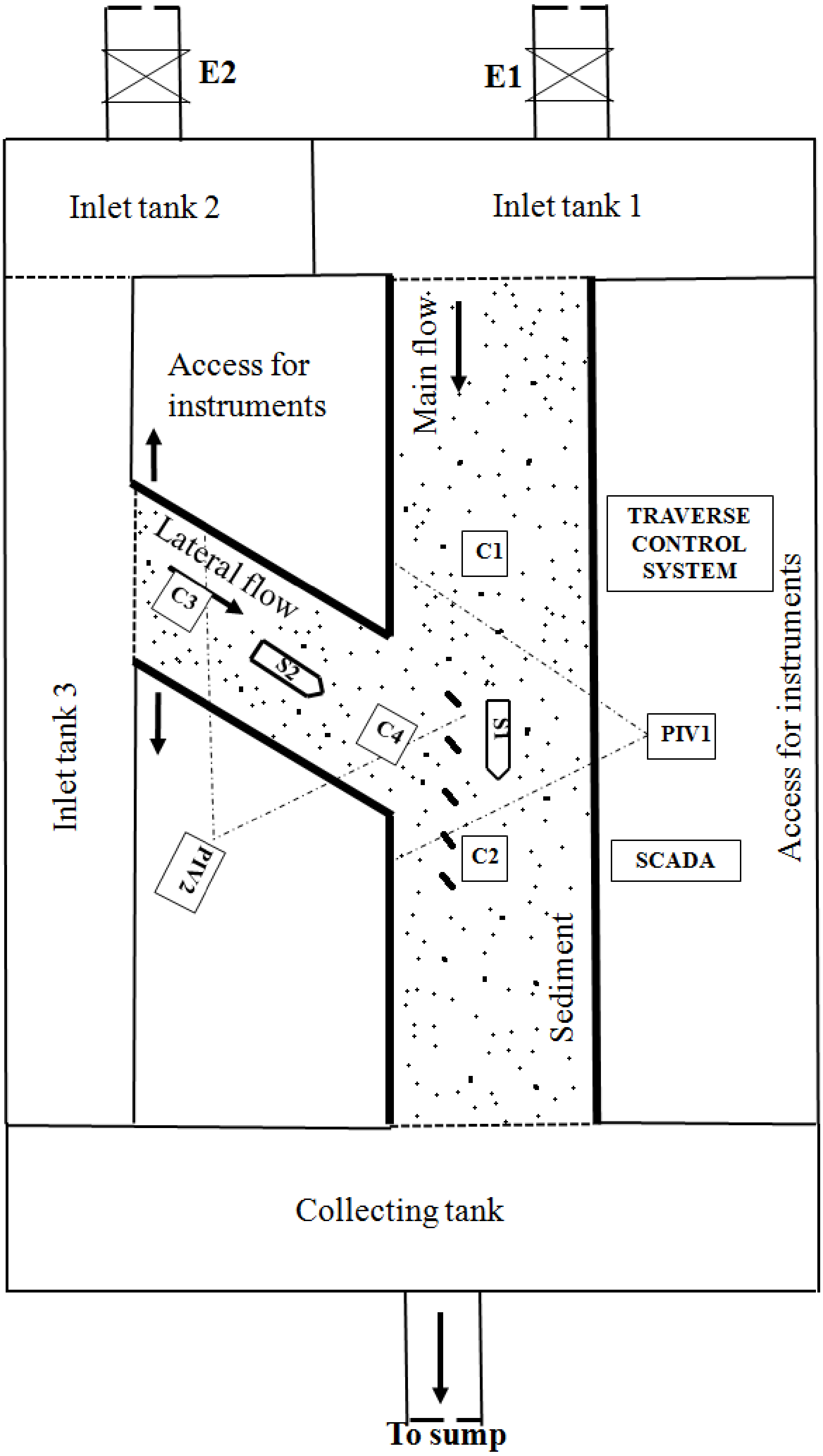
4. Experimental setup and instruments used:

Experiments will be conducted in a river confluence model at Hydraulic Engineering laboratory, IIT Madras. Field visits will be conducted to various river confluences in India to collect data such as flow discharges, widths, cross-sectional data and sediment samplesandwill be used in designing the experimental setup. The experiments will be conducted in three phases with (i) rigid bed model, (ii) mobile bed model, and (iii) mobile bed model with vanes (or piles). The experiments with rigid bed models are conducted to obtain data on flow hydrodynamics at the confluence with and without ship models. Mobile bed model experiments are performed to understand the impact of ship waves on sediment transport and bank erosion at the confluence. The experiments with vanes (or piles) are performed in a mobile bed model to improve the installation of the vanes or piles at the confluence for safe operation of vessels with sufficient clearing space. The above mobile bed models have mobile boundaries to clearly capture the bank erosion and failure phenomena.

Figure 1 shows the schematic diagram of the experimental setup used to conduct experiments. The widths of both main and lateral channels can be adjusted by using metal sheets at desired distances. The confluence angle between the main and lateral channels can be altered by moving the side walls of the lateral channel as shown in Figure 1. The flow in both the channels is re-circulated with a pipe network. The discharge in main and lateral flows is controlled and monitored using a Supervisory control and data acquisition (SCADA) system with electromagnetic flowmeters eliminating manual power required in measuring the discharge. The water surface elevations in both the channels will be measured using Laser surface sensor and image processing using commercially available software to obtain the data remotely. The data from image processing will be validated using digital point gauges. The wave heights and extent are measured using wave gauges along with Laser surface sensor and image processing similar to water surface elevations. The flow velocities are measured using Particle Image Velocimeter (PIV) which is mounted to a computer operated traverse system which can traverse in both longitudinal and lateral directions precisely. In addition to obtaining flow velocities, pressure sensors are mounted on the banks (glass walls) to obtain pressure variation. The bed morphology at the confluence region is obtained using both Bed profiler and also Image processing. The various data that will be collected from the experiments and the techniques for data collection are summarized in Table 1. The experimental setup can be modified to study river bends by completely obstructing main flow and allowing flow in only lateral channel.

Table 1: Instruments required for data collection

Sl. No	Instruments (nos.)	Purpose
1	a) Electromagnetic flowmeters (2nos.) b)Air compressor (1nos.) c)PC	To measure flow discharge
2	a)Laser surface sensor (2nos.) b)Digital Cameras(4nos.) c)Digital point gauge (2 nos.) d)Wave gauges (4nos.)	To get water surface elevations
3	PIV setup (2nos.)	To measure flow velocities
4	Pressure sensors	To obtain pressure at the banks
5	a)Bed profiler (2nos.) b)Digital Cameras (4nos.) c)Software (1no.)	To analyze bed morphology
6	Pump sampler (4nos.)	For collecting water-sediment samples



C1, C2 & C3, C4 – Cameras for Image processing
E1 & E2 – Electromagnetic flowmeters
PIV1 & PIV2 – Particle Image Velocimeters
S1 & S2 – Ship models
\ – Vanes

Figure 1: Schematic diagram of experimental setup

4.1 Methodology:

A test section to be identified at the confluence region and divided into a number of small grids to collect various experimental data. First, experiments will be conducted in a rigid bed model to identify the flow pattern at the confluence without vessel models. The flow velocities and water surface elevation are measured when the flow is steady at the test section. Also, the pressure on the banks due to the flow is continuously monitored using pressure sensors. Later, vessel models are towed along the flow and the above procedure is repeated. Later, experiments are conducted in mobile bed model with mobile boundaries to identify scour hole and bank erosion at the confluence. The initial bed topography of the test section before start of the experiment is obtained using both Bed Profiler and image processing. The experiments are run until equilibrium scour is attained and the final bed topography is measured. From the initial and final bed topographies, the erosion can be identified at the confluence. The vessel models are then used in the experiments and the impact of ship waves on sediment transport and bank erosion at the confluence are studied.

The above experimental procedure is repeated using vanes (or piles) installed at the confluence in the mobile bed model with and without vessels. The results are compared to earlier experiments to observe the flow hydrodynamics and sediment transport (mixing and morphology) with introduction of vanes (or piles) at the confluence. Later, with vanes or piles installed at the test section, vessel models are then towed using a computer operated traverse system (with ability to control vessel velocity) along the flow. Then, the wave heights and the wave extent at the confluence are recorded. Flow velocities and pressure on the banks are obtained similar to earlier experiments. The experiments are performed with varying confluence angle, discharge ratio, width ratio, vanes (or piles) arrangement, position and size of the vessels in order to obtain in detail understanding of the ship wave impact on the bed and bank of a navigation channelat the confluence. The results from these experiments are compared with results without vessel models. Similar experiments can be conducted by obstructing the main flow to create river bends. The above procedure can be used to perform experiments on river bends using same methodology with same instruments.

In addition to the above experimental measurements, water samples are collected periodically using a pump sampler to analyze the sediment concentration at different grid points in the test section. The water samples of different experiments with and without vessels are analyzed for sediment concentration and are compared to understand the impact of ship waves on sediment mixing at the confluence.

5. Study Outcomes:

The overarching aim of this research is to study in detail the flow hydrodynamics, mixing processes and sediment transport at the confluence of two navigation channels with and without vanes (or piles) to ensure operational safety of vessels.This study helps in understanding the potential bank failures due to ship waves at the confluence of navigation channels. Also, the existing guidelines for installation of vanes or piles will be improved by considering the clearing distance required for navigation at the confluence. Further, this study helps in understanding and ensuring both natural processes and navigation at the confluence.

6. Budget:

The budget is presented in two tables consists of (i) the instruments cost (ii) the overall budget including manpower, consumables, contingency and travel with institute over head charges.

6.1. Budget for instruments:

Sl. No	Instrument	Quantity (nos.)	Unit Price (INR)	Cost (INR)
1	SCADA System	1	40,00,000	40,00,000
3	Electromagnetic flowmeters	2	75,000	1,50,000
2	Laser surface sensors	2	1,00,000	2,00,000
3	Digital Cameras	4	2,50,000	10,00,000
4	Digital point gauges	2	1,00,000	2,00,000
5	Wave gauges	4	10,000	40,000
6	PIV Setup	2	1,00,00,000	2,00,00,000
7	Pressure sensors	6	40,000	2,40,000
8	Bed profiler (laboratory)	2	14,00,000	28,00,000
9	Pump Sampler	2	10,000	20,000
10	Laser distancemeter	1	15,000	15,000
11	Acoustic Doppler Velocimeter	1	10,00,000	10,00,000
12	Bed Profiler (Field scale)	1	15,00,000	15,00,000
13	Pump sampler (Field scale)	2	20,000	40,000
14	Desktop Computer	2	70,000	1,40,000
15	Traverse system for vessel models	1	30,00,000	30,00,000
			Total	**3,43,45,000**

6.2. Overall Budget for full three years:

Sl. No.	Head	1st Year	2nd Year	3rd Year	Total
1.	Instruments	3,43,45,000	NIL	NIL	3,43,45,000
2.	Manpower	12,00,000	14,00,000	16,00,000	42,00,000
3.	Consumables	3,00,000	1,00,000	1,00,000	5,00,000
4.	Travel	2,00,000	2,00,000	2,00,000	6,00,000
5.	Contingency	3,00,000	1,00,000	1,00,000	5,00,000
6.	Total Project Cost	3,63,45,000	18,00,000	20,00,000	4,01,45,000
7.	Overhead Costs (@20% of project cost)	72,69,000	3,60,000	4,00,000	80,29,000
8.	Total	4,36,14,000	21,60,000	24,00,000	**4,81,74,000**

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(v) June 2006 – September 2007 : DAAD Fellow, KIT Germany.
(vi) March 2003 – July 2004 : Lecturer, CST, Bhutan.
(vii) August 2002 – December 2002 : Project Assistant, I.I.T. Kanpur.

RESEARCH GUIDANCE:

A. Ph.D : Currently guiding: 2
B. Master of Science(by research) : Completed: 1
C. Master of Technology : Completed: 2, Ongoing: 1

PUBLICATIONS AND RESEARCH PROJECTS:

Sl. No	Item	Number
1	Refereed International Journals	4 (2 more communicated)
2	Sponsored Projects	4

Resume of B.S. Murty

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M.E: Civil Engineering, 1984, Indian Inst. of Science (Distinction)
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(i) January 2004 – till date: Professor, I.I.T. Madras
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(viii) July 1984-July 1985: Project Associate, I.I.Sc., Bangalore

RESEARCH GUIDANCE:

A. Ph.D : Completed: 9; currently guiding: 6
B. Master of Science(by research) : Completed: 4
C. Master of Technology : Completed: 41

PUBLICATIONS AND RESEARCH PROJECTS:

Sl. No	Item	Number
1	Refereed Indian Journals	5
2	Refereed International Journals	51
3	Sponsored Projects	6
4	Research based industrial consultancy	4