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Experimental and numerical modelling of flow and sediment characteristics in open channel junctions

Kalyani Dissanayake

University of Wollongong

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EXPERIMENTAL AND NUMERICAL MODELLING OF FLOW AND SEDIMENT CHARACTERISTICS IN OPEN CHANNEL JUNCTIONS

A thesis submitted in fulfilment of the requirements for the award of the Degree of

Doctor of Philosophy

from

UNIVERSITY OF WOLLONGONG

by

KALYANI DISSANAYAKE, MSc Eng (Hons)

School of Civil Mining and Environmental Engineering

2009
THESIS CERTIFICATION

I, Kalyani Dissanayake, declare that this thesis, submitted in fulfilment of the requirement for the award of Doctor of Philosophy, in the School of Civil, Mining and Environmental Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

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Kalyani Dissanayake

October 2009
ABSTRACT

Open channel confluences are present in many natural and man-made waterways. The dynamics of the flow in and around the junction are complex; in particular, immediately downstream of the junction, the flow develops a zone of separation on the inner wall, with accompanying secondary re-circulation patterns. The structure of this complex flow is a function of several parameters such as flow rates in both channels, angle of confluence, channel geometry including longitudinal slope and bed discordance, boundary roughness and intensity of turbulence and has a major influence on bed erosion, bank scouring, etc. If in addition, one or both streams are sediment-laden, the structure of the downstream flow becomes even more complex due to additional variables such as variation in sediment particle size and sediment concentration. This makes detailed experimental investigation of such flows very challenging.

In order to investigate the junction flow behavior, laboratory experiments and numerical simulations were performed in an equal-width, equal-depth and 90° flat bed open channel junction. Two separate computational codes PHOENICS and CFX were used for numerical simulations. Water heights, water velocities and sediment particle tracks were computed for different flow ratios and feed concentrations.

For investigating the junction flow behavior experimentally, a laboratory scale open channel junction was designed and constructed at the hydraulics laboratory of the University of Wollongong. Experiments were conducted for clean water and sediment laden flows with different flow ratios and feed concentrations. The downstream Froude number was kept constant (0.37) for all experiments. In sediment laden flow experiments, Corvic vinyl was introduced uniformly to the branch channel as sediment and then captured at the downstream end of the main channel to facilitate clean water
flow through the main channel and sediment laden flow through branch channel. Water heights and turbidity were measured at different locations of the main channel utilizing point gauges and a custom made optical turbidity probe respectively.

Numerical predictions showed higher water levels upstream of the junction followed by a sudden drop of water levels immediately downstream of the junction. This phenomenon is accompanied by flow separation at the inner bank. Higher velocities were generated adjacent to the outer bank and velocities were diminished towards the inner bank. The separation zone length and width were diminished with increasing flow ratio $q^*$ ($q^*=$main channel flow / total flow). Using a ‘body-fitted’ computational mesh, conforming to the shape of the free surface, and carrying out a ‘water-only’ simulation imposing free slip boundary condition for the free surface produced accurate velocity patterns near the bed and the free surface, showing a good agreement with experimental results.

In laboratory experiments higher sediment concentrations were observed adjacent to the inner wall immediately downstream of the junction, indicating particle deposition in the low-velocity separation region. It was observed that with increasing source sediment concentration from the branch channel, the turbidity downstream of the confluence increased while covering a larger area across the width of the main channel. Low sediment concentrations were observed upstream of the junction in all experiments. Higher turbidity gradients exist close to the junction whereas the turbidity gradients gradually diminish along the downstream of the main channel.

The sediment concentrations across the main channel were controlled by the location of the shear layer. This layer was moved towards inner wall with increasing discharge ratios showing higher sediment concentration adjacent to inner wall of the
main channel. For lower discharge ratios $q^*=0.25$ and $q^*=0.417$, sediment particles were dispersed across the entire channel width of the main channel while in higher discharge ratios $q^*=0.583$ and $q^*=0.75$, flow from the main channel occupied most of the cross section and therefore branch channel sediment was confined to a small area adjacent to the inner wall. Similar scenario was observed in simulated particle paths as more particle tracks were shifted towards the outer wall direction for lower discharge ratios $q^*=0.25$ and $q^*=0.417$ than for higher discharge ratios $q^*=0.583$ and $q^*=0.75$. The shape factor of the separation zone (defined as the ratio of maximum separation zone width $w_s$ to separation zone length $L_s$) was found to vary between 0.12 to 0.15 for all experimental conditions tested. However the shape factor for clean water is found to be lower compared to sediment laden flow at all $q^*$ values.

The current study provides new data contributing to a better understanding of flow and sediment dynamics at channel junctions. The application of this new knowledge will lead to improved design of river bank protection works and urban flood and erosion control structures adjacent to the junction of branching channels.
DEDICATION

This thesis is dedicated with love and devotion at the divine lotus feet of Bhagavan Sri Sathya Sai Baba, Chancellor, Sri Sathya Sai University, Puttaparthy, India who gave me power and intellect to change what I in my selfish ignorance have created. Let His divine light show me the way to the goal of liberation. Without His grace, this piece of work couldn’t have been completed.
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I worship my late parents who were not only my parents but were also teachers in my early grades at school. They taught me to be helpful to our fellow man.

Lastly I extend my utmost thanks to my beloved husband Sarath Fernando and daughter Thanoja Fernando for their helps, patience and sacrifice throughout the course of this study.
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**Symbols**

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<th>Definition</th>
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<tr>
<td>( b )</td>
<td>Breadth of channel (m)</td>
</tr>
<tr>
<td>( C )</td>
<td>Chezy roughness coefficient</td>
</tr>
<tr>
<td>( C_D )</td>
<td>Particle drag coefficient</td>
</tr>
<tr>
<td>( C_k )</td>
<td>Mean sediment concentrations in the Kaskaskia River (g/L)</td>
</tr>
<tr>
<td>( C_s )</td>
<td>Mean sediment concentrations in the Copper Slough (g/L)</td>
</tr>
<tr>
<td>( C_t )</td>
<td>Ratio of the branch channel upstream depth and the branch entrance depth</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>Main channel mean suspended sediment concentration (g/L)</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>Branch channel mean suspended sediment concentration (g/L)</td>
</tr>
<tr>
<td>( c_m )</td>
<td>Turbulent mixing energy loss coefficient</td>
</tr>
<tr>
<td>( D_{50} )</td>
<td>Average particle size</td>
</tr>
<tr>
<td>( d_p )</td>
<td>Particle diameter (mm)</td>
</tr>
<tr>
<td>( F_d )</td>
<td>Downstream Froude number</td>
</tr>
<tr>
<td>( F_m )</td>
<td>Froude number at maximum separation zone width</td>
</tr>
<tr>
<td>( F_2 )</td>
<td>Branch channel Froude number</td>
</tr>
<tr>
<td>( F )</td>
<td>The total force acting on the particle</td>
</tr>
<tr>
<td>( g )</td>
<td>Gravity (m/s²)</td>
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<tr>
<td>( h_m )</td>
<td>Loss of energy head in the junction (m)</td>
</tr>
<tr>
<td>( h^* )</td>
<td>Normalized water depth (m)</td>
</tr>
<tr>
<td>( K )</td>
<td>Separation zone shear coefficient</td>
</tr>
<tr>
<td>( K^* )</td>
<td>Coefficient of interfacial shear</td>
</tr>
<tr>
<td>( L )</td>
<td>Length of the control volume (which was taken as double the width) (m)</td>
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<tr>
<td>( L_S )</td>
<td>Separation zone length (m)</td>
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<td>( M_t )</td>
<td>Branch channel momentum flux/ Main channel momentum flux</td>
</tr>
<tr>
<td>( m_p )</td>
<td>Mass of conveyed discrete particles (kg)</td>
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<td>( n_u, n_d, n_b )</td>
<td>Depth ratios in comparison to the downstream depth, subscripts ( u ), ( d ) &amp; ( b ) denote upstream, downstream and branch respectively</td>
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<td>( p )</td>
<td>Relative static pressure head</td>
</tr>
<tr>
<td>( p_d )</td>
<td>Relative static pressure downstream</td>
</tr>
<tr>
<td>( p_b )</td>
<td>Relative static pressure branch</td>
</tr>
<tr>
<td>( p_u )</td>
<td>Relative static pressure upstream</td>
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<tr>
<td>( p^* )</td>
<td>Average pressure exerted on side wall of branch channel (kg/m²)</td>
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<td>( Q_r )</td>
<td>Discharge ratio: Discharge in the tributary / Discharge in the main channel</td>
</tr>
<tr>
<td>( Q_u )</td>
<td>Upstream channel discharge (m³/s)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
<td>$Q_d$</td>
<td>Downstream channel discharge (m³/s)</td>
</tr>
<tr>
<td>$Q_b$</td>
<td>Branch channel discharge (m³/s)</td>
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<tr>
<td>$Q_m$</td>
<td>Main channel discharge (m³/s)</td>
</tr>
<tr>
<td>$q^*$</td>
<td>Discharge ratio: $Q_{main}/Q_{total}$</td>
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<tr>
<td>$S_r$</td>
<td>Sediment concentration ratio = $C_2/C_1$</td>
</tr>
<tr>
<td>$S_0$</td>
<td>Slope of the channels (m/m)</td>
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<tr>
<td>$S_\phi$</td>
<td>Source/sink term for $\phi$</td>
</tr>
<tr>
<td>$U$</td>
<td>Velocity (m/s)</td>
</tr>
<tr>
<td>$u^*$</td>
<td>Streamwise bed velocity or surface velocity (m/s)</td>
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<tr>
<td>$v^*$</td>
<td>Non-dimensionalised crosswise velocity</td>
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<tr>
<td>$V_T$</td>
<td>Average velocity of flow downstream (m/s)</td>
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<tr>
<td>$v_t$</td>
<td>Turbulent viscosity (m²/s)</td>
</tr>
<tr>
<td>$v_l$</td>
<td>Laminar viscosity (m²/s)</td>
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<tr>
<td>$w$</td>
<td>Width ratio to the downstream width</td>
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<td>$w^*$</td>
<td>Non-dimensionalised vertical velocity by the downstream average velocity</td>
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<td>$w_s$</td>
<td>Separation zone width (m)</td>
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<td>$x^*$</td>
<td>Distance in x direction/Channel width</td>
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<tr>
<td>$y^*$</td>
<td>Distance in y direction/Channel width</td>
</tr>
<tr>
<td>$z^*$</td>
<td>Distance in z direction/Channel width</td>
</tr>
<tr>
<td>$Y^*$</td>
<td>Depth ratio (Ratio of upstream to downstream water depth)</td>
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<tr>
<td>$\alpha_\upsilon$</td>
<td>Energy correction coefficient, upstream</td>
</tr>
<tr>
<td>$\alpha_\beta$</td>
<td>Energy correction coefficient, branch</td>
</tr>
<tr>
<td>$\alpha_m$</td>
<td>Energy correction coefficient, maximum separation zone width</td>
</tr>
<tr>
<td>$\beta_\upsilon$</td>
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<td>$\delta$</td>
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List of Symbols and Abbreviations

\( \vec{v}_f \)  Velocity of fluid (m/s)
\( \vec{v}_p \)  Velocity of particle (m/s)
\( \rho \)  Density (kg/m\(^3\))
\( \rho_\pi \)  Particle material density (kg/m\(^3\))
\( \rho_\phi \)  Fluid density (kg/m\(^3\))
\( \omega \)  Orientation of depth average velocity vector
\( \Gamma_\phi \)  Diffusive exchange coefficient for \( \phi \)
ADV  Acoustic Doppler Velocimeter
CFD  Computational Fluids Dynamics
LES  Large Eddy Simulation
NTU  Nephelometric Turbidity Unit
FIT  Fiber optic in-stream transmissometer
F.C  Feed concentration
1. INTRODUCTION

1.1. PREAMBLE

Natural alluvial rivers are subject to significant changes in their boundaries that are subject to erosion and deposition of sediment. Part of the sediment which is carried by rivers is dragged or rolled along the bed while the remainder is suspended and travels with the water. Sediment particles can become suspended in the water as a result of erosion in streams or on beaches, or from wave-induced re-suspension of particles from the bottom. Increasing amounts of suspended sediment and associated nutrients entering rivers have negative consequences for water quality and light penetration. Ecosystem functions such as photosynthesis are affected by increased sediment concentration and the sediment can also smother the habitat of fish and other aquatic living creatures.

Open channel junctions are a common occurrence which exhibit complex flow behaviour in natural and man-made river systems. Flow in channel junctions is controlled by many factors such as stream discharge, junction angle, channel geometry, longitudinal slope, bank and bed resistance to flow (geology including types of sediment) and Froude number. Sediment transport at junctions brings additional complications to the flow behaviour. Therefore a clear understanding of the links between flow dynamics, sediment transport and bed morphology is crucial in controlling local sedimentation processes, channel scouring and sidewall erosion and flooding, and thus in sustainable river management.

In the past different approaches have been used to investigate the dynamics of confluence flow. Many laboratory studies (Weber et al. 2001, Guram et al. 1997),

The entry of a lateral flow into the main channel causes an increase in the hydraulic resistance to the flow resulting in turbulent mixing and energy losses. Due to the mutual obstruction effects of the main and branch channel flows, the water depths before the junction are increased. Another distinguishing feature of open-channel junction flows is the appearance of a shear plane skewed to a lesser or greater extent, depending upon the difference in flow velocities of the branch and main channel flows. The branch flow causes the main flow to be deflected towards the opposite bank generating an unstable separation zone at the downstream corner of the junction. This reduces the available channel capacity for the combined flow, thereby accelerating the downstream flow and causing bed scouring and bank erosion. The products of erosion may be deposited immediately below where erosion has occurred or may be transported over considerable distances to be deposited further downstream in the channels. Fine sediment that is carried in suspension with the main stream increases the turbidity of the water.
The erosion and deposition processes which occur at these sites gradually change the channel morphology and deposition of fine sediment at the bottom of channels could raise the channel bed levels reducing channel capacities.

1.2. JUSTIFICATION OF RESEARCH

Channel confluences involve with complex flow behaviour and sediment transport at these sites makes the problem more difficult to understand. Previous studies on sediment transport at channel confluences were mostly based on natural river confluences where conditions are difficult to control. Little research has been conducted on the combined aspects of flow and sediment dynamics at junctions. Detail investigation on water depth changes and separation zone shape index changes in relation to discharge ratio for sediment laden flows has not been carried out. Therefore previous studies of river channel confluences have yielded incomplete understanding of flow and sediment dynamics.

Laboratory investigation under controlled conditions and numerical modelling of junction flows provide important information for the researcher. They provide an opportunity to observe various flow phenomena creating different flow conditions in experiments. Hence current research is focused on investigating junction flow behaviour through laboratory experiments and numerical modelling.

1.3. AIMS AND OBJECTIVES

The overall aim of this research is to obtain a detailed description of flow and sediment transport behaviour at open channel confluences.
The specific objectives are to:

- Conduct a critical literature review of existing knowledge in open channel junction flows with and without sediment transport and identify the knowledge gaps in the research area.

- Design, construct and commission an open channel junction flow facility to observe clean water and sediment laden flow behaviour at the junction.

- Conduct experiments for clean water and sediment-laden flows with sub-critical flow conditions.

- Perform numerical simulations of junction flows.

- Compare experimental results with numerical predictions.

### 1.4. SCOPE OF THE STUDY

To achieve the above mentioned objectives this study was carried out phase by phase:

- The literature review mainly focused on studies presented in journals, books and conference publications, to find out how previous studies in junction flows were conducted, and what conclusions and recommendations were drawn from their results and experiences. The information obtained through literature review helped to identify the knowledge gaps in junction flows and to set out the objectives for the current study.

- The experimental flume was designed, constructed and commissioned at the Hydraulics Laboratory of the University of Wollongong. The
A series of experiments were conducted to investigate various flow scenarios in subcritical flow condition. Turbidity was measured along and across the main channel at three different levels for four flow conditions and three feed concentrations. Water heights were measured along and across the main and branch channels in the vicinity of the junction for each experiment.

Computational Fluid Dynamic codes PHOENICS and CFX were used to simulate 90° open channel junction flow behaviour with clean water and sediment-laden flows. Disregarding the slight temporal fluctuations (due to turbulence) in actual flow parameters, a steady-state three dimensional numerical simulation was carried out. Set of differential equations for mass and momentum balance are solved iteratively from an initially guessed flow field. The water heights, water velocities, and particle tracks are subsequently computed for different flow and sediment feeding concentrations.

Results of the numerical simulations are compared with the present experimental results and previous research data.
1.5. STRUCTURE OF THE THESIS

Following this introductory chapter, Chapter 2 presents a comprehensive survey of the literature associated with open channel junction flows. Studies conducted in natural and laboratory confluences and numerical simulations are reviewed in detail.

Chapter 3 explains the development of 90° laboratory open channel junction and the experimental procedures conducted to investigate the junction flow behaviour with clear water and sediment-laden flows.

Chapter 4 describes three-dimensional numerical modelling procedures conducted on investigating various flow scenarios at 90° open channel junction.

Chapter 5 presents the discussion of experimental observations conducted for clear water and sediment laden flows with different flow conditions and sediment feed concentrations.

Chapter 6 describes the comparison of numerical results with experimental observations and other available research data.

Chapter 7 presents the conclusions of the current research and its limitations as well as recommendations for further research on open channel junctions flows.

Figure 1.1 shows a schematic diagram of the research works conducted for this thesis.
Chapter 1 Introduction

Fig 1.1. Structure of thesis

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2 REVIEW OF CHANNEL JUNCTION FLOWS

2.1 INTRODUCTION

Channel junctions are important elements in river systems as they influence the channel morphology and hydrology upstream and downstream of the junction. Numerous channel junction configurations exist in nature and the flow and sediment transport behaviour at these sites is a function of its geometric and hydraulic conditions. Rapid and enormous changes occur at junctions in the channel hydraulic geometry (Richards 1980, Roy and Roy 1988), discharge (Richards 1980, Best 1988) and fluid mixing (Best 1987, 1988, Best and Roy 1991, Gauted and Roy, 1995). Patterns of sediment dispersal within a junction are controlled by flow dynamics and bed morphology and this in turn affects a feedback upon both the flow and sediment transport pathways (Best 1987). Therefore, a clear understanding of channel flow behaviour is crucial in predicting the sediment flux and water through channel networks and in assessing the dispersal of sediments and pollutants (Gaudet and Roy 1995).

In the past numerous studies have been conducted and have highlighted the importance of understanding the interaction between flow and sediment transport in open channel junctions (Best and Reid 1984; Best 1987; Bradbrook et al. 1998; Bradbrook et al. 2001). Substantial attention has been paid to the morphological influence of discordant beds on the structure of the flow at channel confluences (Best and Roy 1991, Biron et al. 1996a, 1996b). They confirmed that the presence of a tributary step gives rise to a lateral motion of fluid from the deeper channel towards the shallower tributary. This results in a distortion of the mixing layer between the two flows and fluid upwelling in the tributary channel. Field studies revealed
that mixing of two flows significantly enhanced such distortion (Gaudet and Roy, 1995) and widen the zone influenced by the mixing layer (Biron et al. 1993a). These effects have significant importance on solid dispersal and contaminant transport, mixing and deposition in alluvial river systems (Axtmann et al. 1997).

Previous studies based on physical modelling produced key advances in understanding the principal factors controlling confluence morphology and flow dynamics (Mosley, 1976, Best 1987, 1988) and yielded conceptual models (Best 1987, 1988) which have been tested at field sites (Roy and Roy 1988, Biron et al. 1993). Although several studies have been conducted on sediment transport in channel junctions, suspended sediment concentration has not been modelled or measured extensively within open channel confluences. Previous studies either highlight the flow features visually, or measure the mixing properties of the flow. More research is needed on suspended sediment transport in open channel junctions.

2.2 NATURAL CHANNEL JUNCTIONS

Research on natural river environments is complicated by the wide variety of planforms and configurations encountered. River junctions exhibit different in confluence angles, flow conditions such as shallow to narrow, concordant to discordant, gently curved to sharply curved, small to large scale, smooth to rough etc. Local sedimentary processes, channel scouring, and sidewall erosion in these junctions are controlled by the above mentioned factors through their influence on flow patterns.
The Figure 2.1 illustrates the natural river system in New South Wales, Australia. As can be seen in this map, channel junctions are an integral part of the natural river environment. There are diverse types of natural channel configurations, as illustrated in the figures below.

The Darling River is the longest river in Australia, flowing 2,739 km from northern New South Wales to its confluence (Figure 2.2) with the Murray River at Wentworth, New South Wales. The toxic blue-green algae (cyanobacteria) bloom, which occurred in late 1991 in the Darling River system, was attributed principally to a high concentration of phosphorus in the river. The total supply of phosphorus to the Darling River is closely related to sediment transport as a substantial proportion of the phosphorus load is absorbed to fine sediment particles. This is because in large river systems, the sediment is transported in suspension over great distances and is repeatedly deposited.
Figure 2.2 Murray River and Darling River confluence in Australia
(www.adelora.com.au)

Figure 2.3 shows the confluence of Hawkesbury River and MacDonald River at Wiseman's Ferry in Australia. The Macdonald River has undergone river metamorphosis as a result of a series of floods in the late 1940s and early 1950s. Catastrophic changes had resulted in the channel mainly due to widening through bank erosion and sand deposition. The lack of riverbank vegetation was a major contributor to the channel change. Much of the main river channel is choked with the highly invasive black willow and this strand of willow is thought to be a source of the seed to other sub-catchments of the Hawkesbury Nepean (www.devilcatboats.com.au/_borders/Hawkesbury). Changes in channel morphology that occurred along the MacDonald River between 1949 and 1955 are often cited as an example of catastrophic channel change (ibid).
However, the question of whether these changes represented one component of a cyclical evolutionary pattern, or a systematic and persistent shift to a new morphologic state remains to be clearly defined (ibid).

The Curdies River estuary (Figure 2.4) is defined as extending from the entrance at Peterborough to the confluence of the Curdies River with Becketts Creek, which is the physical extent of the estuarine reach (Curdies River Estuary Management Plan). Like many estuaries in Victoria, the Curdies estuary intermittently closes following formation of a sandbar at the estuary entrance. Several factors interact to determine when an estuary closes and how long it remains closed. While water movement from freshwater discharge and ebb tide flow removes sand from the entrance and acts to keep the estuary open, currents and swells re-suspend and deposit sand at the estuary mouth and this will eventually cause the estuary to close (Curdies River Estuary Management plan, 624/R02Draft 1, December 2001).
The rocky headland to the west of the Curdies entrance interrupts the movement of sand suspended in currents. If the currents are easterly which prevail over the summer months the headland promotes sand deposition at the estuary entrance (Curdies River Estuary Management Plan, 2008).

The Minnesota River is threatened by mercury pollution and water drawdowns from a proposed coal-fired power plant just over the border in South Dakota (www.minnesota.publicradio.org).

Figure 2.5 illustrates the pollution and sediment that is contained in the Minnesota River. Unfortunately, the Minnesota River has been cited as one of the state's most polluted rivers (www.minnesota.publicradio.org). Studies have indicated that the Minnesota River is a major source of pollution to the Mississippi River. Considerable attention and support has been given to clean-up efforts. Many water
quality challenges relate to land uses including attempts to minimize agricultural
runoff and urban point-source discharges (http://mrbdc.mnsu.edu/mnbasin/vtour/vt
13.html).

The Feather River is a principal tributary of the Sacramento River, 270 km in
length, in Northern California in the United States. When water is needed, Lake
Oroville releases water into the Feather River. It travels down the river to where the
river converges (Figure 2.6) with the Sacramento River, the state’s largest waterway.
Gold miners used mercury to extract gold from mined materials and discharged the
waste into nearby water bodies, such as the Feather River, where the mercury
accumulated in the sediment. Some species of fish in the lower Feather River contain
elevated levels of mercury and could pose a health risk to people who eat them
frequently (California Environmental Protection Agency 1998).
Chapter 2 Review of Channel Junction Flows

Figure 2.6 The confluence of Sacramento River and Feather River in Northern California (www.publicaffairs.water.ca.gov/swp/swptoday.cfm)

Figure 2.7 shows the flow at the confluence of the Potomac and Shenandoah rivers in USA. The calm and clear water comes from the Potomac, while the muddy water comes from the Shenandoah. Perhaps it had rained a lot up in the mountains the week before the picture was taken (flickr.com/photos/gemstone/281427872/).

The confluence of the Waikato River and Waipa River in New Zealand, (Figure 2.8) in flood (July 1998 flood) graphically shows the mixing of the two currents. The Waikato River becomes increasingly turbid and the water colour changes from green to brown. Higher bacteria levels in the lower river are the result of the combined discharges from farm and storm water runoff, farm dairies and sewage treatment plants (http://www.ew.govt.nz/environmental-information/Rivers-lakes-and-wetlands/healthyrivers/Waikato-River/How-clean-is-the-Waikato-River/).
Figure 2.7 The confluence of the Potomac and Shenandoah rivers in West Virginia (flickr.com/photos/gemstone/281427872/)

Figure 2.8 Waikato and Waipa river confluence at Ngaruawahia in New Zealand (www.ew.govt.nz/ )
Figure 2.9 Bor, confluence in Serbia, Ukraine

(www.ukar.ca/Danube)

The Figure 2.9 illustrates the Bor confluence of the Borska River on the right (dead because of acid mine drainage) and the Kriveljska River on the left, contaminated by wastewater from a battery factory (www.ukar.ca/Danube).

Figure 2.10 Yusengi Confluence of rivers in Russia

(www.salomonkroonenberg.nl/wetenschap.html)

The Yusengi Confluence (Figure 2.10) of rivers shows granitic sediment (yellow,
left) and volcanic sediment (brown, right), in the Caucasus in Russia (www.salomonkroonenberg.nl/wetenschap.html).

Figure 2.11 Confluence of rivers Kali Gandaki (left) and Andhi Khola (right) in Nepal (www.fao.org/docrep/005/y4633e/y4633e06.htm).

Figure 2.11 shows the confluence of the Kali Gandaki and Andhi Khola rivers in Nepal. It demonstrates high penetration and impingement on the opposite bank due to extremely high momentum flux from the tributary.

Figure 2.12 Missouri-Osage confluence in USA (www.airphotona.com/stockimg/thumbs/00807.jpg)
Figure 2.12 shows high momentum flux from the Missouri river which penetrates across the junction of Osage River-Missouri River confluence in USA. The photo on the right illustrates the accumulation of sand bar inside the separation zone.

![Image of Missouri and Osage Rivers confluence](www.airphotona.com/images.asp?catnum=11200...)

Figure 2.13 Confluence of Milk River and Missouri River in USA
(www.airphotona.com/images.asp?catnum=11200...)

The Milk River and Missouri River confluence at Glasgow in eastern Montana in USA (Figure 2.13) shows the distance required by the lateral flow to fully mix with the main channel flow. The reason for its hue is that it drains a broad valley containing weathered, silty glacial till and shale, as well as sand, and passes through a layer of white clay within its middle reaches (http://lewis-clark.org/content/content-article.asp?ArticleID=1420).
The confluence of the Dog River with Moore Creek, Halls Mill Creek, and Rabbit Creek in USA (Figure 2.14) shows mucky water after a heavy rainfall. The Dog River is relatively clean because it drains the older developed part of the city of Mobile. It picks up sediment load from the Moore Creek/Montlimar Canal system (in the upper left of the picture) and then an even greater load from Halls Mill Creek (in the lower left). Rabbit Creek, not quite as dirty as Halls Mill, enters the Dog River in the lower center of the picture (www.southhalabama.edu).
Rangeet is one of the important tributaries of the Teesta (Figure 2.15) in India which originates from glaciers in Kabru, and comes from Phalut in Sangalila National Park in Darjeeling district. Its course then acts as a natural boundary to the states of West Bengal and Sikkim (http://www.trekearth.com/gallery/Asia/India/East/West_Bengal/Darjeeling/photo105639.htm).

The Kansas-Missouri confluence in USA (Figure 2.16) shows the sediment laden Kansas River entering the clean Missouri River. The Kansas River has been commercially mined for sand and gravel since the early 1900s. Dredging activities have been documented to have caused significant damage to the riverbed, habitat, and water quality. Since the 1960s “head cutting” has become more common as the river continues to fill the holes caused by dredging. When “head cutting” takes place, the particles of sand tend to fill the hole but the particles of dirt tend to stay suspended in the water. Therefore habitat and water quality are damaged.
by the increased presence of dirt particles suspended in the water (www.kansasriver.org/content/sand_and_gravel_dredging).

Figure 2.16 Kanas Missouri confluence in USA (www.airphotona.com/images.asp?catnum=11200... )

The Confluence of Green River and Colorado River (Figure 2.17) illustrates different flow scenarios through the junction. It is clearly visible that the location of the shear layer is changed with respect to the flow condition. "Apparent colour" is derived from the presence of suspended solids in water. Insoluble oxidized iron (rust) can give water a red tint, manganese oxide causes a black discoloration, and a combination of the two can yield a yellow-brown hue. The presence of dissolved constituents, such as iron, manganese, and copper, can produce striking blue-green colours in streams (www.waterencyclopedia.com/Re-St/Senses-Fresh-Water-and-the.html).
Chapter 2 Review of Channel Junction Flows

Figure 2.17 Confluence of Colorado River and Green River

Above pictures of natural channel confluences clearly show that the types of channel configuration and the flow discharge of channels play an important role on flow and sediment behaviour within the junction.
2.3 MAN-MADE CHANNEL JUNCTIONS

The knowledge acquired through studies of channel junction flows could be applied in designing and construction of artificial channel networks such as irrigation canal systems, fish passage conveyance structures, wastewater treatment facilities and stormwater drainage systems. The pictures below illustrate artificial channel networks made in a range of situations.

Figure 2.18 Man-made irrigation channel system in Southern France
(www.euwma.org)

The gravitation canal irrigation system in Southern France shown in Figure 2.18 illustrates a number of man-made junctions within the channel system.

Figure 2.19 Gravity-fed irrigation canals in Central Arizona
(www.scenic.com)
A satellite photo of a gravity-fed irrigation canals in central Arizona (Figure 2.19) illustrates several 90° open channel junctions in the system.

Figure 2.20 Woodbridge irrigation (Courtesy photograph/Alan Macisaac)

The Woodbridge irrigation district fish screen (Figure 2.20), which is now in operation and running to keep fish from entering the irrigation canal and continue their swim upstream, is a further example of a man-made open channel confluence.

2.4 PREVIOUS STUDIES

In the past, different approaches have been undertaken to investigate the junction flow dynamics in open channels. These studies can be mainly categorized as (a) laboratory experiments, (b) field studies and (c) numerical modeling of junction flows.

2.4.1 Laboratory experiments

Natural confluences have a complex geometry and boundary conditions with varying scales. Their flow conditions are unsteady and complex. Obtaining instantaneous flow information with adequate accuracy is difficult or often impossible
in many cases. Therefore laboratory experimental studies of hydraulic problems using physical models, offer great advantage.

Previous studies of channel junction flows were mainly based on laboratory scale model experiments with simplified flow conditions in which variables were controlled rather easily. Most laboratory experiments used fixed-bed channels and the key characteristics investigated were depth ratio, separation zone, effect of discordant beds, and location of shear layers, stagnation point and secondary flow current. In the most common and traditional approach, confluence characteristics have been determined in prismatic channels in laboratories (Taylor, 1944: Webber and Greated, 1966: Lin and Soong, 1979: Ramamurthy et al. 1988: Biron et al. 1996a, 1996b: Hsu et al. 1998a). However, subsequent predictions were based on several assumptions related to idealistic flow conditions using simplified channel geometries and small-scale physical models.

Taylor (1944) studied the flow characteristics at a junction of two horizontal channels with rectangular cross sections. He applied the momentum equation to analyse the combined flow and verified the predictions with experimental data for junction angles of 45° and 135°. However, his theoretical predictions were applicable only for smaller junction angles. There was no acceptable agreement for large junction angle such as 135°. It was believed that this was due to the velocity distribution downstream of the junction that was distorted and the flow did not remain parallel to the channel walls. In Taylor’s study (1944) he recognized that failure to measure the pressure on the walls of the branch channel or failure in the estimation of the momentum transfer from branch to main channel constitutes an important shortcoming.
Chapter 2 Review of Channel Junction Flows

Moseley (1976) conducted a detailed experimental study of channel junctions. His experimental setup consisted of a laboratory tray (which was 1.3 m wide and 2.8 m long) containing sand-silt-clay mixture. Two streams which started from the upstream corners of the tray were controlled to join and form a “y” shaped confluence at the central region of the tray. Flow discharges were independently controlled and sediments were introduced at the upstream corners. Several runs were carried out to study the influence of discharge ratio and sediment discharge ratio on confluence features. In his study he observed lens-shaped scour hole, avalanche faces which drip in to scour hole at the end of each upstream, two back-to-back helical flows in the region of score hole, water surface super elevation over the scour hole and two zones of sediment transport with no sediment movement at the centreline of the scour. His observation showed an increase in scour depth with increased junction angle and decreased flow ratio and decrease in scour hole depth with increased sediment load from upstream branches. These observations can be explained as being due to the associated increased curvature of streamlines resulting strong helical flow. Decrease in scour hole depth with increased upstream sediment load is due to the fact that the flow adjusts itself to transport all the sediments bought into the scour hole Moseley (1976).

Lin and Soong (1979) investigated the head loss in open channel junctions. The turbulent mixing loss was found to be of the same order of magnitude as the boundary friction loss and was expressed as a function of the discharge ratio. Best and Reid (1984) conducted experiments in a confluence with channels of equal width. They summarised the variation of the size of separation zone at channel junctions with both junction angle and the discharge ratio. The results showed that
size of recirculation zone increases with increasing junction angle and decreasing discharge ratio. Tada (1987) conducted propeller anemometer measurements in a 60° junction. Training levees were used to allow two upstream flows to mix gradually by reducing the effective junction angle. Hager (1989) reported propeller anemometer measurements in supercritical and transitional flow junctions. His work also illustrated the sharp changes in water depth at critical flow conditions. It was observed that the recirculation zone either disappeared or was negligibly small under higher discharge ratios ($q^*=Q_{\text{main}}/Q_{\text{total}}$).

An experimental study of confluence flow was conducted by utilizing laboratory channel apparatus to gain an insight of the physical processes associated with a flow in a confluence by Weerakoon (1990). This included an extensive flow visualization study, discrete measurements of three-dimensional velocity field, water depth and bed shear stress under flat bed and movable bed conditions. In the flat bed experiments, he observed two secondary flow cells which rotate in opposite directions, along with free surface super elevation towards the right bank of the main channel. It was noticed that the size of the separation zone which formed at the left bank corner of the junction became smaller with increasing distance from the free surface. Large eddies that transfer momentum from the main stream to the recirculation zone and also eddies along the mixing layer were observed with increased velocities near the bed. On the other hand, in mobile-bed experiments, the existence of scour hole, sand bars in both upstream branches and downstream corner of the confluence, erosion of downstream banks and free surface super elevation over the scour hole area were reported.

Weber, et al. (2001) conducted experiments in an equal width, equal depth, and
flat bed 90° laboratory open channel junction with rectangular geometry for different flow conditions. Velocities and water depth were measured in the vicinity of the junction using the Acoustic Doppler Velocimeter (ADV) technique and a point gauge respectively. A data set was compiled which fully describes the complex three-dimensional flow conditions present in an open channel junction for the selected flow conditions. This comprehensive information was used to explain the dominant flow features. They observed that the difference between the branch channel entrance angle near the bed and near the surface is less for the conditions of high discharge ratio $q^*$. For higher $q^*$, the velocity vectors in the main channel showed less deflection toward the outer wall through the junction region. The velocity field was seen to be more uniform across the channel at a shorter distance downstream from the junction for higher $q^*$. The stagnation point near the upstream junction corner was seen to migrate from the branch channel wall for large $q^*$ and to the main channel wall for smaller $q^*$.

### 2.4.2 Field studies

Compared to laboratory experiments, there is a shortage of data available from field studies on natural confluences. Field investigations are largely based on point measurements of the velocity field. A large number of sample sites are required to obtain a reasonable representation of the spatio-temporal process characteristics (Lane et al. 1999). Mamedov (1989) conducted field investigations measuring velocity field and sediment concentration of the flow. He identified major characteristic zones such as separation zone and stagnation zone in the Kura River in Russia. It was noticed that an increase of flow velocity immediately downstream of the confluence and the presence of a contracted section were the main cause
of channel deformation. The sediment concentration in the Karasu River (one of the main tributaries of Kura River) was found to be considerably higher than that of the Kura River. Sediments were found to be deposited immediately after the junction of Kura River and Karasu River and farther downstream of the junction. Change of channel form was noticed after the confluence and it was explained as being due to shifting the velocity toward the opposite bank, causing bank erosion. The sediments entering from the lateral branch were deposited close to the inner bank side of the main stream. Kenworthy and Rhoads (1995) conducted field investigations at an asymmetrical 60° confluence of the Kaskaskia and Copper Slough rivers (in east-central Illinois, USA) that had similar widths but different suspended sediment concentrations. Sediment sampling was conducted at one cross-section on each channel upstream of the confluence (Fig. 2.21) and at three cross-sections immediately downstream of the confluence (A, C and E) for several flows with varying sediment loads. Mean sediment concentrations in the Kaskaskia River ($C_k$) and Copper Slough ($C_s$) were computed from several individual samples collected at the two upstream cross-sections. Samples were also collected at six to ten positions along cross-sections A, C, and E to document cross-stream and longitudinal variations in sediment concentration downstream of the confluence. The relationship between incoming hydraulic conditions and spatial patterns of suspended sediment concentration were evaluated with a conceptual model using suspended-sediment data collected at the site (Figure 2.22).
Figure 2.21 Site map of the confluence of the Kaskaskia River and Copper Slough (Kenworthy and Rhoads, 1995)

Figure 2.22 Hydrologic inputs and suspended sediment concentration relationship (Kenworthy and Rhoads, 1995)

$C_1, C_2$ – Main and branch channel mean suspended sediment concentrations respectively; $M_r = $ Momentum flux ratio of incoming flows ($M_r = \text{Branch channel momentum flux/ Main channel momentum flux}$), $S_r = $ Sediment concentration ratio ($S_r = C_2 / C_1$).
Kenworthy and Rhoads, (1995) found that patterns of normalized sediment concentrations at a cross-section near the exit of the confluence are a function of the ratios of momentum flux and mean sediment concentration in the upstream channels. These patterns reflected a shift in the location of the shear layer toward the outer bank with increase in the momentum ratio. However, the data collected in this study consists of only depth-integrated sediment samples and measurements of bulk upstream hydraulic variables. Therefore, a rigorous analysis of the mixing process in terms of flow mechanics was not possible.

Bed discordance is a common channel confluence feature, and it has been studied in the past to understand its effect on flow features at channel junctions. It is observed that bed discordance of a junction creates a distortion of the mixing layer towards the shallower tributary with upwelling of flow from the deeper channel into the shallower channel (Best and Roy 1991, Biron et al. 1996a, 1996b). Also bed discordance limits the flow deflection at the bed and the flow acceleration in the contraction zone is reduced due to the absence of separation zone at the bed (Biron et al. 1996a, 1996b. Rhoads and Kenworthy 1995, 1998, Rhoads and Sukhodolov 2001 and Rhodes 1996) investigated a natural confluence in east central Illinois, USA and provided extensive information on the time-averaged flow structure of the asymmetrical stream confluences with various flow conditions.

De Serres et al. (1999) reported detailed three-dimensional data of mean and turbulent structure of flow for the natural discordant bed confluence of Bayonne River and Berthier River in Quebec, Canada for various flow conditions. They could identify the major characteristics of the confluence flow dynamics such as the zone of acceleration, stagnation zone and the zone of flow deflection. They were not able to detect the separation zone although a very low velocity was measured in the
downstream junction corner. The upwelling of the flow similar to the laboratory experiment with discordant bed from Biron et al. (1996a) was also noted close to the avalanche face at the mouth of the tributary. It was found that the shear layer region was characterized by high turbulence intensity and turbulence kinetic energy in discordant channel junctions. Lateral distortion of the mixing layer attributed to bed discordance was found and in agreement with previous laboratory studies (Best and Roy 1991, Biron et al. 1996a, 1996b).

Orfeo et al. (2001) conducted research on the confluence of the Paraguay and Parana’ rivers in South America. They analyzed the major hydraulic, morphological and sedimentological features of the Parana’ River upstream and downstream of the confluence with the Paraguay River in order to evaluate the influence of this major tributary on the main stream. The influence of the Paraguay River (the main tributary of the Parana’ River) explained most of the modifications downstream of the confluence, especially the changes in the discharge and suspended load.

2.4.3 Numerical simulation studies

The turbulent nature, irregular geometry of channels, time dependence and complex sediment transport phenomena make the predictions of flow in natural channel junctions extremely difficult. Therefore use of the computational approach is rapidly developing today for investigating complex flow problems in river environments. In recent times more emphasis has been placed on computational studies to provide predictions of mixing characteristics that are directly applied to natural confluences. Validation is also easier with laboratory data with fixed flow conditions than with natural confluence data.
In numerical simulation, partial differential equations expressing the governing physical laws are solved incorporating the constitutive models based on numerical methods. It is a technique that allows the alteration of one variable at a time, so assessment of the relative importance and interaction of different controls becomes possible.

Previous numerical studies of flow and sediment transport in open channels have been conducted using 1D and 2D simulations (Shimizu and Itakura 1989, Tingsanchali and Maheswaran 1990, Bridge and Gabel 1992, Lane et al. 1995). These models do not account for the complex secondary flow structures that are observed in channel confluences. However recent developments in the techniques of computational fluid dynamics (CFD) offer the possibility that these details could also be predicted (Olsen 1999). Furthermore, well calibrated three-dimensional models can even overcome the limitations of field and laboratory experiments. They also provide an improved insight into the complex flow dynamics of junction flows (Lane et al. 1999; Bradbrook et al. 2000a).

Development of sophisticated three-dimensional models requires a considerable increase in computational resources and increasing sophistication also implies a greater need to identify the primary assumptions behind model development (Lane et al.1999). Furthermore, computational grid should represent the physical domain accurately and also inadequate specification of boundary conditions will limit the quality of model predictions.

Considering all the above-mentioned facts, Tamai and Ueda (1987) conducted a three-dimensional modelling of a confluence using the k-ε turbulence model. They used the SIMPLE algorithm of Patankar and Spalding (1972) and the
partially parabolic computation procedure of Pratap and Spalding (1976). They could simulate the occurrence of two back-to-back flow cells in 30° confluence. Their model is restricted to smaller confluence angles caused by specification of computational grids in functional form which caused severe non-orthogonality in the grids, giving rise to convergence problems. Also the model could be used only for junctions with flat beds and no flow recirculation due to the parabolic computation procedure.

Weerakoon (1990) used three types of computational models for economical use in different classes of confluence flows. The models have the general form to be applicable to confluences irrespective of the geometric complexity when coupled with the grid generation and coordinate transformation. Weerakoon et al. (1991) used an elliptic three dimensional model successfully, based on a finite volume method and k-ε turbulence model to investigate three dimensional flow structures in a channel confluence with rectangular sections.

Bradbrook et al. (1998) used the computational fluid dynamics code PHOENICS to simulate a confluence of unequal depth channels. Lane et al. (1999) assessed the applicability of the three dimensional numerical model to a river channel confluence in a gravel bed river. The model had limitations in implementing certain boundary conditions in obtaining accurate results. Numerical predictions of flow fields of a laboratory confluence with rectangular channel showed better accuracy than that of natural confluences due to the simplified boundary conditions used in laboratory confluences.

Experimental observations and natural river confluence studies showed the presence of super elevation and depression of water surface
immediately downstream of the junction (Moseley 1976, Ashmore 1982, Weerakoon and Tamai 1989, Bridge and Gabel 1992, Rhodes 1996 and Weber et al. 2001). However three dimensional models used with a rigid lid or plane of symmetry condition at the free surface are not capable of predicting the free surface elevation changes. Bradbrook et al. (1998, 2000a) and Lane et al. (1999) applied the porosity concept of free surface approximation for a river confluence. Bradbrook et al. (2000b) used Large Eddy Simulation (LES) for river channel confluences with the porosity concept.

Huang et al. (2002) developed a three-dimensional numerical model to investigate the open-channel junction flow. The main objective was validation of a three-dimensional numerical model with high-quality experimental data and compare additional simulations with one dimensional water surface calculations. The three-dimensional model is first validated using the Weber et al. (2001) experimental data for a 90° junction flow under two flow conditions. Good agreement was obtained between the model simulation and the experimental measurements. The model was then applied to investigate the effect of the junction angle on the flow characteristics. At the beginning of the computation, the free surface was assumed flat, and a mesh was generated based on this assumed flat surface. During the iterative solution process, the kinematic boundary condition was enforced through the vertical velocity boundary condition while the dynamic condition was used to obtain the free-surface elevation. The results were consistent with the findings by Hsu et al. (1998b).

Weerakoon et al. (2003) presented a depth-averaged elliptic computational model in curvilinear coordinates for velocity and depth computations in shallow water river confluences of any geometry.
Duan, J.G. and Nanda, S.K. (2006) used a two-dimensional depth-averaged hydrodynamic model to simulate suspended sediment concentration distribution in the Groyne River. The governing equations were depth-averaged two-dimensional Reynolds’ averaged momentum equations and the continuity equation in which the density of sediment laden-flow varied with the concentration of suspended sediment.

The depth-averaged two-dimensional convection and diffusion equation was solved to obtain the depth-averaged suspended sediment concentration. Laboratory experiments were used to verify the simulated flow field (Figure 2.23) whereas the suspended sediment concentration distribution was verified using a meandering channel (Figure 2.24).
The model utility was demonstrated in a field case study focusing on the confluence of the Kankakee and Iroquois Rivers in Illinois, United States, to simulate the distribution of suspended sediment concentration around spur dikes. The model was used to simulate the hydrodynamic flow field and concentration distribution of the suspended sediment for three alternative management scenarios: (1) take no action (Figure 2.25); (2) install three short dikes (Figure 2.26); and (3) install three long dikes (Figure 2.27). The developed 2-dimensional depth-averaged numerical model differs from the classical 2-dimensional model in treating the density as a variable changing with the concentration of suspended sediment and in including the bed shear stress correction terms in the momentum equations. Additionally, the difference between entrainment and deposition of suspended sediment from the bed surface was calculated as a source term in the 2-dimensional convection and diffusion equations. The modeling results clearly showed suspended sediment...
concentration was high in the flow separation zone downstream of the dike structure.

Figure 2.25 Simulated surface elevation, velocity vector, and suspended sediment concentration distribution (a) Velocity vector and surface elevation, (b) Concentration field with no control measures (Duan, J.G. and Nanda, S.K. (2006))
Figure 2.26 Simulated surface elevation, velocity vector, and suspended sediment concentration distribution. (a) Velocity vector and surface elevation and (b) Concentration field with short dikes (Duan, J.G. and Nanda, S.K. (2006))
Figure 2.27 Simulated surface elevation, velocity vector, and suspended sediment concentration distribution. (a) Velocity vector and surface elevation and (b) Concentration field with using long dikes (Duan, J.G. and Nanda, S.K. (2006))

Xiao-gang and Zhong-Min (2007) carried out three dimensional numerical simulations to simulate flow in a “Y” shaped open-channel confluence (Figure 2.28).
It was proved that the model was capable of undertaking quantitative assessment of the flow at confluences.

Figure 2.28 Y shape open channel junction (Xiao-gang and Zhong-Min 2007)

The numerical model employed in this study was based on the standard time-averaged Navier-Stokes equations and linear Renormalization Group (RNG) turbulence model using finite-volume technique for decretization. Tracking the interface between the phases was accomplished by solving a conservation equation for the volume fraction of the water phase. They recommended use of the non-equilibrium wall functions in complex flows involving separation, reattachment and impingement where the mean flow and turbulence were subjected to severe pressure gradients and rapid changes. Simulation results of concordant bed confluence, downstream velocity contours and u-v vector patterns were in good agreement with experimental data (Figure 2.29). Similar trends were observed with generation of separation zone in the side of the branch channel in both simulation and experiment. Near-bed contours of downstream velocities showed shifting of higher velocity zone towards the main channel for discordant confluence (Figure 2.30). Generation of a separation zone was observed in near-surface contours of the downstream velocity
Figure 2.29 Contours of downstream velocity and u-v vector \( q^* = 0.74 \)

(Xiao-gang and Zhong-Ming, 2007)
component for discordant bed confluence (Figure 2.30). It was concluded that at a “Y” shaped junction with discordant bed:

(1) The separation zone disappears near the bed while it presents near the water
surface at the side of tributary channel. The region of separation zone near water surface at the side of main channel decreases.

(2) The maximum velocity zone near water surface is pushed towards the side of main channel.

(3) The flow near the bed in the shallower tributary transfers towards the tributary side of the Post-confluence where a low pressure zone exists.

(4) The bed height discordance distorts the mixing layer and increases the intensity of turbulence and secondary flow at the side of tributary channel.

The results of CFD simulations are themselves dependent on the adequacy of the mathematical models and the boundary conditions that represent the actual flow situation. They must therefore be validated against detailed experimental results.

The present study was aimed at an investigation of flow and sediment transport behavior. This was done using two commercially available CFD simulation packages. The following paragraphs examine previous investigations directed at specific features of the flow at open-channel junctions.

2.5 FLOW FEATURES

The main flow features of an open channel junction flow include the separation zone, stagnation point, contracted flow, skewed shear layers, secondary recirculation patterns, and flow recovery zone (Figure 2.31).

2.5.1 Separation zone

In channel confluences, the streamlines are separated from the banks just after the
confluence at the downstream corner of the junction. Gurram et al. (1997) asserted that this is caused by the flow separating from the side wall, traveling across the main channel into a flow contraction adjacent to the separation zone before the flow returns to the full width of the channel.

![Figure 2.31 Main flow features of the junction flow](Modified from Weber et al. 2001)

The separation zone is a critical component of the flow dynamics in channel confluences. Its size and shape are determined by the discharge ratio and by the junction angle (Modi et al. 1981, Best and Reid 1984, Best 1987). The geometry of the separation zone was calculated using conformal mapping by Modi et al. (1981), Best and Reid, (1984). Their model overestimated the width of the separation zone and therefore underestimated the area of the channel occupied by the free stream. The length and width of the separation zone increase with decreasing values of $q^*$ and increasing junction angle $\theta$ (Gurram et al. 1997). However, the extent of separation was found to decrease with increase in the Froude number due to acceleration of the flow through the contracted area.

Gurram et al. (1997) proposed the following empirical relationships between
the separation zone width \( (w_s) \) and length \( (L_s) \) in relation to the discharge ratio \( (q^* = Q_{\text{main}} / Q_{\text{total}}) \), \( w \) – channel width and downstream Froude number \( (F_d) \):

\[
\frac{w_s}{w} = \frac{1}{2} \left( F_d - \frac{2}{3} \right)^2 + 0.45 \sqrt{1 - q^* \left( \frac{\theta}{90^\circ} \right)} \]  \hspace{1cm} (2-1)
\[
\frac{L_s}{w} = 3.8 \sin^3 \theta \left( 1 - \frac{1}{2} F_d \right) \sqrt{1 - q^*} \quad ; \quad F_d < 1 \]  \hspace{1cm} (2-2)

Hsu, Wu and Lee (1998a) sought to find an empirical solution of the maximum separation zone width using a one dimensional approach. This was achieved by applying the conservation of mass, momentum and energy principles to a control volume. The outcome of this analysis was a series of empirical formulae based on the assumption that the maximum width of separation zone occurred at twice the width of the branch channel.

\[
\frac{w_s}{w} = 1 - \xi_2 q^2 - \xi_1 q^* + \xi_3 \]  \hspace{1cm} (2-3)

The separation zone has been identified as important as its size increases, it results in a narrower flow path in the main channel which can increase scour and sediment transport in the area, and increased sedimentation in the separation zone. Best and Reid (1984) conducted a study which focused specifically on the separation zone, and built on the findings of previous studies. They conducted experiments on a flume with junction angles of 15°, 45°, 70° and 90° for sub-critical flows with a Froude number between 0.1 and 0.3. It was found that, with decreasing flow ratio \( q^* \) the maximum width and length of the separation zone increase. It was also found that the effect of decreasing flow ratio \( (q^*) \) on the width and length became less pronounced at smaller junction angles. Regardless of size, the separation zone
Hsu et al. (1998a) calculated the shape index (Shape index = Maximum separation zone width/separation zone length) of the separation zone for different flow conditions. Their results were scattered between 0.15 and 0.20, with an average of 0.17. This value corresponds well with Best and Reid’s (1984) data which had slightly more scatter and an average of 0.19. Due to the difficulty in measuring the unstable streamline, a scatter within the results was presumed to be which bounds the separation zone (Hsu et al. 1998a). Studies by Fujita (1990) cited in Weerakoon (1990) showed a shape factor lower than these studies (0.1 to 0.15). Weber et al. (2001) found the shape factor to be 0.13 for a flow ratio of 0.25. This value does not correspond with the previous studies of Hsu et al. (1998a) and Best and Reid (1984). However, they are in the range of the other studies mentioned (Fujita (1990) cited in Weerakoon 1990, that is between 0.1 and 0.15. Huang et al. (2002) found that the length of the separation zone (Ls) was approximately 1.4 and 0.5 times the channel width for junction angles 60° and 45° respectively. The separation zone was found to disappear for the 30° junction angle completely and this was explained in terms of energy loss, stating that more energy was lost when the junction angle was large as the lateral flow momentum had to be turned to the main stream flow leading to a larger separation zone and higher upstream water surface.

2.5.2 Depth variation

A lateral flow entering a main channel raises the upstream water levels and reduces the downstream water levels near the inner wall of the main channel within the separation zone. It generates super-elevation near the outer bank side of the main
channel immediately after the junction.

Previous research on combined flows has mostly focused on prediction of depth ratio $Y^*$, defined as the ratio of the upstream to downstream water depth. Depth ratio is an important parameter associated with over-bank flooding at channel confluences. In the study of the middle Yellow River confluence (China), flood frequency analysis showed upstream flooding was more frequent than downstream flooding (Hongming et al. 2007).

(Taylor 1944) used an empirical model to calculate the depth ratio using studies for junction angles of $45^\circ$, $90^\circ$ and $135^\circ$. He based his predictive equation on the principle of conservation of momentum. The findings in this study were then improved in numerous subsequent studies to more accurately predict the depth ratio. Taylor (1944) proposed a simple model to predict water elevation changes through a $90^\circ$ open-channel junction based on the inflow discharge ratio, the junction angle, and the branch channel Froude number. He utilized a parameter $k$ that was related to the branch channel Froude number by $k = 0.5F_2 (F_2 - \text{branch channel Froude number})$. The studies of junction flows by Taylor (1944), and Weber et al. (1966) improved the predictive equation of the depth ratio.

Significant flow depth changes are seen even for relatively small junction angles (Taylor, 1944, Weber et al. 1966, Lin and Soong 1979, Ramamurthy et al.1988). Greater head differences however occur at relatively large junction angles (Weber et al. 1966). Weber et al. (1966) proposed an experimental correction factor introducing further dependence upon junction angle and discharge ratio. The influence of this correction factor increases as $q^*$ decreases. Several analytical models have been proposed to estimate the depth changes and the energy losses
through the junction (Taylor 1944, Lin and Soong 1979, Ramamurthy et al. 1988, Gurram et al. 1997 and Hsu et al. 1998a, 1998b). The occurrence of super-elevation has also been observed in the contracted zone (Moseley 1976, Weerakoon 1990). Previous analytic models on confluences were based on the assumption of equal water depths in the upstream branches. It was verified by Weber et al. (2001) that this common assumption was appropriate for junctions of channels of equal channel width. Ramamurthy et al. (1988) proposed the following mathematical relationship for the depth ratio of combining two open channels:

\[ Y^3 - 3Y + 2\left(q^2 + (1 - q^*)\right)^2 \cos \theta = 0 \] (2-4)

He used the principles of conservation of mass and momentum to formulate this model for 90° junction angle. Hager (1989) refined his model to suit additional junction angles, as shown below:

\[ Y^* = 1 + 0.92 \sqrt{\left(1 - q^*\right)q^* + \left(1 - q^*\right)\sin^2\left(\frac{\theta}{2}\right)} \] (2-5)

Hsu et al. (1998a) proposed a relationship for depth ratio based on three governing equations, conservation of mass, momentum and energy, as seen below.

\[ Y^* = 1 + \frac{1}{\xi_1 \xi_2} - 2 \frac{\xi_5}{\xi_2} Y^* \left[ Y^3 + \left( \frac{\xi_3}{\xi_2} \right)^2 - \frac{\xi_4}{\xi_1 \xi_2} \right] Y^*^2 - 2 \left( \frac{\xi_3 \xi_5}{\xi_2^2} \right) Y^* + \left( \frac{\xi_5}{\xi_2} \right)^2 = 0 \] (2-6)
\[ \xi_1 = 0.5 \left[ \frac{\alpha_u}{\alpha_m q^*} + \frac{\alpha_b}{\alpha_m (1 - q^*)} \right] \]

With
\[ \xi_2 = 2 \left[ \frac{\beta_u}{\beta_m q^*} + \frac{\cot \delta \times \beta_b}{\beta_m (1 - q^*)^2} \right] \]
\[ = \frac{1}{2} \left( 1 + \cot \delta - \cot \delta \times C_x \right) \frac{\alpha_m}{\beta_m} \]
\[ = \frac{1}{2} \left( 1 + \cot \delta - \cot \delta \times C_x \right) \frac{\alpha_m}{\beta_m} \]
\[ = \frac{1}{2} \left( 1 + \cot \delta - \cot \delta \times C_x \right) \frac{\alpha_m}{\beta_m} \]

\[ \xi_3 = 2 \left[ \frac{\beta_u}{\beta_m q^*} + \frac{\cot \delta \times \beta_b}{\beta_m (1 - q^*)^2} \right] \left[ 1 + \frac{1}{2} \right] - \frac{1}{2} F_m \left( 1 + K_c \right) \]
\[ \xi_4 = 1 + 0.5 F_m \left( 1 + K_c \right) \]
\[ \xi_5 = \frac{1}{2 F_m} \left( \frac{\alpha_m}{\beta_m} \right) \]
\[ F_m = \sqrt{\frac{\alpha_m q_m^2}{\left[ g \left( \frac{1 - w_s^2}{w} \right) \right]^{w^2} y_m^2}} \]

Where \( \alpha, \beta \) and \( \delta, C_r, F_m \) are the energy correction coefficient, momentum correction coefficient, the average flow angle, ratio of the branch channel upstream depth and the branch entrance depth and the Froude number at maximum separation zone width respectively. \( u, b \) and \( m \) are subscripts for upstream, branch and maximum separation zone width respectively.

A one-dimensional theoretical model for sub-critical flows in open channel junctions was developed by Shabayek et al. (2002). The model was based on applying the momentum principle in the streamwise direction to two control volumes in the junction; together with overall mass conservation (The two-control volume approach chosen for this model is distinct from previous theories in that it does not assume equality of the upstream depths). This model accounts for the
interfacial shear force between the two fluids, the separation zone shear force, the
weight component in the direction of the slope and the boundary friction force, as
shown in the equations 2.7 and 2.8. Predictions based on this approach are shown to
agree favourably with existing experimental data, previous theories, and conventional
junction modelling approaches. The main advantages of the proposed model are that
the model does not assume equal upstream depths and that the dynamic treatment of
the junction flow is consistent with that of the channel reaches in a network model.

\[(1 - q^*)\frac{w}{w_u n_u} - \frac{1}{8F_d^2} \left[ w_u \left( 3n_u^2 - 2n_u n_b - n_b^2 \right) + (1 - Q^*) \left( n_u^2 + 2n_u n_b + n_b^2 - 4 \right) \right] + \frac{1}{2F_d^2} \left( \frac{L_u S_0}{Y_d} \right) (w_u n_u + (1 - q^*)) - K^* \left[ \left( \frac{1 - q^*}{w_u n_u} \right)^2 - \left( \frac{q^*}{w_u n_u} \right)^2 \right] + (n_u + n_b) \left( 2q^* (1 - q^*) \right) \] (2-7)

\[- \frac{L_u}{w_s C^2} \left( 1 + \frac{w_s}{w_d} (1 - q^*) \right) - L^* \frac{q^*}{w_s^2 n_b} \]

with

\[K^* = -0.0015 \theta + 0.30\]

\[K = 0.0092 \theta + 0.1855\]

Where

\[K^* = \text{Coefficient of interfacial shear}\]

\[K = \text{Separation zone shear coefficient}\]

\[C = \text{Chezy roughness coefficient}\]

\[w = \text{Width ratio to the downstream width,}\]

\[L = \text{Length of the control volume (which was taken as double the width)}\]

\[n = \text{Depth ratios in comparison to the downstream depth}\]
\( S_0 = \text{Slope of the channels} \)

Subscripts \( u, d, b \) denote upstream, downstream and branch respectively.

When the upstream water depths are equal, for zero bed slopes of channels and for equal channel widths the above equation can be simplified as below:

\[
1 - \frac{1}{Y^*} = \frac{1}{2F_d^2} \left[ Y^{*2} - 1 \right] - K^* \left[ \left( \frac{1 - q^*}{Y^*} \right)^2 - \left( \frac{q^*}{Y^*} \right)^2 \right] 4Y^* q^* - \frac{2}{C^2} \left( \frac{1}{1 - q^*} + \frac{w^*}{Y_d^*} \right)
\]  

(2-9)

\[
q^* - \frac{q^*}{Y^*} = \frac{1}{2F_d^2} \left( Y^{*2} - 1 \right) \left( 1 - q^* \right) + K^* \left[ \left( \frac{1 - q^*}{Y^*} \right)^2 - \left( \frac{q^*}{Y^*} \right)^2 \right] 4Y^* q^* \left( 1 - q^* \right)
\]

(2-10)

Modi et al. (1981) used conformal mapping to predict the depth ratio. They sought to broaden the use of the predictive equation to numerous junction angles and different bed widths. The results of the empirical predictions were in good agreement with experimental data for low values of Froude numbers. However, they did not account for energy losses (Best and Reid 1984).

Weber et al. (2001) conducted experiments for a sub-critical flow condition (\( Fr=0.37 \)) using 90° equal-depth, equal-width laboratory channel junction. Depth measurements were made using a point gauge and a 2-dimensional mapping of the water surface was performed on a 76.2 mm square grid at the channel junction. Their experiments indicated that the maximum difference in the average upstream depths was only 1.4% and decreased with increasing flow ratio \( q^* \). The main channel upstream water level was horizontal before the junction. However, in the branch channel, the depth was found to decrease as \( x^* (x^* = \text{distance in x direction / channel width}) \) approached 1.00 and it was found that, for low flow ratios \( (q^*) \), the decrease
was substantial. Nevertheless, for higher flow ratios \((q^*)\) cross-section profiles show smaller cross channel variations. The coordinate system defined for this testing had the positive \(x\)-axis oriented in the upstream direction of the main channel. The positive \(y\)-direction points to the main channel wall opposite of the channel junction. Thus the positive \(z\)-axis is upward in the vertical direction.

The latest developments in the prediction of depth ratio have been established by computational fluid dynamics. However, model predictions should be validated with available experimental data. The data provided by Weber et al. (2001) provide the possibility of validating such models.

Huang et al. (2002) have used computational fluid dynamics to simulate junction flows. Their results showed that the depth immediately downstream of the channel junction was slightly over predicted.

### 2.5.3 Velocity variation and secondary flow structures

More detailed analyses of the velocity field within channel junctions were conducted by Best (1987). He sampled velocity over one minute interval using a miniature current meter. The values obtained were then averaged for calculating the mean velocity. Best (1987) was primarily interested in flow dynamics and its relationship to bed morphology and sediment transport. He conducted experiments with mobile bed conditions, having well sorted sand with a \(D_{50}\) of 0.49mm. He found that velocities within the separation zone can be as small as 5 percent of those in the adjacent combined flow stream. The maximum velocity was also described by Best (1987) as being adjacent to the maximum separation zone and having an increased value for a junction angle of 90°. He observed that the maximum velocity values were lower for all other angles due to less constriction occurred in the
channel immediately below the junction. Best (1987) then related these flow features to bed morphology characteristics and showed that the deflection of flow and increased velocity produced avalanche faces and a scour zone, and a bar within the separation zone (due to sediment deposition at lower velocities).

Fujita (1990) studied three dimensional flow structures that develop within channel junctions. Fujita and Komura (1989) used a visualization technique to study secondary circulation of the flow characteristics. They realized that within the channel junction, each branch flow was well separated due to the high pressure produced by the stagnation zone (Fujita and Komura, 1989 cited by Weerakoon 1990). This was an important development in the analysis of flow within channel confluences because it showed the three dimensional flow structures within the confluence. Weerakoon (1990) carried out a comprehensive study in which experiments were conducted on a 60° junction angle, taking numerous velocity and depth measurements. He could provide detailed experimental results on secondary flow structures measuring two velocity components using an electromagnetic velocimeter. He also noted that in branch channel there was a more dominant cell and concluded that this was due to the larger streamline curvature of the branch channel. Notably, in a study in the following year, Weerakoon, et al. (1991) found that downstream of the junction, this dominating branch channel cell increased in cross sectional area until it took up the entire area of the channel, before completely diminished.

Weerakoon (1990) developed three computational models and tested them with the experimental data. An assumption made in these models was that the water surface was a rigid lid rather than a free surface. The three computational techniques involved (1) a three-dimensional partially parabolic model using the $k-\varepsilon$ turbulence
model, (2) a three-dimensional fully elliptic model using the $k-\varepsilon$ turbulence model and (3) a two-dimensional depth-averaged elliptical model that employs a depth correction equation. The partially parabolic model was applied to simulate simple problems such as developing duct flow and a parallel confluence and the model was able to predict the flow satisfactorily. The three-dimensional fully elliptic model was employed to predict the flow in a 60º confluence and the computed velocity vectors at different levels were of reasonable agreement with the experimental results. However the size of the recirculation zone under predicted by about 30%. The two-dimensional depth averaged elliptical model produced good correlation with experimental results and was further tested on an actual application to a river confluence (Tsurumi River, Japan). The two-dimensional model performed well with its application to the natural river. Biron et al. (1996a) measured the effect of bed discordance on the complex flow structures in a channel junction. They measured the velocities in the longitudinal and vertical directions and observed a significant change within the shear plane. There was an upwelling of the deeper channel flow to the shallower channel flow, creating a distortion within the shear plane. Another observation made by Biron et al. (1996a) was that the separation zone at the bed was absent due to the difference in elevation of the flows and was present at the surface. It was concluded that bed discordance must be taken into account in future numerical models.

Previous experimental and numerical studies show that the secondary flow starts immediately downstream of the junction where the center of the secondary flow is near the bottom of the channel. The center of the secondary vortex moves away from the bottom as the fluid flows further downstream. Two counter-rotating helical cells are observed in symmetrical confluences where the contraction zone
over the scour hole by Moseley (1976) and Ashmore (1982). The presence and the
effect of these helical cells are however still a matter of controversy (Best and Roy
1991, Biron et al. 1996a 1996b). Most confluences have an asymmetrical shape and
only one of the tributaries is angled with respect to the main flow. In these situations
only a single helical cell develops when the flow and curvature of the tributary is
dominant and the confluence becomes similar to a single meander (Rhodes and
Kenworthy 1995, Bradbrook et al. 2000a). In Weerakoon (1990) experiments (flat-
bed deep water confluences) detailed two-component velocity measurements were
taken for the discharge ratio 0.8. His experiments clearly showed the existence of
two counter-rotating secondary flow vortices.

Lane at al (2000) paid attention to the representation of secondary circulation
in river confluences. One of the common problems faced was the dependence of the
observed secondary flow structures upon the rotation plane for which they were
determined. Different researches have used different rotation planes, making a
comparison of results from different field sites difficult. Lane et al. (2000) used a
numerical model to explain that different analytical methods do result in very
different estimates of the strength of secondary recirculation. He investigated
representation of secondary circulation sampling of the output from each set of
model predictions \((v_x, v_y)\) for a single cross section orthogonal to the main channel
direction. The depth-averaged velocity vector was calculated for each vertical and
the primary \(v_p\) and the secondary components \(v_s\) of each point velocity in each
vertical were determined from:

\[
v_p = (v_x^2 + v_y^2)^{0.5} \cos(\eta - \omega) \quad (2-11)
\]
\[ v_s = (v_x^2 + v_y^2)^{0.5} \sin(\eta - \omega) \]  \hspace{1cm} (2-12)

Where,

- \( \eta \) - Orientation of the point velocity vector
- \( \omega \) - Orientation of depth average velocity vector

The downstream and cross-stream components of both \( v_p \) and \( v_s \) were calculated from:

\[ v_{py} = v_p \sin \omega \]  \hspace{1cm} (2-13)

\[ v_{px} = v_p \cos \omega \]  \hspace{1cm} (2-14)

\[ v_{sy} = v_s \cos \omega \]  \hspace{1cm} (2-15)

\[ v_{sx} = v_s \sin \omega \]  \hspace{1cm} (2-16)

Weber et al. (2001) compiled a detailed data set that described the complex, three-dimensional flow conditions present in a 90° open-channel junction for selected flow conditions. They measured three-dimensional velocity and turbulence parameters for six flow conditions. In their experiments vector fields for \( q^* = 0.25 \), \( v^* - w^* \) showed two clockwise and counter-clockwise helical cells with diminishing \( v^* \)-component as the flow propagates downstream as shown in Figure 2.32 (Where \( v^* \) and \( w^* \) are non-dimensionalised crosswise velocity and non-dimensionalised vertical velocity by the downstream average velocity).
Bradbrook et al. (2001) identified that the bed discordance could increase the intensity of secondary circulation and enhance the mixing of flow.

Figure 2.32 Secondary recirculation patterns at different locations across the main channel (Weber et al. 2001)

Figure 2.33 Vectors of velocity, $x_d = 0.5$, $Q_r = 0.6$ (Xiao-gang and Zhong-Min 2007)
Xiao-gang and Zhong-Min (2007) concluded that bed discordance enhances greatly the intensity of the secondary flow in the downstream junction zone (which can be seen in Figures.2.33). The upwelling is responsible for the absence of a separation zone near the bed (Where $x_d - \frac{1}{2}$ channel width downstream of the junction and $Q_r$ - discharge ratio tributary to main channel).

Helical cell circulation and its identification relates to both the supposed importance of zones of surface convergence and bed divergence. Such as for the formation of channel scour holes (Moseley 1976) and for the role of circulation processes in the transport of solutes through confluence zones and hence for pollutant mixing processes. In his study, from the identification of the cross stream patterns of secondary velocity, it was concluded that the likely direction of vertical velocities and hence the effects of helical motion upon the core of main velocity. Where the vertical velocity is depressed by down welling, it is considered that shear stresses will increase and whereas the vertical velocity is elevated due to upwelling, that they will reduce (Lane et al. 2000).

One of the problems with field studies of secondary circulation is that the most appropriate methodology is often defined by limitations of measurement technology (Lane at al 2000). Such methods may be prone to error, notably due to instrument positioning and velocity fluctuations.

2.5.4 Stagnation point

The stagnation point is one of the main flow features in open channel confluences. It is an area on the upstream side of the junction, in which the flow velocity is minimal.
due to obstruction effects from the branch flow. Modi et al. (1981) used conformal mapping techniques to describe the junction flow features, especially the stagnation point. They found that for large flow ratios, the majority of the stagnation points were located in the branch near the upstream junction corner. For low flow ratios, the majority were located in the main channels, and for even flow ratio $q^* = 0.5$ those were located directly at the junction corner. This is due to the skewed velocity distribution across the channel section towards the downstream side of the branch channel and the side opposite the branch in the main channel creates a low velocity point. He also found that the stagnation area increases with the junction angle.

Gurram et al. (1997) found that for all angles and Froude numbers tested that the depths on either side of the upstream corner (stagnation point is located) of the junction that the depths were almost equal. This is important as a number of studies since Taylor (1944) have used this assumption, and all computations have been based on this.

2.5.5 Shear layer

There have been several studies on confluences due to the imperative environmental implications of river confluences for pollutant dispersal in a river system. The studies of laboratory channel confluences with discordant bed show that distortion of the shear layer towards the shallow tributary enhances the mixing processes (Best and Roy 1991, Brion et al. 1996a, 1996b, Gaudet and Roy 1995). The study site of the Bayonne-Berthier (Canada) confluence showed a bed discordance characteristic similar to the laboratory investigation of discordant bed confluence (Biron et al. 1996a, 1996b). Their study also supports the enhanced mixing due to the discordant bed configurations of confluences. They measured the electrical
conductivity to trace the mixing patterns at cross sections located at distances ranging from 0.5 to 50 times of channel width. They also measured the confluence characteristics for different flow conditions and found the height difference between the beds relative to the mean flow depth was more important, so that the effect of discordance was more dominant. The results show that the higher width to depth ratio leads to a higher mixing rate.

Weber at al (2001) found that shear layer plays a critical role in the mixing process and its location depends on the flow condition of combining channels. On the Figure 2.34 it is depicted as a simple curve, but this is a time-averaged representation of the plane between the two combining flows. Also the shear layer is characterized by the strong vortices that initiate the mixing of merging flows. These combined with secondary circulation are key features for the mixing processes. Biron et al. (2004) also stated that lateral mixing can be markedly enhanced when the tributary channel was shallower than the main channel.

Figure 2.34 Shear layers in the junction flow (modified from Weber et al. 2001)
2.5.6 Junction losses

Lin and Soong (1979) proposed from their study that energy loss in junctions could be split into two components: boundary friction loss and turbulent friction loss. Boundary friction occurs along the wetted perimeter, and results in drag and an inconsistent flow velocity across the channel cross section. When the length of the junction is short, the primary mechanism for energy transfer comes from turbulent mixing. The equation they used to express the energy loss is given below:

\[ h_m = c_m \frac{(V_T)^2}{2g} \]  \hspace{1cm} (2-17)

where:

- \( h_m \) = loss of energy head in the junction (m)
- \( c_m \) = turbulent mixing energy loss coefficient
- \( V_T \) = Average velocity of flow downstream (m/s).

Only a portion of the change of energy head is due to losses through turbulent mixing, with the rest being transferred from the main to the branch channel flow or vice versa. Ramamurthy et al. (1994) suggested that in transitional flows, the mixing loss was negligible at the junction until the downstream hydraulic jump occurs. Hager (1989) used the data set to present a theoretical solution in a discussion for the paper by Best and Reid (1984). He based it on the principle that there was no energy loss for flows with converging streamlines, and assumed that the Froude number approached zero so as to simplify computations. Using Bernoulli’s equation and accounting for nearly uniform flow velocities and hydrostatic pressure distributions.
The following equation was developed.

\[ p_{n}b + \frac{Q_{n}^2}{2gb^2} + p_{b}b \cos \theta + \frac{Q_{b}^2 \cos \theta}{gb} = p_{n}b + \frac{Q_{i}^2}{g\mu b} + p^{*}b \cos \theta \]  \hspace{1cm} (2-18)

Where:

- \( Q_{n} \): Upstream channel discharge (m³/s)
- \( Q_{b} \): Branch channel discharge (m³/s)
- \( Q_{d} \): Downstream channel discharge (m³/s)
- \( g \): Gravity (m/s²)
- \( p \): Relative static pressure head
- \( b \): Breadth of channel (all channels equal) (m)
- \( \theta \): Junction angle (°)
- \( \mu \): Contraction coefficient
- \( p^{*} \): Average pressure exerted on side wall of branch channel (kg/m²)

The contraction coefficient, \( \mu \) was calculated using above equation and found that it
was accurate for small $\theta$, but overestimated for $\theta = 90^\circ$.

An analytical approach for solving both the upstream to downstream depth ratio and the energy loss through junctions of equal–width for sub-critical flows over horizontal beds was conducted by Chung et al. 1998. The method was based on three experimental tests with three junction angles $30^\circ$, $45^\circ$, and $60^\circ$. In this approach it was able to express the energy loss coefficient $k_e$ through the junction as a function of discharge ratio $Q_{up}/Q_{total}$, downstream Froude number $F_{rd}$ and depth ratio $Y$.

In this study it is found that for $F_{rd} < (4Y^3 + 2)^{1/2} - 2Y^3$, energy loss coefficient $k_e$ increases with increasing junction angle $\theta$ and Froude number $F_{rd}$.

Figure 2.35 Schematic layout of experimental flume and control volume

(Chung et al. 2008)
For the control volume ABEFDC shown in Fig 2.35, the conservation of mass is

\[ Q_u + Q_b = Q_d \]  \hspace{1cm} (2-20)

Assuming the hydrostatic pressure distribution can be used and the friction force neglected, the conservation of momentum in the main flow direction for 1D open channel junction flow over a horizontal bed can be written as:

\[ gW_u Y_u^2 / 2 + \beta_u Q_u^2 / W_u Y_u + \cot \delta \beta_t Q_t^2 / W_t Y_t = gW_d Y_d^2 / 2 + \beta_d Q_d^2 / \mu W_d Y_d \]  \hspace{1cm} (2-21)

Where \( Q \) = flow discharge

\( W \) = Channel width,

\( Y \) = depth, \( \beta \) = Momentum correction coefficient  and the subscript \( u,b,d \) and \( t \) indicate main channel upstream, branch channel upstream, main channel downstream sections and the branch channel entrance respectively. The third term of the left hand side of equation 2-21 represents main flow direction momentum transformed from the branch channel to the main channel.

For the control volume EGHF, the momentum equation in the main flow direction of the branch channel is:

\[ \frac{g}{2} \frac{W_b}{Y_b} Y_b^2 + \frac{\beta_b Q_b^2}{W_b Y_b} = \frac{g}{2} W_t Y_t^2 + \beta_t Q_t V_t \cos(\theta - \delta) \]  \hspace{1cm} (2-22)

Where \( V_t \) = cross sectional mean velocity at the branch channel entrance.
The energy equation for the control volume ABEGHFDC is:

\[ Q_u (Y_u + \frac{\alpha_u Q_u^2}{2gW_u^2 Y_u^2}) + Q_b (Y_b + \frac{\alpha_b Q_b^2}{2gW_b^2 Y_b^2}) = Q_d (Y_d + \frac{\alpha_d Q_d^2}{2g\mu W_d^2 Y_d^2})(1 + K_e) \]  

(2-23)

Where: \( \alpha \) = energy correction coefficient and \( K_e \) = energy loss coefficient including the eddy loss and friction loss from both inflows to outflow across the junction. Relationship between discharge ratio and measured correction coefficient at downstream end of recirculation zone was found as shown in the Figure 2.36 below.

![Figure 2.36 Measured Energy Correction Coefficient, \( \alpha \), at downstream end of recirculation zone for \( 30^\circ \leq \theta \leq 60^\circ \)](image)

The results of the analytical approach were found to be in fairly good agreement with the experimental values and the values obtained by other studies.
The energy loss resulting from a junction of closed conduit and an open channel, studied by Nedelac and Gay (2008). Considering the portions of the channel free surface in both the upstream and downstream directions were nearly horizontal, defined the energy loss coefficient \( Ke \) as

\[
\frac{\Delta E}{\rho g} = Q(Z_u + \frac{A_u Q^2}{2gW^2h_u^2}) + q(Z_u + \frac{\alpha_u q^2}{2g(\frac{d^2}{4}(-\sin(\theta_u)\cos(\theta_u)))^2})
\]

\[- (Q + q)(z_d + \frac{A_d (Q + q)^2}{2gW^2h_d^2}) = K_e (Q + q)(Z_d + \frac{A_d (Q + q)^2}{2gW^2h_d^2}) \]

Where:

\( A \) and \( \alpha \) = correction coefficients for energy (considered as equal to 1)

\( Z_\text{vertical} \) free-surface or piezometric level

\( Z_u \) in the channel and in the pipe are supposed to be nearly equal

\( \theta \) = angular variable representative of free-surface elevation above the pipe invert, defined as the angle between a radius extending from the pipe’s bottom to the central axis, and a radius extending from the central axis to the point of contact between the free surface and pipe:

\[
\theta = \Pi - 2Arc\cos\left(\frac{h}{d}\right) \quad (2-25)
\]

Sere et al. (1997) introduced 2 coefficients defined by

\[
\frac{\Delta E}{\rho g} = [Q + q][Kud + \frac{Q^2}{2gw^2hu^2}] + q\{Kbu + \frac{Q^2}{2gw^2hu^2}\} \quad (2-26)
\]

Neglecting the friction loss energy in equation (2-26), the combination of equations
(2-24) and (2-26) yields

\[
K_e = \frac{[Q + q][K_{sd} + \frac{(Q + q)^2}{2gw^2h_d^2}] + q(K_{bu} + \frac{Q^2}{2gw^2h_d^2})}{(Q + q)[Z_d + \frac{(Q + q)^2}{2gw^2h_d^2}]}
\] (2-27)

The values of \( K_e \) calculated from experimental data and those computed from Serre et al. (1994) are then compared as shown in Figure 2.37.

Figure 2.37 Comparison of energy loss coefficients \( K_e \), computed from experimental data versus those computed from Serre et al. (1994) formulas

(x) – Computation with observed upstream and downstream water levels

△ - Computation considering only downstream (\( Z_u = Z_d \)) water level

The dash line is the line of perfect agreement
2.6 SUMMARY

Open channel junctions are common in natural and man-made waterways. Flow and sediment transport through junctions involve complex three-dimensional behavior and are difficult to document. Over the last two decades, interest in the dynamics of flow and sediment transport at junctions of river channels has significantly increased. Different approaches have been used through laboratory investigations, field studies and numerical simulations to describe the flow and sediment behavior at channel junctions. Investigations of junction flows with clear water yielded better understanding of flow features such as separation zone, water depth variations, velocity changes, and shear layer and stagnation zone. When one or both streams are sediment-laden, the structure of the downstream flow becomes different and more complex due to additional variables such as variation in sediment particle size and sediment concentration. Though several studies had been conducted on those sites knowledge of sediment transport behavior at these sites remain still incomplete. Better understanding of sediment-flow interaction is needed. A better understanding of flow and sediment transport behaviour at junctions is needed for the efficient use, protection and control of open channel networks for sustainable river management.
3 EXPERIMENTAL SETUP AND PROCEDURE

3.1 INTRODUCTION

Experimental studies of hydraulic problems using physical models have significant advantages. They allow precise control of variables, enabling the experimenter to isolate one key variable in order to observe its effect on some other variable. The technique provides an opportunity to study various flow scenarios and their relative importance to the problem in hand. Furthermore, experimental observations provide the necessary data for validating numerical models.

Extensive research has been conducted on open channel junction flows with clear water. However the current understanding of the sediment transport characteristics at open channel junctions remains incomplete. Therefore the current research is focused on investigating the sediment transport behaviour at an open channel junction using a laboratory experimental setup. This chapter explains the development (design, fabrication and commissioning) of a 90° open channel junction. A detailed account is provided of the measurement techniques, data acquisition system, sediment feeding and catching systems, type of sediment and the experimental method used for investigating the flow and sediment behaviour at the junction. A series of experiments were conducted, initially with clean water and subsequently with sediment laden flows for varying flow conditions and sediment feed concentrations, all for a sub-critical flow condition (When \( Fr = 0.37 \)). Weber et al. (2001) reported comprehensive study at 90° channel open channel junction with \( Fr = 0.37 \) for clear water flows. Therefore in the current study also it was considered
to investigate the same flow condition with the $Fr = 0.37$, in order to make detail comparison of results.

### 3.2 EXPERIMENTAL FACILITY

An open channel junction was designed and constructed at the Hydraulics Laboratory of the University of Wollongong as part of this PhD project. The size of the experimental facility was adjusted to suit the constraints on the available space. The experimental facility consists of a 90° junction of two equal-width, equal-depth flat bed channels with two separate water recirculation systems, particle feeding apparatus (sediment rake, peristaltic pump and slurry mixing tank), turbidity measuring instruments (a custom-made turbidity probe), sediment catching system, water height measuring system and a data acquisition system using the LabView programme, along with other experimental control devices.

![Figure 3.1 Schematic of experimental arrangement (not to scale)](image-url)
Figure 3.2 Schematic diagram of flume (plan view)

Figure 3.3 Cross sectional view of main channel
The experimental setup was designed and constructed according to the dimensions given in Figure 3.1, Figure 3.2 and Figure 3.3 above. The flume was fabricated using 6 mm thick perspex sheets. It has a low Manning’s value, around 0.009. The sharp corners at the junction were not rounded off. The sediment feeding system was designed and constructed for introducing sediments uniformly into the branch channel at the branch channel inlet. Clean water flow was established in the main channel. The sediment was collected at the downstream outlet, using a sediment-catching box made with a stainless steel frame and covered with 85 micron stainless steel netting.

3.2.1 Flume construction

The flume is made of 6 mm perspex sheets fastened together by small 2.5 mm bolts. Particular attention was paid to the location of the bolt holes. After assembling and correctly squaring into position, the perspex joints were secured using chloroform. In order to prevent water leaks a thin film of silicon was applied to the outside of the flume joints and as such did not change the cross section of the flume. Wherever a slight misalignment of joined perspex sheets was observed, a small amount of silicon sealant was applied to smoothen the surface.

3.2.2 Flume supporting structure

A supporting structure (Figure 3.4) was constructed to support the flume at a predefined height (1.05 m above ground level) in order to have easy access when taking measurements and to make sure that the head tanks and receiving tank were located under the channel.
The flume support structure comprised of twelve uprights, with two braces on either side, made of 50 millimetre steel angle. The lateral supports consist of two pieces of steel angle 5.97 metres long, with twenty one cross-timber supports measuring 50 mm x 25 mm. The support structure was bolted to the ground using 8 mm bolts. The flume support structure was levelled using a theodolite and packing under the upright supports.

The branch section of the flume support structure (Figure 3.5) was fitted with locking...
to make sure that they did not move during the experiment. Two rails were fixed on top of the main channel to carry the measuring instrumentation.

### 3.2.3 Plumbing

The flow in both flumes was generated using two separate pumps (Figure 3.6) connected to two separate water header tanks. Water is recirculated from the receiving tank in to the header tanks and back to the receiving tank, providing two separate water recirculation systems. For monitoring the flow rates in the two channels, two electromagnetic flow meters (F-2000 from Blue White Industries Ltd) were fixed on the plumbing system with the necessary valves and fittings.

![Figure 3.6 Main channel and branch channel pumps](image)

Most of the pipe work and connections used 50 mm diameter fittings. For releasing the excess pressure produced by the pumps, bleed valves were incorporated in the plumbing system. Transition pieces were used to connect the tanks outlets with
the flumes. Flow straighteners were installed at the entrance of the channels to prevent the formation of large-scale disturbances in order to facilitate uniform flow. The water depth at the downstream outlet is regulated using a tailgate weir.

3.2.4 Experimental setup

The flume is designed to have a flat bed (Figure 3.7). After placing the channels on the supporting structure, they were surveyed using an automatic level in order to ensure equal bed levels for both channels. The flume was checked for sagging when the channels were filled with water and the supporting structure ensured minimum sagging. Keeping a constant total flow rate and a water height (74 mm) at the downstream outlet it was able to maintain a sub-critical flow condition \( \text{Fr} = 0.37 \).

![Figure 3.7 Completed channel junction](image)

3.2.4.1 Sediment feeding system

Using the equation 5.1 required mass of corvic powder was found to make relevant concentrations. Batches of slurry with the required concentrations were then prepared
in a separate tank and pumped into the branch channel using a peristaltic pump and sediment rake (Figures 3.8 and 3.9). In order to achieve near-uniform feeding at the feeding point, the sediment rake was constructed with ten feeding tubes located at two different levels.

![Figure 3.8 Sediment feeding system](image)

![Figure 3.9 Slurry Feeding System](image)

3.2.4.2 Turbidity measurement

ANALITE NEP185 (10mm DIA PROBE, 105 DEG C 0-10,000 NTU) custom-made turbidity probe from McVan Instruments Pty Ltd was used for measuring turbidity in experiments (Figure 3.10). The probe uses optical retro-scatter technology to
measure very high turbidity levels up to 10,000 NTU with the repeatability @ 25°C ±2%.

![Turbidity measuring system](image)

Figure 3.10 Turbidity measuring system

The probe consists of an L-shaped tube similar to a Pitot - static tube, allowing measurements angle close to the channel bed. Turbidity readings were taken by inserting the probe into the water and readings were recorded in the computer using RS232 output at user-set periodic intervals. The turbidity probe and a point gauge were fixed on a moving trolley mounted on rails, so that it was able to move the measurement point anywhere horizontally and vertically in the main channel.

**3.2.4.3 Sediment collection system**

In order to ensure clean water flow through the main channel, the sediment particles were collected using a sediment catching box placed at the downstream outlet (Figure 3.11). Proportion of sediment which escaped from the catching box was negligible (This was ensured by measuring the turbidity of water in the receiving tank). The sediment accumulated inside the catching box was removed from time to time.
time in order to facilitate free flow though the netting.

![Sediment collection system](image)

Figure 3.11 Sediment collection system

### 3.2.5 Data acquisition

The LabView Program was used for data collection in the experiment. It was designed to set up three panels which are used for data collection, previewing and setting of calibration factors. The data collection panel provided all the necessary information about each run (such as averaging time, sample rate, flow rates in main and branch channels etc).

Data was collected simultaneously from three inputs to the DAQ card, two flow meters and one turbidity probe (Figure 3.12). Each input was separately averaged to reduce noise. Sampling speed was kept constant except when noisy signals were observed. The graphs in the data collection panel displayed the instantaneous measurements of main and branch channel flow rates (l/min) and the turbidity (NTU) as the data was collected, showing all collected points for the current run. The digital readouts at the top left of each graph display the actual averaged values being plotted.
3.2.5.1 Preview

The preview tab displays the Preview window. The three graphs in this window operate as a scrolling display (data appears on the right hand side and disappears off the left hand side). The idea was to show live signals from the 3 instruments so that it was possible to see what the data looked like before it was recorded. The averaging time and sampling rate was as set on the previous tab.

3.2.5.2 Setting parameters

The “Set Parameters” tab setting of various parameters which are used during data collection. The information here is stored in a setup file which is read every time the lab view data collection program is run.
3.2.5.3 Flow meter calibration constants

Flow meter calibration constants are pre-set in the Blue-White Industries F-2000 Model RT flow meters. The Low Analog output value (as set in the flow meters) is the flow rate in l/min which corresponds to 0 volts output from the flow meter. The High Analog output value is the flow rate in l/min which corresponds to 10 volts output. In the lab view data collection program flow rate is calculated using the following equation:

\[
\text{FlowRate}(L/min) = V \frac{\text{HighOutValue} - \text{LowOutValue}}{10} + \text{LowOutValue}
\]  

(3.1)

Where \( V \) is voltage reading of the flow meter.

3.2.5.4 Turbidity scale factor

The Turbidity Scale Factor was set as specified by the manufacturer of the ANALITE NEP185 Turbidity Probe. Its value was 10,000 (i.e. 1 Volt \( \equiv \) 10,000 NTU). The response is claimed to be linear up to 5,000 NTU by the manufacturer. These settings are used each time the data collection program is run.

3.2.5.5 Data saving

Readings were recorded for main channel flow rate, branch channel flow rate and turbidity for all experimental conditions and saved immediately in Excel files as shown in Figure 3.13.
Name of the person who conduct the experiment - Kalyani
Date 23/02/2008
Location- xstar minus 1.5, point A
Flow ratio- q* = 0.25

Averaging Time (s): 5
Sample Rate (Hz): 10
Main Low: 0 300
Branch Low: 0 300
Turbidity Scale: 10000

<table>
<thead>
<tr>
<th>Time</th>
<th>Main channel flow rate(l/min)</th>
<th>Turbidity (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18:26.3</td>
<td>82.6</td>
<td>17</td>
</tr>
<tr>
<td>18:31.1</td>
<td>81.8</td>
<td>17</td>
</tr>
<tr>
<td>18:36.1</td>
<td>82.3</td>
<td>24</td>
</tr>
<tr>
<td>18:41.1</td>
<td>81.5</td>
<td>17</td>
</tr>
<tr>
<td>18:46.1</td>
<td>82.4</td>
<td>23</td>
</tr>
<tr>
<td>18:51.1</td>
<td>83.5</td>
<td>30</td>
</tr>
<tr>
<td>18:56.1</td>
<td>82.3</td>
<td>29</td>
</tr>
<tr>
<td>19:01.1</td>
<td>82.4</td>
<td>18</td>
</tr>
<tr>
<td>19:06.1</td>
<td>83.6</td>
<td>22</td>
</tr>
<tr>
<td>19:11.1</td>
<td>83.1</td>
<td>34</td>
</tr>
<tr>
<td>19:16.1</td>
<td>82</td>
<td>20</td>
</tr>
<tr>
<td>19:21.1</td>
<td>81</td>
<td>17</td>
</tr>
</tbody>
</table>

Figure 3.13 Typical Excel file showing data saved

### 3.2.6 Flow meter calibration

Blue-White Industries DIGI-METER™ F-2000 flow meters were used for measuring the flow rates in both channels. Both flow meters were calibrated in the laboratory using the time to collect a fixed volume of water as shown in figure 3.14 and Figure 3.15. The $r^2$ (r- squared ) values 0.9921 and 0.9999 shown in the figure 3.14 and Figure 3.15 indicate that flow meters are accurate and its response to varying flow rate is linear.
Chapter 3 Experimental Setup and Procedure

Figure 3.14 Main channel flow meter calibration graph

Figure 3.15 Branch channel flow meter calibration graph
3.2.7 Turbidity probe calibration

The probe is factory calibrated using APS AEPA solutions with two points 0 and 10,000 NTU. In this research preliminary experiments were carried out to determine the relationship between probe readings (NTU) and sediment (Corvic vinyl-described in 3.2.8) concentration g/L using 5 different sediment concentrations ranging from 1 g/L to 5g/L. It was observed that Probe output (NTU) and concentration g/L has a linear relationship as shown in the (Figure 3.16).

\[ y = 0.0027x \]
\[ R^2 = 0.9964 \]

Figure 3.16 Relationship between turbidity and Sediment Concentration (g/L)

Relationship between voltage and the NTU also followed a perfect linear relationship for a wide range of Turbidity values as shown in the figure 3.17.
3.2.8 Sediment characteristics

In this experiment Corvic Vinyl was the sediment material chosen. It consists of near-spherical shaped white particles forming a free-flowing powder insoluble in water. Corvic Vinyl is not considered a health hazard, although the usual occupational health and safety precautions had to be taken when handling a fine powder. The specific gravity of Corvic Vinyl is 1.37, and average particle size $D_{50}$ is 100 micron.
3.3 EXPERIMENTAL METHOD

3.3.1 Water heights measurement

The flow in each channel was set according to the required discharge ratio by adjusting the inline valves. The downstream water height was adjusted using a tail gate weir to achieve required water level at downstream in order to establish sub-critical junction flow condition with Fr = 0.37. Once this was done, the water heights were measured at set locations manually (Figures 3.18 and 3.19) using point gauges for both clean water and sediment laden flows. The point gauges were mounted on a simple sliding base which moves over the rails along the channels and the measurements were taken when the tip of the point gauge just touched the water surface at pre-determined locations. Water depths were measured at five different locations across the main channel for clear water and at three different locations for sediment laden flows. The number of measurement point was reduced to three in sediment laden flow experiments in order to trim down the total time spent at each location thereby reducing the quantity of sediment accumulation in the catching basket.

3.3.2 Turbidity measurement

In sediment laden flow experiments, first the flows in each channel were set according to the required flow ratio by adjusting the inline valves. Slurry was prepared in a separate tank according to the required concentration. The slurry was continuously stirred in the tank to prevent the particles from settling. The sediment catching box was put in place at the downstream outlet and the slurry was fed
uniformly in to the branch channel using a peristaltic pump and sediment rake. The turbidity was measured by positioning the probe at pre-determined measuring points (Figure 3.20). The probe was fixed to a sliding plate so that it could be moved easily to different locations across and along the channels. After completing each and every experiment, the remaining sediment particles were removed from the catching box. The system was then filled with clean water for the next experiment. Experiments were repeated for four different flow ratios and three different slurry feeding concentrations as given below.

Flow ratios considered were $q^*=0.25$, $q^*=0.417$, $q^*=0.583$ and $q^*=0.75$ and slurry feed concentrations used were 2000 NTU, 5000 NTU and 10000 NTU.

![Figure 3.18 Water Height measurement locations for Clear water flows (Dimensions in mm)](image)

### 3.3.3 Encountered problems

Numerous velocity measurement techniques were studied and attempted to use in the experiment. Unfortunately as explained in following sections, none of the available techniques could be used satisfactorily.
3.3.3.1 Digimage

The water flow was seeded with particles and the location of which was tracked through time producing images of the flow. For that purpose vertical light sheet was produced across the main channel and the images of the flow were captured by the Super VHS video tape recorder. However it was found that subsequent analysis of the tracking data was not able to process due to high velocities generated inside the channel.
3.3.3.2 High speed photography

In this method it was found that images captured with particles were not clear enough to process due to smaller size of the particles (Corvic powder which has the uniform size of particles 100 micron) used in experiments.

3.3.3.3 Acoustic Doppler Velocimeter (ADV)

Preliminary experiments were conducted to measure water velocity using ADV 10-MHZ SPLASH-PROOF SYSTEM, 10-MHZ PROBE. Unfortunately it was found that the large probe diameter (51 mm) had high influence on the measured velocities as the channel width was 229 mm.

3.3.3.4 Particle Image Velocimetry (PIV)

This technique was the appropriate method to be considered in the current research. However, the instrument owned by the university was not operational during the planned periods for experiments (one laser beam was out of order) and therefore, it was not possible to use the instrument for the current study.

3.4 SUMMARY

For investigating junction flow behaviour, there was no such facility existed at the University of Wollongong. Therefore as a part of this PhD project a new open channel junction system with a 90° confluence angle was designed constructed and commissioned at the Hydraulics Laboratory of the University of Wollongong. This experimental facility consisted of equal-width, equal-depth, flat bed rectangular cross section channels. A sediment feeding and catching systems were incorporated to the
channel junction to generate sediment laden flow through branch channel. Flow through the channels could be precisely controlled to replicate a series of different flow conditions. This research was focused to investigate suspended sediment transport behaviour at the junction. Several types of materials were tested for suitability and Corvic Vinyl (with uniform size of 100 microns) was the chosen material to feed as suspended sediment in this experiment. Feeding was accomplished by preparing slurry in a separate tank and then pumping it into the branch channel uniformly using a peristaltic pump and ten-tube rake close to the branch channel inlet.

For measuring turbidity and water heights at the junction, a custom-made optical turbidity probe and point gauges were used respectively. The flow rates were recorded by two electromagnetic flow meters. The LabView data Collection Program was used for data collection and three simultaneous parameters were recorded from the two flow meters and the turbidity probe. A series of experiments was conducted for clean water and sediment laden flows under sub-critical flow condition maintaining the downstream Froude number at 0.37. Four different flow ratios and three different sediment feeding concentrations were considered and turbidity and water heights were measured in the vicinity of the channel junction.
4 NUMERICAL MODELLING

4.1 INTRODUCTION

Most of flow situations in river hydraulics are three dimensional, turbulent and time dependent, and cannot be explored analytically by solving the non linear time averaged equations. One of the alternative methods of studying fluid flow phenomena is the numerical simulation approach. Numerical methods are extremely powerful problem-solving tools and they are capable of handling large systems of equations, nonlinearities, and complicated geometries that are common in engineering practice. Modelling complex problems involves a number of simplifications and approximations in solving the resulting governing equations.

The numerical approach has advantages over experimental studies or field measurements because it can simulate almost the full spectrum of scenarios rather easily. In the laboratory it is very difficult or rather not possible to simulate the true conditions of the actual situations. In numerical modelling it is possible to obtain information not available by other means. The limitations of numerical modelling are computer storage capacity, and approximations. Other limitations arise as a result of the inability to understand and mathematically model certain complex phenomena such as three phase flows.

Mathematical modelling of flow, sediment transport and morphological evolution started many years ago and to date, a variety of mathematical models have been developed and are in widespread use (Weerakoon 1990, Kenworthy and Rhoads 1995, Bradbrook et al 1998, Olsen 1999, Lane et al 2000, Bradbook 2000, Bradbrook
et al 2001, Huan et al 2001 and Duan, and Nanda, 2006. An explosion in computational capabilities and the availability of computational fluid dynamics software are rapidly changing the approach to hydraulic modelling. The numerical modelling technique allows the alteration of one variable at a time, so an assessment of the relative importance and interaction of different factors becomes possible.

With the advancement of computer technology, three-dimensional modelling has been becoming more and more attractive because of very detailed information that can be acquired from these models in contrast to simplistic one- and two-dimensional models. However the quality of mathematical models still remains uncertain and need to be developed and verified further. Three-dimensional modelling of turbulent flows is mostly built upon the Reynolds Averaged Navier-Stokes (RANS) equations with the aid of a turbulence closure module. This involves a large number of partial differential equations to be solved using a limited number of assumptions and a computer code.

There are numerous factors (size, shape, slope, angle between the combining channels, Froude number in the downstream flow, channel roughness, discharge ratio and variation of fluid properties) which influence the flow characteristics at a junction of two open channels (Weber et al. 2009). Hence addressing the problem theoretically in closed form solution is extremely difficult, if not impossible.

In the past, numerous computational approaches had been attempted to describe the junction flow behaviour (Shimizu and Itakura 1989, Tingsanchali and Maheswaran 1990, Bridge and Gabel 1992, Lane et al. 1995). Prior studies have focused on simplified mathematical approximations of different junction flow characteristics with limited data collected to validate the theoretical
models. The collected data in previous studies was limited to one or two velocity components and was often dependent on dye trace visualization for flow descriptions.

Shabayek et al. (2002) developed a one-dimensional theoretical model for sub-critical flows in combining open channel junctions. The model was based on applying the momentum principle in the streamwise direction to two control volumes in the junction together with overall mass conservation. The main advantages of the model are that it does not assume equal upstream depths and that the dynamic treatment of the junction flow is consistent with that of the channel reaches in a network model.

Some of the earliest attempts of 3D numerical modelling were undertaken by Weerakoon and Thamai (1989) and Weerakoon et al. (1991) for clear water flows. A 3D mathematical model with rigid lid approximation with basic two equation model was attempted by Weerakoon and Thamai (1989) for modelling confluence flow processes. Weerakoon et al. (1991) used a parabolic treatment limited model but adopted a fully elliptic treatment for a confluence with 60° junction angle. They compared qualitative aspects of the flow patterns at the bed and at the surface to conclude that the predictions agreed reasonably well with the experimental results. The length of the recirculation zone was the main discrepancy in the downstream direction, which was 30% too short. This discrepancy was attributed to numerical diffusion which resulted from the discretization together with basic form of $k$-$\varepsilon$ turbulence model, and the treatment of the water surface as a rigid lid. Bradbrook et al. (1998) used numerical methods to simulate a confluence with a zero junction angle. Bradbrook et al (2001) studied a laboratory open-channel junction using 3D,
elliptic solution of the Reynolds-averaged Navier-Stokes equations, including a
method for approximating the effects of water surface elevation patterns and a
renormalization group modified form of the $k$-$\varepsilon$ turbulence model. Although
Bradbrook et al. (2001) model was unable to provide quantitative flow details,
significant aspect of the experimental observations could be reproduced for clear
water flows. Huang et al. (2002) developed a three-dimensional numerical model to
investigate the open-channel junction with clear water flow and the model was
verified with Weber et al. (2001) experimental results. He selected the $k$-$\varepsilon$ model of
Wilcox (1993) and used the kinematic and dynamic boundary condition for more
accurate treatment of the free surface. At the beginning of the computation a free
surface was assumed flat and the mesh was generated based on the assumed flat
surface. During the iterative solution process the kinetic boundary condition was
enforced through the vertical velocity boundary condition while the dynamic
condition was used to obtain free surface elevation. Once the new surface elevation
was obtained, the mesh was regenerated through stretch or compression to conform
to the new free-surface shape using the hyperbolic tangent stretching function
(Vinokur 1983). It is clear that all previous researchers have attempted to
numerically simulate the clear water flows at channel junctions.

The writer’s simulations are conducted employing two computational fluid
dynamics packages: PHOENICS 3.5 and CFX 5. Junction flow features with clear
water and sediment laden flows are simulated. The latter is one of the significant and
new contribution in this research work by the writer. A number of assumptions are
made to simplify the problem to fit into the numerical framework and the accuracy of
CFD codes is assessed by validation with well-documented data from other
researchers and experimental observations in the current project.

4.2 GOVERNING EQUATIONS

The models solve the full three-dimensional Navier-Stokes equations that are based on fundamental principles of physics: conservation of mass and momentum. These equations relate the local pressures and velocities within the body of moving fluid.

4.2.1 General form of governing equations

The continuity equation and the Navier-Stokes equations can be written in a general conservation form (Equation 4.1), so they can be applied to numerical programming conveniently. This helps to simplify and organize the logic in a given computer program. The basic balance or conservation equation is that the net source within the cell is the difference between the outflow from the cell and the inflow into the cell. The quantities being balanced are the dependent variables such as mass of phase. The equations expressing the conservation of mass, momentum and turbulence quantities can be written in the following form in terms of the general conserved variable “φ” (PHOENICS 3.5 Manual).

\[
\frac{\partial}{\partial t} \rho \phi + \frac{\partial}{\partial X_k} \left[ \rho U_k \phi - \Gamma_{\phi} \frac{\partial \phi}{\partial X_k} \right] = S_{\phi} \tag{4.1}
\]

In the balance equation there are four terms which describe convection, diffusion, time variation and source terms.

Here \( \phi \) can stand for the velocity components \( u, v, w \), the turbulence quantities \( k \) and \( \varepsilon \), etc.

\( \rho \) - Fluid density (kg/m\(^3\))
\( U \) - Fluid velocity (m/s)

\( \Gamma_\phi \) - Diffusive Exchange Coefficient for \( \phi \) (kg/ m·s)

\( S_\phi \) - Source/sink term for \( \phi \) (kg/m\(^2\)-s\(^2\))

\[ \Gamma_\phi = \rho (\nu_t + \nu_l) \text{ (kg/m·s)} \]

Where \( \nu_t \) (m\(^2\)/s) and \( \nu_l \) (m\(^2\)/s) are the turbulent and laminar viscosities respectively.

The balance equations in differential form are discretised and solved numerically.

### 4.3 DISCRETISATION

Analytical solutions of partial differential equations are closed-form expressions that yield dependent variables that are continuous throughout the domain. However, numerical solutions can give answers only at discrete points in the domain termed as grid points. This is done by replacing the partial differential equations with a system of algebraic equations that can be readily solved for the values of the flow field variables at discrete grid points only. This discretisation requires the definition of discrete time-steps and the division of space into discrete units.

The discretisation techniques used in both PHOENICS and CFX are based on the ‘finite volume’ technique. In this method, the physical space of interest (computational domain) is split up into smaller non-overlapping volumes (‘cells’), yielding a ‘computational mesh’. The partial differential equations are integrated over each of these volumes. Then the variables are approximated by their average values in each volume and the changes through the surfaces of each volume are approximated as a function of the variable in neighbouring volumes. The resulting algebraic equations are solved iteratively, starting from initially
guessed values, until the conservation laws are satisfied for each cell, to the required
tolerance. Since the cells are contiguous, this implies that the conservation laws are
satisfied over the entire computational domain (The PHOENICS reference manual,

4.4 GRID GENERATION

One of the most important stages in flow modelling is to define a suitable mesh upon
which to perform the calculations (Olsen 1999). The coarser the mesh, the more the
likelihood of errors by numerical diffusion, but the finer the mesh, the longer the
solving time. Therefore a balance between the two must be attained. Depending on
how the domain is discretised and the quality of grid, the solutions may not be
accurate, due to many errors such as discretisation and interpolation errors. To obtain
accurate predictions, certain characteristics need to be controlled. It is important to
use an optimum cell distribution to obtain the required accuracy.

In the present study it was possible to represent the physical problem in a ‘box-
shaped’ computational domain (Figure 4.4, Figure 4.10, Figure 4.43 and Figure 4.51
and Figure 4.55). The overall dimensions of the computational domain are slightly
greater than the physical dimensions of the flow in the experiment. This allows the
simulated flows in the two channels to be developed at locations sufficiently
upstream of the junction. This is analogous to the experimental method of using
perforated plates and honeycomb screens to ensure a uniform flow at the inlets.

4.5 CONVERGENCE

Getting a solution in CFD takes iterations to reach the convergence starting from the
initial guessed value. The non-linearity of the Navier-Stokes equations and the pressure term which is an unknown variable included in the equations require this iterative method. Modified Strongly Implicit Procedure (SIP) is used as a solver for the matrix for a scalar like pressure. This procedure can get solutions at all grid points implicitly, so as to accelerate convergence. SIP is applied for each slab of the mesh in the three dimensional grid. Two types of relaxation methods, the ‘linear’ relaxation and ‘false-time-step’ relaxation were used to promote convergence. The relaxation coefficients should normally be between 0 and 1. If the solution diverges or does not converge because of instabilities, the normal measure is to reduce the relaxation coefficients.

4.6 TURBULENCE MODELLING

One of the most distinct characteristics of confluence flow is the existence of a turbulent mixing layer and therefore selecting the most appropriate turbulent model is very important. Turbulence is inherently three-dimensional, time-dependent, dissipative and strongly diffusive. The complete description of turbulent flows requires an enormous amount of information. The Navier –Stokes equations combined with the continuity equation are considered to provide a valid description of laminar and turbulent flows. For the present study k-ε turbulent model was used to simulate the flows.
4.7 SIMULATION PROCEDURE IN PHOENICS 3.5

PHOENICS is a CFD software package that has been available since 1981 from CHAM Ltd, UK. It consists of a pre-processor (‘Satellite’), a processor (‘Earth’), and a post-processor (‘Photon’) (Figure 4.1). Satellite takes the input file (known as a ‘q1’ file), and creates a data file which can be read by the processor Earth. Earth solves the flow equations iteratively and produces a result file which can be read by Photon to produce a graphic representation of the flow. The model uses a finite volume method in one, two or three dimensions in solving the governing equations for either laminar or turbulent flow. A staggered grid is used such that the velocity values are computed on the walls of the cells whilst scalars such as pressure and concentrations are computed at the centers of the cells. It contains the $k-l$ and $k-\varepsilon$ turbulence models to close the time-averaged flow equations, which can be selected.
according to the application. In order to use the flow solver the pre-processor
(Satellite) requires the information to be input using a ‘q1’ file on grid definition,
fluid properties such as density and viscosity, initial and boundary conditions and

PHOENICS allows computations upon regular or irregular orthogonal grids
and non-orthogonal (‘body-fitted’) grids. By defining fluid properties PHOENICS
can provide flow solutions for a wide variety of fluids, therefore the properties of the
particular fluid must be entered in the ‘q1’ file. PHOENICS solves the governing
equations implicitly. There are as many algebraic equations as there are cells in the
domain. These equations are strongly coupled so PHOENICS solves them in an
iterative ‘guess-and-correct’ manner, the object of which is to reduce the imbalance
between the left and right sides of every equation to a magnitude which is small
enough to be negligible (The PHOENICS reference manual CHAM 1989).

In the course of an iteration cycle, the guessed solutions to the equations are
regarded as temporarily constant, so that linear equation solvers can be used to solve
the equation sets. On the next cycle the solutions are updated from the latest values
and the linear equations are re-assembled and solved. These iterations are known as
sweeps and over successive sweeps the solution should converge. The progress
towards convergence can be tracked by choosing a 'monitor point' which displays
graphically the current value of each variable at one point in the flow domain for
each sweep (The PHOENICS reference manual, CHAM 1989).

For a 'steady-state' simulation, as the number of sweeps increases the variables
at this point should approach a constant value. To check this, the residual errors in
the equations over the whole field should be examined. As the iterations progress, the
residual errors from each equation should reduce.
4.8 FREE SURFACE TRACKING TECHNIQUE

In open channel confluences the zone of stagnation and the mixing layer are characterized by super-elevation, and a zone of separation present on the tributary side at the downstream junction corner with low water levels. Also in confluences dominated by strong helical flow cells during active sediment transport that super-elevation of the surface occurs when the tributary channels initially merge together (Mosley 1976, Bridge and Gabel 1992, Rhoads 1996). Although it is necessary to identify the relationship between water surface geometry and the flow field, it is quite difficult to collect actual free surface elevation data for large-scale natural channels.

In previous numerical studies different models were used for tracking the free surface. Most of the previous three-dimensional models used the solid-lid approximation for the treatment of water surfaces. While this approach is adequate for some flows, it is found to be inadequate for many other cases. As described before, Huang et al. (2002) used different method for simulating the free surface at a 90° channel confluence. Bradbrook, et al. (2001) used a ‘porosity correction’ concept for simulating the free surface. This is the technique, where the deviation of the free surface from the planar is represented by variable porosity in the surface layer cells.

PHOENICS offers two different methods, the Scalar Equation Method (SEM) and the Height of Liquid (HOL) method, for tracking the free surface. In both HOL and SEM employ a one-velocity-set solution procedure, and the different fluids separated by the distinct interface have only one value of each velocity component for each computational cell. Through the specification of the physical properties (density, viscosity, etc) the relevant governing equations are solved in a
conventional single-phase manner. The SEM technique can be applied only to unsteady incompressible flows. It can simulate convoluted and overturning surfaces and perform well with highly non-orthogonal grids. The HOL method however, is applicable to both steady and unsteady incompressible isothermal flows and cannot be applied for overturning free surfaces (Figure 4.2).

The HOL technique involves treating the flow of water (and the air above the water surface), as a single-phase incompressible flow. The free surface is located on the basis of fluid density (assumed as 998.0 kg/m$^3$ for water and 1.189 kg/m$^3$ for air, at 20º C), the total mass of water in any vertical column of cells, and that in all cells below any specific cell in the column. The HOL method is fully implicit and therefore suffers no restrictions, for unsteady cases, on the time-step increments.

In the present study, no ‘overturning’ of the free surface is expected or seen, so that in any given vertical (z direction) column of cells, only the lower cells will be occupied by water (Figure 4.2). This allows use of the Height of Liquid (HOL) technique for the free surface flow simulation.

![Typical column of computational cells](image)

Figure 4.2 Nature of free surface

Simulations conducted using CFD code PHOENICS 3.5 are discussed below.
4.8.1 Free surface flow modelling with cartesian mesh using PHOENICS

Three dimensional numerical modelling was carried out for 90 degree open channel junction (Weber et al 2001. experimental condition) using CFD package PHOENICS (versions 3.5 ) for flow condition $q^*=0.25$. (Where $q^*=Q_{main}/Q_{total}$).

![Figure 4.3 Schematic of experimental arrangement (Weber et al. 2001)](image)

4.8.1.1 Experimental condition

Weber et al (2001) performed laboratory experiments in a 90° combining flow flume as shown in Figure 4.3. The experimental facility was capable of establishing different flow conditions. Header tanks on both main and branch channels supplied the varying discharge. Perforated plates and 100 mm thick honeycomb were placed at the main and branch channel inlets in order to reduce eddy generated at inlets. To minimize losses on bends the channel transition piece were made smooth from vertical to horizontal and the floor of the entire facility was kept horizontal. The main channel and branch channel are 21.95m and 3.66 m long respectively. The junction occurs 5.49 m downstream of the flume entrance. The branch channel, main channel
and the downstream combined flow channel are 0.914 m in width and 0.51 m in depth. The total combined flow, 0.170 m$^3$/s, and the tail-water depth, 0.296 m, were held constant, yielding a constant downstream Froude number (0.37), and a constant tail-water average velocity (0.628 m/s).

### 4.8.1.2 Assumptions

In order to simulate above mentioned junction flow, the following assumptions were made to simplify the situation.

The flow was considered as incompressible and steady with average velocity components $u$, $v$ and $w$ in the $x$, $y$ and $z$ directions, respectively.

Water depth in the main and branch channels were considered equal immediately above the junction. This has been proved in previous analytical models as well as in experimental observations (Taylor 1944, Weber et al. 2001, Huang 2002, Gurram et al. (1997) and Hsu et al. (1998)).

Bed and side walls were considered as smooth walls.
4.8.1.3 Boundary conditions

The following boundary condition types were used for the simulation:

Table 4-1 Boundary conditions for free surface flow modelling (Two phase flow)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Boundary Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>u</strong> - Velocity component in the x direction</td>
<td>Main channel inlet = 0.139 m/s; Branch channel inlet = 0 m/s; Solid walls = 0 m/s</td>
</tr>
<tr>
<td><strong>v</strong> - Velocity component in the y direction</td>
<td>Main channel inlet = 0 m/s; Branch channel inlet = -0.420 m/s; Solid walls = 0 m/s</td>
</tr>
<tr>
<td><strong>w</strong> - Velocity component in the z direction</td>
<td>Main channel inlet = 0 m/s; Branch channel inlet = 0 m/s; Solid walls = 0 m/s</td>
</tr>
<tr>
<td><strong>P1</strong> - static pressure</td>
<td>Vertical extremity of the computational domain in both channels, vertical planes above the water inlets in both channels and at the outlet Zero gauge pressure</td>
</tr>
<tr>
<td><strong>k</strong> - Turbulent kinetic energy</td>
<td>Main channel inlet - 25% turbulence intensity; Branch channel inlet - 25% turbulence intensity</td>
</tr>
<tr>
<td><strong>ε</strong> - Turbulent kinetic energy dissipation rate</td>
<td>Main channel inlet - 25% turbulence intensity; Branch channel inlet - 25% turbulence intensity</td>
</tr>
</tbody>
</table>

Simulation was carried out as two phase flow (Water and Air). The boundary conditions used in this study were relatively simple and easy to implement (Table 4.1). Inlet velocities and inlet water heights for both main and branch channels were determined solving the momentum equation in the main flow direction and assuming equal water depths in the branches upstream of the junction. The computed main and branch channel inlet streamwise velocities and water depths were
0.139 m/s, 0.420 m/s and 0.33 m in both channels respectively and supplied as input data. At the solid walls (channel floors and sides), the no-slip boundary condition was applied. Zero gauge pressure boundary condition was applied at the vertical extremity of the computational domain in both channels, at vertical planes above the water inlets in both channels and at the outlet and the free surface is considered as a wall with slip.

### 4.8.1.4 Computational domain and mesh

The computational domain used for the simulation of free surface was like a single ‘box’ as shown in the Figure 4.4. This allows a structured Cartesian mesh to be used, provided the space not occupied by the flow itself is rendered impervious (‘blocks’) to the flow. The dimensions of the computational domain were slightly greater than the physical dimensions of the flow in the experiment: 22.95 m, 5.07 m and 0.51 m in the x, y and z directions, respectively. This allowed the simulated flows in the two channels to be uniform at locations sufficiently upstream of the junction, and was analogous to the experimental method of using perforated plates and honeycomb screens to achieve the same effect of Weber et al, (2001). The blocks shown in Figure 4.4 ensure that the numerical simulation of flows are confined to the main and branch channels. The mesh itself had 155, 60 and 8 cells in the x, y, and z directions respectively (Figure 4.5), with a denser cell population around the channel junction, especially in the downstream direction, where significant gradients in the flow parameters were expected.

### 4.8.1.5 Numerical technique

Disregarding the slight temporal fluctuations (due to turbulence) in the
actual flow parameters, a steady-state numerical simulation was carried out. Also, no ‘overturning’ of the free surface was expected or seen, so that in any given vertical (z direction) column of cells, only the lower cells would be occupied by water. Therefore, Height Of liquid (HOL) technique was used for tracking the free surface. The equations of continuity and momentum, discretised according to the control-volume technique, were solved iteratively from an initially guessed flow field, until mass and momentum balances were achieved for each computational cell.

Figure 4.4 Computational domain
4.8.1.6 Simulation results

Figure 4.5 Computational mesh for two phase flow

Figure 4.6 Simulated water surface- entire flow field
Figure 4.7 Simulated water surface detail near junction

Figure 4.8 Simulated water height contours

Figure 4.9 Simulated non-dimensional water height ($h^*$) contours in main channel

$q^* = 0.25$ ($h^* = h/w$, $h$ is the water depth and $w$ is channel width)
From Figure 4.6 to Figure 4.9 show computed water heights in the vicinity of the junction. It can be seen that higher water levels are generated before the junction and along the outer bank side of the main channel after the junction whereas water depression is observed immediately after the junction in the separation zone area. This is because of the obstruction effect caused by the lateral flow on the main channel flow.

### 4.8.2 Modelling of sediment transport using PHOENICS

Numerical simulations were conducted for UOW experimental conditions for four flow ratios. The assumptions, boundary conditions and mesh arrangement near the junction are similar to those in section 4.8.1. The computational domain is as shown in Figure 4.10. In this simulation, sediment is introduced into branch channel at the branch channel inlet. The ‘sediment’ is a massless additional variable that is solved for. Its branch inlet value is 1 (maximum possible), and main inlet value is 0, so that the contours of sediment concentration produced are “normalized” with respect to the maximum value at the branch channel inlet. The ‘sediment’ follows the flow passively as the flow develops. As it spreads in the computational domain with the flow, its local values change, eventually giving the concentration profiles. Also, since the “sediment” is a massless quantity that is tracked as the flow develops; it does not reflect the tendency of real sediment to sink towards the channel bed due to its weight. Thus the contour plots only give an indication of how the branch channel flow penetrates into the main channel flow, under different flow conditions (flow ratios).
Figure 4.10 Computational domain

Table 4-2 Input data for sediment laden flows

<table>
<thead>
<tr>
<th>Discharge ratio ( q^* = Q_m/Q_t )</th>
<th>Inlet water depth ( (m) )</th>
<th>Main channel flow velocity ( (m/s) )</th>
<th>Branch channel flow velocity ( (m/s) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.083</td>
<td>0.074</td>
<td>0.222</td>
</tr>
<tr>
<td>0.417</td>
<td>0.082</td>
<td>0.119</td>
<td>0.166</td>
</tr>
<tr>
<td>0.583</td>
<td>0.081</td>
<td>0.169</td>
<td>0.121</td>
</tr>
<tr>
<td>0.75</td>
<td>0.079</td>
<td>0.222</td>
<td>0.074</td>
</tr>
</tbody>
</table>
4.8.2.1 Simulation results

Figure 4.11 Normalized sediment concentration contours: channel bed \((q^* = 0.25)\)

Figure 4.12 Normalized sediment concentration contours: 0.0125 m from bed \((q^* = 0.25)\)
Figure 4.13 Normalized sediment concentration contours: 0.0375 m from bed

\[ q^* = 0.25 \]

Figure 4.14 Normalized sediment concentration contours: 0.0625 m from bed

\[ q^* = 0.25 \]
Figure 4.15 Velocity vector field: close to bed ($q^* = 0.25$)

Shape index = $w_s/L_s = 0.15$

Figure 4.16 Velocity vector field: 0.0125 m from bed ($q^* = 0.25$)

Shape index = $w_s/L_s = 0.152$
The concentration contours show that the branch channel flow enters at a larger angle to the main channel flow near the free surface than near the bed (From Figure 4.11 to Figure 4.14). The entering angle of branch flow reduces towards the bed. The velocity vector fields plotted for $q^* = 0.25$ (from Figure 4.15 to Figure 4.18) clearly show this trend.
show the extent of the separation zone at different heights from the channel bed. It was observed that, regardless of the presence of sediment in the branch channel, the separation zone shape index values are confined to a narrow band (around 0.15). The shape index value is also independent of the depth at which it is measured, although the physical size of the separation zone increases from the bed to the free surface. This may indicate the possibility of different bank-scouring effects at different depths.

Figure 4.19 Normalized sediment concentration contours: channel bed ($q^* = 0.417$)
Figure 4.20 Normalized sediment concentration contours: 0.0125 m from bed

\( (q^* = 0.417) \)

Figure 4.21 Normalized sediment concentration contours: 0.0375 m from bed

\( (q^* = 0.417) \)
Figure 4.22 Normalized sediment concentration contours: 0.0625 m from bed  

\[(q^* = 0.417)\]

Figure 4.23 Velocity vector field: close to bed (q* = 0.417)

Shape index = \(W_s/L_s \sim 0.15\)
Chapter 4 Numerical Modelling

Figure 4.24 Velocity vector field: 0.0125 m from bed ($q^* = 0.417$)

Shape index = $W_y/L_x \sim 0.154$

Figure 4.25 Velocity vector field: 0.0375 m from bed ($q^* = 0.417$)

Shape index = $W_y/L_x \sim 0.153$

Figure 4.25 Velocity vector field: 0.0375 m from bed ($q^* = 0.417$)
Figure 4.26 Velocity vector field: 0.0625 m from bed ($q^* = 0.417$)

Shape index = $W_s/L_s = 0.153$

Figure 4.27 Normalized sediment concentration contours: channel bed ($q^* = 0.583$)
Chapter 4 Numerical Modelling

Figure 4.28 Normalized sediment concentration contours: 0.0125 m from bed

\((q^* = 0.583)\)

Figure 4.29 Normalized sediment concentration contours: 0.0375 m from bed

\((q^* = 0.583)\)
Figure 4.30 Normalized sediment concentration contours: 0.0625 m from bed

\( q^* = 0.583 \)

Figure 4.31 Velocity vector field: close to bed (\( q^* = 0.583 \))

Shape index = \( W_s/L_s \approx 0.15 \)
Chapter 4 Numerical Modelling

Figure 4.32 Velocity vector field: 0.0125 m from bed ($q^* = 0.583$)

Shape index = $W_s / L_s \sim 0.14$

Figure 4.33 Velocity vector field: 0.0375 m from bed ($q^* = 0.583$)

Shape index = $W_s / L_s \sim 0.15$
Figure 4.34 Velocity vector field: 0.0625 m from bed (q* = 0.583)

Shape index = $W_s/L_s \sim 0.14$

Figure 4.35 Normalized sediment concentration contours: channel bed (q* = 0.75)
Figure 4.36 Normalized sediment concentration contours: 0.0125 m from bed

\( (q^* = 0.75) \)

Figure 4.37 Normalized sediment concentration contours: 0.0375 m from bed

\( (q^* = 0.75) \)
Figure 4.38 Normalized sediment concentration contours: 0.0625 m from bed

\[(q^* = 0.75)\]

\[
\text{Shape index } = \frac{W_s}{L_s} \sim 0.15
\]

Figure 4.39 Velocity vector field: close to bed \((q^* = 0.75)\)
Chapter 4 Numerical Modelling

Figure 4.40 Velocity vector field: 0.0125 m from bed (q* = 0.75)

Shape index = Ws/Ls ~ 0.14

Figure 4.41 Velocity vector field: 0.0375 m from bed (q* = 0.75)

Shape index = Ws/Ls ~ 0.14
The sediment concentration contours plotted for \( q^* = 0.417, q^* = 0.583 \) and \( q^* = 0.75 \) (Figures 4.19, 4.20, 4.21, 4.22, 4.27, 4.28, 4.29, 4.30, 4.35, 4.36, 4.37 and 4.38) showed similar patterns as in the case of \( q^* = 0.25 \). However the difference of branch flow entering angle between near the free surface and near the bed is reduced with increasing main channel flow (with increasing \( q^* \)). The shape index calculated for \( q^* = 0.483 \) and \( q^* = 0.583 \) and \( q^* = 0.75 \) at different depths also found to be confined to a narrow band around 0.15.

4.8.3 Numerical modelling with BFC mesh using PHOENICS

Numerical simulation was conducted for Weber et al (2001) experimental condition as explained above using the CFD code PHOENICS 3.5. A body-fitted mesh was constructed conforming to the free-surface shape which had been obtained from free surface modeling (section 4.8.1). The mesh was constructed for different \( YZ \) planes and then made a smooth transition from a grid mesh of one shape to another of a different shape using GSET transfer command in PHOENICS 3.5.
4.8.3.1 Assumptions

The flow was considered to be steady with average velocity components \( u \), \( v \) and \( w \) in the \( x \), \( y \) and \( z \) directions, respectively.

Water depth in the main and branch channels were equal immediately upstream of the junction. The flow was considered incompressible and bed and side walls were considered as smooth walls.

4.8.3.2 Boundary conditions

The simulation was carried out as a one phase flow (water only). The boundary conditions used for the simulation are shown in Table 4.2. The main and branch channel inlet velocities and water depths were 0.139 m/s, 0.420 m/s and 0.33 m respectively and supplied as input data. Inlet velocities and inlet water heights for both main and branch channels were determined solving the momentum equation in the main flow direction and assuming equal water depths in the branches upstream of the junction. At the solid walls (channel floors and sides), the no-slip boundary condition was applied. At the downstream outlet, zero gauge pressure condition was applied whereas at both inlets, inflows were given as mass flux. Wall like boundary condition was applied for the vertical extremity of the computational domain (Velocity across the vertical extremity of the computational domain is zero while the velocity along the vertical extremity has a value).

The following boundary condition types were used for the simulation:
### Table 4-3 Boundary conditions for one phase flow (Water-only flow)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Boundary Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>u - Velocity component in the x direction</td>
<td>Main channel inlet = 0.139 m/s; Branch channel inlet=0 m/s; Solid walls =0 m/s</td>
</tr>
<tr>
<td>v - Velocity component in the y direction</td>
<td>Main channel inlet = 0 m/s; Branch channel inlet=-0.420 m/s; Solid walls = 0 m/s</td>
</tr>
<tr>
<td>w - Velocity component in the z direction</td>
<td>Main channel inlet =0 m/s; Branch channel inlet =0 m/s; Solid walls : 0 m/s</td>
</tr>
<tr>
<td>P1- (in terms of) Mass flux</td>
<td>Main channel inlet-mass flux = ρu; Branch channel inlet-mass flux=ρv; outlet: Zero gauge pressure</td>
</tr>
<tr>
<td>k - Turbulent kinetic energy</td>
<td>Main channel inlet- 25% turbulence intensity; Branch channel inlet- 25% turbulence intensity</td>
</tr>
<tr>
<td>ε - Turbulent kinetic energy dissipation rate</td>
<td>Main channel inlet- 25% turbulence intensity; Branch channel inlet – 25% turbulence intensity</td>
</tr>
<tr>
<td>Free Surface</td>
<td>Wall like boundary condition</td>
</tr>
</tbody>
</table>

### 4.8.3.3 Computational domain and mesh

It was possible to fit the physical flow domain in a ‘box’, as shown in Figure 4.43. The upper surfaces of the channels in the computational domain conform to the shape of the free surface (Figure 4.6 and Figure 4.7) as computed earlier. Its x- and y-dimensions were slightly greater than the physical dimensions of the flow in the experiment. This allowed the simulated flows in the two channels to be developed at locations sufficiently upstream of the junction. The mesh itself had 116, 40 and 15 cells in the x, y and z directions respectively (Figure 4.44 and Figure 4.45), with a denser cell population around the channel junction. Near the ‘wall-like’ free surface where the velocity gradients were not as high as near the bed, the cells were larger (Large cells were populated where the velocity gradients were not high as near the bed). Greater cell density populated in regions where large velocity gradients were
expected (e.g. near solid walls, and immediately downstream of junction).

Figure 4.43 Computational domain in a box

Greater cell density in regions where large velocity gradients are expected (e.g. near solid walls and immediately downstream of junction)

Figure 4.44 Computational mesh for water only flow
4.8.3.4 Numerical technique

The computational domain was divided into a number of non-overlapping cells and the four terms of equation (4.1) were discretised according to the control-volume technique. This yielded a set of algebraic equations, connecting the values of the dependent variables at each cell with those at the ‘neighbouring’ cells, through ‘influence coefficients’, calculated using the hybrid scheme. The set of algebraic equations were then solved iteratively using a variant of the SIMPLE algorithm.

4.8.3.5 Simulation results

Figure 4.46 Near-bed streamwise velocities u (m/s), q*=0.25
Figure 4.47 Near-free surface streamwise velocities $u$ (m/s), $q^* = 0.25$

The computed velocity contours (Figure 4.46 and Figure 4.47) and velocity vector plots near the bed and near the free surface (Figure 4.48) show higher velocities close to the outer bank of the main channel after the junction. Upstream-directed low velocities exist inside the separation zone showing flow recirculation. It is also noticed that the extent of the separation zone is larger near the free surface than near the bed.

Figure 4.48 Velocity vectors, $q^* = 0.25$

Figure 4.48 demonstrates velocity vector patterns near bed and near free surface when $q^* = 0.25$. It is clear that near bed velocity vectors are more skewed
towards the inner bank side of the main channel. This generates a separation zone that is smaller near the bed than near the free surface. Upstream directed velocity vectors are observed inside the separation zone both near the bed and near the free surface. Large velocity vectors are observed immediately after the junction close to outer wall of the main channel and magnitudes of vectors gradually diminished towards the downstream. This can be explained due to the fact that reductions of available channel width for the combined flow after the junction due to flow separation. Calculated shape index ($W_s/L_s$) for near surface is 0.13 whereas for near bed is 0.135.

Figure 4.49 shows main channel near free surface streamwise velocity (u) components around the confluence. As expected, even distribution of velocities are observed at $x^* = +1$. The streamwise velocity however is significantly reduced.
towards the inner wall at $x^* = -2$ where the separation zone exists. Higher velocities are generated towards the outer bank of the main channel where the contracted zone at $x^* = -2$. The flow tends to recover from the junction effect showing more uniform distribution of velocities towards downstream direction at locations $x^* = -4$, $x^* = -6$ and $x^* = -7$.

Figure 4.50 Secondary recirculation patterns at locations downstream of the junction ($q^* = 0.25$)

It is observed that secondary flow and horizontal vortices induced by shear instability (Figures 4.50) are generated at the junction. The simulation shows the presence of two counter-rotating secondary vortices across the depth near the outer wall of the main channel at $x^* = -2$ and $x^* = -3$ and magnitude of the vectors are gradually diminished towards downstream direction.

### 4.9 SIMULATION PROCEDURE IN CFX 5

Numerical modeling of junction flows for clean water and sediment laden flows had been carried out using the computational fluid dynamics code CFX-5. The CFD code is capable of using unstructured meshes and a variety of turbulence
closure schemes based on the finite volume approach. There are several turbulence models available in CFX 5 and most commonly used standard $k - \varepsilon$ model was used for the present simulations. This model uses empirical correlations called ‘wall laws’ to define the boundary conditions at walls. Alternatively, the low Reynolds number $k - \varepsilon$ model computes the flow up to the wall. This method requires the use of a grid fine enough to resolve the wall boundary layer.

Numerical grid was constructed after creating suitable geometry which represented the present physical problem. The number of elements was deliberately kept low as the complexity of the geometry would generate additional difficulties that were likely to require a higher processing power. In addition, small spurious elements might also be created, as the grid becomes finer. They are known to be a source of difficulty, especially in the numerical treatment of turbulence terms at the walls, which could cancel out the benefits of the finer resolution by impeding convergence.

CFX-5 includes a variety of multiphase models to allow the simulation of multiple fluid streams, bubbles, droplets, solid particles and free surface flows. Two distinct multiphase flow models available in CFX-5, are Eulerian–Eulerian multiphase model and a Lagrangian Particle Tracking multiphase model. Within the Eulerian-Eulerian model, the inter-phase transfer terms can be modeled using either the Particle Model, the Mixture Model or the Homogeneous Model.

CFX-5 utilise a finite–volume approach to solve the governing equations of fluid motion numerically on a user–defined computational grid. The flow solution procedure consists of first generating the computational grid. A pre- processor is
available in the software that is used to perform this simulation. Second solution options such as inlet and boundary conditions, turbulence model and discretisation scheme are specified. The final step is running the flow solver to generate the actual flow field simulation.

CFX-5 contains several models for turbulence behaviour. Isotropic and non-isotropic turbulence models are available, in addition, a multitude of discretisation schemes are available to obtain the most accurate flow solution possible. For this simulation $k - \varepsilon$ turbulence model and a upwind discretisation scheme were used. The control-volume-discretised Eulerian equations of mass and momentum conservation, written for tetrahedral cells for the continuous phase, were iteratively solved for the numerical simulation along with Lagrangian equations for the discrete phase. Then particles were tracked from their injection point until they escape the domain or to its final destination.

4.9.1 Free surface flow modelling with hexahedral mesh using CFX

Free surface flow refers to a multiphase situation where the fluids are separated by a distinct resolvable interface. In this study interfaces involved were water and air. A geometry which represents a 90° equal width equal depth channel junction was created in ANSYS workbench in CFX. A hexahedral mesh was constructed separately using ACFM meshing code and then imported into CFX. After specifying flow conditions together with boundary conditions in CFX pre, governing equations were then solved using CFX solver. The 3D equations expressing the conservation of Mass, Momentum and Turbulence Quantities were calculated simultaneously for the mass and momentum balance equations over discrete
elements of space and time (Finite volume). The dependent variables of these equations are mass or volume fraction, velocity and pressure.

### 4.9.1.1 Assumptions

The flow was assumed to be steady with average velocity components $u$, $v$ and $w$ in the $x$, $y$ and $z$ directions, respectively.

Water depth in the main and branch channels were considered as equal immediately above the junction.

Flow was considered incompressible.

Bed and side walls were considered as smooth walls.

### 4.9.1.2 Boundary conditions

The following boundary condition types were used for the simulation:

- **Solid walls (Channel floors and sides)** - as smooth walls with ‘No slip’.

- **Vertical extremity of the computational domain (Free surface)** in both channels - as walls with ‘Free slip’.

- **Inlet turbulence intensity** (at both inlets) - specified as 25%.

- **Velocity at both inlets** - specified as the magnitude of the resultant normal velocity at the boundary.

- **Downstream Outlet** - zero gauge pressure.

### 4.9.1.3 Computational domain and mesh

The dimensions of the computational domain (Figure 4.51) were slightly
greater than the physical dimensions of the flow in the experiment (Figure 3.1): 6.488 m, 2.229 m and 0.150 m in the x, y and z directions, respectively. This allowed the simulated flows in the two channels to be uniform at locations sufficiently upstream of the junction. Hexahedral mesh (Figure 4.52) was constructed using ICEM meshing technique and used for the simulation. The mesh has 742, 23 and 16 cells in the x, y, and z directions respectively.

Figure 4.51 Computational domain for CFX simulation
Figure 4.52 Mesh arrangements near junction

4.9.1.4 Simulation results

Figure 4.53 Non-dimensional water depth contours (h*), q*=0.25
A depth decrease from the flow upstream of the junction to the downstream flow is evident in both water depth contours (Figure 4.53 and Figure 4.54) for q*=0.25 and q*=0.75 respectively. Maximum difference of upstream to downstream water surface elevation is approximately z*= 0.074, equivalent to 17 mm, for q*= 0.25 and is much less at z*=0.05, or 12 mm for q*=0.75. For both flow conditions the water surface generally display a depth decrease towards the inner bank as the flow enters the contracted region and then increases as the flow expands to the entire channel width downstream of the separation zone.

### 4.9.2 Sediment laden flow modelling using CFX

CFX 5 code contains a Lagrangian particle tracking algorithm which numerically predicts trajectories of solid particles, droplets or bubbles through the flow field simulation. The code is capable of coupling the particle equation of motion with the flow solution. Fully coupled with the motion of the continuous conveying medium, the motion of conveyed discrete particles (mass $m_p$) is described by Lagrangian equations of the form:
\[ m_p \frac{d\vec{v}_p}{dt} = \vec{F} \]  

(4.2)

Where \( \vec{v}_p \) is the particle velocity, and \( \vec{F} \) the total force acting on it. In the most general case, \( \vec{F} \) is composed of various components: viscous drag due to relative motion between particle and fluid, due to pressure gradients in the enveloping fluid, force to accelerate the virtual mass of fluid in the volume occupied by the particle, buoyancy force due to gravity, Bassett force resulting from the previous history of the motion, and centripetal and Coriolis forces. In the present case, the conveyed particles were assumed spherical, and were denser than the conveying medium. The motion occurs in a non-rotating frame of reference. Under these conditions, the equation of particle motion becomes:

\[
\rho_p \frac{\pi d_p^3}{6} \frac{d\vec{v}_p}{dt} = \frac{1}{8} \pi \rho_f d_p^2 C_D \left| v_f - v_p \right| \left( \vec{v}_f - \vec{v}_p \right) + \frac{\pi d_p^3}{6} \left( \rho_p - \rho_f \right) g
\]

(4.3)

Where \( \rho_p \) and \( \rho_f \) are particle material density and fluid density respectively, \( d_p \) is the particle diameter, \( \vec{v}_f \) and \( \vec{v}_p \) are velocities of fluid and particle respectively, and \( C_D \) is the particle drag coefficient (CFX-5 reference manual, 2001).

In this simulation, sediment particles (equivalent of Corvic Vinyl: \( d_{50}=0.1\)mm) were introduced close to the branch channel. Sediment particle tracks were computed for different flow conditions with uniform and non uniform particle feeding conditions. The particles were tracked from their injection point until they escape the domain or to its final destination. For uniform size sediment feeding 0.1 mm size particles were used whereas for non uniform feeding the range of particles was from 0.1 to 2mm. For the simulation, a total of 40 discrete particles were introduced to the
branch channel and only 20 particle tracks were drawn for better visualization of tracks.

### 4.9.2.1 Computational domain and mesh

In this simulation it was possible to fit the physical flow domain in a ‘box’, as shown in Figure 4.55. A tetrahedral mesh was used with dense cell population near the solid walls as shown in figure 4.56 and 4.57 for the simulation.

![Computational domain for CFX simulation](image1)

Figure 4.55 Computational domain for CFX simulation

![Computational mesh for CFX simulation](image2)

Figure 4.56 Computational mesh for CFX simulation
4.9.2.2 Boundary conditions

The following boundary condition types were used for the simulation:

For Solid walls- channel floors and sides, ‘smooth’ walls with ‘no slip’ condition

Vertical extremity of the computational domain in both channels: ‘smooth’ wall with slip to simulate free surface

Inlet turbulence intensity at both inlets specified as 25%

Velocity at both inlets - specified as the magnitude of the resultant normal velocity at the boundary

Outlet - zero gauge pressure

Particle velocity at branch inlet was taken same as water velocity at the branch inlet

4.9.2.3 Assumptions

Flow was assumed to be steady and the fluid is incompressible.

Water surface was considered as flat for the discrete phase movement (sediment particle movement), it was assumed that only weight and drag force were important.
Flow was considered as two phase flow (water only simulation carried out, interfaces were water and sediment particles).

4.9.2.4 Input data for sediment laden flows

Input data for sediment laden flows are as shown in Table 4.4 below. Simulations were conducted for four varying flow ratios having different flow velocities at branch and main channel inlets. These numerical simulations were conducted for the University of Wollongong’s newly constructed channel dimensions and flow.

<table>
<thead>
<tr>
<th>Discharge ratio ( q^* = Q_m/Q_t )</th>
<th>Inlet water depth (m)</th>
<th>Main channel flow velocity (m/s)</th>
<th>Branch channel flow velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.083</td>
<td>0.074</td>
<td>0.222</td>
</tr>
<tr>
<td>0.417</td>
<td>0.082</td>
<td>0.119</td>
<td>0.166</td>
</tr>
<tr>
<td>0.583</td>
<td>0.081</td>
<td>0.169</td>
<td>0.121</td>
</tr>
<tr>
<td>0.75</td>
<td>0.079</td>
<td>0.222</td>
<td>0.074</td>
</tr>
</tbody>
</table>

Discharge ratio \( q^* \) is defined as the ratio of the upstream main channel flow \( Q_m \) to the total flow \( Q_t \). The nondimensionalized coordinates are called \( x^* \), \( y^* \), and \( z^* \) for \( x/w \), \( y/w \), and \( z/w \), respectively. Where \( x, y \) and \( z \) are distance in \( x \), \( y \) and \( z \) directions respectively. \( w \) is channel width.
4.9.2.5 Simulation results

Figure 4.58 Dimensionless streamwise velocity (u*) Contours
(Near bed, q*=0.25)

Figure 4.59 Dimensionless streamwise velocity (u*) contours
(Near surface, q*=0.25)
As seen in Figures 4.58, 4.59, 4.60 and 4.61, the extent of the separation zone is smaller near the channel bed both in the downstream and cross-stream directions than near the free surface for both flow conditions $q^*=0.25$ and $q^*=0.75$. Also it is clear that there is an increase of streamwise velocities after the junction in both $q^*=0.25$ and $q^*=0.75$ flow conditions. As expected, the separation zone extent is reduced with increasing $q^*$, due to the larger contribution from the main channel flow, as seen in Figures 4.60 and Figure 4.61.
As the branch channel flow enters the main channel, the main channel must accommodate the additional flow, while still maintaining the overall mass balance. This causes the longitudinal flow velocities in the main channel to rise after the junction. At the same time, the channel bed and side walls behave as no-slip walls, while the free surface is akin to a wall with slip. The overall effect is to cause a twist in the shear plane between the two interacting streams, resulting in the varying size of the separation zone from the bed to the free surface. The twist in the shear plane is clearly seen in Figure 4.62.

Figure 4.62 Dimensionless streamwise velocity contours (u*)
(Across the depth at x*=−2, q*=0.25 and q*=0.75)
The $u^*-v^*$ vector fields of Figure 4.63 and Figure 4.64 illustrate that the entrance conditions of the branch channel flow is significantly different between the surface and the bed. Branch flow near the bed is considerably skewed towards the downstream direction and the surface flow is entering at a larger angle to the main channel. Therefore, smaller separation zone generate near the bed than near the free surface.
Chapter 4 Numerical Modelling

Figure 4.65 Relative separation zone widths for different discharge ratios

At the downstream corner of the junction, flow separates from the side wall forming a recirculation zone. Its maximum width and length were normalised by dividing by the channel width and compared as shown in Figure 4.65 and Figure 4.66 for different discharge ratios. It is apparent that with increasing discharge ratio both separation zone width and length are decreased. This could be explained that for
lower discharge ratios, higher flow is coming from the branch channel and the main channel flow is pushed more towards the outer bank direction than for lower discharge ratios forming a larger separation zone.

Figure 4.67 $v^*-w^*$ Vector field at different locations across the main channel ($q^*=0.25$)

Figure 4.67 demonstrates $v^*-w^*$ Vector Field as flow propagates downstream from $x^*=-1.33$ to $x^*=-7$ when $q^*=0.25$. The flow at $x^*=-1.33$ shows the surface water approaching the junction opposite wall, at $y^*=1.00$ as a result of the lateral momentum being larger near the surface than near the bed. The surface water has a considerable velocity component in the wall and therefore the water is deflected slightly by the oncoming main channel flow. It is observed that secondary recirculation pattern diminishes as the flow travels downstream and downward by the weight of the water itself. In the PHONICS simulation using Weber et
al. (2001) data, there were two counter-recirculation cells observed across the depth of the channel. Whereas in this CFX simulation, there is only one. This discrepancy is possibly due to unsteadiness of the shear flow.

For discharge ratios of 0.417, 0.583 and 0.75, in uniform sediment feeding simulation, Figure 4.68 shows that one particle is settled much faster than the remaining particles inside the stagnation zone (the upstream corner of the junction) although later on it entrained with the main stream. It is because the particle

Figure 4.68 Particle tracks for uniform size feeding (Particle size =0.1mm)
from its injection location traveled through the stagnation zone and then settled there due to low velocities in that region. This shows that the stagnation zone has significant effect on particle deposition.

Figure 4.69 Particle tracks (range of particle sizes)

Sediment settling patterns (Figure 4.69, 4.70 and 4.71) were almost the same in all discharge ratios but more particles were trapped in the separation zone for lower discharge ratios while more particles were washed away for higher discharge ratios. This could be explained that generation of larger separation zone for lower discharge ratios encouraged more particle deposition inside the separation zone.
Also it is noticed that more particles have penetrated towards the outer bank (Figure 4.69 and Figure 4.70) of the main channel for smaller discharge ratios due to
the fact that generation of wider shear layer for smaller discharge ratios encourages more intense mixing of sediments at the channel junction. Figure 4.71 clearly showed that as expected larger particles are settled close to the injection point whereas smaller particles are entrained with the main stream.

4.10 SUMMARY

Three-dimensional numerical simulations for 90° open channel junction flows were carried out using two different computational fluid dynamics codes: PHOENICS and CFX. Free surface profiles, velocity contours, velocity vector patterns, and sediment particle tracks were computed for different flow scenarios under a sub-critical flow condition. It is shown clearly that the two chosen numerical models were capable of producing detailed junction flow features in the vicinity of the junction. Higher velocities were generated just downstream of the junction in the contracted zone. The flow was seen to separate from the main channel wall (on the branch channel side) immediately after the junction generating a low pressure re-circulation zone adjacent to main channel inner wall. The separation zone size is larger near the free surface than near the bed. Higher water levels are generated before the junction and super elevation is observed close to the outer bank of the main channel after the junction. Computed sediment particle tracks showed that with increasing branch channel flow more sediment particles tend to be trapped in the separation zone. Larger and heavier particles tend to settle faster and close to the injection point whereas the lighter ones travel long enough to be entrained into the main flow. Particles which are away from the confining walls could travel away and not get trapped in the recirculation zone. For a larger recirculation zone, the possibility of particles getting trapped there was seen to increase.
Chapter 5 Experimental Investigation

5 EXPERIMENTAL INVESTIGATION

5.1 INTRODUCTION

Open channel junctions form important morphological elements of every river system, at which rapid changes in flow, sediment discharge and hydraulic geometry take place. Obtaining instantaneous flow information with an acceptable accuracy at these sites is quite difficult. Therefore researchers often turn to laboratory investigations of junction flows with simplified flow conditions which allow easy control of variables.

This chapter presents an account of experimental investigations conducted at the University of Wollongong using a 90° equal-width equal-depth flat bed open channel junction. Experiments were performed with clean water and sediment laden flows with four flow conditions and three sediment feed concentrations. Water height and turbidity were measured respectively by using point gauges and a custom-made optical turbidity probe over a grid defined (Figures 3.18 and 3.19 and 3.20) throughout the junction region.

5.2 WATER HEIGHTS: CLEAR WATER FLOWS

Water heights were measured at set locations (Figure 3.18) using five point gauges which were mounted on a simple sliding base. For each of four different flow conditions, the sliding base was moved along the channels recording the water heights at five different locations across the channels simultaneously. Water depth contours were then plotted for each and every flow condition as illustrated below.
Figure 5.1 Normalised water depth (h*) contours in the main channel

Figure 5.2 Water surface profile along the main channel (Clear water, q*=0.25)
Figure 5.3 Water surface profile along the main channel (Clear water, $q^* = 0.417$)

Figure 5.4 Water surface profile along the main channel (Clean water, $q^* = 0.583$)
Shown above water depth contour maps and water surface profiles in the main channel (From Figure 5.1 to Figure 5.5) it was observed that higher water depths were generated before the junction. The free surface profile along the main channel showed a sudden depression immediately after the junction, followed by recovery after about 7-8 channel widths from junction. Upstream to downstream depth difference was higher for lower discharge ratios and highest difference was observed for \( q^* = 0.25 \) flow condition. Super elevation exists adjacent to outer bank after the junction for all flow conditions. This water depths pattern is generated due to the obstruction effect caused by the lateral stream associated with turbulence mixing and energy losses at the junction. Measured water depths for flow conditions \( q^* = 0.25 \) and \( q^* = 0.75 \) were then compared with CFX simulation predictions and Weber et al. (2001) experimental observations and found they are in good agreement showing the similar pattern of free surface profile changes at the junction.
5.3 WATER HEIGHTS: SEDIMENT LADEN FLOWS

Water heights and turbidity were measured using a point gauge and a turbidity probe which were mounted together on a sliding trolley. The sliding trolley could be moved along the channel while both instruments were moving across the channel in order to position the instruments at predefined locations. The water heights and turbidity were recorded for locations as described in Figures 3.19 and 3.20. In this chapter turbidity representing (turbidity in the sediment mixing tank) at the time of feeding were given as 2000 NTU, 5000 NTU and 10000 NTU. Colour bar in contour diagrams indicates the measured concentration value inside the main channel in NTU. Relationship between concentration and turbidity is as given below.

Concentration (g/L) = 0.0027 * Turbidity (NTU)  \hspace{1cm} (5.1)

<table>
<thead>
<tr>
<th>Feed concentration (NTU)</th>
<th>q*=0.25</th>
<th>q*=0.417</th>
<th>q*=0.583</th>
<th>q*=0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance above channel bed (cm)</td>
<td>12.5</td>
<td>37.5</td>
<td>62.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Sediment concentration at the source (NTU)</td>
<td>42</td>
<td>37</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>2000</td>
<td>88</td>
<td>79</td>
<td>72</td>
<td>101</td>
</tr>
<tr>
<td>5000</td>
<td>125</td>
<td>115</td>
<td>107</td>
<td>172</td>
</tr>
<tr>
<td>10000</td>
<td>125</td>
<td>115</td>
<td>107</td>
<td>172</td>
</tr>
</tbody>
</table>
Figure 5.6 Normalised water depth ($h^*$) contours (Feed concentration = 2000 NTU)

Figure 5.7 Normalised water depth ($h^*$) contours (Feed concentration = 5000 NTU)
From the experimental results depicted in Figures 5.6 to 5.8 (normalised water depth contours), it can be seen that an increase of depth ratio ($Y^*$) occurs with decreasing discharge ratios. Higher depth gradient exists towards the inner bank for lower discharge ratios. For a particular value of flow ratio $q^*$, large variations in the sediment source concentration do not have an appreciable effect on the water heights. This is because the average concentration of sediment at the entrance to the main channel is only of the order of 2% of the source concentration. This effect is enhanced by the fact that sediment material sinks towards the floor, and the slower the branch channel inlet velocity, the greater is the tendency to sink.
Figure 5.9 Water surface profiles in the main channel
(Depth average turbidity at the source = 38 NTU, q*=0.25)
(Feed concentration = 2000 NTU)

Figure 5.10 Water surface profiles in the main channel
(Depth average concentration at the source = 25 NTU, q*=0.417)
(Feed concentration = 2000 NTU)
Figure 5.11 Water surface profiles in the main channel
(Depth average concentration at the source = 36 NTU, q*=0.583)
(Feed concentration = 2000 NTU)

Figure 5.12 Water surface profiles in the main channel
(Depth average concentration at the source = 42 NTU, q*=0.75)
(Feed concentration = 2000 NTU)
Longitudinal water surface profiles drawn for feed concentration 2000 NTU (From Figure 5.9 to Figure 5.12) show depth ratio decrease from the flow upstream of the junction to the downstream flow for all flow conditions. Highest water depth depression was observed adjacent to inner wall immediately after the junction. Depth ratio \(Y^* = \frac{\text{Upstream water depth}}{\text{Downstream water depth}}\) was increased with decreasing discharge ratios (Figure 5.21).

Figure 5.13 Water surface profiles in the main channel
(Depth average concentration at the source = 80 NTU, \(q^* = 0.25\))
(Feed concentration = 5000 NTU)
Figure 5.14 Water surface profiles in the main channel
(Depth average concentration at the source = 90 NTU, q*=0.417)
(Feed concentration =5000 NTU)

Figure 5.15 Water surface profiles in the main channel
(Depth average concentration at the source = 146 NTU, q*=0.583)
(Feed concentration =5000 NTU)
Figure 5.16 Water surface profiles in the main channel
(Depth average concentration at the source = 103 NTU, q*=0.75)
(Feed concentration =5000 NTU)

Longitudinal water surface profiles drawn for feed concentration= 5000 NTU(Figure 5.13 to Figure 5.16) show the similar trend of depth changes in the main channel as shown in 2000 NTU feed concentration flow condition. Depth ratio (Y*) was increased with decreasing discharge ratio (q*). Slightly higher depth ratio (Y*) was observed compared to 2000 NTU feed concentration flow condition.
Figure 5.17 Water surface profiles in the main channel

(Depth average concentration at the source = 116 NTU, $q^*=0.25$)

(Feed concentration =10000 NTU)

Figure 5.18 Water surface profiles in the main channel

(Depth average concentration at the source = 154 NTU, $q^*=0.417$)

(Feed concentration =10000 NTU)
Figure 5.19 Water surface profiles in the main channel
(Depth average concentration at the source = 157 NTU, $q^*=0.583$)
(Feed concentration =10000 NTU)

Figure 5.20 Water surface profiles in the main channel
(Depth average concentration at the source = 180 NTU, $q^*=0.75$)
(Feed concentration =10000 NTU)

Water surface profile along and across the main channel for 10000 NTU feed concentration(Figure 5.17 to Figure 5.20) show similar trend of depth changes as observed for 2000 NTU and 5000 NTU feed concentration flow
conditions. Higher depth ratio ($Y^*$) was observed compared to both 2000 NTU and 5000 NTU feed concentration flow conditions (Figure 5.21 and Table 5.2).

![Figure 5.21 Comparison of depth ratio](image)

**Table 5.2 Depth ratio ($Y^*$) for different flow conditions**

<table>
<thead>
<tr>
<th>$q^*$</th>
<th>Clear Water (experiment)</th>
<th>Feed concentration (2000 NTU)</th>
<th>Feed concentration (5000 NTU)</th>
<th>Feed concentration (10000 NTU)</th>
<th>Weber et al. (2001)</th>
<th>CFX simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>1.241</td>
<td>1.254</td>
<td>1.257</td>
<td>1.273</td>
<td>1.203</td>
<td>1.242</td>
</tr>
<tr>
<td>0.417</td>
<td>1.224</td>
<td>1.229</td>
<td>1.245</td>
<td>1.249</td>
<td>1.192</td>
<td></td>
</tr>
<tr>
<td>0.583</td>
<td>1.193</td>
<td>1.194</td>
<td>1.208</td>
<td>1.223</td>
<td>1.157</td>
<td></td>
</tr>
<tr>
<td>0.75</td>
<td>1.144</td>
<td>1.139</td>
<td>1.149</td>
<td>1.160</td>
<td>1.12</td>
<td>1.165</td>
</tr>
</tbody>
</table>
Water depth contours and water surface profiles shown above showed a similar trend of depth changes at the junction in both clear water and sediment laden flows. However water depths observed in sediment laden flows are slightly higher than in clean water flows.

Upstream water surface profile is found uniform across the both upstream channels for all flow conditions. As the lateral flow enters the main channel, main channel flow was pushed towards the outer bank. Therefore stream lines of the main flow were separated from the inner bank generating low pressure zone (Separation zone - Figure 5.68). This scenario was clearly seen in water depth contours. The water surface displayed a drawdown longitudinal profile as the flow enters the contracted region and then displayed a depth increase as the flow develops over the entire channel width downstream of the separation zone. The flow seems to have recovered from the junction effect showing flat water surface across the main channel after about 7-8 channel widths of the junction in all flow conditions.

Experimental observations showed significant changes in water surface elevation with respect to discharge ratio. Depth ratio\(Y^*\) was increased with decreasing flow ratios and increasing source concentrations (Figure 5.21 and Table 5.2).
5.4 TURBIDITY VARIATIONS

Sediment concentration contours in the main channel are plotted for three different feed concentrations and four different discharge ratios as illustrated below.

Figure 5.22 Concentration contours for $q*=0.25$ (Feed concentration = 2000 NTU)

Figure 5.23 Concentration contours for $q*=0.417$ (Feed concentration = 2000 NTU)
Figure 5.24 Concentration contours for $q^* = 0.583$ (Feed concentration = 2000 NTU)

Figure 5.25 Concentration contours for $q^* = 0.75$ (Feed concentration = 2000 NTU)
Figure 5.26 Concentration contours for \( q^* = 0.25 \) (Feed concentration = 5000 NTU)

Figure 5.27 Concentration contours for \( q^* = 0.417 \)
(Feed concentration = 5000 NTU)
Figure 5.28 Concentration contours for $q^* = 0.583$

(Feed concentration = 5000 NTU)

Figure 5.29 Concentration contours for $q^* = 0.75$ (Feed concentration = 5000 NTU)
Figure 5.30 Concentration contours for $q^* = 0.25$ (Feed concentration = 10000 NTU)

Figure 5.31 Concentration contours for $q^* = 0.417$

(Feed concentration = 10000 NTU)
Figure 5.32 Concentration contours for $q^* = 0.583$
(Feed concentration = 10000 NTU)

Figure 5.33 Concentration contours for $q^* = 0.75$
(Feed concentration = 10000 NTU)

Sediment concentration contours drawn for feed concentration = 2000 NTU (From Figure 5.22 to 5.25) show higher concentration in the zone of
recirculation. Sediment concentration increased towards the bed. For lower discharge ratios sediment were dispersed across the entire channel width than for higher discharge ratios. This could be explained with the location of shear layer for different discharge ratios. For increased discharge ratios (For increased main channel discharge), the location of shear layer move towards the inner wall due to the high momentum of the main channel flow. Therefore more sediment concentration was observed adjacent to inner wall. For lower discharge ratios the shear layer moves towards the outer bank of the main channel encouraging more particle dispersion across the main channel. Therefore higher concentration was observed across entire main channel width. Higher concentration gradient was observed immediately after the junction. Concentration gradient across the main channel reduced towards the downstream for all flow conditions. For lower discharge ratios low concentration was observed in the upstream section of the main channel.

Sediment concentration contours drawn for 5000 NTU and 10000 NTU feed concentrations, show similar trend of concentration changes along and across the main channel. However concentration in the main channel was increased with increasing feed concentration for all discharge ratios.
Figure 5.34 Concentration contours at 12.5 mm above bed (Feed concentration = 2000 NTU)

Figure 5.35 Concentration contours at 37.5 mm above bed (Feed concentration = 2000 NTU)
Figure 5.36 Concentration contours at 62.5 mm above bed
(Feed concentration = 2000 NTU)

Figure 5.37 Concentration contours at 12.5 mm above bed
(Feed concentration = 5000 NTU)
Figure 5.38 Concentration contours 37.5 mm above bed 
(Feed concentration = 5000 NTU)

Figure 5.39 Concentration contours at 62.5 mm above bed 
(Feed concentration = 5000 NTU)
Figure 5.40 Concentration contours at 12.5 mm above bed
(Feed concentration = 10000 NTU)

Figure 5.41 Concentration contours at 37.5 mm above bed
(Feed concentration = 10000 NTU)
Figures 5.34, 5.35 and 5.36 illustrated that at a particular depth and for a particular feed concentration, when flow ratio decreases, the concentration inside the main channel increased. For increased feed concentrations, in this case 5000 NTU it is observed similar trend of concentration variations with decreasing flow ratio as illustrated in Figures 5.37, 5.38 and 5.39. However more particle deposition can be observed within the separation zone. For higher feed concentration 10000 NTU, same trend, as illustrated above was observed (Figure 5.40, 5.41 and 5.42). In this case compared to the previous cases, significantly higher deposition was observed. The extend of the deposition increased along the channel.
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Figure 5.43 Concentration contours at 12.5 mm above bed ($q^*=0.25$)

Figure 5.44 Concentration contours at 37.5 mm above bed ($q^*=0.25$)
Figure 5.45 Concentration contours at 62.5 mm above bed (q*=0.25)

Figure 5.43 compares the sediment concentration variation for different feed concentrations at a particular depth, at 12.5 mm above the bed. It is clearly seen that increased sediment deposition with increased feed concentrations occur mainly inside the separation zone. Figure 5.44 and Figure 5.45 show comparison of the same for different depths, 37.5 mm and 62.5 mm above the bed. Similar trend was observed in these two cases, however higher concentration was observed at lower depths. It is observed that when the main channel flow increases that is q*=0.417, q*=0.583 and q*=0.75, concentration at the junction decreases significantly (From Figure 5.46 to Figure 5.54).
Figure 5.46 Concentration contours at 12.5 mm above bed (q*=0.417)

Figure 5.47 Turbidity contours at 37.5 mm above bed (q*=0.417)
Figure 5.48 Concentration contours at 62.5 mm above bed (q*=0.417)

Figure 5.49 Concentration contours at 12.5 mm above bed (q*=0.583)
Figure 5.50 Concentration contours at 37.5 mm above bed (q*=0.583)

Figure 5.51 Concentration contours at 62.5 mm above bed (q*=0.583)
Figure 5.52 Concentration contours at 12.5 mm above bed (q* = 0.75)

Figure 5.53 Concentration contours at 37.5 mm above bed (q* = 0.75)
Figure 5.54 Concentration contours at 62.5 mm above bed ($q^* = 0.75$)

In experimental concentration contours, it was observed that higher sediment concentrations occur adjacent to inner wall for all flow conditions. More sediment was dispersed across the main channel (towards outer wall) for lower discharge ratios than for higher discharge ratios. Sediment concentration diminished towards the free surface. Higher concentration gradient was observed at the junction and the concentration gradient was gradually diminished towards downstream showing more uniform concentration across the main channel after about 4 channel widths downstream of the junction.

5.5 QUANTITATIVE SEDIMENT ANALYSIS

5.5.1 Separation zone

Separation zone widths and lengths were measured using concentration contours (From Figure 5.22 to Figure 5.54) obtained in experimental observations.
and compared (From Figure 5.55 to Figure 5.60) with CFX simulation predictions and other research data (Weber et al. 2001, Huang et al. 2002) with respect to the flow ratios. The Shape Index of the separation zone was then calculated and compared with Weber et al. (2001) and Huang et al. (2002) research data together with CFX predictions as shown in figures from Figure 5.61 to Figure 5.64. The separation zone index for different flow ratios and sediment feed concentrations together with other research data are presented in the Table 5.3. From above mentioned comparisons it was revealed that the separation zone size (Both width and length) increases with decreasing discharge ratios. This was due to increase of lateral momentum from the branch channel flow with decreasing discharge ratios and increasing sediment concentration. Main channel flow was pushed more towards the outer wall generating larger separation zone adjacent to inner wall.

![Figure 5.55 Separation zone length comparison, z*=0.06](image-url)
Figure 5.55 shows the relative separation zone length comparison with respect to discharge ratios. It is observed that with the decreasing discharge ratio, relative separation zone length increased for all feed concentrations. This is due to increased lateral momentum with increasing branch channel flow pushes the main flow more towards the outer bank generating larger separation zone adjacent to inner wall.

![Figure 5.56 Separation zone width comparison, z*=0.06](image)

![Figure 5.57 Separation zone length comparison, z*=0.16](image)
With increasing discharge ratio the relative separation zone width decreases. This behaviour is depicted in Figures 5.56, 5.58, and 5.60. Trend of relative separation zone length variation is also similar to the trend as relative separation zone width.

Figure 5.58 Separation zone width comparison, $z^*=0.16$

Figure 5.59 Separation zone length comparison, $z^*= 0.27$
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Figure 5.60 Separation zone width comparison, \( z^* = 0.27 \)

Figure 5.61 Comparison of Separation zone shape index, at \( z^* = 0.06 \)
Figure 5.62 Separation zone shape index comparison, $z^*=0.16$

Figure 5.63 Separation zone shape index comparison, $z^*=0.27$
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Figure 5.64 Comparison of separation zone shape index (at free surface)

Table 5-3 Comparison of shape index (near the free surface)

<table>
<thead>
<tr>
<th>Discharge ratio (q*)</th>
<th>q*=0.25</th>
<th>q*=0.417</th>
<th>q*=0.583</th>
<th>q*=0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weber et al (2001)</td>
<td>0.120</td>
<td>0.118</td>
<td>0.120</td>
<td>0.095</td>
</tr>
<tr>
<td>CFX simulation</td>
<td>0.115</td>
<td>0.111</td>
<td>0.103</td>
<td>0.095</td>
</tr>
<tr>
<td>2000 NTU</td>
<td>0.136</td>
<td>0.135</td>
<td>0.124</td>
<td>0.138</td>
</tr>
<tr>
<td>5000 NTU</td>
<td>0.150</td>
<td>0.153</td>
<td>0.150</td>
<td>0.143</td>
</tr>
<tr>
<td>10000 NTU</td>
<td>0.155</td>
<td>0.137</td>
<td>0.133</td>
<td>0.120</td>
</tr>
<tr>
<td>Gurram et al (1997)</td>
<td>0.16</td>
<td>0.165</td>
<td>0.170</td>
<td>0.174</td>
</tr>
</tbody>
</table>
From comparison of shape factor (Table 5.3 and Figure 5.64) it is observed that the predicted shape index by the equations of Gurram et al. (1997) is slightly higher than the experimentally measured values. However the entire data set in table 5.3 is within the expected range of the shape index of the separation zone (0.1-0.25). The shape factor for clean water is found to be lower compared to sediment laden flows at all q* values.

5.6 LOCATION OF THE SHEAR LAYER

Figure 5.65 Formation of shear layer when q*=0.417
(Feed concentration = 10000 NTU)
It was noticed that the location of the shear layer play an important role in particle dispersion within the junction. For lower discharge ratios ($q^*=0.25$ and $q^*=0.417$) the location of the shear layer moved towards the outer bank of the main channel whereas for higher discharge ratios ($q^*=0.583$ and $q^*=0.75$) it was directed towards the inner bank side of the main channel. Therefore for lower discharge ratios...
sediment particles were dispersed across the channel width covering a larger proportion of the main channel width while for larger discharge ratios the sediment particles were confined to inner wall side as seen in above shown concentration contour plots and photos of shear layers (Figure 5.65 to Figure 5.67).

5.7 FORMATION OF THE SEPARATION ZONE

Figure 5.68 shows the separation zone generated in the main channel for the $q^* = 0.583$. Water depth depression is clearly visible inside the separation zone adjacent to inner wall of the main channel immediately after the junction.

Figure 5.68 Separation zone when $q^* = 0.583$ (feed concentrations= 10000 NTU)
5.8 FORMATION OF RIPPLES

During this experiment, it was noticed a ripple formation inside the branch channel as shown in the Figure 5.69 for the discharge ratio $q^*=0.417$.

5.9 SUMMARY

Laboratory experiments were conducted at a 90° laboratory open channel junction system which was constructed at the University of Wollongong. Experiments were performed for clear water and sediment laden flows with four different discharge ratios and three different sediment feed concentrations. Water heights and sediment concentrations were measured at the vicinity of the junction and compared with CFX simulation predictions and other research data.

Both water surface profiles for clear water and sediment laden flows followed a similar trend of depth changes around the junction. Higher water depths were
observed in both upstream channels for all flow conditions. However water depths in sediment laden flows were greater than in clear water flows. It is observed that depth ratio increases with decreasing flow ratios and increasing sediment concentrations.

Sediment concentration contours showed higher concentrations near the bed than near the free surface as expected due to settling of particles. Sediment concentration diminished towards the free surface and towards the outer bank of the main channel. Area of high concentration was increased towards the bed showing higher concentration near the bed than near the free surface. More particles were dispersed towards the outer bank for lower discharge ratios. For higher discharge ratios more particles were confined adjacent to inner wall of the main channel. Calculated separation zone dimensions (both width and length) showed that these values increase with decreasing flow ratios. Calculated separation zone index shows an increase of value with decreasing discharge ratios and increasing sediment concentrations. The separation zone index for all flow conditions was higher compared to clear water flow conditions for all corresponding discharge ratios. The results obtained in these experiments provided new data for understanding sediment-flow behaviour at open channel junctions.
6 COMPARISON OF NUMERICAL SIMULATIONS WITH
EXPERIMENTAL OBSERVATIONS

6.1 INTRODUCTION

With the advancement of computer technology, three-dimensional numerical modelling has been becoming more and more attractive for detailed investigations of junction flow features. Still there are limitations to numerical modelling because not all the conditions found in nature can be mathematically formulated. Valid approximations and assumptions are required. The accuracy of model predictions relies on the assumptions and boundary conditions imposed and the quality of the mesh used in the simulations. Comprehensive data are required to validate the numerical models.

This chapter presents the validation of three-dimensional numerical modeling conducted for 90° degree open channel junction flows using the computational fluid dynamics codes PHOENICS 3.5 and CFX 5. Sub-critical junction flows were simulated and water surface profiles, velocity fields, and sediment particle tracks were computed for clean water and sediment laden flows. Suspended sediment concentrations could be calculated by solving for a weightless ‘marker’ fluid that is passively carried with the flow. The numerical predictions were then compared with available experimental and numerical data together with experimental observations obtained from the newly constructed flume at the University of Wollongong.
6.2 FREE SURFACE FLOW MODELLING WITH CARTESIAN MESH USING PHOENICS 3.5

Three-dimensional numerical modelling was carried out using a Cartesian mesh for 90° degree open channel junction to simulate q*=0.25 flow condition. Results of the numerical simulations were compared with experimental data from previous researchers (Weber et al, 2001).

6.2.1 Free surface

![Figure 6.1 Comparison of non-dimensional water depth contours q*=0.25](image)

Figure 6.1 Comparison of non-dimensional water depth contours q*=0.25
Figure 6.2 Water depths at various locations of the main channel, $q^*=0.25$ (x axis – distance across the main channel (m), y axis – water depth (m))

- Numerical prediction
  - Experimental observation
Chapter 6 Comparison of Numerical Simulations with Experimental Observations

Figure 6.1 shows a comparison of non-dimensional water depth contours in the vicinity of the junction. It can be seen that the overall water depth patterns show very similar trends in both simulation and experiment. In particular, the depression downstream of the junction across and along the channels is shown clearly. Further comparisons between computed and experimental dimensional water depths are shown in Figure 6.2. It can be seen that the agreement between experiment and simulation is good at the upstream end of the junction.

At further downstream locations, there is an increasing discrepancy between experimental observation and simulation within the high turbulence zone, although the shape of the free surface is accurately reproduced. A possible reason for this is a slight mismatch between the exact locations of the experimental data collection points, and the mid-points of the computational cells where the data is stored after calculations. In addition, presence of high turbulence at the junction generates complexity in modelling of junction flow features.

The maximum depth difference between upstream and downstream (Figure 6.1) in the simulation is 0.08 m (73 mm) whereas the maximum depth difference in the experiment is 0.07 m (64 mm). Therefore, the simulation results show 14% discrepancy in water heights. In reality it is virtually impossible to simulate exactly the actual flow conditions which exist in real situations. Furthermore, flow through open channel junctions is inherently three dimensional and unsteady. Therefore, appropriate assumptions were made to simplify the problem which results in discrepancy between predictions and experimental observations.
6.3 NUMERICAL MODELLING WITH BFC MESH USING PHOENICS 3.5

PHOENICS 3.5. was used for simulating Weber et al (2001) experimental condition and the body-fitted mesh which conformed to the free surface shape was used for the simulation. This is because junction flow is a complex flow phenomenon. Solving for free surface solution together with high turbulence occurring at the junction complicate the solving procedure. Therefore in order to simplify the calculation procedure, two steps procedure was used. Velocity contours, velocity vectors and secondary recirculation patterns were plotted in the vicinity of the junction.

6.3.1 Velocity patterns

Numerical predictions were compared with experimental observations obtained from Weber et al. (2001). Figure 6.3 and Figure 6.4 present a comparison of dimensional experimental and simulated contours of the velocity component parallel to the main channel (u) plotted near the bed and near the free surface for \( q^* = 0.25 \). Both simulation and experiment are in good agreement showing similar trends of velocity changes along and across the main channel. Higher velocities are generated adjacent to the outer bank whereas lower velocities are generated adjacent to the inner bank of the main channel. The flow patterns near the bed and free surface are different and show narrower separation zone near the bed than near the free surface. Near the bed the maximum streamwise velocity (u) difference between the simulation and experimental data obtained by Weber et al. (2001) are 1.8 m/s and 2.02 m/s respectively. Near the free surface the maximum streamwise velocity (u) difference in the simulation and Weber et al. (2001) data are 1.9 m/s and 2.02 m/s.
respectively. The simulated velocities show 11% discrepancy of near the bed velocities and 6% discrepancy of near free surface velocities. Reason for this may be the mismatch of the location of data collection points and the data saving locations in the computational mesh. Also high turbulence occurring in the junction could lead to numerical error in simulations.

![Figure 6.3 Streamwise velocity (m/s) contours near bed when q*=0.25](image1)

![Figure 6.4 Streamwise velocity (m/s) contours near free surface when q*=0.25](image2)
Chapter 6 Comparison of Numerical Simulations with Experimental Observations

Figure 6.5 Near free surface velocity vectors ($q^*=0.25$)

Weber et al. (2001) experiment

Simulation

Figure 6.6 Near bed velocity vectors ($q^*=0.25$)

Weber et al. (2001) experiment

Simulation
Figure 6.5 and Figure 6.6 show comparison of velocity vectors in the main channel near free surface and near bed respectively. There is good agreement in the extent of the separation zone immediately downstream of the junction: about one channel width near the bed, and about 2-3 channel widths near the free surface. This indicates that the shear plane has a twisted shape.

Figure 6.7 Streamwise velocity (u) profiles near free surface, q* = 0.25
(Horizontal Axis: Distance across Main Channel from Outer Wall (m);
Vertical Axis: Velocity (m/s)
- Numerical prediction
• Experimental observation

It is seen that the greatest discrepancy is at $x^* = -2$ and $x^* = -4$ (Figure 6.7). In the upstream regions $x^* = +1$ and $x^* = 0$ (Figure 6.7) the velocity is evenly distributed.
across the main channel whereas the flow distribution after the junction is quite non-uniform across the main channel. However after about 7 channel widths, the flow begins to recover from the junction effect showing even distribution across the main channel (Figure 6.7) in both simulation and experiment.

It is observed that secondary flow and horizontal vortices induced by shear instability (Figure 6.8) are generated at the junction in both experimental and numerical simulations. However, the simulation shows the presence of two counter-rotating secondary vortices near the outer wall of the main channel, while the experimental data indicates only one clockwise secondary vortex. In reality, it is likely that the shear instability gives rise to an unsteady vortex pattern, akin to that in the wake of a blunt object, so that the directions of the secondary vortices alternate with time. This may also account for the discrepancy in Figure 6.7 mentioned above.
6.4 FREE SURFACE FLOW MODELLING WITH HEXAHEDRAL MESH USING CFX 5

Three dimensional free surface flow modeling was carried out using CFX 5 model for a 90° open channel junction (for UOW experimental condition, Figure 3.1) using a hexahedral mesh for clean water flow with two different flow conditions $q^*=0.25$ and $q^*=0.75$. An initial attempt was made using tetrahedral mesh for the simulation. However, it was noticed that the use of tetrahedral mesh for simulation of this
particular flow scenario was not clearly distinguishing the water-air interface. This may be due to the flow that is skewed towards the downstream direction just after the junction and the streamlines are not parallel to the walls. Therefore hexahedral mesh was finally chosen for the simulation. The model predictions were compared with Weber, et al. (2001) and observations from the writer’s experiments.

6.4.1 Water heights

Non-dimensionalised water depth contours at the vicinity of the junction are plotted and compared with Weber et al. (2001) experimental data and writer’s own experimental observations (Figure 6.9 and Figure 6.10). CFX prediction shows good correlation with Weber et al experimental observation whereas the UOW experimental observations show higher water depths throughout the main channel. This may be due to the difficulty faced in measuring the water heights by naked eye using point gauges. Due to high turbulence occurred inside the channel, it was difficult to judge the exact water heights. Also the flow may not be developed due to the small size of channels (short length in both channels before they meet).
The free-surface models yield a fair comparison of the water surface profiles near the junction, showing a sudden depression immediately after the junction; followed by recovery for both flow conditions. The flow is separated immediately after the junction.
junction and water surface depression is observed in the separation zone. The extent of the recirculation zone is smaller near the bed and larger near the free surface. In both flow conditions, flat water surface with higher water levels is generated just before the junction. A depth decrease from upstream to downstream is apparent in both simulation and experiments.

Higher water depth difference from upstream to downstream is demonstrated for $q^* = 0.25$ (Figure 6.9) than $q^* = 0.75$ (Figure 6.10). This is due to increased energy loses for lower discharge ratios. The maximum depth difference (upstream to downstream) is approximately $z^* = 0.075$ for $q^* = 0.25$ and is much less, $z^* = 0.048$ for $q^* = 0.75$. The water surface shows a drawdown longitudinal profile as the branch flow enters the contracted region. Also the flow tends to recover from the junction effect from about seven channel widths downstream of the junction. The computed water surface elevations are in good agreement with experimental observations for both flow conditions.

### 6.5 SEDIMENT LADEN FLOW MODELING USING CFX 5

Three dimensional numerical simulations were carried out for a 90° open channel junction with clear water and sediment laden flows for UOW experimental condition (Figure 3.1). The computational fluid dynamics code CFX.5 was used for the simulation. The simulations were conducted for different flow conditions. The results for clear water and sediment laden flow simulations are compared with experimental data as illustrated in figures from 6.11 to 6.22.
6.5.1 Simulation results - Velocity patterns (Clear water)

Figures 6.11 and 6.12 show comparisons between the non-dimensional streamwise velocity component plotted near the bed and free surface for $q^* = 0.25$ respectively. Figures 6.13 and 6.14 present comparisons between non-dimensional streamwise velocity component plotted near the bed and free surface for $q^* = 0.75$ respectively.

The flow is separated immediately downstream of the junction. Positive (upstream-directed) low velocities were observed inside the separation zone for both flow conditions. Overall the separation zone is larger near the free surface than near the bed and the separation zone size for lower discharge ratio case ($q^* = 0.25$) is greater than that for the higher discharge ratio ($q^* = 0.75$) in both CFX simulations. This is in agreement with previous findings (Weber et al, 2001 and Huang et al 2002) and also with the writer’s PHOENICS simulations. Higher velocity contracted zone is observed adjacent to outer bank of the main channel for both flow conditions after the junction. Also higher velocity zone near the bed for $q^* = 0.25$ is larger than for $q^* = 0.75$. The flow tends to recover from the junction effect further downstream of the junction showing a uniform velocity distribution across the main channel.
Figure 6.11 Comparison of non-dimensional streamwise bed velocity $u^*$, $q^*$=0.25
Figure 6.12 Comparison of non-dimensional streamwise surface velocity $u^*$, $q^*$=0.25
Figure 6.13 Comparison of non-dimensional streamwise bed velocity $u^*$, $q^*=0.75$
Figure 6.14 Comparison of non-dimensional streamwise surface velocity $u^*$, $q^* = 0.75$

In the CFX simulation, computed maximum $u^*$ (non-dimensional) velocity near the bed and near the free surface for $q^* = 0.25$ and $q^* = 0.75$ is 1.2 whereas for Weber et al. (2001) and Huang et al. (2002) this value is 1.4. Therefore there is a 14% discrepancy between CFX predictions of maximum velocity and that of Weber et al. (2001), and Huang et al. (2002). Overall, the CFX predictions are in good agreement with the observations of Weber et al. (2001) and Huang et al. (2002) data.
6.5.1.1 Separation zone velocity comparison

Figure 6.15 Comparison of non-dimensional stream wise velocity distribution at x*=-2 (The left side of the figure is the junction side)

For a more detailed understanding of the flow behaviour, cross sectional profile (Figure 6.15) through the middle of the separation zone was compared for q* = 0.25 and q* = 0.75. Varying size of the separation zone from the bed to the free surface is apparent and the higher velocity zone is extended towards the inner bank of the main channel for lower flow ratio q* = 0.25 in both simulation and experiment (Weber et al. 2001, Huang et al., 2002). Also a twist in the shear plane is clearly seen and the
separation zone width is reduced with increasing $q^*$. Therefore, CFX predictions are in good agreement with Weber et al. (2001) and Huang et al. (2002) data.

Figure 6.16 Comparison of velocity vectors near bed $q^*=0.25$

Figure 6.17 Comparison of velocity vectors near free surface $q^*=0.25$
Figure 6.16 and Figure 6.17 show comparisons of velocity vectors near the bed and near the free surface respectively for $q^* = 0.25$. It is observed that the entrance conditions of the branch channel flow are considerably different between near the free surface and near the bed. The extent of the separation zone near the free surface is larger than near the bed. Branch channel flow near the bed is significantly skewed towards the inner bank of the main channel comparing the angle of entry with that of near the free surface. The above results clearly indicate that numerical predictions using CFX are in good agreement with experimental observations.

6.5.1.2 Secondary recirculation

Figure 6.18 shows the $v^*$-$w^*$ vector fields (non-dimensional cross-wise ($v^*$) and depth-wise ($w^*$) velocity vector fields) for $q^*=0.25$ as flow develops downstream from $x^* = -1.33$ to $x^* = -7$. The flow at $x^* = -1.33$ shows the surface water approaching the outer bank of the main channel (at $y^* = 1$) due to greater lateral momentum near the free surface than near the bed. The surface water approaches the wall with significant velocity component and continually dictates that the flow is stopped by the outer bank of the main channel and therefore, the surface water is deflected downstream direction by the main channel flow. The ‘$v$’ component (crosswise velocity) of the velocity diminishes as the flow travels downstream in the main channel and downward due to the weight of the water itself. The negative ‘$w$’ (depth-wise component) component exists along the outer bank of the main channel and therefore, creates a secondary current as shown in Figure 6.18. Similar flow patterns are evident for $q^*=0.417$, 0.583 and 0.75 to a lesser extent (Figure 6.19).
Figure 6.18 \(v^*-w^*\) vector fields illustrating secondary flow patterns for \(q^*=0.25\)
Chapter 6 Comparison of Numerical Simulations with Experimental Observations

Figure 6.19 $v^*-w^*$ vector fields illustrating secondary flow patterns for $q^* = 0.417$, $0.583$ and $0.75$ (Channel junction is in the left side of figures)

The simulation predictions are in good agreement with Weber et al. (2001) experimental observations. However there is little discrepancy between the simulation and the Weber et al (2001) experimental observation possibly due to the slight mismatch between the exact locations of the experimental data collection points, and the mid-points of the computational cells.

6.5.1.3 Separation zone

Figure 6.20 and Figure 6.21 show comparison of separation zone width and length for varying flow ratios respectively. Separation zone index presented for
sediment laden flows are obtained from the experimental observations conducted by the writer at the University of Wollongong. All, simulations and experiments show similar pattern of changing separation zone. It is shown that with increasing flow ratio both separation zone width and length are reduced in all experimental and numerical observations. Further comparison of separation zone index was made as shown in the Figure 6.22.

Figure 6.20 Comparison of separation zone width for different flow ratios
Chapter 6 Comparison of Numerical Simulations with Experimental Observations

Figure 6.21 Comparison of separation zone length for different flow ratios

Figure 6.22 Comparison of separation zone shape index
It is observed that separation zone shape index (Maximum separation zone width/separation zone length) computed in CFX simulations are in good agreement with Weber et al. (2001) experimental observations and Huang et al. (2002) data (Figure 6.22). The separation zone shape index in sediment laden flows was found to be varying between 0.12 to 0.15 for all experimental conditions tested and the computed shape index for clear water flow is lower compared to sediment laden flow at all $q^*$ values.
6.5.1.4 Comparison of sediment concentration profiles with particle tracks

Sediment concentration contours obtained in PHOENICS simulations were compared with the particle tracks computed in CFX simulations and the concentration contours measured during experiments at UOW.

Figure 6.23 Comparison of sediment bar size (near the bed, $q^*=0.25$)
Figure 6.24 Comparison of sediment bar size (near the bed, q* = 0.417)
Figure 6.25 Comparison of sediment bar size (near the bed, \( q^* = 0.583 \))
Figure 6.26 Comparison of sediment bar size (near the bed, $q^*=0.75$)
Figure 6.27 Comparison of shape factor of the sediment bar (near bed)

The trend of changing the size of the sand bar near the bed is found to be similar in both simulations and experiments (Figure 6.23, 6.24, 6.25 and 6.26). As more flow enters from the main channel, i.e., as $q^*$ increases, the length of the sand bar also increased. This is due to increased momentum from the main channel flow that shifts the branch flow towards the inner bank. Therefore more sediment particles tend to be deposited adjacent to inner wall lengthening the sediment bar size.

Apparently the shape index of the sand bar near the bed tends to increased to a certain level with increasing the flow ratio and then gradually decreased with further increasing the flow ratio (Figure 6.27). This could be associated with the particles deposited on the bed being washed away by the main flow. The length of the sand bar is thus reduced, decreasing the shape factor of the sand bar. Therefore there appears to be a limit to the growth of the sand bar which builds immediately after the junction.
6.6 SUMMARY

Detail 3D numerical simulations of a horizontal-bed open-channel water flow with a 90° equal-width, equal-depth junction were carried out using two different CFD codes PHOENICS and CFX. Numerical modelling conducted with Cartesian mesh yielded accurate water heights at the vicinity of the junction. Using a body-fitted mesh conforming to the shape of the free-surface obtained from the previous simulation could predict velocity changes including recirculation patterns around the junction. Free surface flow modelling with hexahedral mesh using CFX could accurately predict water height changes at the junction showing greater height difference in q* = 0.25 than in q* = 0.75. Near free surface and near bed the maximum main channel velocities for q*=0.25 and q*=0.75 were different by about 14% from previous experimental data (Weber et al, 2001 and Huang et al 2002). The models were capable of showing secondary recirculation patterns and separation zone features. It is shown that with increasing flow ratio both separation zone width and length are reduced in all experimental and numerical observations. Predicted separation zone width and length are in good agreement with other researchers. The overall results of water heights, velocity vectors and particle tracks are generally are in good agreement with available research and writer’s data. Therefore three dimensional modelling of junction flows are adequately describe flow features around the junction.
7. **CONCLUSIONS AND RECOMMENDATIONS**

**7.1. GENERAL**

Open channel junctions are a common feature in man-made and natural waterways. The study of open channel junctions has a direct application in the design of open channel networks in water and wastewater plants, drainage systems and river engineering. Flow through channel junctions involves complex phenomena and sediment transport at junctions makes the situation further complicated.

Considerable research on open-channel flows has been undertaken in the past and yet the description of sediment-laden flow behaviour at channel junctions is incomplete. Therefore, the present study was aimed at further investigation of junction flow behavior both with and without sediment transport through comprehensive experimental and numerical techniques.

A new experimental facility was designed and commissioned for this research project. Extensive laboratory tests and a number of numerical simulations were conducted for a 90° open channel junction for varying discharge ratios and sediment feed concentrations under a sub-critical flow condition \( (Fr = 0.37) \). The choice of the sub-critical flow condition and the scale of the experimental facility enabled comparison with previously reported research with clean water (Weber et al, 2001).

This was followed by experiments and numerical simulations of sediment-laden flows. Spatial patterns of suspended sediment concentration were determined using the data collected at different locations in the main channel with a custom-made turbidity probe. Numerical predictions were then compared with experimental observations and other researchers’ published data (Weerakoon 1990, Weber et al
In the current study two computational fluid dynamics codes, PHOENICS and CFX, were used. There are advantages and disadvantages in both codes. CFX offers a built-in algorithm for constructing a tetrahedral mesh, but this is unsuitable for the current project. PHOENICS offers various alternatives for simulating free-surface flows, and considerable flexibility in its mesh-generating algorithms. This made possible a two-stage PHOENICS simulation: Free-surface simulation using a simple Cartesian mesh to determine the shape of the free surface, followed by a calculation using a ‘BFC’ (body-fitted coordinates) mesh that conformed to the shape of the free surface. The considerably more user-friendly particle-tracking algorithms in CFX were used to good effect.

The current study provides new data, particularly on the geometry of the recirculation region immediately downstream of the junction, contributing to a better understanding of flow and sediment dynamics at open channel junctions.

7.2. **CLEAN WATER AND SEDIMENT LADEN FLOWS**

The water surface profile remains flat in both channels upstream of the junction. Experimental observations for all tested flow conditions \((q^* = 0.25, q^* = 0.417, q^* = 0.583\) and \(q^* = 0.75\)) and numerical predictions of CFX and PHOENICS demonstrated this scenario. This is consistent with the assumptions used in previous analytical models (such as Taylor, 1944 and Gurram et al. 1997).

The normalized water depth \((h^* = \text{ water depth/ channel width})\) in the main channel increases with decreasing discharge ratio \((q^*)\) for both clear water and sediment laden flows. The numerical predictions and experimental observations showed
significant changes in water surface elevation (in the main channel) with respect to
discharge ratio. Both CFX simulations and experiments for clear water showed that
the maximum $h^*$ difference of upstream to downstream water surface is
approximately 0.074, equivalent to 17 mm, for $q^* = 0.25$ and is much less at 0.05, or
12 mm for $q^* = 0.75$. Sediment laden flow experiment (feed concentration = 10000
NTU) showed that maximum normalized depth ($h^*$) difference of upstream to
downstream water surface elevation is approximately 0.08, equivalent to 19 mm, for
$q^* = 0.25$ and is much less at 0.05, or 13 mm for $q^* = 0.75$.

The water surface displayed a drawdown longitudinal profile as the flow enters the
contracted region and then displayed a depth increase as the flow develops over the
entire channel width downstream of the separation zone. This was clearly shown in
water depth contours of experimental observation drawn for clear water and sediment
laden flows and in computed water depth contours obtained in PHOENICS and CFX
simulations. Water depth contours and water surface profiles for sediment laden
flows showed a similar trend of depth changes at the junction as the clean water
flows. However, water depths observed in sediment laden flows are higher than in
clear water flows (Figure 5.1 to Figure 5.21). Slightly higher depth ratios were
observed for sediment laden flows than clear water flows (Figure 5.21). With
increasing source sediment concentration, the depth ratio increases (Figure 5.21).

The size of the separation zone (width and length) increased with decreasing
discharge ratios $q^*$ (with increasing branch channel flow) and decreased towards the
bed showing larger separation zone near the free surface than near the bed.
Computed sediment particle tracks using CFX (Figure 4.68) clearly demonstrated
this phenomenon, showing more particle deposition inside the separation zone with decreasing discharge ratios. The computed velocity field showed reverse flow within the separation zone (Figure 4.48, Figure 4.63 and Figure 4.64).

The measured shape index from the experimental observations and numerical simulations show good correlation with previous research data (Figure 6.22). The shape index of the separation zone was found to vary between 0.12 to 0.15 for all experimental conditions tested and the shape index for clean water is found to be lower compared to sediment laden flow at all q* values (Table 5.3).

A strong secondary flow field was generated for lower discharge ratios (q*) and the intensity of secondary flow field gradually diminishes with increasing flow ratio. Also the intensity of secondary flow field weakens as the flow proceeds downstream. CFX predictions of secondary flow clearly showed this feature; i.e. intense secondary flow field was generated for q*=0.25 flow condition than in q*=0.417, q*=0.583 and q*=0.75 flow conditions.

The secondary flow cell shifts towards the inner bank near the free surface and to the outer bank near the bed as the combined flow proceeds downstream. Numerical predictions obtained in CFX simulations clearly showed these flow patterns and the predictions are in agreement with Huang et al. (2002) observations. However PHOENICS simulations showed the presence of two counter-rotating secondary vortices near the outer wall of the main channel at x*=−2 and x*=−3 while the experimental data of Weber et al. (2001) indicated only one clockwise secondary vortex. In reality, it is likely that the shear instability gives rise to an unsteady vortex...
pattern, akin to that in the wake of a blunt object, so that the directions of the secondary vortices may alternate with time. This is an indication that turbulence has a significant impact on secondary circulation as reported by Lane et al. (1999).

Longitudinal velocity patterns near the bed and free surface are distinctly different. Flow near the bed is significantly skewed towards the downstream direction than near the free surface. Higher velocities generate adjacent to outer wall of the main channel where the contracted zone and near bed velocities in the contracted zone are greater than near free surface velocities. Simulated streamwise velocity vectors and velocity contours of both PHOENICS and CFX simulations clearly demonstrated this characteristic. Numerical predictions further showed that near bed velocity vectors are more skewed towards the inner bank than near the free surface generating smaller separation zone near the bed than near the free surface (Figure 4.48, Figure 4.63 and Figure 4.64). This is in line with the observations by Weber et al. (2001) and Huang et al. (2002).

With decreasing discharge ratios (q*), the higher velocity zone near the bed and the velocity gradients across the main channel (after the junction) increases. This behavior is clearly visible in CFX simulations for q*=0.25 and q*=0.75 and in Huang et al. (2002) predictions. The flow recovers from the junction effect after about 6 to 7 channel widths downstream of the junction. This is shown with diminishing of velocity gradients across the main channel. Streamwise velocity profiles across the main channel obtained in PHONICS simulation show more uniform velocity distribution about 6 channel widths downstream of the junction. Streamwise near-bed and near-free-surface velocity contours computed in CFX
simulations for $q^*=0.25$ and $q^*=0.75$ demonstrate this scenario having uniform distribution of velocities across the main channel. Similar observation had been reported by Weber et al. (2001) and Huang et al (2002).

Smaller discharge ratios ($q^*$) encourage more particle deposition within the separation zone than in higher discharge ratios. Computed particle tracks in CFX simulations clearly showed this characteristic having more particle deposition within the separation zone with decreasing discharge ratios. This was the same in laboratory experimental observations. Higher concentrations shown within the separation zone and the size of the higher concentration zone reduced with increasing discharge ratios (with increasing main channel flow).

Substantial cross-channel mixing occurs within a distance about four channel widths downstream of the junction. Concentration contours of experimental observations showed less concentration gradient after about four channel widths in all flow conditions.

More particles seem to be trapped inside the separation zone for lower discharge ratios as shown in particle tracts computation using CFX. This is in agreement with the experimental observation. Higher sediment concentration was observed inside the separation zone and the area of maximum concentration reduced with increasing discharge ratios. Near bed concentration profiles demonstrate that the area of maximum concentration is greater for discharge ratios $q^*=0.25$, $q^*=0.417$ than $q^*=0.583$ and $q^*=0.75$. Hsu et al. (1998a) identified the separation zone as an important factor as it increases the sedimentation.
Chapter 7 Conclusions and Recommendations

Sediment concentration diminish towards the outer bank and downstream of the junction. Higher sediment concentrations occur near the bed than near the free surface. This is inline with the experimental observations. Concentration contours of experimental observation demonstrated higher concentrations near the bed and adjacent to inner wall of the main channel.

Sediment concentrations across the main channel width are controlled by the location of the shear layer. With increasing discharge ratios, location of the shear layer moves towards the inner wall and therefore, higher sediment concentration occurs adjacent to inner wall of the main channel. This was clearly shown in concentration contours drawn for experimental observations. For lower discharge ratios \(q^*=0.25\) and \(q^*=0.417\), sediment particles were dispersed across the entire channel width of the main channel while in higher discharge ratios \(q^*=0.583\) and \(q^*=0.75\), branch channel sediment was confined to a small area adjacent to the inner wall. Similar characteristics were observed in simulated particle tracks as more particle tracks were shifted towards the outer wall direction for lower discharge ratios \(q^*=0.25\) and \(q^*=0.417\) than for higher discharge ratios \(q^*=0.583\) and \(q^*=0.75\).

The studies conducted in this research provide greater insight towards the understanding of the flow and sediment transport characteristics. It is revealed that flow dynamics at open channel junctions may have important effects on the dispersal of dissolved or suspended substances in headwater areas of channel networks. Data obtained in this study is useful in controlling sediment erosion and deposition processors and flooding at channel junctions.
7.3. IMPORTANT OUTCOMES

7.3.1. Physical modelling innovations

1. Design, fabrication and commissioning of a new experimental facility, including channels, water recirculation systems, sediment recovery system, flow meters.

2. Custom-made turbidity probe

3. Custom-made apparatus for uniform feeding of sediment slurry

4. Custom-made data-logging system within the LabView framework

7.3.2. Numerical modelling innovations

7.3.2.1. A two-step treatment of CFD simulation

Firstly, the shape of the free surface was deduced using the “HOL” (height of liquid) technique. (This also enabled calculation of the water heights in the junction region from the hydrostatic equation); Secondly, a BFC (body-fitted coordinates) computational mesh was constructed that conforms to the shape of the free surface to simulate the velocity patterns in junction flows (This involved imposing a “wall-with-slip” boundary condition on the “free surface”, which reconstructs the physically observed fact that the streamwise component of the water velocity is not zero at the free surface.)

7.3.2.2. Creating particle tracks

Computed particle tracks showed the particles trapped in the recirculation region,
hence providing an alternative ‘visualization’ technique to deduce the shape index.

7.3.2.3. New observations on the shape index

It was observed that, regardless of the presence of sediment in the branch channel, the separation zone shape index values are confined to a narrow band (around 0.15). The shape index value is also independent of the depth at which it is measured, although the physical size of the separation zone increases from the bed to the free surface. This may indicate the possibility of different bank-scouring effects at different depths.

7.4. LIMITATIONS AND RECOMMENDATIONS

In this research the channel sizes had to be restricted to suit the available space in the hydraulic laboratory. Therefore small channel sizes could have an effect on the flow behavior. The location of the weir could influence on the water depths in channels generating the backwater effect. Also the influence on the flow field by the turbidity probe size could be significant.

There were limitations on total number of elements in the computational domain based on the license type owned by the University of Wollongong. Therefore, there were limitations for further mesh refinements of the computational mesh. The quality of the mesh could effect on the accuracy of predictions. Densed cell population in areas of higher flow parameter changes enabled to simulate accurate flow fields.

Initial simulations using CFX showed that the default tetrahedral mesh generated was not conducive to the situation at hand. This is because in reality, most of the free surface (water-air interface) is flat and horizontal. A computational mesh that
also has flat and horizontal cell faces is thus much more compatible with the physical situation. The simulations yielded results in which the air-water interface could not be identified with sufficient accuracy due to lack of adequate resolution. It was thus necessary to resort to a hexahedral mesh. To accomplish this, the ICEM code had to be used and then the mesh had to be imported into CFX for conducting simulations. There were limitations for using some functions for refining the hexahedral mesh. Therefore it was unable to refine the junction area with fine cells.

The current study focused on suspended sediment transport. Obtaining a sediment material that had suitable characteristics (particle size, particle material density close to that of water, low tendency to agglomerate, etc) proved difficult. The used material, Corvic vinyl, was selected because of its availability, average particle size, and free-flowing property, despite the fact that the material had a specific gravity of about 1.37. This made the sediment material sink towards the bed when it was conveyed by the water, causing discrepancies with the simulation results. This tendency could only be partially simulated in the CFX particle tracks, which also accounted for the particle size distribution to a certain extent.

Comprehensive velocity measurements could provide more detailed explanation on flow patterns including vortices which directly influence sediment particle movement at the junction. Incorporating instantaneous velocity contours together with particle tracks and sediment concentration contours will provide clear understanding about sediment flow interaction on the junction flow behavior. In the current study, different techniques were attempted to measure the water velocities but unfortunately none of those were utilized due to various reasons as indicated in section 3.3.3.
Hopefully non-intrusive velocity measuring technique such as Particle Image Velocimeter (PIV) or Acoustic Doppler Velocimeter (ADV) will be an appropriate way of measuring velocities since the flow field will not be disturbed by the measuring technique. Also such instantaneous velocity data could be used to validate the velocity predictions of CFX and PHOENICS simulations conducted in this study.

In the present study an intrusive method of measuring the turbidity was used. The channel width was 229 mm and the probe size was 10 mm therefore, there could be an influence on the flow field by the probe. Hence it is more appropriate to use non-intrusive turbidity measuring technique such as a Fiber-optic In-stream Transmissometer (FIT) to measure suspended sediment concentration in the channel.

The current study was based on a 90 degree open channel junction. Though this confluence angle produces maximum obstruction to the main channel flow among most channel configurations in nature are of small confluence angles such as 30°, 45° and 60°. Flow fields in such channel junctions are different. (Obtuse confluence angles also exist in nature. Most commonly those sites have hard rocks. Increased velocities will not be a crucial issue for such sites). Therefore, it is recommended to conduct further studies on such channel configurations investigating flow and sediment characteristics.

In numerical simulations eddy viscosity is considered as isotropic and modeled as an average for all three directions. According to Schall (1972) as cited by Olsen (1999), the eddy viscosity in the streamwise direction is almost one magnitude greater than
in the cross-stream direction. The Reynolds stress turbulence model therefore could give more accurate results. In the current study that option was not considered.

In sediment laden flow modelling it is appropriate to employ time-dependent movable boundaries in order to scope with the real scenario with erosion and deposition processes. In the current study that option was not considered in order to simplify the simulation.
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APPENDIX 1

EXAMPLE OF A CFX™ OUTPUT FILE (Q25_001.out)

This run of the CFX-5.7.1 Solver started at 18:40:35 on 15 Sep 2005
by
user kd09 on ENG-PG4G33B (intel_p4.sse2_winnt5.1) using the command:
"C:\Program Files\ANSYS Inc\CFX\CFX-5.7.1\bin\perllib\cfx5solve.pl"
-stdout-comms -batch -ccl -
Setting up CFX-5 Solver run ...

+ ---------------------------------------------------------------------------------------------------------------------
+ |
+ +--------------------------------------------------------------------
+ |
+ | CFX Command Language for Run |
+ |
+ +--------------------------------------------------------------------
+ | LIBRARY: |
+ | MATERIAL: Water |
+ | Material Description = Water (liquid) |
+ | Material Group = Water Data, Constant Property Liquids |
+ | Option = Pure Substance |
+ | Thermodynamic State = Liquid |
+ | PROPERTIES: |
+ | Option = General Material |
+ | Thermal Expansivity = 2.57E-04 [K^-1] |
+ | DYNAMIC VISCOSITY: |
+ | Dynamic Viscosity = 8.899E-4 [kg m^-1 s^-1] |
+ | Option = Value |
+ | END |
+ | REFRACTIVE INDEX: |
+ | Option = Value |
+ | Refractive Index = 1.0 [m m^-1] |
+ | END |
+ | SCATTERING COEFFICIENT: |
+ | Option = Value |
+ | Scattering Coefficient = 0.0 [m^-1] |
+ | END |
+ | ABSORPTION COEFFICIENT: |
+ | Option = Value |
+ | Absorption Coefficient = 1.0 [m^-1] |
+ | END |
+ | THERMAL CONDUCTIVITY: |
+ | Option = Value |
+ | Thermal Conductivity = 0.6069 [W m^-1 K^-1] |
+ | END |
+ | EQUATION OF STATE: |
+ | Density = 997.0 [kg m^-3] |
+ | Molar Mass = 18.02 [kg kmol^-1] |
+ | Option = Value |
+ | END |
+ | SPECIFIC HEAT CAPACITY: |
+ | Option = Value |
+ | Reference Pressure = 1 [atm] |
+ | Reference Specific Enthalpy = 0.0 [J/kg] |
+ | Reference Specific Entropy = 0.0 [J/kg/K] |
+ | Reference Temperature = 25 [C] |
+ | Specific Heat Capacity = 4181.7 [J kg^-1 K^-1] |
+ | Specific Heat Type = Constant Pressure |
+ | END |
+ | EXECUTION CONTROL: |
+ | PARALLEL HOST LIBRARY: |
HOST DEFINITION: engpg4g33b
Remote Host Name = ENG-PG4G33B
Installation Root = C:\Program Files\ANSYS Inc\CFX\CFX-5.7.1
Host Architecture String = intel_p4.sse2_winnt5.1
END

PARTITIONER STEP CONTROL:
Multidomain Option = Independent Partitioning
Runtime Priority = Standard
MEMORY CONTROL:
Memory Allocation Factor = 1.0
END

PARTITIONING TYPE:
MeTiS Type = k-way
Option = MeTiS
Partition Size Rule = Automatic
END

RUN DEFINITION:
Definition File = d:/cfx/z-cfx/T_Junct_Q26.def
Interpolate Initial Values = Off
Run Mode = Full
END

SOLVER STEP CONTROL:
Runtime Priority = Standard
EXECUTABLE SELECTION:
Double Precision = Off
END

MEMORY CONTROL:
Memory Allocation Factor = 1.0
END

PARALLEL ENVIRONMENT:
Number of Processes = 1
Start Method = Serial
END

FLOW:
SOLUTION UNITS:
Angle Units = [rad]
Length Units = [m]
Mass Units = [kg]
Solid Angle Units = [sr]
Temperature Units = [K]
Time Units = [s]
END

SIMULATION TYPE:
133
Option = Steady State
END

OUTPUT CONTROL:
RESULTS:
File Compression Level = Default
Option = Full
END

DOMAIN: Fluid
Coord Frame = Coord 0
Domain Type = Fluid
Fluids List = Water
Location = Assembly
DOMAIND MODELS:
BUOYANCY MODEL:
Option = Non Buoyant
END

DOMAIN MOTION:
Option = Stationary
END

REFERENCE PRESSURE:
Reference Pressure = 0 [Pa]
END
END

FLUID MODELS:
COMBUSTION MODEL:
Option = None
END
HEAT TRANSFER MODEL:
Option = None
END
THERMAL RADIATION MODEL:
Option = None
END
TURBULENCE MODEL:
Option = k epsilon
END
TURBULENT WALL FUNCTIONS:
Option = Scalable
END
END

BOUNDARY: MainIN
Boundary Type = INLET
Location = MainIN
BOUNDARY CONDITIONS:
FLOW REGIME:
Option = Subsonic
END
MASS AND MOMENTUM:
Normal Speed = 0.0692 [m s^-1]
Option = Normal Speed
END
TURBULENCE:
Option = Medium Intensity and Eddy Viscosity Ratio
END
END

134
BOUNDARY: Walls
Boundary Type = WALL
Location = Default 2D Region
BOUNDARY CONDITIONS:
WALL INFLUENCE ON FLOW:
Option = No Slip
END
WALL ROUGHNESS:
Option = Smooth Wall
END
END

BOUNDARY: Top
Boundary Type = WALL
Location = Top
BOUNDARY CONDITIONS:
WALL INFLUENCE ON FLOW:
Option = Free Slip
END
END

BOUNDARY: BranchIN
Boundary Type = INLET
Location = BranchIN
BOUNDARY CONDITIONS:
FLOW REGIME:
Option = Subsonic
END
MASS AND MOMENTUM:
Normal Speed = 0.1898 [m s^-1]
Option = Normal Speed
END
TURBULENCE:
Option = Medium Intensity and Eddy Viscosity Ratio
END
END
BOUNDARY: Outlet
Boundary Type = OUTLET
Location = Outlet
BOUNDARY CONDITIONS:
FLOW REGIME:
Option = Subsonic
END
MASS AND MOMENTUM:
Option = Average Static Pressure
Relative Pressure = 0 [Pa]
END
PRESSURE AVERAGING:
Option = Average Over Whole Outlet
END
END
END
SOLVER CONTROL:
ADVECTION SCHEME:
Option = High Resolution
END
CONVERGENCE CONTROL:
Length Scale Option = Conservative
Maximum Number of Iterations = 100
Timescale Control = Auto Timescale
END
CONVERGENCE CRITERIA:
Residual Target = 1.E-4
Residual Type = RMS
END
DYNAMIC MODEL CONTROL:
Global Dynamic Model Control = On
END
END
COMMAND FILE:
Version = 5.7
Results Version = 5.7.1
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Host computer: ENG-PG4G33B
Job started: Thu Sep 15 18:40:53 2005

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- Checking for Isolated Fluid Regions -

No isolated fluid regions were found.

- The Equations Solved in This Calculation -

Subsystem Name: Momentum and Mass
U-Mom
V-Mom
W-Mom
P-Mass
Subsystem Name: TurbKE and Diss.K
K-TurbKE
E-Diss.K
CFD Solver started: Thu Sep 15 18:41:08 2005

- Convergence History -
| Equation | Type | Timescale |
|----------------------+------------------------+---------------------|
| U-Mom | Auto Timescale | 8.88954E-01 |
| V-Mom | Auto Timescale | 8.88954E-01 |
| W-Mom | Auto Timescale | 8.88954E-01 |
| P-Mass | Auto Timescale | 8.88954E-01 |

| Equation | Rate | RMS Res | Max Res | Linear Solution |
|----------------------+---------+---------+---------+-----------------|
| U-Mom | 2.41 | 1.4E-02 | 7.2E-02 | 1.8E-02 OK |
| V-Mom | 1.50 | 1.4E-02 | 1.2E-01 | 9.4E-03 OK |
| W-Mom | 99.99 | 9.5E-04 | 1.7E-02 | 1.4E-01 ok |
| P-Mass | 0.17 | 2.1E-04 | 8.9E-03 | 9.4 3.6E-02 OK |

OUTER LOOP ITERATION = 1 CPU SECONDS = 1.15E+01

| Equation | Rate | RMS Res | Max Res | Linear Solution |
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| U-Mom | 0.58 | 8.2E-03 | 5.2E-02 | 2.0E-02 OK |
| V-Mom | 0.48 | 7.0E-03 | 6.9E-02 | 1.3E-02 OK |
| W-Mom | 0.54 | 5.1E-04 | 1.5E-02 | 2.0E-01 ok |
| P-Mass | 1.73 | 3.7E-04 | 4.7E-02 | 9.4 5.0E-02 OK |

OUTER LOOP ITERATION = 2 CPU SECONDS = 5.22E+01

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| V-Mom | 0.48 | 7.0E-03 | 6.9E-02 | 1.3E-02 OK |
| W-Mom | 0.54 | 5.1E-04 | 1.5E-02 | 2.0E-01 ok |
| P-Mass | 1.73 | 3.7E-04 | 4.7E-02 | 9.4 5.0E-02 OK |

OUTER LOOP ITERATION = 3 CPU SECONDS = 8.77E+01

<p>| Equation | Rate | RMS Res | Max Res | Linear Solution |
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| V-Mom | 0.48 | 7.0E-03 | 6.9E-02 | 1.3E-02 OK |
| W-Mom | 0.54 | 5.1E-04 | 1.5E-02 | 2.0E-01 ok |
| P-Mass | 1.73 | 3.7E-04 | 4.7E-02 | 9.4 5.0E-02 OK |</p>
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OUTER LOOP ITERATION = 23 CPU SECONDS = 7.87E+02

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<td>0.87</td>
<td>3.4E-04</td>
<td>9.5E-03</td>
<td>5.6 4.3E-02 OK</td>
</tr>
<tr>
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<td>1.7E-02</td>
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OUTER LOOP ITERATION = 30 CPU SECONDS = 1.03E+03

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<tbody>
<tr>
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</tr>
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</tr>
<tr>
<td>U-Mom</td>
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<tr>
<td>V-Mom</td>
</tr>
<tr>
<td>W-Mom</td>
</tr>
<tr>
<td>P-Mass</td>
</tr>
<tr>
<td>K-TurbKE</td>
</tr>
<tr>
<td>E-Diss.K</td>
</tr>
<tr>
<td>Equation</td>
</tr>
<tr>
<td>----------</td>
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<tr>
<td>U-Mom</td>
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<tr>
<td>V-Mom</td>
</tr>
<tr>
<td>W-Mom</td>
</tr>
<tr>
<td>P-Mass</td>
</tr>
<tr>
<td>K-TurbKE</td>
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<tr>
<td>E-Diss.K</td>
</tr>
<tr>
<td>U-Mom</td>
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<tr>
<td>V-Mom</td>
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<td>W-Mom</td>
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<td>V-Mom</td>
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<tr>
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Outer Loop Iteration = 35 CPU Seconds = 1.21E+03

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<tr>
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<td>Auto Timescale</td>
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</tr>
<tr>
<td>E-Diss.K</td>
<td>Auto Timescale</td>
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Outer Loop Iteration = 36 CPU Seconds = 1.24E+03

Timescale Information:

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<th>Max Res</th>
<th>Linear Solution</th>
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<tbody>
<tr>
<td>U-Mom</td>
<td>0.93</td>
<td>1.4E-04</td>
<td>4.7E-03</td>
<td>4.2E-02 OK</td>
</tr>
<tr>
<td>V-Mom</td>
<td>0.96</td>
<td>5.9E-05</td>
<td>1.5E-03</td>
<td>5.1E-02 OK</td>
</tr>
<tr>
<td>W-Mom</td>
<td>0.96</td>
<td>1.9E-05</td>
<td>6.2E-04</td>
<td>5.4E-02 OK</td>
</tr>
<tr>
<td>P-Mass</td>
<td>0.90</td>
<td>8.3E-06</td>
<td>5.1E-04</td>
<td>9.4 3.4E-02 OK</td>
</tr>
<tr>
<td>K-TurbKE</td>
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<td>2.3E-04</td>
<td>6.9E-03</td>
<td>5.5 4.0E-02 OK</td>
</tr>
<tr>
<td>E-Diss.K</td>
<td>0.97</td>
<td>4.0E-04</td>
<td>1.2E-02</td>
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Outer Loop Iteration = 37 CPU Seconds = 1.28E+03

Timescale Information:
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<th>Max Res</th>
<th>Linear Solution</th>
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</thead>
<tbody>
<tr>
<td>U-Mom</td>
<td>0.93</td>
<td>1.3E-04</td>
<td>3.9E-03</td>
<td>4.3E-02 OK</td>
</tr>
<tr>
<td>V-Mom</td>
<td>0.96</td>
<td>5.6E-05</td>
<td>1.5E-03</td>
<td>5.2E-02 OK</td>
</tr>
<tr>
<td>W-Mom</td>
<td>0.96</td>
<td>1.8E-05</td>
<td>5.5E-04</td>
<td>5.3E-02 OK</td>
</tr>
<tr>
<td>P-Mass</td>
<td>0.90</td>
<td>7.5E-06</td>
<td>3.9E-04</td>
<td>9.4 3.5E-02 OK</td>
</tr>
</tbody>
</table>

+-----------------------+---------+---------+---------+------------------+
| K-TurbKE  | 0.94 | 2.2E-04 | 6.6E-03 | 5.6 4.2E-02 OK |
| E-Diss.K  | 0.97 | 3.9E-04 | 1.2E-02 | 7.3 1.5E-02 OK |

+-----------------------+---------+---------+---------+------------------+

OUTER LOOP ITERATION = 38 CPU SECONDS = 1.31E+03

-----------------------------------------------

<table>
<thead>
<tr>
<th>Equation</th>
<th>Rate</th>
<th>RMS Res</th>
<th>Max Res</th>
<th>Linear Solution</th>
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</thead>
<tbody>
<tr>
<td>U-Mom</td>
<td>0.94</td>
<td>1.2E-04</td>
<td>3.2E-03</td>
<td>4.3E-02 OK</td>
</tr>
<tr>
<td>V-Mom</td>
<td>0.97</td>
<td>5.5E-05</td>
<td>1.5E-03</td>
<td>5.3E-02 OK</td>
</tr>
<tr>
<td>W-Mom</td>
<td>0.97</td>
<td>1.8E-05</td>
<td>5.0E-04</td>
<td>5.3E-02 OK</td>
</tr>
<tr>
<td>P-Mass</td>
<td>0.91</td>
<td>6.9E-06</td>
<td>2.8E-04</td>
<td>9.4 3.5E-02 OK</td>
</tr>
</tbody>
</table>

+-----------------------+---------+---------+---------+------------------+
| K-TurbKE  | 0.93 | 2.0E-04 | 6.5E-03 | 5.5 4.5E-02 OK |
| E-Diss.K  | 0.97 | 3.8E-04 | 1.1E-02 | 7.3 1.6E-02 OK |

+-----------------------+---------+---------+---------+------------------+

OUTER LOOP ITERATION = 39 CPU SECONDS = 1.35E+03

-----------------------------------------------

<table>
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</thead>
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<tr>
<td>U-Mom</td>
<td>0.95</td>
<td>1.1E-04</td>
<td>2.7E-03</td>
<td>4.4E-02 OK</td>
</tr>
<tr>
<td>V-Mom</td>
<td>0.97</td>
<td>5.3E-05</td>
<td>1.6E-03</td>
<td>5.4E-02 OK</td>
</tr>
<tr>
<td>W-Mom</td>
<td>0.97</td>
<td>1.7E-05</td>
<td>4.1E-04</td>
<td>5.2E-02 OK</td>
</tr>
<tr>
<td>P-Mass</td>
<td>0.93</td>
<td>6.4E-06</td>
<td>2.2E-04</td>
<td>9.4 3.7E-02 OK</td>
</tr>
</tbody>
</table>

+-----------------------+---------+---------+---------+------------------+
| K-TurbKE  | 0.91 | 1.9E-04 | 6.4E-03 | 5.6 4.6E-02 OK |
| E-Diss.K  | 0.96 | 3.7E-04 | 1.0E-02 | 7.3 1.6E-02 OK |

+-----------------------+---------+---------+---------+------------------+

OUTER LOOP ITERATION = 40 CPU SECONDS = 1.38E+03

-----------------------------------------------

<table>
<thead>
<tr>
<th>Equation</th>
<th>Rate</th>
<th>RMS Res</th>
<th>Max Res</th>
<th>Linear Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-Mom</td>
<td>0.96</td>
<td>1.1E-04</td>
<td>2.3E-03</td>
<td>4.4E-02 OK</td>
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<tr>
<td>V-Mom</td>
<td>0.98</td>
<td>5.2E-05</td>
<td>1.6E-03</td>
<td>5.4E-02 OK</td>
</tr>
<tr>
<td>W-Mom</td>
<td>0.98</td>
<td>1.7E-05</td>
<td>4.0E-04</td>
<td>5.3E-02 OK</td>
</tr>
<tr>
<td>P-Mass</td>
<td>0.94</td>
<td>6.0E-06</td>
<td>2.2E-04</td>
<td>9.4 3.9E-02 OK</td>
</tr>
</tbody>
</table>

+-----------------------+---------+---------+---------+------------------+
| K-TurbKE  | 0.90 | 1.7E-04 | 6.0E-03 | 5.6 4.7E-02 OK |
| E-Diss.K  | 0.95 | 3.5E-04 | 9.1E-03 | 7.3 1.6E-02 OK |

+-----------------------+---------+---------+---------+------------------+

OUTER LOOP ITERATION = 40 CPU SECONDS = 1.38E+03

-----------------------------------------------

| Timescale Information |

271
| Equation | Type | Timescale |
|----------------+------------------------+-------------------|
| U-Mom | Auto Timescale | 8.88954E-01 |
| V-Mom | Auto Timescale | 8.88954E-01 |
| W-Mom | Auto Timescale | 8.88954E-01 |
| P-Mass | Auto Timescale | 8.88954E-01 |
| K-TurbKE | Auto Timescale | 8.88954E-01 |
| E-Diss.K | Auto Timescale | 8.88954E-01 |

OUTER LOOP ITERATION = 41 CPU SECONDS = 1.42E+03

| Equation | Rate | RMS Res | Max Res | Linear Solution |
|----------------+---------+---------+---------+------------------|
| U-Mom | 0.95 | 1.0E-04 | 2.0E-03 | 4.5E-02 OK|
| V-Mom | 0.98 | 5.1E-05 | 1.5E-03 | 5.4E-02 OK|
| W-Mom | 0.98 | 1.6E-05 | 3.9E-04 | 5.3E-02 OK|
| P-Mass | 0.95 | 5.7E-06 | 2.1E-04 | 9.4 4.0E-02 OK|
| K-TurbKE | 0.90 | 1.5E-04 | 5.5E-03 | 5.6 4.7E-02 OK|
| E-Diss.K | 0.95 | 3.3E-04 | 8.3E-03 | 7.3 1.6E-02 OK|

OUTER LOOP ITERATION = 42 CPU SECONDS = 1.45E+03

CFD Solver finished: Thu Sep 15 19:07:32 2005
CFD Solver wall clock seconds: 1.5840E+03
Execution terminating:
all RMS residual AND global imbalances
are below their target criteria.

Boundary Flow and Total Source Term Summary

| Equation | Rate | RMS Res | Max Res | Linear Solution |
|----------------+---------+---------+---------+------------------|
| U-Mom | 0.96 | 9.7E-05 | 2.0E-03 | 4.5E-02 OK|
| V-Mom | 0.98 | 4.9E-05 | 1.3E-03 | 5.4E-02 OK|
| W-Mom | 0.98 | 1.6E-05 | 3.9E-04 | 5.3E-02 OK|
| P-Mass | 0.95 | 5.5E-06 | 1.9E-04 | 9.4 4.0E-02 OK|
| K-TurbKE | 0.90 | 1.3E-04 | 4.8E-03 | 5.5 4.6E-02 OK|
| E-Diss.K | 0.94 | 3.1E-04 | 7.4E-03 | 7.3 1.6E-02 OK|

CFD Solver finished: Thu Sep 15 19:07:32 2005
CFD Solver wall clock seconds: 1.5840E+03
Execution terminating:
all RMS residual AND global imbalances
are below their target criteria.
Boundary : BranchIN 1.1358E-08
Boundary : MainIN 1.4109E+00
Boundary : Outlet -1.3380E+00
Boundary : Top -2.3049E-08
Boundary : Walls -7.1313E-02
---------
Domain Imbalance : 1.5474E-03
Domain Imbalance, in %: 0.0023 %
+--------------------------------------------------------------------
+ | V-Mom |
+--------------------------------------------------------------------
+ Boundary : BranchIN -1.9476E+00
Boundary : MainIN 1.1529E-07
Boundary : Outlet 6.1528E-03
Boundary : Top -6.4655E-06
Boundary : Walls 1.9413E+00
---------
Domain Imbalance : -1.5318E-04
Domain Imbalance, in %: -0.0002 %
+--------------------------------------------------------------------
+ | W-Mom |
+--------------------------------------------------------------------
| 151 |
Boundary : BranchIN -1.3161E-05
Boundary : MainIN -3.1909E-06
Boundary : Outlet -1.9907E-03
Boundary : Top -6.8501E+01
Boundary : Walls 6.8503E+01
---------
Domain Imbalance : -3.8147E-04
Domain Imbalance, in %: -0.0006 %
+--------------------------------------------------------------------
+ | P-Mass |
+--------------------------------------------------------------------
+ Boundary : BranchIN 3.6475E+00
Boundary : MainIN 1.3299E+00
Boundary : Outlet -4.9774E+00
---------
Domain Imbalance : 3.1948E-05
Domain Imbalance, in %: 0.0006 %
=====================================================================
= Wall Force and Moment Summary
=====================================================================
Note: Pressure integrals exclude the reference pressure. To include it, set the expert parameter 'include pref in forces = t'.
+--------------------------------------------------------------------
+ | Pressure Force On Walls |
+--------------------------------------------------------------------
+ X-Comp. Y-Comp. Z-Comp.
Top 0.0000E+00 0.0000E+00 6.8492E+01
Walls -3.3728E-01 -1.8749E+00 -6.8504E+01
+--------------------------------------------------------------------
+ | Viscous Force On Walls |
+--------------------------------------------------------------------
+ X-Comp. Y-Comp. Z-Comp.
Top 2.3049E-08 6.4655E-06 8.9584E-03
Walls 4.0861E-01 -6.6440E-02 1.0195E-03

273
<table>
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<tr>
<td>X-Comp. Y-Comp. Z-Comp.</td>
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<td>X-Comp. Y-Comp. Z-Comp.</td>
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<td>Top 7.8704E-05 -1.0241E-02 5.1462E-06</td>
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<td>V-Mom</td>
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<td>W-Mom</td>
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<td>K-TurbKE</td>
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<td>V-Mom</td>
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<td>W-Mom</td>
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<td>V-Mom</td>
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<td>W-Mom</td>
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<td>P-Mass</td>
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<tr>
<td>K-TurbKE</td>
</tr>
<tr>
<td>E-Diss.K</td>
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<tr>
<td>Average Scale Information</td>
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Domain Name : Fluid
Global Length = 5.6241E-01
Minimum Extent = 8.4173E-02
Maximum Extent = 7.2290E+00
Density = 9.9700E+02

Dynamic Viscosity = 8.8990E-04
Velocity = 2.1218E-01
Advection Time = 2.6506E+00
Reynolds Number = 1.3370E+05

Variable Range Information

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<tr>
<td>Velocity v</td>
<td>-3.84E-01</td>
<td>1.33E-01</td>
</tr>
<tr>
<td>Velocity w</td>
<td>-2.73E-02</td>
<td>3.57E-02</td>
</tr>
<tr>
<td>Pressure</td>
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</tr>
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<tr>
<td>Turbulence Eddy Dissipation</td>
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CPU Requirements of Numerical Solution

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<tr>
<th>Subsystem Name</th>
<th>Discretization</th>
<th>Linear Solution</th>
<th>(secs. %total)</th>
<th>(secs. %total)</th>
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<tbody>
<tr>
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<td>7.86E+02</td>
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<td>52.8 % 11.8 %</td>
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<tr>
<td>TurbKE and Diss.K</td>
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<td>1.56E+02</td>
<td>14.8 % 10.5 %</td>
<td></td>
</tr>
<tr>
<td>Subsystem Summary</td>
<td>1.01E+03</td>
<td>3.32E+02</td>
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<tr>
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<td>2.52E+01</td>
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<td>Miscellaneous</td>
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<td>Total</td>
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Job Information

Host computer: ENG-PG4G33B
Job finished: Thu Sep 15 19:07:43 2005
Total CPU time: 1.496E+03 seconds
or: ( 0: 0: 24: 55.953 )
( Days: Hours: Minutes: Seconds )
Total wall clock time: 1.611E+03 seconds
or: ( 0: 0: 26: 51.000 )
( Days: Hours: Minutes: Seconds )
End of solution stage.
The results from this run of the CFX-5 solver have been written to d:\cfx\z-cfx\T_Junct_Q26_001.res.

This run of the CFX-5 Solver has finished.
APPENDIX 2

EXAMPLE OF PHOENICS q1 INPUT FILE

TALKT=;RUN( 1, 1)

********************************************************************************
Q1 created by VDI menu, Version 3.5, Date 08/10/02
CPVNAM=VDI;SPPNAM=Core
********************************************************************************

IRUNN = 1 ;LIBREF = 0
********************************************************************************

Group 1. Run Title
TEXT(T-junction open channel flow )
********************************************************************************

Group 2. Transience
STEADY = T
********************************************************************************

Groups 3, 4, 5  Grid Information
* Overall number of cells, RSET(M,NX,NY,NZ,tolerance)
RSET(M,116,40,15)
* Set overall domain extent:
*        xulast  yvlast  zwlast
  name
* Set overall domain extent:
*        xulast  yvlast  zwlast
  name
XSI= 1.000000E+00; YSI= 1.000000E+00; ZSI= 1.000000E+00
RSET(D,CHAM )
* Set objects: x0     y0     z0
*        dx     dy     dz
  name
XPO= 0.000000E+00; YPO= 5.000000E-01; ZPO= 0.000000E+00
XSI= 2.155172E-01; YSI= 5.000000E-01; ZSI= 1.000000E+00
RSET(B,BLOK1 )
XPO= 3.879310E-01; YPO= 5.000000E-01; ZPO= 0.000000E+00
XSI= 6.120690E-01; YSI= 5.000000E-01; ZSI= 1.000000E+00
RSET(B,BLOK2 )
XPO= 0.000000E+00; YPO= 0.000000E+00; ZPO= 0.000000E+00
XSI= 0.000000E+00; YSI= 5.000000E-01; ZSI= 1.000000E+00
RSET(B,IN1 )
XPO= 2.155172E-01; YPO= 1.000000E+00; ZPO= 0.000000E+00
XSI= 1.724138E-01; YSI= 0.000000E+00; ZSI= 1.000000E+00
RSET(B,IN2 )
XPO= 1.000000E+00; YPO= 0.000000E+00; ZPO= 0.000000E+00
XSI = 0.000000E+00; YSI = 5.000000E-01; ZSI = 1.000000E+00
RSET(B,OUT)
XPO = 0.000000E+00; YPO = 0.000000E+00; ZPO = 0.000000E+00
XSI = 1.000000E+00; YSI = 0.000000E+00; ZSI = 1.000000E+00
RSET(B,SDMS)
XPO = 0.000000E+00; YPO = 0.000000E+00; ZPO = 0.000000E+00
XSI = 1.000000E+00; YSI = 5.000000E-01; ZSI = 0.000000E+00
RSET(B,FLOR1)
XPO = 2.155172E-01; YPO = 5.000000E-01; ZPO = 0.000000E+00
XSI = 1.724138E-01; YSI = 5.000000E-01; ZSI = 0.000000E+00
RSET(B,FLOR2)
XPO = 0.000000E+00; YPO = 0.000000E+00; ZPO = 1.000000E+00
XSI = 1.000000E+00; YSI = 5.000000E-01; ZSI = 0.000000E+00
RSET(B,CEIL1)
XPO = 2.155172E-01; YPO = 5.000000E-01; ZPO = 1.000000E+00
XSI = 1.724138E-01; YSI = 5.000000E-01; ZSI = 0.000000E+00
RSET(B,CEIL2)

Group 6. Body-Fitted coordinates
BFC = T
READCO(vr-xyz)
********
NONORT = T
NOGRID = T

Group 7. Variables: STOREd, SOLVEd, NAMEd
ONEPHS = T
* Non-default variable names
NAME(146) = PRPS ; NAME(147) = ENUT
NAME(148) = WCRT ; NAME(149) = VCRT
NAME(150) = UCRT
* Solved variables list
SOLVE(P1,U1,V1,W1)
* Stored variables list
STORE(UCRT,VCRT,WCRT,ENUT,PRPS)
* Additional solver options
SOLUTN(P1,Y,Y,Y,N,N,N)
TURMOD(KEMODL)

Group 8. Terms & Devices

Group 9. Properties
SETPRPS(1, 67)
DVO1DT = 1.180000E-04
PRT(EP) = 1.314000E+00

Group 10. Inter-Phase Transfer Processes

Group 11. Initialise Var/Porosity Fields
RESTRT(ALL)
No PATCHes used for this Group

INIADD = F

Group 12. Convection and diffusion adjustments
No PATCHes used for this Group

Group 13. Boundary & Special Sources

INLET (IN1 ,WEST ,3,0,0,0,0,1,1)
VALUE (IN1 ,P1 , 1.397200E+02)
VALUE (IN1 ,U1 , 1.400000E-01)
VALUE (IN1 ,KE , 5.000000E-05)
VALUE (IN1 ,EP , 5.000000E-05)

INLET (IN2 ,NORTH ,4,0,0,0,0,0,1,1)
VALUE (IN2 ,P1 , 4.191600E+02)
VALUE (IN2 ,V1 , -4.200000E-01)
VALUE (IN2 ,KE , 5.000000E-05)
VALUE (IN2 ,EP , 5.000000E-05)

Group 14. Downstream Pressure For PARAB

Group 15. Terminate Sweeps
LSWEEP = 200
RESFAC = 1.000000E-03

Group 16. Terminate Iterations

Group 17. Relaxation
RELAX(P1 ,LINRLX, 7.000000E-01)
RELAX(U1 ,FALSDT, 9.421183E-01)
RELAX(V1 ,FALSDT, 9.421183E-01)
RELAX(W1 ,FALSDT, 9.421183E-01)
RELAX(KE ,FALSDT, 4.710591E-01)
RELAX(EP ,FALSDT, 4.710591E-01)

Group 18. Limits
VARMAX(U1 ) = 1.000000E+06 ;VARMIN(U1 ) =-1.000000E+06
VARMAX(V1 ) = 1.000000E+06 ;VARMIN(V1 ) =-1.000000E+06
VARMAX(W1 ) = 1.000000E+06 ;VARMIN(W1 ) =-1.000000E+06

Group 19. EARTH Calls To GROUND Station
USEGRD = T ;USEGRX = T
GENK = T
Group 20. Preliminary Printout
ECHOO = T

************************************************************
Group 21. Print-out of Variables
OUTPUT(P1 ,N,Y,Y,Y,Y,Y)
OUTPUT(U1 ,N,Y,Y,Y,Y,Y)
OUTPUT(V1 ,N,Y,Y,Y,Y,Y)
OUTPUT(W1 ,N,Y,Y,Y,Y,Y)
OUTPUT(KE ,N,Y,Y,Y,Y,Y)
OUTPUT(EP ,N,Y,Y,Y,Y,Y)
************************************************************
Group 22. Monitor Print-Out
IXMON = 65 ;IYMON = 5 ;IZMON = 10
NPRMON = 100000
NPRMNT = 1
TSTSWP = 12345
************************************************************
Group 23.Field Print-Out & Plot Control
NPRINT = 100000
ISWPRF = 1 ;ISWPRL = 100000
No PATCHes used for this Group
************************************************************
Group 24. Dumps For Restarts
GVIEW(P,5.773503E-01,5.773503E-01,5.773503E-01)
GVIEW(UP,-4.082483E-01,8.164966E-01,-4.082483E-01)
> DOM, SIZE, 1.160000E+02, 4.000000E+01, 1.500000E+01
> DOM, MONIT, 6.500000E+01, 5.000000E+00, 1.000000E+01
> DOM, SCALE, 1.000000E+00, 1.000000E+00, 1.000000E+00
> DOM, SNAPSIZE, 1.000000E-02
> OBJ, NAME, BLOK1
> OBJ, POSITION, 0.000000E+00, 2.000000E+01, 0.000000E+00
> OBJ, SIZE, 2.500000E+01, 2.000000E+01, 1.500000E+01
> OBJ, CLIPART, BLOK1
> OBJ, TYPE, BLOCKAGE
> OBJ, MATERIAL, 198

> OBJ, NAME, BLOK2
> OBJ, POSITION, 4.500000E+01, 2.000000E+01, 0.000000E+00
> OBJ, SIZE, 7.100000E+01, 2.000000E+01, 1.500000E+01
> OBJ, CLIPART, BLOK2
> OBJ, TYPE, BLOCKAGE
> OBJ, MATERIAL, 198

> OBJ, NAME, IN1
> OBJ, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ, SIZE, 0.000000E+00, 2.000000E+01, 1.500000E+01
> OBJ, CLIPART, IN1

280
> OBJ, TYPE, USER_DEFINED

> OBJ, NAME, IN2
> OBJ, POSITION, 2.500000E+01, 4.000000E+01, 0.000000E+00
> OBJ, SIZE, 2.000000E+01, 0.000000E+00, 1.500000E+01
> OBJ, CLIPART, IN2
> OBJ, TYPE, USER_DEFINED

> OBJ, NAME, OUT
> OBJ, POSITION, 1.160000E+02, 0.000000E+00, 0.000000E+00
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> OBJ, CLIPART, OUT
> OBJ, TYPE, OUTLET
> OBJ, PRESSURE, 0.000000E+00
> OBJ, TEMPERATURE, -1.026000E+04
> OBJ, COEFFICIENT, 1.000000E+03
> OBJ, TURBULENCE, -1.026000E+04,-1.026000E+04

> OBJ, NAME, SIDMS
> OBJ, POSITION, 0.000000E+00, 0.000000E+00, 0.000000E+00
> OBJ, SIZE, 1.160000E+02, 0.000000E+00, 1.500000E+01
> OBJ, CLIPART, SIDMS
> OBJ, TYPE, PLATE

> OBJ, NAME, FLOR1
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> OBJ, SIZE, 1.160000E+02, 2.000000E+01, 0.000000E+00
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> OBJ, TYPE, PLATE

> OBJ, NAME, FLOR2
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> OBJ, TYPE, PLATE

> OBJ, NAME, CEIL1
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> OBJ, CLIPART, CEIL1
> OBJ, TYPE, PLATE

> OBJ, NAME, CEIL2
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> OBJ, SIZE, 2.000000E+01, 2.000000E+01, 0.000000E+00
> OBJ, CLIPART, CEIL2
> OBJ, TYPE, PLATE
STOP
APPENDIX 3

EXAMPLE OF PHOENICS GXMONI (OUTPUT FILE) FILE

T-junction open channel flow

**Spot Values at (65, 5, 10)**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Max</th>
<th>% Error</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>1.0E+01</td>
<td>6.0E-03</td>
<td>-1.24E-04</td>
</tr>
<tr>
<td>U1</td>
<td>1.0E+05</td>
<td>2.11E-00</td>
<td>-2.60E-02</td>
</tr>
<tr>
<td>V1</td>
<td>1.0E+04</td>
<td>2.59E+00</td>
<td>-4.75E-02</td>
</tr>
<tr>
<td>W1</td>
<td>1.0E+05</td>
<td>4.66E+01</td>
<td>-1.09E+00</td>
</tr>
<tr>
<td>KE</td>
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<td>-1.00E-01</td>
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<td>EP</td>
<td>1.0E+05</td>
<td>2.41E+01</td>
<td>-1.54E-01</td>
</tr>
</tbody>
</table>

**Min** | **Max** | **Spot Value** | **Change**

-3.00E+01 | -2.00E+01 | -2.79E+01 | -9.77E-04
9.00E-01  | 1.00E+00  | 9.53E-01  | -1.19E-07
-2.00E-02 | -1.00E-02 | -1.65E-02 | -6.15E-08
1.00E-02  | 2.00E-02  | 1.34E-02  | -1.86E-09
1.00E-04  | 2.00E-04  | 1.45E-04  | 0.00E+00
4.00E-05  | 5.00E-05  | 4.82E-05  | 0.00E+00

**NX NY NZ ISWEEP 500 TIME**

116 40 15 IZSTED OFF Working

Press a character key to interrupt.
APPENDIX 4

EXAMPLE OF A LAB-VIEW data saving file

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<th>Time</th>
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Point A

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Point D

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<td>xstarₜ₋₁·₅</td>
<td>Date 23/02/2007</td>
</tr>
<tr>
<td>NTU 10</td>
<td>000 Downstream water height 74mm_with wier</td>
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