Flow structures in dividing open channels: a review

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Abstract. The supply of water for human consumption starts with the abstraction of ‘raw’ water from various sources. Most of these facilities convey raw water by pumping it directly from rivers via lateral channels to nearby water treatment plants, but this is badly affected by debris and sediment clogging at the intake structures. Lateral intakes are actually special cases of river bifurcations, where the channel naturally divides into two different branches, each carrying part of the flow and sediment. Many researchers have completed studies on bifurcations/diversions to understand the behaviour of water flow and sediment transport. However, a complete understanding of the phenomenon, especially in relation to secondary flows and vortices, is lacking up to this day. In fact, if this can be overcome, it will greatly contribute to the fundamental study of hydrodynamics at asymmetric fluvial bifurcations as well as in optimal design of diversions. Thus, the distribution of water flow in both main and lateral channels requires further detailed investigation. A review of the current state of research is discussed in this paper, with the objective of identifying the grey areas and gaps specifically in the investigation of complex turbulent behaviour of flow structures in open channels with lateral diversions.

Keywords: Open-channels, bifurcations, diversions, lateral intakes, hydrodynamics, turbulence.

1. Introduction

The hydrodynamic behaviour and sediment transport processes that occur when water flows in divided open-channel systems have been investigated since the early part of the last century. This was mainly triggered by the problems faced by engineers in confronting fluvial rivers, especially at bifurcations, as well as in constructing flow diversions, junctions and intake structures. In most cases, when the flows become very turbulent and distorted resulting from such channel division, secondary circulatory patterns emerged that affected the behaviour of sediments being transported. The efficient conveyance of particles was impeded as they could be easily eroded and deposited at several locations within the bifurcated/diverted region.

Bifurcations in fluvial rivers are natural divisions in the flow and sediment transport to two distinct channels that occur due to morphological processes. A diversion is a particular case of an asymmetric bifurcation where one channel remains on the original course; this is almost always manmade for several applications, as water supply, irrigation, and recently, reclamation of deltas [1]. In Figure 1, the West Bay engineered diversion channel off the Mississippi River is illustrative of an engineered
asymmetric bifurcation. The distribution of water and sediments, denoted by Q and S respectively, were often thought as being equal.

![Figure 1. Mississippi River (Q, S), its West Bay diversion (Q_{side}, S_{side}) and downstream reach (Q_{main}, S_{main}) [1]](image)

Traditionally, a major requirement for diverting flows from natural rivers is the provision of side or lateral intakes for raw water abstraction in irrigation and potable supply. This is typified in Figure 2, depicting the intake structure of a water supply facility on the Ohio River [2].

![Figure 2. Water Supply Intake Adjoining Ohio River [2]](image)

Other types of open channel flow division are junctions [3, 4], lateral cavities [5], and side embayments [6]. River groynes and super dykes can also be considered in this respect, as the structures deflect and divert the main channel flow into cavities/embayments.

2. Issues
Fluvial rivers transport both water and sediments, which are subject to separation and redistribution upon channel division in bifurcations and diversions. As denoted in Figure 1, Q and S in the main and side channels were often thought as being equal – however, investigations in the early part of the last
century repudiated this view [1]. Research findings indicate that the bed-load sediments are more inclined to flow into the lateral channel, even in conditions where the contrary is displayed by the distribution of water. This phenomenon can be both detrimental and desirable – the former with resulting sedimentation in diverted channels [7], and recent developments in reclaiming deltas adversely affected by sea-level rise for the latter [8, 9].

The problem of sediments entering and choking up intake facilities for water supply exists since the early 1900s until now. Upon entering the lateral channel, flow velocities decrease significantly to trigger sedimentation that reduces the effective conveyance for water abstraction [10]. Such a condition has also been affecting power plants and associated machinery as well as irrigation for essential agricultural schemes [11].

In Figure 2, deposited sediments can be seen forming a sandbar at the intake forebay/channel of a facility in the Ohio River [2]. In addition, a significant amount of material is transported into lateral channel, thus adversely affecting plant performance.

3. Investigations and Solutions
The underlying phenomenon in divided open channel flow is the Bulle Effect, ‘discovered’ by H. Bulle from lab experiments conducted in 1926 [1]. In brief, the results from the setup shown in Figure 3 indicated that the bed-load sediments are more inclined to flow into the lateral channel, even in conditions where the contrary is displayed by the distribution of water (Figure 4).

![Figure 3. Schematic setup of the experiments by Bulle [1]](image)

Dutta [1] asserts that the fundamental mechanism causing the Bulle Effect is not well comprehended. In fact, if this can be overcome, it “will not only assist optimal design of diversions, it will also help in the fundamental understanding of the dynamics at asymmetric fluvial bifurcations”. Thus, his PhD thesis addresses the Bulle Effect and related phenomena, such as secondary flows and vorticity-driven sediment transport.

In a recent study on flow typology (types) in bifurcations, the primary issue of past research has been to quantify the delivery of upstream (incoming) discharges into downstream (outgoing) channels [12]. In addition, there is also a need to recognize behaviour of the detailed flow structures within such intersections or junctions. The main reference is the work initiated by Vincent S. Neary in his 1992 MSc study, “Flow Structure at an Open Channel Diversion”, at the University of Iowa.
Figure 4. Percentage of solid (S) and liquid (Q) discharges in the main (Q_{main}, S_{main}) and diverted (Q_{side}, S_{side}) channels, reproduced from the experiments by Bulle (a) 30-degree diversion, (b) different angles of diversion [1]

Based on experimental results, Neary & Osgaard [13] concluded that diversion flow is distinctly three-dimensional and more readily diverted on channel bed/bottom. In addition, a disproportionate amount of bed sediments would enter diversion as compared to main channel. Such complex three-dimensional (3D) flow separation and patterns were also obtained from numerical solutions for steady, laminar [14] and turbulent [2] conditions in rectangular open-channel T-junctions. It is noted here, in that as discerned from Figure 5, the “closed semi-elliptic region developing along the upstream wall of the lateral branch” is inferred to be 2-dimensional.

Figure 5. 3D flow patterns in a lateral intake [2]

In the computational modelling work of Li & Zeng [15], a “recirculation bubble” (with at least one eddy) emerged downstream of the ninety-degree flow junction after flow was directed into lateral channel: The discharge ratio \( Q_b/Q_u \) (main to branch) seems to affect the size of this bubble.
From studies with sediments on mobile beds, the locations of secondary flows in both main channel and branch were apparently determined by scouring and sedimentation patterns [16]. Nevertheless, the “numerical results confirm the flow patterns described in the experimental analysis [2], and are compared with the results in Bulle’s or Barkdoll’s studies [17].” 3D computational models were considerably better than 2D in simulating the complex flow structures observed in experiments.

Some recent investigations, especially by Momplot et al. [12], separate the flow behaviour in a diversion channel into 2D closed and 3D helix-shaped recirculation patterns that are distinct from each other. Experimental tests and computational simulations indicate that these are dependent on and can be estimated by Froude number and the upstream or main channel aspect (flow depth to width) ratio.

4. Critical Review

Based on critical review of literature, the Bulle Effect is still being researched since its advent in 1926. Even the complex 3D flow patterns and hydrodynamics alone (without considering sediments) in the branch or lateral channel are yet to be fully understood, most likely due to the physical limitations of traditional laboratory experiments. With technological advancement in recent decades, the usage of computer models, especially in computational fluid dynamics (CFD) of late, has provided an opportunity for more detailed numerical investigation of the phenomenon in bifurcating open channel flows.

The work of Dutta [1] is excellent as it explored the wide range of CFD techniques presently available in simulating turbulent flows based on the Navier-Stokes equation. It also included a good start to the modelling of sediments with Lagrangian tracking of particles, and successfully conducted high-resolution numerical simulations for model configurations similar to the experiments by Bulle. This came with a steep price in utilizing super-computing facilities to execute Direct Numerical Simulations (DNS) and high-resolution Large Eddy Simulations (LES) runs. The key finding is that the relatively less ‘demanding’ Reynolds Averaged Navier-Stokes (RANS)-based numerical models are valid, with further improvement, for simulating flows in bifurcations or diversions.

In specific reference to the Bulle Effect, Momplot et al. [12] addresses the boundary of flow structures between 2D closed and 3D helix-shaped recirculation patterns – the only study thus far to recognize existence of the latter. It is also part of a body work initiated about ten years ago by Rivière et al. [18], and as such utilizes the same experimental setup (with suitable flow aspect ratios) and empirical closure for discharge ratio for dividing flows of equal widths. A total of 16 CFD model (RANS solution in ANSYS Fluent) runs were successfully implemented, validated by a set of experimental results, resulting in Figure 6 and the embedded equation. It is then logical to continue such research by tackling one of the identified gaps, as the effect of varying both channel widths in defining and deriving flow typology.

5. Further Work

As such, research activities are presently conducted at the Department of Civil Engineering, International Islamic University Malaysia (IIUM) to further investigate 3D flow structures in open-channel diversions. These are summarized below:

- Further examination and characterization of the boundary of flow structures between 2D closed and 3D helix-shaped recirculation patterns in an open channel with side/lateral diversion, based on the work of Momplot et al. [12], and
- Determining the effect of varying lateral widths on turbulent structures, in terms of water flow distribution, Froude number, and width ratios, as well as the Bulle Effect.
Figure 6. Flow typology for the recirculation zone in the lateral branch; the dashed line represents the estimated boundary between a closed recirculation in lateral branch and a helix-shaped one under the present hypotheses [12]

The research questions to be addressed in this work are:
• Variation of discharge ratios, $Q_{\text{diverted}}:Q_{\text{main}}$, with $90^\circ$ lateral channel width (branch to main) ratios.
• Relationship of flow typology, as the boundary between two circulation types in $90^\circ$ lateral channels of varying widths, with the three parameters of Froude number, and aspect and width ratios.

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