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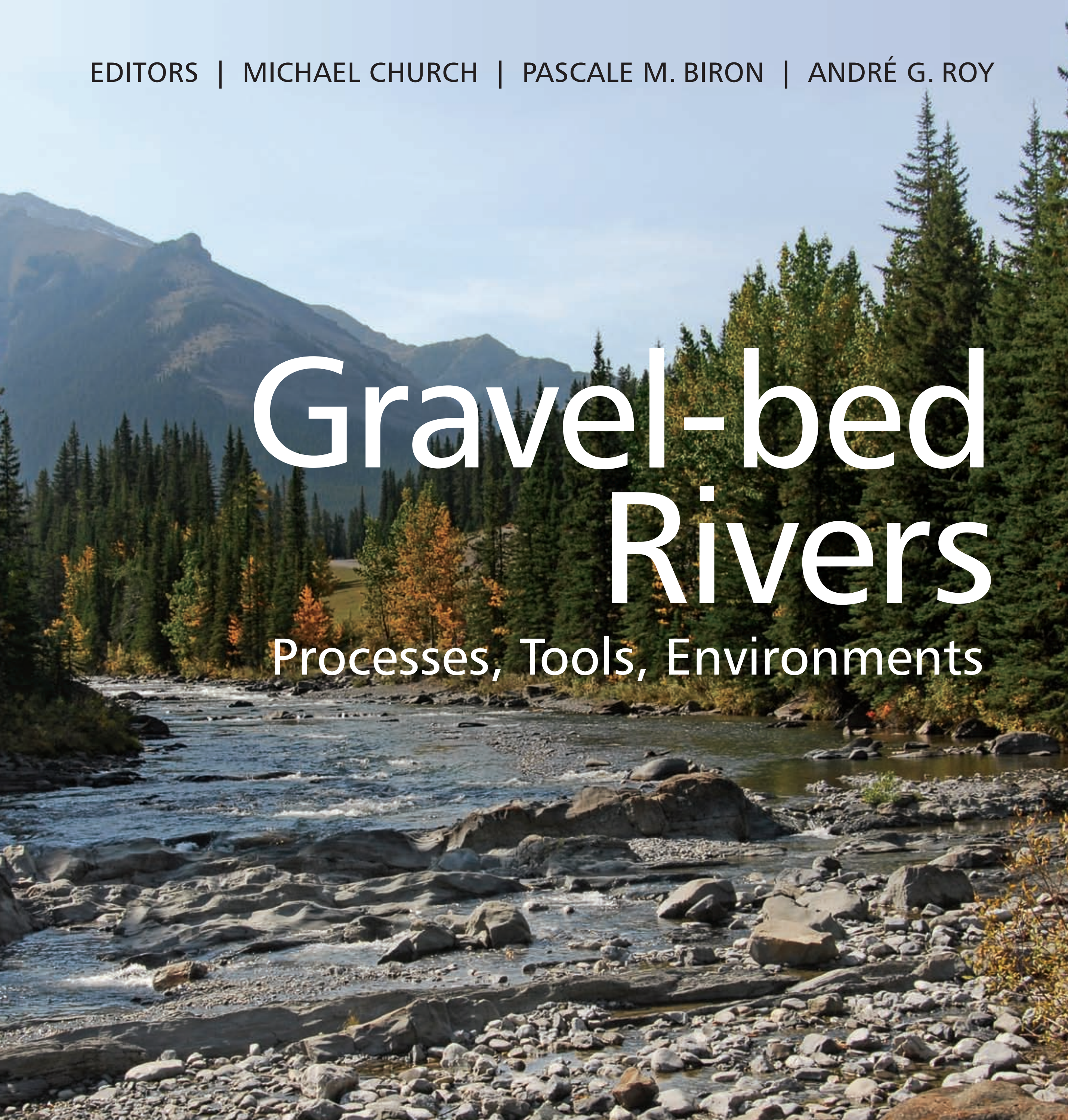

Gravel-bed Rivers

Processes, Tools, Environments

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Gravel-bed rivers

GRAVEL-BED RIVERS: PROCESSES, TOOLS, ENVIRONMENTS

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Preface

The 7th International Gravel Bed Rivers Workshop was held in Canada at Tadoussac, Québec, between 6 and 10 September, 2010. Tadoussac, located on the north shore of the St Lawrence River at the mouth of the Saguenay Fjord, is the oldest settlement in British North America to have been continually occupied by European settlers and their descendents, dating from the establishment of a fur trading station by French colonists in 1600 (the site of a Basque whaling station, intermittently occupied in the late 16th century, is located immediately to the east of Tadoussac). It is still a relatively quiet village and so well fits the tradition of the Gravel Bed Rivers workshops to seek meeting places that permit concentrated discussion, some relaxation, and good meals.

In further keeping with that tradition, the workshop was designed to present an authoritative review of recent progress in understanding the morphology and processes in gravel bed rivers, a review that you have in your hands. Accordingly, the workshop was constructed around a series of invited keynote presentations that reviewed the principal themes selected for the meeting. The format of the workshop was, however, varied from that of past meetings to the extent that formal discussion papers were invited to accompany each keynote paper, the authors of which were the referees of the keynote paper to which they were invited to respond. Those discussions appear in the book as regular chapters.

The themes of the conference, reflected in the title of the book, were processes, tools, and environments. Processes, to provide for reviews of progress in fundamental understanding of gravel bed rivers; tools, to emphasize the important advances of recent years in observing and measuring instruments and methods – particularly advances in remote-sensing methods; environments, to emphasize the diverse conditions that give rise to rivers flowing over coarse-grained materials.

We have, however, introduced some new themes into this conference, in part in recognition of the meeting in Canada, a cold, northern country with abundant rock and fast-flowing rivers, and in part to address emerging topics of high interest. There was a session on ice in gravel bed rivers. Recognizing the importance of hydroelectric power in Canada, a keynote paper specifically considered dams on gravel bed rivers within the larger context of river channel regulation and restoration. In a session on riverine ecology, rivers as the environment for salmonid fishes – a major Canadian resource – was emphasized. Semi-alluvial channels, ones flowing partly on rock, were for the first time considered in a keynote session. At a more fundamental level, the opening theme session was dedicated to secondary flows, an important mediator of river morphology that has not previously been emphasized in the workshops (nor, indeed, sufficiently considered in the discipline). Numerical modelling of gravel bed river morphodynamics, a rapidly advancing art, was featured in another session. River channel change over extended periods was also given theme attention. Sessions on steep channels and on sediment transport – perhaps the most fundamental theme of all – rounded out the meeting.

Our traditional "practical" exercise was also different at this meeting. Always devoted to field work in the past, we felt a bit overwhelmed at the scale of Canadian rivers as a site for a part-day excursion (the St Lawrence opposite Tadoussac is actually a part of an inland sea that occupies a tectonic basin – not gumboot and measuring tape territory). Therefore, we remained in our comfortable hotel and conducted a workshop facilitated by Normand Bergeron and Joanna Eyquem on ecosystem services provided by gravel bed rivers. Again, a new topic for the workshops, but an important and timely one, reported as a full chapter in this volume.

In addition to the keynote and formal discussion papers presented in this book, the meeting attracted 75 poster presentations, many of them by the graduate student contingent, as usual a highly motivated and enthusiastic group. A selection of those posters has become a formal collection presented in a special edition of *Earth Surface Processes and Landforms*, edited by Peter Ashmore and Colin Rennie.

The meeting, as usual, featured field trips before and after the meeting. Thomas Buffin-Bélanger and André Roy conducted a three-day excursion before the meeting that commenced at Rimouski, on the south shore of the St Lawrence and spent two days investigating the rivers of the Gaspésie region – steep, gravel bed rivers significantly influenced by seasonal ice and subjected to a recent history of intensive log-drives to sawmills at the river mouths. On Saturday evening we made the 62 km crossing of the Gulf of St Lawrence between Matane, in Gaspésie, and Baie-Comeau on the north shore, where hydropower rivers were investigated on the third day. After the conference, Normand Bergeron and Michel Lapointe led a trip from Tadoussac to Québec City that examined river habitat in gravel bed salmon rivers, intensively investigated in recent years by members of the Centre Interuniversitaire de Recherche sur le Saumon Atlantique (CIRSA).

There are many people to thank for the success of the meeting. First, our sponsors, Hydro-Québec and Parish Geomorphic; GEOIDE, the Canadian Research Network of Excellence in Geomatics; Boréas, groupe de recherche sur les environnements nordiques; la Chaire de recherche du Canada en dynamique fluviale; Concordia University; l'Institut National de la Recherche Scientifique: Eau, Terre et Environnement (INRS-ETE); McGill University; The University of British Columbia; l'Université de Montréal; The University of Ottawa; l'Université du Québec à Rimouski (UQAR); The University of Western Ontario. Thanks to Laurence Therrien and Hélène Lamarre who greatly helped with the organization and management of the conference, Linda Lamarre who gave organizational and financial advice, the staff of the Tadoussac Hotel, especially Véronique Gaudreault, who delivered highly professional support through all stages of preparing and conducting the meeting. Maxime Boivin, Laurence Chaput-Desrosiers, Sylvio Demers, Geneviève Marquis, Taylor Olsen, and Michèle Tremblay prepared and helped to conduct the field trips and managed the poster sessions. Eric Leinberger, cartographer at the University of British Columbia Department of Geography, made heroic efforts to standardize the presentation of the figures in the book. Finally, the staff at John Wiley & Sons, especially Rachael Ballard and Fiona Woods have been wonderfully helpful in bringing to publication this most important aspect of the meeting – the permanent record. Finally, we must thank our four editorial associates, who have done so much to ensure the timely production of the book.

Thanks also to Professor Rob Ferguson, who entertained the meeting as its featured banquet speaker with the unofficial and nearly entirely correct history of GBR.

We trust that this book, like its predecessors, will become part of the authoritative record of advances in knowledge and understanding of gravel bed rivers. And we wish the hosts of the next meeting, GBR8, to be held in Japan, as much success as we have enjoyed.

Mike Church

Secondary Flows in Rivers

1

Secondary Flows in Rivers: Theoretical Framework, Recent Advances, and Current Challenges

Vladimir Nikora and André G. Roy

1.1 INTRODUCTION

Water currents in rivers have fascinated and inspired researchers (and artists) for centuries, as reflected in numerous observations and paintings from ancient times (e.g., Rouse and Ince, 1963; Levi, 1995). Leonardo da Vinci's famous drawings are probably the most impressive and insightful examples of such observations. In his sketches and notes he highlighted a number of features of river flows whose signatures could be clearly observed at the water surface, especially behind obstacles and at stream confluences (Figure 1.1). 'Spiral' currents are particularly profound among these features and represent a key facet of nearly all of his water drawings. Using an analogy with curling hair, Leonardo summarized his observations as "Observe the motion of the surface of the water, how it resembles that of hair, which has two motions – one depends on the weight of the hair, the other on the direction of the curls; thus the water forms whirling eddies, one part following the impetus of the chief current, and the other following the incidental motion and return flow" (his written comment in Figure 1.1). It is fascinating how this description, given 500 years ago, is similar to a modern view of the mean flow structure as a superposition of the primary flow and the orthogonal secondary flows. Alternatively, Leonardo's comment may also be interpreted as the Reynolds decomposition of the instantaneous velocity into mean (i.e., time-averaged) and fluctuating turbulent components (Tsinober, 2009), although the first interpretation seems better justified.

Leonardo's astute comment on secondary flows was made well ahead of his time and it is nearly 400 years later that this phenomenon has been re-discovered by engineers and scientists working in hydraulics and theoretical fluid mechanics (e.g., Thomson, 1876; Francis, 1878; Wood, 1879;Cunningham, 1883; Stearns, 1883; Leliavski, 1894; Gibson, 1909; Joukowski, 1915). Their studies set up a background for the first fluid mechanical classification of the secondary flows proposed by Prandtl (1926). He suggested that "The phenomenon may be regarded as a combination of the main flow with a 'secondary flow' at right angles to it ..." and that this phenomenon combines two wide classes. The first class, known as Prandtl's secondary currents of the first kind, combines flow motions with streamwise mean (i.e., time-averaged) vorticity enhanced through vortex stretching. Secondary currents observed in curved pipe and river bends or meanders are typical examples provided by Prandtl to illustrate this type of secondary flow. Prandtl goes even further and proposes that the effect of secondary flows on sediment dynamics explains why "where they can, rivers always follow a winding course ('meandering')" (Prandtl, 1952, p. 147). The second class, often defined as Prandtl's secondary currents of the second kind, relates to secondary flows formed as a result of turbulence heterogeneity. These flows are often defined as turbulence-driven secondary currents and no channel curvature is required to generate them. Using rivers again as an example, Prandtl notes that "we may also mention the fact that small objects floating in rivers tend to move to the middle, which is explained by the existence of a surface current from the banks to the middle" (Prandtl, 1952, p. 148).

Typically, turbulence-generated longitudinal vorticity is much weaker than that in curved channels. However, even this seemingly mild three-dimensionality may introduce significant changes in the turbulence structure and should not be neglected. For instance, it is a common

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Figure 1.1 Leonardo da Vinci's Old Man with Water Studies (*c*. 1508–1509). Windsor, Royal Library, #12579.

claim in the experimental literature that the effects of the secondary flow on turbulence structure at the channel centreline are negligible, even in narrow channels. As a result, an assumption of a 2-D flow is often accepted based on the symmetry argument. This assumption ignores the cross-flow gradients of transverse velocities and turbulence parameters that may be (and often are) non-zero even at the channel centerline. Prandtl's secondary currents of the second kind typically occur at channel corners or at transverse bed roughness transitions. Recently, it has also been shown that this kind of secondary current may be formed in buoyancy-driven flows even in straight circular pipes (Hallez and Magnaudet, 2009), where normally this feature does not exist.

While turbulence acts to dissipate the secondary currents of the first kind, it represents a generating mechanism for the second kind of secondary currents. As a consequence, Prandtl's secondary currents of the second king are impossible in laminar flows, while Prandtl's first kind of secondary currents can be observed in both laminar and turbulent flows. Introduced rather intuitively, Prandtl's mechanism-based classification has survived extensive theoretical developments and is currently widely accepted as a starting point in considerations of secondary flows.

Prandtl's classification may additionally be supplemented with a topological classification that distinguishes two types of secondary flows: (1) non-helical cross-flows, and (2) helical flows (Bradshaw, 1987). Combining Prandtl's and Bradshaw's classifications, it is possible to distinguish at least four types of secondary currents: (i) Prandtl's first kind of cross-flow (non-helical); (ii) Prandtl's second kind of cross-flow (non-helical); (iii) Prandtl's first kind of helical flow; and (iv) Prandtl's second kind of helical flow. It is likely that in real river configurations all four types of secondary flow may be observed, either superimposed or separated in space and/or in time (e.g., topology and mechanisms of secondary currents at low flow may differ from those at flood stage; see Rhoads and Kenworthy, 1998). In some cases, one of these types may dominate the flow topology (e.g., Prandtl's first kind of helical flow may be dominant in some meandering rivers), while in other cases all four types can be equally significant (e.g., in braided rivers).

Although the great significance of secondary flows for river processes has long been recognised, their origin, mechanics, effects, and inter-relations with the primary mean flow and turbulence are still a matter of debate and continue to attract close attention from hydrologists, geomorphologists, engineers, and, recently, stream ecologists. It is not surprising therefore that the literature related to secondary flows in open channels is extensive (Scopus shows over 600 journal papers since 1990) and includes frequently appearing reviews reflecting the progress and highlighting unsolved issues.

Prandtl's secondary currents of the first kind, particularly related to meandering rivers, have been extensively discussed in Ikeda and Parker (1989), Rhoads and

Welford (1991), Blanckaert and de Vriend (2004), Seminara (2006, 2010), Camporeale *et al*. (2007), Abad and Garcia (2009a, 2009b), Ikeda and McEwan (2009), and Gyr (2010), among others. In terms of mechanical engineering applications, a comprehensive review of this class of secondary flows has been given by Bradshaw 1987, covering 3-D boundary layers, vortex flows, and jets in cross-flows. Prandtl's secondary currents of the second kind have also attracted significant attention and their discussion has been even more controversial than that of secondary currents of the first kind. Bradshaw's (1987) popular review only slightly touched on this topic (mainly for 3-D free jets and wall jets), probably because a comprehensive treatment of duct flows had already been given in the review by Demuren and Rodi (1984). In relation to open-channel flows, Nezu and Nakagawa's (1993) review of the turbulence-driven secondary currents is still the most comprehensive source, and a recent update of this excellent review is available (Nezu, 2005). There are also a number of in-depth papers reviewing complex flow patterns at river confluences where both kinds of Prandtl's secondary flows are present and are interlinked in a multifaceted way (e.g., Rhoads and Kenworthy, 1998; Bradbrook *et al*., 2000, 2001; Lane *et al*., 2000; Rhoads and Sukhodolov, 2001; Sukhodolov and Rhoads, 2001; Szupiany *et al*., 2009). The wide-ranging set of papers on this topic is also recorded in Rice *et al*. (2008), where extensive references and a thorough assessment of current and future research directions can be found.

The rapid development of measurement and numerical capabilities in recent years has brought new significant results and the authors feel that it may be useful to highlight recent progress in understanding secondary flows, as well as to identify research challenges and opportunities in studying this phenomenon, while keeping overlap with the previous reviews to the minimum. In particular, the focus of this chapter is on: (i) theoretical frameworks for studying secondary flows, (ii) interrelations between turbulence and secondary flows, and (iii) secondary flow effects on hydraulic resistance, sediment dynamics, and mixing. Examples from gravel-bed rivers will be presented. In addition to open-channel flows, some results related to conduits/ducts will also be considered as they are directly relevant to flows in ice-covered rivers (Ettema and Zabilansky, 2004; Buffin-Bélanger *et al*., 2009).

1.2 THEORETICAL FRAMEWORK

Most theoretical and conceptual approaches in studying secondary flows in ducts and open channels have been based on: (i) the time-(ensemble)-averaged momentum equation, (ii) the energy balance equation for the mean flow, (iii) the energy balance equation for turbulence, and (iv) the mean (i.e., time-averaged) vorticity equation. These equations stem from the Navier–Stokes (momentum) equation for instantaneous velocities and pressure, representing its different forms and, thus, essentially containing the same information. However, in various equations this information is presented differently, highlighting particular facets of secondary flows. Most theoretical and experimental studies have been based on one or another equation, rarely involving joint consideration of two or more equations, thus reflecting authors' preferences, specific research questions, and/or data availability. Such a narrowly focused approach could be a reason for discrepancies in the identification and interpretation of the physical mechanisms creating and maintaining secondary flows in straight and curved channels (an example is given in Section 1.2.2). It is therefore instructive to provide a comparative overview of these equations, as well as to highlight other forms of the Navier–Stokes equations which could provide additional insight into the mechanics of secondary flows. In this review, we use Cartesian coordinates, although curvilinear coordinates (cylindrical or natural) have also been extensively used, especially in dealing with curved channels. For our purpose, however, Cartesian coordinates should be sufficient. Equations in the following sections are written using the Cartesian index notation, where $i=1$ is for x and velocity component u (along the flow), $i=2$ is for y and velocity component v (across the flow), and $i=3$ is for z and velocity component w (orthogonal to the bed into the fluid). The repeated indices (known as dummy indices) mean summation.

1.2.1 Reynolds-Averaged Navier–Stokes (RANS) Equation

The time-(ensemble) averaged momentum equation, widely known as the Reynolds-Averaged Navier–Stokes (RANS) equation or just the Reynolds equation, is a logical starting point in the analysis of secondary flows and also a suitable platform to define them. For the benefit of readers who are not closely familiar with this topic, this equation is given below:

$$\underbrace{\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j}}_{\substack{\text{local} \\ \text{convective} \\ \text{accelerations}}} = \underbrace{g_i}_{\substack{\text{gravity} \\ \text{force}}} - \underbrace{\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i}}_{\substack{\text{pressure} \\ \text{force}}} - \underbrace{\frac{\partial \overline{u_i' u_j'}}{\partial x_j}}_{\substack{\text{"turbulent"} \\ \text{force}}} + \underbrace{\frac{\partial}{\partial x_j}\left(\nu \frac{\partial \bar{u}_i}{\partial x_j}\right)}_{\substack{\text{viscous} \\ \text{shear} \\ \text{force}}} \quad (1.1)$$

where p is pressure, ρ is water density, ν is viscosity, overbar denotes time-(ensemble)- averaging and prime denotes deviations of an instantaneous value of f from its mean value in the Reynolds decomposition, i.e., $f = \bar{f} + f'$.

For straight, steady uniform *2-D* open-channel flow, the conditions $\bar{u}_2 = \bar{u}_3 = \overline{u'_1u'_2} = \overline{u'_2u'_3} = 0$ apply and all derivatives in Equation (1.1) along and across the flow are equal to zero. In this case, the flow is defined by the longitudinal velocity $\bar{u}_1$ and vertical momentum flux towards the bed $\tau/\rho = -\overline{u'_1u'_3} + \nu\partial\bar{u}_1/\partial x_3 \approx -\overline{u'_1u'_3}$, while the vertical distribution of pressure may often be assumed to be hydrostatic (i.e., $g(H-z) >> [\overline{u'_3u'_3}(z_{ws}) - \overline{u'_3u'_3}(z)]$, where z_{ws} is the water surface elevation, H is water depth, and S is bed slope). The velocity component $\bar{u}_1$ defines the overall mass flux through the channel cross-section and therefore is often called the primary flow velocity, with $\tau/\rho = -\overline{u'_1u'_3}$ known as the primary Reynolds or turbulent stress. For a more general case of straight, steady uniform *3-D* open-channel flow, we have $\bar{u}_2$, $\bar{u}_3$, $\overline{u'_1u'_2}$, $\overline{u'_2u'_3} \neq 0$ in Equation (1.1), with the overall mass flux being still represented by the primary velocity $\bar{u}_1$ as the cross-sectionally averaged $\bar{u}_2$ and $\bar{u}_3$ are zero (i.e., there is no overall mass flux across the flow or in the vertical direction). For such an idealised 3-D mean open-channel flow, the velocity components $\bar{u}_2$ and $\bar{u}_3$ describe the helical water motions orthogonal to the primary flow and thus are often defined as helical secondary flow(s). For more complex flows in curved channels with irregular banks, the decomposition of the time-averaged water motion into primary flow and helical secondary flow(s) may not be as simple, since $\bar{u}_2$ and $\bar{u}_3$ can also include contributions from a variety of cross-flows which are not necessarily helical. This issue in relation to secondary flows at river confluences has been comprehensively discussed in Rhoads and Kenworthy (1998, 1999) and Lane *et al.* (1999, 2000), with practical field examples in Parsons *et al.* (2007) and Szupiany *et al.* (2009), among others..

The simplified versions of the time-averaged momentum Equation (1.1) have been extensively used for explanation of the origin and mechanics of secondary flows, and for their modelling (e.g., Gessner, 1973; Townsend, 1976; Demuren and Rodi (1984); Bradshaw 1987; Ikeda and Parker (1989);Rodi, 1993; Yang, 2005; Ikeda and McEwan (2009). It has been shown, for example, that it is likely that secondary flows in straight channels are generated by transverse pressure gradients resulting from the turbulence anisotropy or turbulence heterogeneity observed for normal turbulent stresses $\overline{u'_2u'_2}$ and $\overline{u'_3u'_3}$ (e.g., Townsend, 1976). However, Equation (1.1), when used alone, may lead to potential misinterpretation of the secondary flow mechanisms and thus should ideally be supplemented with other flow dynamics equations. Examples of such misinterpretation are given, e.g., in Hinze (1967) and Gessner (1973), and one of them is highlighted in Section 1.2.2 below.

1.2.2 Energy Balance of the Mean Flow

In 1967, Hinze suggested that energy-based considerations are more suitable for analysing the secondary flow mechanics compared to the momentum equation and vorticity Equation (Hinze, 1967). His elegant analysis was mainly based on the turbulent energy balance and will be briefly described in the next subsection. As an alternative to the turbulent energy balance, Gessner (1973) proposed considering the mean flow energy balance. He deduced that the transverse gradients of the Reynolds shear stresses $\overline{u'_1u'_2}$ and $\overline{u'_1u'_3}$ are mostly responsible for the generation of secondary flows along channel corners, while the effects of the normal stresses $\overline{u'_2u'_2}$ and $\overline{u'_3u'_3}$ and the shear stress $\overline{u'_2u'_3}$, highlighted by other researchers based on the momentum and vorticity equations, are of secondary importance. This conclusion, however, seems not to be universal, as follow-up analyses supported earlier findings about the significance of the normal stresses $\overline{u'_2u'_2}$ and $\overline{u'_3u'_3}$ (e.g., Demuren and Rodi (1984)). More recently, Yang and Lim (1997) used the mean flow energy balance to hypothesize that the surplus mean energy in any arbitrary flow volume will be transferred along the direction towards the nearest boundary. They applied this assumption to study the bed shear stress distribution in the presence of the secondary currents in uniform straight channels.

The potential of the mean energy balance for studying secondary flows is high and needs to be better explored. Below we propose an approach to how the mean energy balance can be utilized to look at possible energy fluxes between primary mean flow, secondary mean flow, and turbulence. The balance of the total mean kinetic energy (MKE) for an open-channel flow (and also for conduits/ducts) can be expressed as:

$$\underbrace{\frac{\partial}{\partial t}\left(\frac{\bar{u}_i^2}{2}\right) + \bar{u}_j\frac{\partial}{\partial x_j}\left(\frac{\bar{u}_i^2}{2}\right)}_{\text{rate of change of MKE}} = \underbrace{g_i\bar{u}_i}_{\text{energy income from gravity}} - \frac{\partial}{\partial x_j}\left[\underbrace{\frac{1}{\rho}\bar{u}_i\bar{p}}_{\text{pressure transport}} + \underbrace{\bar{u}_i\overline{u'_iu'_j}}_{\text{turbulent transport}} - \underbrace{\nu\frac{\partial}{\partial x_j}\left(\frac{\bar{u}_i^2}{2}\right)}_{\text{viscous transport}}\right] + \underbrace{\overline{u'_iu'_j}\frac{\partial\bar{u}_i}{\partial x_j}}_{\text{energy transfer between mean flow and turbulence}} - \underbrace{\nu\left(\frac{\partial\bar{u}_i}{\partial x_j}\right)^2}_{\text{dissipation of mean flow energy}} \quad (1.2)$$

This equation follows from the multiplication of Equation (1.1) by $\bar{u}_i$ and from some re-arrangements (e.g., Tennekes and Lumley, 1972). As already mentioned, simplified forms of Equation (1.2) have been used in Gessner (1973) and Yang and Lim (1997). However, for studying energy exchanges between the primary and secondary flows it is beneficial to decompose Equation (1.2) for the total MKE into two separate equations, i.e., for the primary flow MKE and for the secondary flow MKE. The first equation specifies the energy balance for the longitudinal velocity $\bar{u}_1$, while the second equation gives the combined energy balance for $\bar{u}_2$ and $\bar{u}_3$ (Equations (1.3) and (1.4), respectively):

$$\frac{\partial}{\partial t}\left(\frac{\bar{u}_1^2}{2}\right)+\bar{u}_j\frac{\partial}{\partial x_j}\left(\frac{\bar{u}_1^2}{2}\right)=g_1\bar{u}_1-\bar{u}_1\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_1}-\frac{\partial \bar{u}_1\overline{u'_1u'_j}}{\partial x_j}+\nu\frac{\partial}{\partial x_j}\left(\frac{\partial}{\partial x_j}\frac{\bar{u}_1^2}{2}\right)+\overline{u'_1u'_j}\frac{\partial \bar{u}_1}{\partial x_j}-\nu\left(\frac{\partial \bar{u}_1}{\partial x_j}\right)^2 \tag{1.3}$$

$$\frac{\partial}{\partial t}\frac{(\bar{u}_2^2+\bar{u}_3^2)}{2}+\bar{u}_j\frac{\partial}{\partial x_j}\frac{(\bar{u}_2^2+\bar{u}_3^2)}{2}=g_2\bar{u}_2+g_3\bar{u}_3-\bar{u}_2\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_2}-\bar{u}_3\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_3}-\frac{\partial \bar{u}_2\overline{u'_2u'_j}}{\partial x_j}-\frac{\partial \bar{u}_3\overline{u'_3u'_j}}{\partial x_j}+\nu\frac{\partial}{\partial x_j}\left(\frac{\partial}{\partial x_j}\frac{(\bar{u}_2{}^2+\bar{u}_3{}^2)}{2}\right)+\overline{u'_2u'_j}\frac{\partial \bar{u}_2}{\partial x_j}+\overline{u'_3u'_j}\frac{\partial \bar{u}_3}{\partial x_j}-\nu\left(\frac{\partial \bar{u}_2}{\partial x_j}\right)^2-\nu\left(\frac{\partial \bar{u}_3}{\partial x_j}\right)^2 \tag{1.4}$$

Applying Equations (1.3) and (1.4) for steady, uniform (straight) open-channel flow, $(\partial/\partial t=\partial p/\partial x_2=\partial/\partial x_1=0)$ with $g_1=g\sin\alpha\approx gS$, $g_2=0$, $g_3=-g\cos\alpha\approx -g$, and assuming the hydrostatic pressure distribution (i.e., $\rho g\cos\alpha+\partial\bar{p}/\partial x_3\approx 0$), we obtain:

$$\bar{u}_2\frac{\partial}{\partial x_2}\left(\frac{\bar{u}_1^2}{2}\right)+\bar{u}_3\frac{\partial}{\partial x_3}\left(\frac{\bar{u}_1^2}{2}\right)=gS\bar{u}_1-\left(\frac{\partial \bar{u}_1\overline{u'_1u'_2}}{\partial x_2}+\frac{\partial \bar{u}_1\overline{u'_1u'_3}}{\partial x_3}\right)+\left(\overline{u'_1u'_2}\frac{\partial \bar{u}_1}{\partial x_2}+\overline{u'_1u'_3}\frac{\partial \bar{u}_1}{\partial x_3}\right)+VT_1+VD_1 \tag{1.5}$$

$$\bar{u}_2\frac{\partial}{\partial x_2}\frac{1}{2}\left(\bar{u}_2^2+\bar{u}_3^2\right)+\bar{u}_3\frac{\partial}{\partial x_3}\frac{1}{2}\left(\bar{u}_2^2+\bar{u}_3^2\right)=-\left(\frac{\partial \bar{u}_2\overline{u'_2u'_2}}{\partial x_2}+\frac{\partial \bar{u}_2\overline{u'_2u'_3}}{\partial x_3}\right)-\left(\frac{\partial \bar{u}_3\overline{u'_3u'_2}}{\partial x_2}+\frac{\partial \bar{u}_3\overline{u'_3u'_3}}{\partial x_3}\right)+\left(\overline{u'_2u'_2}\frac{\partial \bar{u}_2}{\partial x_2}+\overline{u'_2u'_3}\frac{\partial \bar{u}_2}{\partial x_3}\right)+\left(\overline{u'_3u'_2}\frac{\partial \bar{u}_3}{\partial x_2}+\overline{u'_3u'_3}\frac{\partial \bar{u}_3}{\partial x_3}\right)+VT_{2,3}+VD_{2,3} \tag{1.6}$$

where viscous transport terms VT_1 and $VT_{2,3}$, and viscous dissipation terms VD_1 and $VD_{2,3}$ are:

$$VT_1=\nu\frac{\partial}{\partial x_2}\left(\frac{\partial}{\partial x_2}\frac{\bar{u}_1{}^2}{2}\right)+\nu\frac{\partial}{\partial x_3}\left(\frac{\partial}{\partial x_3}\frac{\bar{u}_1{}^2}{2}\right),$$

$$VT_{2,3}=\nu\frac{\partial}{\partial x_2}\left(\frac{\partial}{\partial x_2}\frac{(\bar{u}_2{}^2+\bar{u}_3{}^2)}{2}\right)+\nu\frac{\partial}{\partial x_3}\left(\frac{\partial}{\partial x_3}\frac{(\bar{u}_2{}^2+\bar{u}_3{}^2)}{2}\right)$$

$$VD_1=-\nu\left(\frac{\partial \bar{u}_1}{\partial x_2}\right)^2-\nu\left(\frac{\partial \bar{u}_1}{\partial x_3}\right)^2,$$

$$VD_{2,3}=-\nu\left(\frac{\partial \bar{u}_2}{\partial x_2}\right)^2-\nu\left(\frac{\partial \bar{u}_2}{\partial x_3}\right)^2-\nu\left(\frac{\partial \bar{u}_3}{\partial x_2}\right)^2-\nu\left(\frac{\partial \bar{u}_3}{\partial x_3}\right)^2$$

Equation (1.5) for the primary flow MKE and Equation (1.6) for the secondary flow MKE suggest that the following energy exchanges are likely to occur:

(1) For steady uniform (straight) open-channel flow, the external energy (i.e., potential gravity energy) is "pumped" into the mean kinetic energy of the primary flow only (term $gS\bar{u}_1$). This energy is then spatially redistributed by molecular and turbulent stresses, partly transferred to the turbulent kinetic energy, and partly dissipated into heat.

(2) The mean kinetic energy balance of the secondary flow Equation (1.6) does not explicitly include an external energy source, suggesting that the secondary flow should be fed only through coupling with the primary mean flow and/or turbulence. Equations (1.5) and (1.6) show that this coupling may occur through turbulent stresses $\overline{u'_1u'_2}$ and $\overline{u'_1u'_3}$ in (1.5) and $\overline{u'_2u'_3}$ in (1.6), as they have common velocity components between them and are involved in turbulent transport terms and in energy transfer between mean flow and turbulence (i.e., terms $\overline{u'_iu'_j}\partial\bar{u}_i/\partial x_j$). The latter terms are most probable candidates for the energy coupling between the primary and secondary flows as the transport terms $\partial\bar{u}_i\overline{u'_iu'_j}/\partial x_j$ in Equation (1.6) have to redistribute the already available energy of $\bar{u}_2$ and $\bar{u}_3$.

(3) Based on Equations (1.5) and (1.6) and some 3-D turbulence data (e.g., Nikora *et al.*, 1998), the following energy pathway may be suggested: (i) the mean primary flow (PF) is fed by gravity through $gS\bar{u}_1$; (ii) PF transfers part of the received gravity energy to turbulent kinetic energy (TKE); (iii) TKE feeds mean secondary flow (SF) energy in particular flow regions through a subset of $-\overline{u'_iu'_j}\partial\bar{u}_i/\partial x_j$; and (iv) SF returns part of the received kinetic energy back to turbulence in particular flow regions through a different subset of $-\overline{u'_iu'_j}\partial\bar{u}_i/\partial x_j$. In other words, this analysis suggests that turbulence serves, very likely, as an energy link between the primary mean flow and secondary mean flow(s). Specifically, this link may occur through helical coherent structures and/or near-bed bursting processes (see Section 1.3 for more discussion).

To elaborate the proposed considerations for specific flow scenarios one would need detailed turbulence measurements involving estimates of velocity derivatives. This task will soon be realistic, even for field experiments.

Another interesting example of how the MKE balance may help in better understanding of secondary flows can also be derived from Equation (1.2), considering this time the total MKE balance. For steady uniform flow we may assume that there is a region in a flow where the combined effect of the transport terms and viscous dissipation in Equation (1.2) may be neglected, leading to:

$$\bar{u}_2\frac{\partial}{\partial x_2}\left(\frac{\bar{u}_i^2}{2}\right)+\bar{u}_3\frac{\partial}{\partial x_3}\left(\frac{\bar{u}_i^2}{2}\right)\approx gS\bar{u}_1+\overline{u'_iu'_2}\frac{\partial\bar{u}_i}{\partial x_2}+\overline{u'_iu'_3}\frac{\partial\bar{u}_i}{\partial x_3}\qquad(1.7)$$

Equation (1.7) explicitly shows that the secondary flows may be generated in flow regions with a significant imbalance between the energy income $gS\bar{u}_1$ and the energy loss $\overline{u'_iu'_j}\partial\bar{u}_i/\partial x_j$ (for turbulence generation), that provides a mechanism for the mean energy re-distribution. As in the previous example, however, this speculation requires support from data. Similar considerations can also be instrumental for flows in curved channels.

1.2.3 Turbulent Energy Balance

Another way to look at the inter-relations between the primary and secondary flows is to use the budget of the turbulent kinetic energy (TKE):

$$\underbrace{\frac{\partial}{\partial t}\frac{\overline{u'_iu'_i}}{2}}_{\text{rate of change of TKE}}+\underbrace{\bar{u}_j\frac{\partial}{\partial x_j}\frac{\overline{u'_iu'_i}}{2}}_{\text{convection of TKE by mean flow}}=\underbrace{-\overline{u'_iu'_j}\frac{\partial\bar{u}_i}{\partial x_j}}_{\text{energy transfer between mean flow and turbulence}}-\frac{\partial}{\partial x_j}\Bigg[\underbrace{\frac{1}{\rho}\overline{p'u'_j}}_{\text{pressure transport}}+\underbrace{\frac{\overline{u'_iu'_iu'_j}}{2}}_{\text{turbulent transport}}-\underbrace{\nu\overline{u'_i\left(\frac{\partial u'_i}{\partial x_j}+\frac{\partial u'_j}{\partial x_i}\right)}}_{\text{viscous transport}}\Bigg]-\underbrace{\frac{\nu}{2}\sum_{i,j}\overline{\left(\frac{\partial u'_i}{\partial x_j}+\frac{\partial u'_j}{\partial x_i}\right)^2}}_{\text{dissipation of turbulent energy}}\qquad(1.8)$$

Equation (1.8) can be derived in a number of ways. For example, multiplying the Navier–Stokes equation by u_i, presenting u_i and p as $u_i=\bar{u}_i+u'_i$ and $p=\bar{p}+p'$, and then averaging, one may obtain the full kinetic energy equation. Subtraction of Equation (1.2) for MKE from this full equation will produce Equation (1.8) for TKE. Based on the available data for pipes, Hinze, 1967 suggested that for the flow regions away from the walls and the pipe centre, Equation (1.8) can be simplified, applying the boundary layer approximation, as:

$$\bar{u}_2\frac{\partial}{\partial x_2}\frac{\overline{u'_iu'_i}}{2}+\bar{u}_3\frac{\partial}{\partial x_3}\frac{\overline{u'_iu'_i}}{2}\approx-\overline{u'_1u'_2}\frac{\partial\bar{u}_1}{\partial x_2}-\overline{u'_1u'_3}\frac{\partial\bar{u}_1}{\partial x_3}-\frac{\nu}{2}\sum_{i,j}\overline{\left(\frac{\partial u'_i}{\partial x_j}+\frac{\partial u'_j}{\partial x_i}\right)^2}\qquad(1.9)$$

Hinze (1967) concluded that Equation (1.9) implies the following general rule: "when in a localised region, the production of turbulence energy is much greater (smaller) than the viscous dissipation, there must be a transport of turbulence-poor fluid into (out of) this region and a transport of turbulence-rich fluid outwards (into) the region." This rule is well supported by observations of the secondary flows formed at channel corners and at bed roughness transitions (Hinze, 1973). It is easy to see that Equation (1.7) proposed in the previous subsection has been inspired by Hinze's Equation (1.9). Summing up these two equations together we can obtain an equation for the simplified balance of the total kinetic energy, i.e.:

$$\bar{u}_2\frac{\partial}{\partial x_2}\left(\frac{\bar{u}_i^2+\overline{u'_iu'_i}}{2}\right)+\bar{u}_3\frac{\partial}{\partial x_3}\left(\frac{\bar{u}_i^2+\overline{u'_iu'_i}}{2}\right)\approx gS\bar{u}_1-\frac{\nu}{2}\sum_{i,j}\overline{\left(\frac{\partial u'_i}{\partial x_j}+\frac{\partial u'_j}{\partial x_i}\right)^2}\qquad(1.10)$$

Equation (1.10) highlights a potentially more general rule for gravity-driven open-channel flows, i.e., the secondary flows are generated as a response to an imbalance in some flow regions between the external energy supply to the mean flow and the energy dissipation (viscous dissipation of the mean flow is neglected in Equations (1.7) and (1.10) as, in most cases, it is much smaller than the turbulent dissipation).

Equations (1.9) and (1.10) mainly relate to flows in straight channels. Detailed experimental analyses of the turbulent energy budget for secondary flows in a meandering channel have been reported in Blanckaert and de Vriend (2004, 2005a, 2005b). In their considerations, the authors combined the vorticity equation and the turbulent energy balance equation and showed that turbulence plays a minor role in the generation of the centre-region cell, which is mainly due to the centrifugal force. Another important observation made by these authors is that there are extensive flow regions within a channel bend where turbulent energy is transferred to the mean flow, playing a significant role in maintaining the outer-bank circulation cell. This observation provides some support to a suggested chain of energy transformations in an open-channel flow described in the previous subsection. The results of these authors will be considered in more detail in Section 1.3.

1.2.4 Mean Vorticity Equation

The idea of explaining the secondary flows in open channels using the mean vorticity equation was proposed by Einstein and Li (1958). The vorticity equation can be obtained by taking the curl of the momentum Equation (1.1) (or by its cross-differentiation). Einstein and Li (1958) focused on an equation for the streamwise vorticity component $\bar{\omega}_1$ that in the absence of the density stratification, and neglecting the Coriolis effect, can be expressed as:

$$\underbrace{\frac{\partial \bar{\omega}_1}{\partial t}}_{\substack{\text{rate of}\\ \text{change}}} + \underbrace{\bar{u}_j \frac{\partial \bar{\omega}_1}{\partial x_j}}_{\substack{\text{convection}\\ \text{by mean}\\ \text{flow}}} = \underbrace{\bar{\omega}_j \frac{\partial \bar{u}_1}{\partial x_j}}_{\substack{\text{vortex}\\ \text{stretching}\\ \text{and tilting}}} + \underbrace{\frac{\partial^2}{\partial x_2 \partial x_3}\left(\overline{u'^2_3} - \overline{u'_2{}^2}\right)}_{\substack{\text{stress-related}\\ \text{vorticity}\\ \text{"generation"}}} + \underbrace{\left(\frac{\partial^2}{\partial x_3{}^2} - \frac{\partial^2}{\partial x_2{}^2}\right)\left(-\overline{u'_3 u'_2}\right)}_{\substack{\text{stress-related}\\ \text{vorticity}\\ \text{"dissipation"}}} + \underbrace{\frac{\partial}{\partial x_j}\left(\nu \frac{\partial \bar{\omega}_1}{\partial x_j}\right)}_{\substack{\text{viscous "dissipation"}\\ \text{of mean vorticity}}}$$
$$+ \underbrace{\frac{\partial}{\partial x_1}\left(\frac{\partial - \overline{u'_1 u'_2}}{\partial x_3} - \frac{\partial - \overline{u'_1 u'_3}}{\partial x_2}\right)}_{\substack{\text{vorticity change due}\\ \text{to non-uniformity}}} \quad (1.11)$$

where the components of the mean vorticity vector $\bar{\omega}_j$ are defined as:

$$\bar{\omega}_1 = \frac{\partial \bar{u}_3}{\partial x_2} - \frac{\partial \bar{u}_2}{\partial x_3}, \ \bar{\omega}_2 = \frac{\partial \bar{u}_1}{\partial x_3} - \frac{\partial \bar{u}_3}{\partial x_1}, \ \bar{\omega}_3 = \frac{\partial \bar{u}_2}{\partial x_1} - \frac{\partial \bar{u}_1}{\partial x_2}$$

Nezu (2005) used Equation (1.11) as a basis for subdivision of secondary flows into Prandtl's first and second kinds. In flow configurations when the vortex stretching and tilting term in (1.11) is dominant, the first kind of secondary current is observed as, for example, in meandering channels. With channel curvature tending to zero (straight channels) this term disappears, as can be explicitly seen in the vorticity equation written in natural coordinates (Blanckaert and de Vriend, 2004). The second kind of secondary current occurs when turbulence terms in Equation (1.11) are dominant, i.e., due to turbulent stress anisotropy and heterogeneity. Of course, in real flow configurations superposition of both mechanisms has to be considered.

Nezu and Nakagawa (1993) reported a comprehensive study of Prandtl's second kind of secondary flows in straight channels, based on a simplified version of Equation (1.11) for steady, uniform open-channel flow:

$$\bar{u}_2 \frac{\partial \bar{\omega}_1}{\partial x_2} + \bar{u}_3 \frac{\partial \bar{\omega}_1}{\partial x_3} = \frac{\partial^2}{\partial x_2 \partial x_3}\left(\overline{u'_3{}^2} - \overline{u'_2{}^2}\right) + \left(\frac{\partial^2}{\partial x_3{}^2} - \frac{\partial^2}{\partial x_2{}^2}\right)\left(-\overline{u'_3 u'_2}\right) + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \bar{\omega}_1}{\partial x_j}\right) \quad (1.12)$$

They concluded that secondary currents are generated as a result of differences between the first RHS term in (1.12), which is a production term, and the second RHS term, representing vorticity "dissipation", i.e., damping. The last term in (1.12) is negligible except very close to the solid boundary. The 18-year-old text by Nezu and Nakagawa (1993) is still the most comprehensive work on Prandtl's second kind of secondary flows in straight open channels.

Interesting results for curved channels based on the vorticity equation in natural coordinates have been recently reported by Blanckaert and de Vriend (2004). Using high-quality laboratory data they performed a combined analysis of the terms of the vorticity equation and the turbulent energy balance. The revealed complex structure of the secondary flow and associated turbulence properties were explained by the interplay of the effects of the centrifugal force and spatial distribution of the turbulent stresses (see also Section 1.3).

Although after Demuren and Rodi's (1984) and Nezu and Nakagawa's (1993) studies vorticity-related considerations are mainly based on Equations (1.11) and (1.12) for streamwise vorticity, it is worth noting that Gessner (1973) pointed out that two other equations, for the transverse and vertical components of the vorticity vector, can be even more important for explaining and predicting the secondary flows. This view, however, has not been properly explored yet.

1.2.5 Mean and Turbulent Enstrophy Balance Equations

The momentum, energy, and vorticity equations, briefly discussed above, have mainly been used for studying time-averaged secondary flows (i.e., mean streamwise vorticity). However, the time-averaged secondary flows are most likely a manifestation of frequently occurring instantaneous helical motions. The involvement of the fluctuating vorticity can be clearly seen if we use an alternative form of the vorticity Equation (1.11), i.e.:

$$\frac{\partial \bar{\omega}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{\omega}_i}{\partial x_j} = \bar{\omega}_j \frac{\partial \bar{u}_i}{\partial x_j} - \underbrace{\frac{\partial}{\partial x_j}}_{\substack{\text{turbulent}\\ \text{convection}}} \underbrace{\left(\overline{\omega'_i u'_j} - \overline{\omega'_j u'_i}\right)}_{\substack{\text{turbulent}\\ \text{stretching}}} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \bar{\omega}_i}{\partial x_j}\right) \quad (1.13)$$

where the Reynolds decomposition is used, i.e., $\omega_i = \bar{\omega}_i + \omega'_i$. The second RHS term represents effects of anisotropy and spatial heterogeneity of turbulent stresses expressed through correlations of fluctuating vorticity and velocity components. The derivative $\partial\overline{\omega'_j u'_i}/\partial x_j$ represents the gain (or loss) of mean vorticity due to stretching/tilting of the fluctuating vorticity by fluctuating strain rates, while the term $\partial\overline{\omega'_i u'_j}/\partial x_j$ represents vorticity transport in the x_j direction (e.g., Tennekes and Lumley, 1972). Similar to the mean energy and turbulent energy, the coupling between the mean and fluctuating vorticities can be expressed using equations for $\bar{\omega}_i^2/2$ and $\overline{\omega'_i\omega'_i}/2$, which represent two components of the mean product $\overline{\omega_i\omega_i}/2 = \bar{\omega}_i^2/2 + \overline{\omega'_i\omega'_i}/2$, where $\omega_i\omega_i$ is known as enstrophy. Although there are some analogies between the MKE and mean enstrophy $\bar{\omega}_i^2/2$ (ME), and between the TKE and the turbulent enstrophy $\overline{\omega'_i\omega'_i}/2$ (TE), their physical nature is different, i.e., the enstrophy represents a measure of the density of the kinetic energy of helical motions rather than of all motions (e.g., Tsinober, 2009). As with Equation (1.2) for MKE, the mean enstrophy balance can be obtained by multiplying Equation (1.13) with $\bar{\omega}_i$, i.e.:

Equations (1.14) and (1.15) have been extensively studied in turbulence research with particular focus on their simplified versions for high-Reynolds-number flows with homogeneous turbulence. There have been no studies, to the writers' knowledge, involving these equations in the analysis of secondary flows. The main reason for this is probably the absence of experimental assessments of the terms of Equations (1.14) and (1.15). However, with recent advances in laboratory and field instrumentation it is quite likely that such experimental data will soon appear. In addition, recent progress in numerical simulation techniques and computing capabilities (e.g., Keylock *et al*., 2005; Lyn, 2008; Zeng *et al*., 2008; Constantinescu *et al*., 2009; van Balen *et al*., 2009; Stoesser *et al*., 2010) also encourages exploration of the potential of Equations (1.14) and (1.15) for studying secondary flows. Thus, the inclusion of the enstrophy balances in this review is justified, as it highlights a potentially fruitful theoretical framework for coupling mean and fluctuating vorticity fields, with the latter formed, most likely, by helical coherent structures. There may be several coupling mechanisms between these fields, with the gradient production term $\overline{u'_j\omega'_i}\partial\bar{\omega}_i/\partial x_j$ being the most obvious candidate as it is

$$\underbrace{\frac{\partial}{\partial t}\left(\frac{1}{2}\bar{\omega}_i^2\right)}_{\substack{\text{rate of}\\ \text{change}\\ \text{of ME}}} + \underbrace{\bar{u}_j\frac{\partial}{\partial x_j}\left(\frac{1}{2}\bar{\omega}_i^2\right)}_{\substack{\text{convection of}\\ \text{ME by mean}\\ \text{flow}}} = \underbrace{-\frac{\partial}{\partial x_j}\bar{\omega}_i\overline{\omega'_i u'_j}}_{\substack{\text{transport of ME}\\ \text{by velocity-vorticity}\\ \text{interactions}}} + \underbrace{\overline{\omega'_i u'_j}\frac{\partial\bar{\omega}_i}{\partial x_j}}_{\substack{\text{gradient}\\ \text{production}\\ \text{of ME}}} + \underbrace{\bar{\omega}_i\bar{\omega}_j S_{ij}}_{\substack{\text{ME}\\ \text{stretching}\\ \text{by mean strain}}} + \underbrace{\bar{\omega}_i\overline{\omega'_j\frac{\partial u'_i}{\partial x_j}}}_{\substack{\text{ME stretching}\\ \text{by turbulent}\\ \text{strain}}}$$
$$+ \underbrace{\nu\frac{\partial^2}{\partial x_j\partial x_j}\left(\frac{1}{2}\bar{\omega}_i^2\right)}_{\substack{\text{viscous}\\ \text{transport}}} - \underbrace{\nu\frac{\partial\bar{\omega}_i}{\partial x_j}\frac{\partial\bar{\omega}_i}{\partial x_j}}_{\substack{\text{dissipation of}\\ \text{mean enstrophy}}} \tag{1.14}$$

where $S_{ij} = 0.5(\partial\bar{u}_i/\partial x_j + \partial\bar{u}_j/\partial x_i)$. The procedure for deriving the turbulent enstrophy balance is identical to that for the TKE balance (1.8), i.e., it involves multiplication of the equation for ω'_i by ω'_i, and then subsequent time-(ensemble)-averaging (or, alternatively, subtraction of the mean enstrophy balance from the total enstrophy balance):

included in both Equations (1.14) and (1.15), similar to the TKE production term $\overline{u'_i u'_j}\partial\bar{u}_i/\partial x_j$ in Equations (1.2) and (1.8).

To summarise this brief overview of potential approaches for studying secondary flows, it should be noted that the recently achieved consensus among researchers is that there should be no preferred equation. Instead,

$$\underbrace{\frac{\partial}{\partial t}\left(\frac{\overline{\omega'_i\omega'_i}}{2}\right)}_{\substack{\text{rate of}\\ \text{change}\\ \text{of TE}}} + \underbrace{\bar{u}_j\frac{\partial}{\partial x_j}\left(\frac{\overline{\omega'_i\omega'_i}}{2}\right)}_{\substack{\text{convection of}\\ \text{TE by mean}\\ \text{flow}}} = \underbrace{-\overline{u'_j\omega'_i}\frac{\partial\bar{\omega}_i}{\partial x_j}}_{\substack{\text{gradient}\\ \text{production of TE}}} \underbrace{-\frac{\partial}{\partial x_j}\frac{\overline{u'_j\omega'_i\omega'_i}}{2}}_{\substack{\text{turbulent}\\ \text{transport}\\ \text{of TE}}} + \underbrace{\overline{\omega'_i\omega'_j\frac{\partial u'_i}{\partial x_j}}}_{\substack{\text{TE production}\\ \text{by turbulent}\\ \text{stretching}}} + \underbrace{\overline{\omega'_i\omega'_j}\frac{\partial\bar{u}_i}{\partial x_j}}_{\substack{\text{change of}\\ \text{TE by}\\ \text{mean strain}}} + \underbrace{\bar{\omega}_j\overline{\omega'_i\frac{\partial u'_i}{\partial x_j}}}_{\substack{\text{“mixed”}\\ \text{production}}}$$
$$\underbrace{\nu\frac{\partial^2}{\partial x_j\partial x_j}\left(\frac{\overline{\omega'_i\omega'_i}}{2}\right)}_{\text{viscous transport}} - \underbrace{\nu\overline{\frac{\partial\omega'_i}{\partial x_j}\frac{\partial\omega'_i}{\partial x_j}}}_{\text{viscous dissipation}} \tag{1.15}$$

better understanding and predictions can only be achieved on the basis of combined approaches.

1.3 SECONDARY CURRENTS AND TURBULENCE

Although the importance of inter-relations between secondary currents and turbulence has been recognized since the beginning of the last century, knowledge concerning these inter-relations remains patchy and there are still significant gaps in our understanding of how they actually depend on each other. There are several conceptual frameworks in studying turbulence that represent different facets of turbulence. The most advanced among them are the Reynolds-averaging framework, the coherent structures concept, and the eddy cascade concept. The existing knowledge within these three directions is mostly related to 2-D (in a time-averaged sense) open-channel flows. The effects of mean flow three-dimensionality and secondary currents on turbulence are less understood and have been mainly studied in terms of bulk turbulence characteristics, with the most systematic and comprehensive work conducted by Nezu and his group for rectangular open-channel flows, as reviewed in Nezu (2005), and by Knight and his group for compound channels, as reviewed in Knight *et al*. (2009a).

The knowledge of these effects in more complex flows is much less complete although recent publications demonstrate some significant advances in studying flows in meandering channels (e.g., Blanckaert and de Vriend, 2004, 2005a, 2005b; Odgaard and Abad, 2008; Abad and Garcia, 2009a, 2009b; Blanckaert, 2009, 2010; Knight *et al*., 2009a; Sanjou and Nezu, 2009; Gyr, 2010; Sukhodolov and Kaschtschejewa, 2010), riffle-pools (e.g., MacVicar and Roy, 2007a, 2007b), tidally- forced channels (e.g., Fong *et al*., 2009), channel expansion-contractions (Papanicolaou *et al*., 2007), at river confluences (e.g., Rhoads and Sukhodolov, 2001; Sukhodolov and Rhoads, 2001; Boyer *et al*., 2006), and even in the complex situations of ice-covered rivers (Ettema, 2008). However, the relations between coherent structures, eddy cascade, and secondary currents remain poorly understood. Recent findings related to these inter-relations are briefly summarized below.

Within the *Reynolds-averaging framework*, turbulence is expressed with bulk parameters arising in the Reynolds-averaged equations for momentum, energy, and/or vorticity. Examples include turbulent energy, Reynolds stresses, absolute and relative turbulence intensities, velocity–vorticity correlations, enstrophy, and higher-order statistical moments such as skewness and kurtosis. The Reynolds-averaged equations represent both turbulence and secondary currents and therefore they seem to be a suitable platform for studying inter-relations between them. In recent studies of secondary currents in straight open channels, the focus has been on flows over rough gravel beds, extending and complementing the well-established results of Nezu's group (Nezu, 2005) for smooth-bed open-channel flows. The major finding that has been independently reported by at least four groups is that secondary flow cells in rough-bed flows cover the whole channel cross-section evenly, even at width-to-depth ratios as high as 20 (Albayrak (2008); Rodriguez and Garcia, 2008; Belcher and Fox, 2009; Blanckaert *et al*. 2010). Figure 1.2 shows an example of the multicellular structures observed in an experiment with smooth side walls and a rough bed (Rodriguez and Garcia, 2008). This finding differs significantly from that for smooth-bed flows, where secondary currents disappear in the centre of the channel at aspect ratios larger than 5.

The most striking feature of the reported multicellular secondary currents is that their origin cannot be linked to sediment motion on the bed or to the transverse heterogeneity in bed roughness, as beds were not water-worked and no particle sorting or topographic variations were observed. Rodriguez and Garcia (2008) explain this phenomenon by the effect of the large gradient in roughness between the smooth glass walls and the gravel bed in their experiments, leading to an enhancement of near-wall cells and transverse transport of vorticity towards the centre of the channel. On the other hand, based on their extensive experiments in rectangular and trapezoidal channels Blanckaert *et al*. (2010) propose that the formation of secondary flow cells over the entre channel width is a result of hydrodynamic instability driven by near-bank secondary currents.

These observations can be supplemented with those of Cooper and Tait (2008) who reported the presence of high-speed longitudinal streaks in the time-averaged fields of streamwise velocity over water-worked gravel beds (no sediment motion was observed during the experiments). Interestingly, Cooper and Tait (2008) found no correlation between the time-averaged velocity streaks and bed topography, suggesting that their origin is not linked to variation in bed roughness or topography. Although the authors reject the presence of secondary currents as the possible explanation of the observed velocity streaks, their data are consistent with signatures of such currents and thus they should perhaps not be readily dismissed as the potential cause of the streaks.

Altogether, the results of these studies suggest that multicellular currents exhibit some form of self-organisation triggered by the pre-existing corner helical flows enhanced by bed roughness. Furthermore, Albayrak's (2008) study hints that the number of cells at a particular aspect ratio may depend on the properties of bed roughness. These observations shed new light on the old

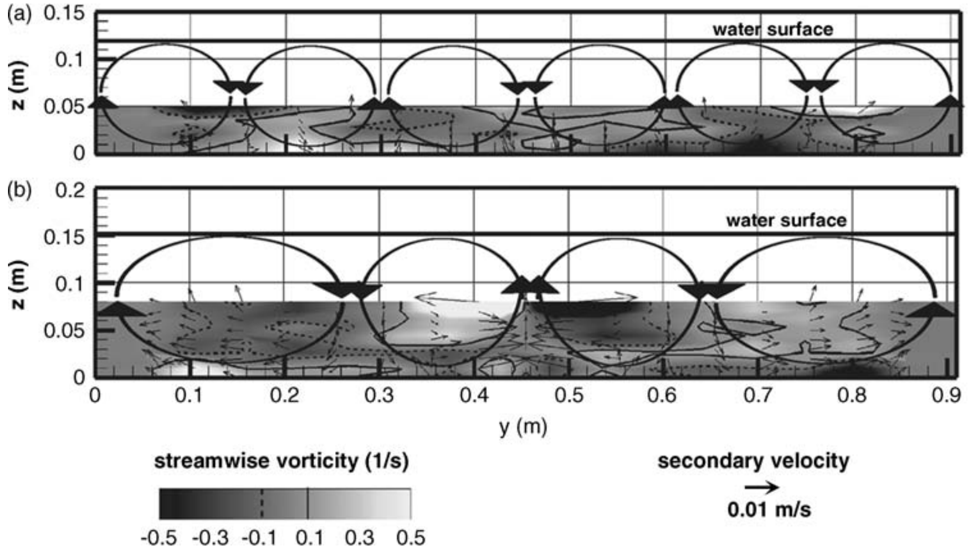

Figure 1.2 The results of a flume experiment with smooth walls and rough beds (Rodriguez and Garcia, 2008) at low flow (a) and high flow (b). The cells are delineated from the changes in direction in the streamwise vorticity and the directions of the secondary velocity. The cell size scales roughly with flow depth.

reports of longitudinal sediment ridges observed in some rivers (e.g., McLean, 1981; Nezu and Nakagawa, 1993) and may help in better formulations for channel morphodynamics. The physical origin of the observed multicellular structure is not yet clear and awaits a proper investigation.

Highlights of recent studies of the relation between secondary currents and turbulence in meandering channels include the detailed analysis of the spatial distribution of bulk turbulence properties by Blanckaert and de Vriend (2004, 2005a, 2005b). These authors performed comprehensive laboratory measurements of velocity vectors in a sharp open-channel bend, focusing on a bicellular pattern of secondary currents and its interrelations with turbulent energy, its production, dissipation, and transport. The revealed circulation pattern includes the classical centre-region helical cell and a weaker and smaller counter-rotating outer-bank cell (believed to play an important role in bank erosion processes). By analysing simultaneously the vorticity equation and the kinetic energy transfer between the mean flow and turbulence, the authors established that the centre-region cell is mainly formed due to the centrifugal force while the turbulence contribution is minor, as one could expect. The data also suggest that the origin of the outer cell can be explained by the interplay of the near-bank turbulence heterogeneity and channel curvature effects. This finding is somewhat consistent with laboratory and LES numerical studies of secondary circulation at the corners formed by a solid vertical wall and flow free surface, i.e., at mixed-boundary corners (e.g., Grega *et al.*, 2002; Broglia *et al.*, 2003). However, in straight channels the mixed-boundary (inner) corner vortex rotates toward the solid wall at the water surface while in a curved channel the vortex rotation is opposite, probably reflecting additional effects of the centrifugal force and the associated centre-region cell. Blanckaert and de Vriend (2005b) proposed that the observed significant deviation of the turbulence structure in a curved channel from its straight channel counterpart is due to the streamline curvature effects. The transverse "stratification" of bulk turbulence properties is explained using an analogy with buoyancy-induced stratification and, therefore, can be quantified with the "curvature-flux-Richardson" number. The recent LES-based numerical study of van Balen *et al.* (2009, 2010) reproduces all key features observed in the laboratory experiments, additionally emphasizing the enhanced TKE and its production in the region of the outer near-bank cell.

Blanckaert and de Vriend's (2004, 2005a, 2005b) experiments covered an idealized situation of an isolated bend where the effects of adjacent bends were not present. A more realistic channel shape was used in recent experiments by Abad and Garcia (2009a, 2009b) who performed extensive velocity measurements in a unique five-bends facility known as the "Kinoshita channel" and reported detailed maps of mean velocity vectors, Reynolds stresses, and TKE. Both fixed-bed and mobile-bed scenarios were examined, particularly focusing on the effects of bend orientation, i.e., upstream or