THE FLUVIAL DYNAMICS OF COMPOUND MEANDER BENDS

BY

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DISSERTATION

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ABSTRACT

The dynamic evolution of the planform of meandering rivers often leads to the development of compound loops with multiple lobes of maximum curvature, also known as compound meander bends. At present, the interaction among spatial patterns of mean flow, turbulence, bed morphology, bank failures and channel migration in compound loops is poorly understood. In particular, field studies of this interaction over the timescale of planform evolution are lacking. The research presented here examines the co-evolution of flow, bed morphology, and channel planform in two compound meander bends. Careful study is given to the interaction of processes over differing spatial and temporal timescales. Results suggest that patterns of flow, sediment entrainment, and planform evolution in compound meander bends are more complex than in simple meander bends. Moreover, interactions among local influences on the flow, such as outer bank blocks, local topographic steering, and locally high curvature, tend to cause compound loops to evolve toward increasing planform complexity over time rather than stable configurations.

The research is comprised of three field investigations. The first study examines the co-evolution of flow, bed morphology, and channel planform in a compound meander loop and relates patterns of near-bank velocity and turbulence to planform change within the loop. Data consist of repeat surveys of channel change in a compound loop over an 11-year period, coupled with Acoustic Doppler Velocimeter (ADV) measurements of 3-D instantaneous velocities for similar magnitude flows at the beginning and end of this period. Results confirm that this compound loop is highly dynamic with major changes in planform occurring over the 11-year period. Spatial patterns of near-bank velocity and turbulence correspond to patterns of bank
erosion and channel migration within the loop; however, these patterns are not strictly a function of planform curvature. Instead, local factors, including deflection of the flow by point bars and failed bank blocks, can enhance or inhibit the development of high near-bank velocities and turbulence kinetic energy. The loop has elongated and become more asymmetric over time—a pattern of development consistent with patterns of near-bank velocities and turbulence at the beginning of the study period. The pattern of near-bank velocities and turbulence for measurements at the end of the period indicate that the loop will continue to elongate in the near future, supporting the hypothesis that compound loops change progressively over time rather than evolving into a stable configuration.

In the second study, Acoustic Doppler Current Profiler (ADCP) measurements of the time-averaged flow structure are examined to evaluate the influence of channel curvature and hydrologic variability (i.e., stage) on the structure of flow within a compound loop and to relate changes in bed morphology to flow structure at various flow stages. Local increases in centerline curvature (or decreases in dimensionless radius of curvature) within the upstream lobe of the bend reduce outer bank velocities at morphologically significant flows, creating a region that protects the bank from high momentum flow and corresponding high bed shear stresses. The upstream lobe of the compound loop, which has a dimensionless radius of curvature about one-third less than that of the downstream lobe, also has an average bank erosion rate less than half of the erosion rate for the downstream lobe. Relatively high bank erosion rates within the downstream lobe corresponds to the shift in a core of high velocity and the zone of high bed shear stresses toward the outer bank as flow moves through the two lobes. This pattern of erosion provides a mechanism for continued migration of the downstream lobe in the near future. The distribution of bed material sizes within the multi-lobed bend corresponds to the spatial pattern
of bed shear stress magnitudes, indicating that bed material sorting within the bend is governed by bed shear stress.

In the last study, field data are used to analyze the characteristics of turbulence near the outer bank of a compound meander loop, and based on this analysis, a conceptual framework of the structure of turbulence in the near outer bank region of meander bends is developed. Specifically, the study determines the structure of turbulence at the outer bank of an actively migrating meander bend, and evaluates the spatial variability of turbulence characteristics in relationship to the curvature-induced mean flow field. Results show that the structure of turbulence is linked to curvature-induced effects through the progressive advection of high momentum fluid toward the outer bank as flow moves through successive lobes of the loop. Contrary to straight-channel bed-generated turbulence, where streamwise turbulent fluctuations are the predominant contributor to Reynolds stresses, curvature-induced secondary circulation in the study bend enhances the strength of cross-stream and vertical turbulent fluctuations, leading to increased contribution to the Reynolds stresses from these components. Additionally, large roughness elements, such as failed bank material, can disrupt the curvature-induced pattern of turbulence. Bank blocks reduce flow velocities and turbulent stress in the immediate lee of the block, a finding supporting the bank-toe protection hypothesis that large roughness elements can protect the outer bank from fluid forces and reduce bank erosion rates (Carson and Kirkby 1972). Furthermore, the findings support the assertion that the effects of local topographic features on erosion and deposition within compound bends can be more important than reach-scale effects associated with channel curvature.
For Jordan, Rebekah, and Benjamin
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# TABLE OF CONTENTS

LIST OF FIGURES .............................................................................................................. xi

LIST OF TABLES ................................................................................................................ xviii

CHAPTER 1 INTRODUCTION .............................................................................................1

1.1 Motivation ....................................................................................................................... 1

1.2 Research Questions ........................................................................................................ 4

1.3 Research Organization .................................................................................................. 4

CHAPTER 2 COMPOUND MEANDER BEND MORPHODYNAMICS AND PLAINFORM MIGRATION: CONCEPTUAL FRAMEWORK ..............................................7

2.1 Introduction .................................................................................................................... 7

2.2 Compound Meander Bend Geometry ........................................................................... 8

2.3 Idealized Flow Structure, Morphology, and Planform Evolution in Meander Bends .... 11

2.4 Mean Flow (Time-averaged) Characteristics ................................................................. 12

2.5 Bend Morphology, Shear Stress and Sediment Transport—the Bar Unit ..................... 15

2.6 Estimating Bed Shear Stress in Bends ........................................................................ 19

2.7 Bank Erosion Mechanisms .......................................................................................... 22

2.8 Turbulence in Meander Bends ..................................................................................... 23

2.9 Summary and Relation to Conducted Research .......................................................... 25
CHAPTER 5 VELOCITY PROFILES AND THE STRUCTURE OF TURBULENCE AT THE OUTER BANK OF A COMPOUND MEANDER BEND

5.1 Introduction .................................................................................................................. 119

5.2 Turbulence in Meandering Rivers: Implications for Bank Erosion ......................... 120

5.3 Study Reach and Channel Evolution History................................................................ 126

5.4 Methods ......................................................................................................................... 131

5.5 Results ....................................................................................................................... 135

5.6 Discussion .................................................................................................................... 152

5.7 Conclusion ................................................................................................................... 159

CHAPTER 6 CONCLUSION .............................................................................................. 162

6.1 Summary of Findings .................................................................................................... 162

6.2 Future Work .................................................................................................................. 166

REFERENCES .................................................................................................................... 170
LIST OF FIGURES

Figure 2.1 Coordinate system definition sketch. ................................................................. 8

Figure 2.2. Plot showing meander centerline planform and continuous curvature in the canonical “Reach 2” of the Beatton River, BC (Hickin and Nanson 1975). Triangles and circles indicate local curvature maxima and inflections, respectively. Note how several of the bends have multiple curvature maximums, defining them as compound. Flow is from left to right. ......................................................... 9

Figure 2.3. Aerial images displaying various meander bend geometry combinations: (A) a simple meander bend on the Missouri River near St. Charles, MO; (B) an elongate meander bend or loop on the Taz River, western Siberia; (C) a symmetrical compound meander bend on the White River, Arkansas; and, (D) several upstream-skewed asymmetrical compound meander bends on the Purus River, Brazil. Flow in all tiles is from left to right. ........................................................................ 10

Figure 2.4. Conceptual diagram of meandering river process interactions. Arrows and associated labels describe relevant processes which contribute to each of the “legs” of the diagram. ................................................................................................................ 12

Figure 2.5. Secondary circulation patterns at an idealized simple meander bend apex. After Markham and Thorne (1992). .................................................................................. 13

Figure 2.6. Helical motion, conceptualized as streamlines connecting the curvature-induced secondary circulation in three-dimensions between cross sections progressively moving downstream. After Frothingham and Rhoads (2003). ................. 14

Figure 2.7. Curvature and bed topography influences on the boundary shear stress distribution. Centrifugal forces coupled with bed topography lead to superelevation of the water surface along the outer bank (labeled “high”) relative to the inner bank (labeled “low”). These 3-D gradients in the water surface elevation create spatial variation of the maximum bed shear from the outer bank to outer bank through consecutive bends. Dashed lines indicate bar faces. After Dietrich (1987). ...................................................................................................................... 16
Figure 2.8. Water depth in cm (A), water surface slope (B), and depth-slope product (C) in a elongate meander bend. Black lines indicate bar fronts. These data were created from figures and results from flume experiments conducted by Whiting and Dietrich (1993c).

Figure 3.1. Location map of the study site (a); planform history within the reach (b); ADV flow measurement techniques and typical channel bank vegetation characteristics (c).

Figure 3.2. Topographic maps of the study bend in 1998 (left), and 2008 (right). Note the two different sets of cross-sections for each date.

Figure 3.3. Repeat transect surveys for each of the 14 cross-sections from 1997 (dashed line), and 2008 (solid line) indicating how the study bend has migrated over the eleven year study.

Figure 3.4. Locations of the outer bank derived from repeat topographic surveys during the eleven year study.

Figure 3.5. Depth averaged flow vectors for the study bend during campaign 1 in 1998 (left) and campaign 2 in 2008 (right).

Figure 3.6. Three-dimensional perspective plot and cross-section plots for campaign 1 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical velocity vectors (arrows) for each transect where flow was measured in 1998.

Figure 3.7. Three-dimensional perspective plot and cross-section plots for campaign 2 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical velocity vectors (arrows) for each transect where flow was measured in 2008.

Figure 3.8. Bank blocks resting on the outer bank that constrict flow at the entrance to lobe 1 in campaign 2. Flow is from left to right.

Figure 3.9. Three-dimensional perspective plot and cross-section plots for campaign 1 showing turbulent kinetic energy (k) magnitudes (contours) for each transect where flow was measured in 1998.
Figure 3.10. Three-dimensional perspective plot and cross-section plots for campaign 2 showing turbulent kinetic energy (k) magnitudes (contours) for each transect where flow was measured in 2008. ................................................................. 52

Figure 3.11. Longitudinal profiles of bed topography along and parallel to the channel centerline. The values of n correspond to the distance of the profile from the centerline in a left-handed curvilinear coordinate system after (Smith and McLean, 1984) (e.g., n = 1 is 1 m to the left of the centerline). The ADV transects are also indicated for reference. ........................................................................ 56

Figure 3.12. Stabilized failed bank material on the outer bank between lobes 1 and 2. Notice colonization by vegetation, and vertical accretion of gravels. Flow is from top to bottom. .......................................................................................... 61

Figure 3.13. Conceptual model of interplay among form and process at different temporal scales in a complex meander bend. Solid arrows are direct influences and dashed arrows are feedbacks. ........................................................................ 64

Figure 4.1. Sketch of flow characteristics in high curvature bends showing location of flow separations zones. Shaded region indicates location of the point bar. After Dietrich (1987) schematic of flow in a meander with a well developed bar. ............... 70

Figure 4.2. Location map of the study site showing the planform migration history within the reach. Flow is from right to left. ........................................................................................................ 73

Figure 4.3. Ground photo of the study bend. View is looking downstream at lobe 2 from approximately 1 channel width upstream of the apex (Near topographic transect B, Figure 4.5). ................................................................. 75

Figure 4.4. Flow measurement cross sections for campaign 1 (red), campaign 2 (blue), and campaign 3 (green). Lettered topographic cross sections are also shown. Air photo taken from the 2010 National Agriculture Imagery Project (NAIP) dataset. ....... 77

Figure 4.5. Topographic map and $D_{84}$ particle size distributions of the study site on Sugar Creek, Illinois. Elevation isosurface derived from a total station survey on July 1, 2010. Sediment samples were taken March 24, 2010. Flow is from upper right to lower left. Contour interval is 20 cm, based on an arbitrary vertical datum ............... 89

Figure 4.6. Repeat topographic transects for each measurement campaign. ........................................ 93
Figure 4.7. Surveyed locations of the outer bank during the three year study. Topographic transects are also shown................................................................. 94

Figure 4.8. Depth-averaged flow vectors for the study bend during campaign 1 in 2010 (A), campaign 2 in 2011 (B), and campaign 3 in 2012 (C) .................................................. 97

Figure 4.9. Cross-section plots for campaign 1 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical vectors (arrows) for each transect where flow was measured in 2010. Thick black arrows indicate the inferred secondary circulation patterns ................................................................. 101

Figure 4.10. Cross-section plots for campaign 2 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical vectors (arrows) for each transect where flow was measured in 2011. Thick black arrows indicate the inferred secondary circulation patterns ................................................................. 102

Figure 4.11. Cross-section plots for campaign 3 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical vectors (arrows) for each transect where flow was measured in 2012. Thick black arrows indicate the inferred secondary circulation patterns ................................................................. 103

Figure 4.12. Bed shear stress vectors for the study bend during campaign 1 in 2010 (A), campaign 2 in 2011 (B), and campaign 3 in 2012 (C) superimposed on a color contour map indicating the largest sediment grain size that can be entrained at any given location for the flow conditions ................................................................. 107

Figure 4.13. Bed shear stress vectors for the study bend during campaign 1 in 2010 (A), campaign 2 in 2011 (B), and campaign 3 in 2012 (C) superimposed on a color contour map indicating the largest percentile of sediment that can be entrained at any given location for the flow conditions ................................................................. 108

Figure 4.14. Conceptual migration trajectory curves (from Hooke (2003)) plotted alongside data from Sugar Creek. The open diamond and square markers represent data computed from bank erosion and curvature changes during the study period, whereas filled diamonds and squares are derived from historical airphoto analysis of planform change over a 14 year period ................................................................. 111

Figure 5.1. Coordinate system definition sketch ................................................................. 121
Figure 5.2. Location map of the study site showing the planform migration history within the reach. Flow is from right to left. ................................................................. 127

Figure 5.3. Curvature in the study bend. Measurement cross-sections are identified with black squares. ................................................................. 128

Figure 5.4. Topographic map and \( D_{84} \) particle size distributions of the study site on Sugar Creek, Illinois. Elevation isosurface derived from a total station survey on July 1, 2010. Sediment samples were taken March 24, 2010. Flow is from upper right to lower left. Contour interval is 20 cm, based on an arbitrary vertical datum................. 130

Figure 5.5. Ground photo of the study bend. View is looking downstream at lobe 2 from approximately 1 channel width upstream of the apex (Near cross section 2-5, Figure 5.4). ................................................................. 131

Figure 5.6. ADV custom mount system being used to measure instantaneous velocity near the outer bank......................................................... 134

Figure 5.7. Cross-section plots for campaign 2 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical vectors (arrows) for each transect where flow was measured in 2011. Thick black arrows indicate the inferred secondary circulation patterns......................................................... 137

Figure 5.8. Vertical profiles of velocity and turbulence components with estimated outer bank profile (left plots) along with profiles of velocity and turbulence components expressed in terms of dimensionless depth (right plots). Time-averaged streamwise \( (u_x) \), cross-stream \( (u_n) \), and vertical \( (u_z) \) velocity components with cross-stream/vertical vectors (top); Reynolds shear stress components \( (\tau_{sz}, \tau_{sn}, \tau_{nz}) \), in kinematic units) (middle); and Reynolds normal stress components with turbulent kinetic energy \( (\tau_{sx}, \tau_{nx}, \tau_{zz}) \), in kinematic units) (bottom) for cross-section 2-5. Vertical black lines denote zero magnitudes for each measured quantity, dark blue lines denote the water surface elevation, and the shaded area denotes estimated bank geometry. ................................................................. 139
Figure 5.9. Vertical profiles of velocity and turbulence components with estimated outer bank profile (left plots) along with profiles of velocity and turbulence components expressed in terms of dimensionless depth (right plots). Time-averaged streamwise ($u_s$), cross-stream ($u_n$), and vertical ($u_z$) velocity components with cross-stream/vertical vectors (top); Reynolds shear stress components ($\tau_{sz}, \tau_{sn}, \tau_{nz}$, in kinematic units) (middle); and Reynolds normal stress components with turbulent kinetic energy ($\tau_{ss}, \tau_{nn}, \tau_{zz}$, in kinematic units) (bottom) for cross-section 2-6. Vertical black lines denote zero magnitudes for each measured quantity, dark blue lines denote the water surface elevation, and the shaded area denotes estimated bank geometry. ................................................................. 140

Figure 5.10. Vertical profiles of velocity and turbulence components with estimated outer bank profile (left plots) along with profiles of velocity and turbulence components expressed in terms of dimensionless depth (right plots). Time-averaged streamwise ($u_s$), cross-stream ($u_n$), and vertical ($u_z$) velocity components with cross-stream/vertical vectors (top); Reynolds shear stress components ($\tau_{sz}, \tau_{sn}, \tau_{nz}$, in kinematic units) (middle); and Reynolds normal stress components with turbulent kinetic energy ($\tau_{ss}, \tau_{nn}, \tau_{zz}$, in kinematic units) (bottom) for cross-section 2-7. Vertical black lines denote zero magnitudes for each measured quantity, dark blue lines denote the water surface elevation, and the shaded area denotes estimated bank geometry. ................................................................. 141

Figure 5.11. Vertical profiles of velocity and turbulence components with estimated outer bank profile (left plots) along with profiles of velocity and turbulence components expressed in terms of dimensionless depth (right plots). Time-averaged streamwise ($u_s$), cross-stream ($u_n$), and vertical ($u_z$) velocity components with cross-stream/vertical vectors (top); Reynolds shear stress components ($\tau_{sz}, \tau_{sn}, \tau_{nz}$, in kinematic units) (middle); and Reynolds normal stress components with turbulent kinetic energy ($\tau_{ss}, \tau_{nn}, \tau_{zz}$, in kinematic units) (bottom) for cross-section 2-8. Vertical black lines denote zero magnitudes for each measured quantity, dark blue lines denote the water surface elevation, and the shaded area denotes estimated bank geometry. ................................................................. 142

Figure 5.12. Vertical profiles of velocity and turbulence components with estimated outer bank profile (left plots) along with profiles of velocity and turbulence components expressed in terms of dimensionless depth (right plots). Time-averaged streamwise ($u_s$), cross-stream ($u_n$), and vertical ($u_z$) velocity components with cross-stream/vertical vectors (top); Reynolds shear stress components ($\tau_{sz}, \tau_{sn}, \tau_{nz}$, in kinematic units) (middle); and Reynolds normal stress components with turbulent kinetic energy ($\tau_{ss}, \tau_{nn}, \tau_{zz}$, in kinematic units) (bottom) for cross-section 2-9. Vertical black lines denote zero magnitudes for each measured quantity, dark blue lines denote the water surface elevation, and the shaded area denotes estimated bank geometry. ................................................................. 143
Figure 5.13. Vertical profiles of the contribution of each fluctuation component to the total $k$ upstream (A) and downstream (B) of the failed bank material. .......................... 149

Figure 5.14. Annotated photographs of the outer bank of the study bend showing characteristic bank material profiles in lobe 2 (A), and lobe 1 (B). Example of hydraulic erosion of sands in lobe 2 (C). Failed bank material with intact grasses resting along the outer bank of lobe 2 (D). ................................................................. 152

Figure 5.15. Conceptual model of turbulence at the outer bank of a meander bend upstream of the apex (A), at the apex (B), and downstream of the apex (C). Also shown in the effect of a bank block on the flow turbulence downstream of the apex (C2). Graphs on the right represent idealized vertical profiles of Reynolds shear stresses and turbulent kinetic energy. ................................................................. 158
LIST OF TABLES

Table 3.1. Average migration rates at each of the 14 channel transects................................. 40

Table 3.2. Dimensionless radius of curvature values for the channel during both campaigns. Note that $H$ is the mean hydraulic depth for each measurement date respectively. .............................................................................................................. 46

Table 3.3. Deviation angles of the flow to the channel centerline.............................................. 55

Table 4.1. Summary of hydraulic characteristics for the study bend.......................................... 78

Table 4.2. Mean bank erosion rates, and total erosion distances for each of the 13 topographic cross sections. .................................................................................................................. 90

Table 4.3. Dimensionless radius of curvature values at flow measurement locations for each campaign. Transect locations are shown in Figure 4.4. Note that $r$ is radius of curvature. .................................................................................................................. 92

Table 5.1. Summary of existing literature on outer bank turbulence in meandering channels.................................................................................................................. 123

Table 5.2. Depth-averaged contributions of each fluctuation component to the total $k........... 150$

Table 5.3. Relative proportion of ensemble-averaged turbulent normal stresses for each cross section .................................................................................................................. 154
CHAPTER 1
INTRODUCTION

1.1 Motivation

River meanders are ubiquitous features of many alluvial networks, and yet the processes underlying dynamic changes within meander bends are not fully understood (Rhoads and Welford 1991). The interaction among channel morphology, turbulent flow structure, and sediment transport often produces complex meander planforms that evolve through lateral and downstream channel migration. As meanders migrate, sinuosity and curvature tend to increase, forming elongate bends with multiple curvature maximums otherwise known as compound bends or loops (Frothingham and Rhoads 2003). Flow moving through simple meander bends is highly three dimensional (Dietrich 1987); however, the relationship among 3-D flow structure, turbulence characteristics, and planform evolution in compound bends is poorly understood. In particular, current understanding of the structure of turbulence near the outer bank of meandering rivers, which should be closely related to the erosional forces acting on the bank, is incomplete. Spatial patterns of turbulence near the outer bank likely are modified by the upstream inherited flow structure, roughness elements such as failed blocks of bank material, local planform curvature, and flow stage. Few, if any, studies have examined the structure of near-bank turbulence in a field setting or the connections among turbulence, outer bank stresses, and patterns of bank erosion. Improved knowledge of near-bank turbulence is important for developing accurate theoretical models for predicting the planform evolution of meandering rivers.
An underlying assumption of many theoretical models of planform evolution is that erosion of the outer banks occurs as an empirical function of near bank velocity (Ikeda, Parker and Sawai 1981, Parker, Sawai and Ikeda 1982, Blondeaux and Seminara 1985, Johannesson and Parker 1985). In some models, bank shear stresses are computed by a closure using a dimensionless friction factor, and erosion resulting in movement of the channel centerline is determined using an empirically fitted migration coefficient (Hasegawa 1989). Linear meander migration models incorporating such simple representations of bank erosion have been used to successfully simulate the planform evolution of natural rivers (e.g., Parker and Andrews 1986); however complex planform patterns, such as compound bends, cannot be predicted by simple linear models (Güneralp and Rhoads 2009). More recently, RVR Meander, a basic linear model of planform migration (Abad and Garcia 2006), has been coupled with the CONCEPTS model of bank retreat and failure (Langendoen and Alonso 2008, Langendoen and Simon 2008, Langendoen et al. 2009). The coupling of physically-based modeling of bank erosion with 2-D depth-averaged modeling of flow in curved channels yields predictions of planform migration that include the development of complex meander forms, such as compound loops (Motta et al. 2012). Yet this coupled model still neglects the effects of turbulence near the outer bank of meander bends on the distributions of stresses acting on the bank face and toe. Additionally, most models of channel migration consider planform evolution in a temporally averaged sense, using a single flow, usually the bank full discharge, and a constant width to represent channel change. Only recently have approaches incorporated methods allowing the channel to evolve with non-uniform widths, and/or unsteady flood hydrographs (Parker et al. 2011, Pittaluga and Seminara 2011, Motta et al. 2012, Asahi et al. 2013). Despite these advances, most models simplify bend hydrodynamics by employing 2-D layer-averaged equations of mean flow, and
thus cannot account for turbulence generation in the near-bank boundary layer from bank roughness elements or inherited flow structure, which may greatly influence shear stresses, sediment transport at the bank toe, and ultimately migration rates (Blanckaert and de Vriend 2005a). Though these models serve as an important step in understanding planform evolution, they are oversimplifications of a complex, dynamic system. To better understand the influences of bank roughness and turbulence on shear stress distributions and planform evolution in compound bends, direct measurement of the flow in the field is necessary. Though some recent work has begun to examine flow three dimensionality within compound meander loops in field situations (Frothingham and Rhoads 2003), the role of turbulence and near-bank roughness have not been considered. The effects of channel curvature and secondary circulation should produce turbulence characteristics in bends that differ substantially from those in straight channels (Blanckaert and de Vriend 2005a, Abad and Garcia 2009a). Distinctive patterns of near outer bank turbulence should affect sediment transport distributions, bed morphology and bend evolution through time. Investigations of the connection between near-bank flow and bank erosion are needed to develop a refined theoretical understanding of meander dynamics and to formulate improved process-based models of planform evolution.

The purpose of this research is to explore process interactions among the time-averaged three-dimensional velocity field, bed shear stress, near-bank turbulence, bank erosion, and planform evolution in compound meander bends. A critical need exists for field studies to evaluate and inform current theoretical models of channel change in river meanders. Moreover, detailed field studies of compound meander bends are rare, and this research is an important contribution towards generating a more comprehensive explanation of the process dynamics of these complex meander forms.
1.2 Research Questions

The ultimate goal of this research is to produce an improved understanding of the complex process dynamics of river meandering by evaluating the interaction among mean flow patterns, turbulence production and structure, bank characteristics, channel planform, and flow stage in compound meander bends. Specific research questions that are addressed are:

1. How do the 3-D turbulent flow structure, bed morphology, bank failures, and channel planform in a compound meander bend co-evolve over the timescale of planform change?
2. What is the relationship between near outer-bank flow turbulence, and long-term planform evolution in a compound meander bend?
3. What is the effect of stage variation on the patterns of sediment entrainment, development of channel morphology and patterns of bank erosion in a compound bend?
4. What is the spatial structure of turbulence near the outer bank of a compound meander bend, and how does this structure vary spatially in relation to the evolving pattern of the three-dimensional flow (time-averaged velocities) as water moves through the bend?

This research elucidates process interactions occurring among channel form, flow, and near-bank processes that drive planform evolution in compound loops. The results and interpretations of the study inform current theories of meander migration, and advance the understanding of flow turbulence in complex, natural river settings.

1.3 Research Organization

Compound meander bends arise from complex interactions between fluid dynamic forces on deformable channel boundaries (bed and banks), and planform evolution processes over a large range of spatial and temporal timescales. To put the research questions into context, Chapter 2 provides a brief review of the literature concerning meander dynamics and planform
migration. The chapter starts by reviewing flow and morphology processes in simple bends. It then continues to expand on this understanding for the specific case of compound bends. Finally, gaps in our understanding of compound bend dynamics are highlighted in the context of the research questions.

Chapter 3 describes the interactions between mean flow structure, turbulence, and planform evolution observed in a compound meander bend on the Embarras River, a small creek in Champaign County, Illinois. By investigating the patterns of mean flow characteristics and turbulent statistics throughout the bend at two time periods a decade apart, the contribution of local planform and channel bed configurations to the ultimate evolution of the bend through time is evaluated.

Chapter 4 builds on the findings of Chapter 3 by evaluating the relationships between the structure of the mean flow, bed shear stress magnitudes, and short-term bank migration patterns in a compound meander bend on Sugar Creek, a meandering stream in McLean County, Illinois. By analyzing detailed measurements of the mean flow at three different flow stages, the study evaluates how dimensionless curvature—which varies with depth— influences the structure of the mean flow, patterns of bed shear stress, and sediment entrainment in compound meander bends.

Chapter 5 focuses on the mechanisms of planform evolution by examining velocity profiles and Reynolds stress distributions near the outer bank of a compound meander bend. The structure of turbulence near the outer bank of compound meander bends is investigated by analyzing instantaneous velocities measured via Acoustic Doppler Velocimeters (ADV) in a compound bend on Sugar Creek, Illinois (the same bend studied in Chapter 4). Insights about outer bank erosion, and the relations among the structure of near-bank turbulence, the pattern of
three-dimensional flow through the bend, and the influence of near-bank obstacles, such as failed blocks of bank material, enable development of a conceptual model of turbulence characteristics in the outer bank region of meander bends.

Chapter 6 summarizes the main findings of this research and offers direction for future work. The main research outcomes are discussed in terms of the stated research questions. Limitations and challenges encountered in the field research are discussed. Finally, the chapter closes with potential directions for future research derived from knowledge gained in this study.
CHAPTER 2
COMPOUND MEANDER BEND MORPHODYNAMICS AND PLANFORM
MIGRATION: CONCEPTUAL FRAMEWORK

2.1 Introduction

Complex meander planforms like compound meander bends are a ubiquitous feature of lowland alluvial channel systems (Allen 1984, Seminara 2006, Güneralp and Rhoads 2008, Seminara 2010, Guneralp and Rhoads 2011). Despite a considerable amount of research on the coevolution of flow structure, channel morphology, and planform migration, the complex dynamics that create these elegant forms are not yet fully understood. The purpose of this chapter is not to provide a comprehensive review of the literature on meandering rivers, but instead to examine in detail topics relevant to the objectives of research on compound meander bends (see chapter 1). These topics include the geometric characteristics of compound bends; flow structure, morphology and planform evolution in meander bends; estimating shear stress in meander bends; bank erosion in meandering rivers; and turbulence in meander bends.
2.2 Compound Meander Bend Geometry

Figure 2.1 Coordinate system definition sketch.

The characteristic geometry of meander bends can be described using a right-handed modified cylindrical coordinate system with a streamwise axis \( (s) \) along the channel centerline, cross-stream axis \( (n) \) normal to \( s \) positive in the left direction, and a vertical axis \( (z) \) (Figure 2.1). Using this frame of reference, channel curvature \( (C) \) at any location along the centerline can be expressed as a function of the angle of the centerline to the down-valley direction \( (\alpha) \):

\[
C = \frac{\partial \alpha}{\partial s} = r^{-1}
\]  

(2.1)

The simplest way to characterize meander curvature is to fit circles with various radii \( (r) \) to each bend (or lobe) centerline (Brice 1974, Hickin and Nanson 1975). A limitation of this method is that it assumes curvature is constant through an arc-fitted bend, and discontinuous between adjacent bends (Güneralp and Rhoads 2008). Rates of change in curvature \( (\partial \alpha / \partial s) \) can be determined from discrete linearization of the change in direction along a centerline (Hickin and Nanson 1975, Howard and Hemberger 1991), but this approach is highly sensitive to the digitization interval. A superior approach is to compute a continuously differentiable curvature series of a meander centerline from fitting piecewise cubic splines to appropriately digitized
discrete centerline coordinates (Güneralp and Rhoads 2008). In this manner, continuous curvature of the channel centerline becomes a function of the first and second derivatives (prime and double-prime marks respectively) of the Cartesian coordinates \((x, y)\) of the centerline (Figure 2.2):

\[
C = \frac{x'y'' - y'x''}{(x'^2 + y'^2)^{3/2}}
\]

Figure 2.2. Plot showing meander centerline planform and continuous curvature in the canonical “Reach 2” of the Beatton River, BC (Hickin and Nanson 1975). Triangles and circles indicate local curvature maxima and inflections, respectively. Note how several of the bends have multiple curvature maximums, defining them as compound. Flow is from left to right.

Meander bend geometry can be classified into four categories based on arcs of curvature observed in the planform of the channel centerline (Brice 1974, Frothingham and Rhoads 2003). If the bend can be generalized with a single arc of curvature (i.e., only one local maximum), and the absolute value of the angles of the centerline to the downvalley direction \(|\alpha|\) sum to less than 180°, it is a simple bend (Figure 2.3A), whereas if the angle sums to 180° or greater, it is an elongate bend (or loop, Figure 2.3B). A meander is considered a compound bend or loop when it contain multiple local curvature maxima (i.e., more than one arc of curvature between inflection points), and \(|\alpha|\) is 180° or more (Frothingham and Rhoads 2003). Meandering channels in alluvial, unconstrained valleys often tend to develop multilobe forms (i.e., compound loops)
(Hooke 1995). The most basic multilobe shape comprises of two lobes having equal radii of curvature, termed a symmetrical compound bend (Figure 2.3C). If the radii of curvature are not equal within a multilobed meander, it is termed an asymmetrical compound bend (Figure 2.3D). Asymmetrical compound meander bends are common planform configurations. One of the first studies to discuss this planform in the literature was Kinoshita (1961), who described meander loops which tended to skew upstream in their valleys (i.e., the lobe with the lower value of $r$ is positioned upstream). The bends in “Reach 2” of the Beatton River (Figure 2.2) and the Purus River, Brazil (Figure 2.3D) display this upstream-skewed planform characteristic (Hickin and Nanson 1975).

Figure 2.3. Aerial images displaying various meander bend geometry combinations: (A) a simple meander bend on the Missouri River near St. Charles, MO; (B) an elongate meander bend or loop on the Taz River, western Siberia; (C) a symmetrical compound meander bend on the White River, Arkansas; and, (D) several upstream-skewed asymmetrical compound meander bends on the Purus River, Brazil. Flow in all tiles is from left to right.
2.3 Idealized Flow Structure, Morphology, and Planform Evolution in Meander Bends

Flow structure in river meanders is a function of the resultant forces caused by channel curvature, curvature changes, and bed topography. Flow response to these controlling factors determines the distribution of boundary shear stresses, and thus sediment transport rates and planform evolution patterns. Though implicitly linked, the time scales over which flow, bed, and planform responses operate are considerably different, with flow responding much quicker than sediment transport and planform evolution (Figure 2.4). In the following sections, each sub-process is described individually to give an overall understanding of the dynamics of river bends. Special attention is given to the case of compound meander bends.
2.4 Mean Flow (Time-averaged) Characteristics

Meander bend curvature has a strong impact on the time-averaged velocity field through flow response to local curvature. As flow enters a bend, the local curvature of the channel boundaries (i.e., banks) results in a centrifugal force on the flow directed outward perpendicular to the channel centerline. This centrifugal force leads to superelevation of the water surface along the outer bank, and a cross-stream gradient of the free surface toward the inner bank (Bridge and Jarvis 1976, Bridge and Jarvis 1982). This cross-stream gradient generates an inward-directed opposing pressure gradient force that counterbalances the outward-directed
centrifugal force. However, due to boundary resistance, the centrifugal force near the bed, where velocities are low, is less than the pressure-gradient force and the flow is directed inward. Conversely, the centrifugal force near the surface, where velocities are high, exceeds the pressure-gradient force, and here flow is directed outward. The local imbalance of the centrifugal and pressure-gradient forces through the water column results in secondary circulation in the plane of the cross section (Figure 2.5), which in three dimensions results in large-scale helical motion of the flow as it moves through the bend (Figure 2.6). This pattern of flow through bends has been documented both experimentally (Rozovskii 1957, Einstein and Shen 1964, Whiting and Dietrich 1993b, Whiting and Dietrich 1993c, Whiting and Dietrich 1993a, Blanckaert and Graf 2001, Blanckaert and de Vriend 2004, Blanckaert and de Vriend 2005a, Peakall, Ashworth and Best 2007, Abad and Garcia 2009a, Abad and Garcia 2009b, Termini 2009, Jamieson, Post and Rennie 2010, Blanckaert 2011), as well as in field studies (Hey and Thorne 1975, Jackson 1975, Bathurst, Thorne and Hey 1979, Dietrich, Smith and Dunne 1979, Dietrich 1987, Frothingham and Rhoades 2003, Engel and Rhoads 2012, Sukhodolov 2012).

**Figure 2.5.** Secondary circulation patterns at an idealized simple meander bend apex. After Markham and Thorne (1992).
Figure 2.6. Helical motion, conceptualized as streamlines connecting the curvature-induced secondary circulation in three-dimensions between cross sections progressively moving downstream. After Frothingham and Rhoads (2003).
2.5 Bend Morphology, Shear Stress and Sediment Transport—the Bar Unit

Distortion of the water-surface topography associated with flow through bends (i.e., superelevation) creates lateral variations in streamwise water surface gradients across the channel, which, in turn, produce both lateral and longitudinal variations in boundary shear stresses and patterns of erosion and deposition (Figure 2.7). Superelevation of the water surface due to curvature causes water surface gradients along the outer bank of a meander to be steeper than the gradient along the inner bank downstream of the bend apex (Figure 2.7). Upstream of the apex, water surface gradients are steeper along the inner bank than along the outer bank. Thus, along the outer bank, water surface gradients and bed shear stresses ($\tau_b$) increase around the bend apex, resulting in scour and the formation of a pool, while gradients and shear stress decrease along the inner bank, leading to the formation of a point bar. When considered through an entire bend sequence, shear stress maxima are routed from the inner to the outer banks of subsequent bends. Thus, there is a spatial variation in the boundary shear stress through the bend, leading to increases in shear stress along the outer bank pool, and decreases in shear stress along the inner bank.
Figure 2.7. Curvature and bed topography influences on the boundary shear stress distribution. Centrifugal forces coupled with bed topography lead to superelevation of the water surface along the outer bank (labeled “high”) relative to the inner bank (labeled “low”). These 3-D gradients in the water surface elevation create spatial variation of the maximum bed shear from the outer bank to outer bank through consecutive bends. Dashed lines indicate bar faces. After Dietrich (1987).

The spatial distribution of shear stresses, deposition, and scour through successive bends generates the familiar pool-riffle bed morphology (Keller 1971, Beschta and Platts 1986, Wohl 2007). However, a genetic linkage of the bed morphology from the pool at the upstream bend apex to the point bar at the downstream apex has been recognized in the definition of a linked bar unit morphology (Dietrich 1987) (Figure 2.7). The topographic low of the upstream bend is the beginning of a unit, which shoals into an oblique bar front in the downstream bend. Bar-unit morphology accentuates secondary currents by topographically deflecting, or forcing, flow laterally toward the outer bank (Dietrich and Smith 1983). This flow convergence enhances the bed shear stress and scour in the pool near the outer bank.

Bar units represent a fundamental morphological form in meandering rivers. Whereas bar units in simple bends (Figure 2.3A) alternate from bank to bank; bar units in elongate and compound bends (Figure 2.3B, C, D) wrap around the same bank, creating so-called “shingle” bar forms (Kinoshita 1961, Whiting and Dietrich 1993b, Abad and Garcia 2009b, Termini 2009) (Figure 2.8). Multiple pools develop along the concave bank, with the deepest scour located upstream of the apex (Figure 2.8A). Water surface gradients increase laterally, as in a simple bend, with the highest gradients located at the pool-bar front interfaces (Figure 2.8B). Comparing
the trend of the depth-slope product (Figure 2.8C), which is proportional to shear stress, with the pool locations indicates that patterns of scour mirror patterns of high shear stress. The influence of this spatial variation in water surface gradients and shear stresses on bank erosion and planform evolution is potentially significant, but has yet to be explored in detail. Moreover, the structure of bar units in compound bends may be strongly influenced by spatially varying channel curvature associated with the development of distinct lobes within such bends. Spatial variation in curvature and corresponding variation in water surface topography through a series of lobes can produce spatial variation in bed shear stress, resulting in distinctive patterns of erosion and deposition on the channel bed. In an upstream skewed orientation (upstream lobe has higher curvature than downstream lobe), bar expression is greatest upstream of the apex, and the between bar units are indistinct (Abad and Garcia 2009b). In a downstream skewed orientation (downstream lobe has higher curvature than upstream lobe), bar units are more clearly defined than for the upstream skew case, and pool scour is greatest at the locus of maximum curvature (Abad and Garcia 2009b). Thus, elongate, compound bends characterized by multiple lobes of maximum curvature may have multiple loci of bank erosion, which should promote complex patterns of bend evolution, including the development of asymmetrical compound forms.
Figure 2.8. Water depth in cm (A), water surface slope (B), and depth-slope product (C) in an elongate meander bend. Black lines indicate bar fronts. These data were created from figures and results from flume experiments conducted by Whiting and Dietrich (1993c).

Cohesionless particle entrainment (i.e., sediment transport) occurs when the balance between drag, lift, and buoyant forces acting upon a grain is overcome (Shields 1936). Convective acceleration of the streamwise and cross-stream flow brought about by the alternating topography (i.e., bar units) in successive bends produces distinctive spatial variation in bed shear stress fields. In particular, the zone of maximum bed shear stress shifts from the inner to outer bank as flow through moves the bend apex (Figure 2.7) (Dietrich and Smith 1983, Dietrich and Whiting 1989, Clayton and Pitlick 2007). Helical motion induced by the interaction between centrifugal and pressure-gradient forces produces an inward-directed component of shear stress near the bed in the central region of the channel. Shoaling of flow along the inner bank as it moves over the point bar leads to lateral deflection of the flow toward the pool. Thus near-bed velocity and shear-stress vectors usually have an outward-directed component as flow is topographically deflected around the bar (Dietrich and Smith 1983). On a cross-stream sloping bed, body forces also have a cross-stream component that is proportional to the cube of the grain diameter, whereas lift and drag forces are proportional to the square of grain diameter. Therefore, for the same bed shear stress, large grains will tend to move outward, and small grains inward.
(Odgaard 1981, Ikeda 1984, Parker and Andrews 1986, Dietrich 1987, Nelson and Smith 1989). In gravel bed meandering rivers, where most bed material is only mobilized at high stages, downstream reductions or increases in shear stress magnitudes are a primary mechanism for sediment sorting (Clayton 2010, Clayton 2012). Coarse material unable to transit the bar top in decreasing shear stresses should move outward toward the point bar “crest”, where it may avalanche into the pool to be transported downstream by high shear stresses. Equilibrium morphology is obtained when the point bar side slope allows just enough inward directed cross-stream shear stress to sweep fine sediment inward while coarse sediment avalanches outward to be transported by higher stresses in the thalweg (Dietrich and Smith 1984).

2.6 Estimating Bed Shear Stress in Bends

In straight, open-channel uniform flows, bed shear stress is often expressed as a magnitude. However, in reality the bed shear stress is a vector quantity, having both a magnitude and direction. In a meander bend, with curvature-induced secondary circulation, shear stress acting on the channel bed will have a component that is not necessarily in the streamwise direction, but is instead directed inward due to inward directed near-bed flow. Therefore, to model grain entrainment in a bend, it is necessary to treat the bed shear stress as a vector, having components in the streamwise (s) and cross-stream (n) directions. Several approaches to quantify bed shear stress ($\tau_b$) have been used in natural channels (Whiting and Dietrich 1990, Wilcock 1996, Biron et al. 2004). These methods include estimating boundary shear from turbulent statistics, logarithmic law of the wall, and quadratic stress approximations. The first method requires direct measurement of the instantaneous velocities at a point close to the bed for an extended period of time. Fluctuations of the instantaneous velocities about the mean are used to quantify the near-bed Reynolds shear stresses responsible for exerting shear force to the bed.
(i.e., $\tau_b \equiv -\rho \overline{u_z' u_z'}$, where $\rho$ is fluid density, and $u_z'$, $u_z'$ denote fluctuations of velocity from the mean in the $s$ and $z$ directions respectively). The second method estimates bed shear stress from the gradients of velocity occurring over a range of height from the bed ($z$) where the velocity profile is logarithmic and can be described by the “law of the wall”:

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \left( \frac{z}{z_o} \right)$$

(2.3)

where $u_* = \sqrt{\tau_b/\rho}$ is the shear velocity, $\kappa = 0.41$ is the von Karman constant, and $z_o$ is a small positive roughness height above the bed where velocity goes to zero (no-slip condition). In cases where the assumption of a logarithmic velocity profile is confirmed, $u_*$ and thus $\tau_b$ can be computed from measurements of velocity over depth by simple linear regression of $\ln(u)$ against $z$. This method is highly sensitive to variations in roughness and the presence of secondary circulation, which may produce non-logarithmic velocity profiles (Wilcock 1996). The latter problems usually make it a poor choice for determining bed shear stresses in meander bends. The final approach is to relate the bed shear stress ($\tau_b$) to the 2-D depth-averaged flow (represented as a vector $\mathbf{U}$ having streamwise $U_s$ and cross-stream $U_n$ component magnitudes) based upon a quadratic formulation of the relationship between roughness and the flow velocity:

$$\|\tau_b\| = \rho C_f \|\mathbf{U}\|^2$$

(2.4)

where $\rho$ is the fluid density,

$$\|\mathbf{U}\| = \sqrt{U_s^2 + U_n^2}$$

(2.5)

and $C_f$ is a roughness coefficient that can be computed using the Manning-Strickler formula (or other similar friction equation):

$$C_f = \left[ \alpha_r \left( \frac{H}{k_s} \right) \frac{1}{3} \right]^{-2}$$

(2.6)
where $\alpha_r$ is set equal to 8.1 (Parker 1991), and $k_s$ equal to $2.95D_{b4}$ as specified by Whiting and Dietrich (1990). The magnitude of the streamwise component of bed shear stress ($\tau_{bs}$) can be found by taking the scalar projection of $\vec{\tau}_b$ on the $s$ axis:

$$\tau_{bs} = \|\vec{\tau}_b\| \cos \theta = \rho C_f \|\vec{U}\| \|\vec{U}\| \cos \theta$$  \hspace{1cm} (2.7)

where $\theta$ is the angle between the vector $\vec{\tau}_b$ and the streamwise direction. Noting that $U_s = \|\vec{U}\| \cos \theta$, Equation (2.7) can be rewritten as:

$$\tau_{bs} = \rho C_f U_s \sqrt{\frac{U_s^2}{U_s^2 + U_n^2}}$$  \hspace{1cm} (2.8)

Likewise, the magnitude of the cross-stream component of bed shear stress ($\tau_{bn}$) can be found as:

$$\tau_{bn} = \rho C_f U_n \sqrt{\frac{U_n^2}{U_s^2 + U_n^2}}$$  \hspace{1cm} (2.9)

noting that $U_n = \|\vec{U}\| \cos \phi$, and $\phi = 90^\circ - \theta$. This method of computation of bed shear stress is less sensitive than the “law of the wall” linear regression model because it relies on depth-averaged velocities and is calibrated by measures of the channel roughness. Additionally, if two- or three-dimensional velocities are measured over the flow depth, this method allows for easy computation of the components of shear stress as a vector quantity. However, implicit in the quadratic approach is the assumption that a logarithmic profile exists. This assumption may not hold in meander bends, where strong secondary circulation changes the shape of the velocity profiles. Nevertheless, this method can give valuable insight into the likely shear stress field occurring in natural alluvial channels, so long as the assumptions in the method are acknowledged.
2.7 Bank Erosion Mechanisms

To produce planform migration, the channel banks must retreat. Conceptual models of bank retreat typically emphasize interactions among hydraulic forces acting on the bank toe, geotechnical forces, and gravitational forces acting on the bank itself (Carson and Kirkby 1972, Thorne et al. 1998). Cohesionless material at the bank toe is removed by fluvial entrainment, increasing the height and angle of the adjacent bank until mass failure occurs. The most common streambank failure mechanism is planar failure, where bank material calves off along a single plane (Thorne et al. 1998). The likelihood of failure depends on several factors, including the type of bank material, specific weight, apparent cohesion due to matric suction, and extant porewater pressures of the potential failure (Simon et al. 2000, Wood et al. 2001). Some researchers have produced models of bank retreat that incorporate these hydraulic, geotechnical, and gravitational processes (Darby and Thorne 1994, Langendoen and Alonso 2008, Langendoen and Simon 2008), and Darby and Delbono (2002) have applied a model to meander bends with limited success. As understanding of the physical processes involved in bank failure has increased, so has the sophistication of modeling approaches. Probably the most advanced model of bank failure and channel erosion/deposition processes to date is the CONservational Channel Evolution and Pollutant Transport System model, or CONCEPTS (Langendoen and Alonso 2008, Langendoen and Simon 2008, Langendoen et al. 2009). CONCEPTS, while employing a relatively simple 1-D unsteady flow approximation, is capable of modeling sediment transport, channel widening, and near-bank channel restoration outcomes for alluvial channels. Recently, the CONCEPTS model has been combined with a long-term model of channel migration, RVR Meander (Abad and Garcia 2006), to simulate 2-D flow and channel centerline migration (Motta et al. 2012). This combined modeling approach successfully simulates complex meander forms.
such as high skewness, sharp necks, and compound meander bends with multiple lobes of curvature (Motta et al. 2012). A limitation of current models of meander migration is that these models do not directly include the influence of near-bank turbulence on bank erosion, nor do they address the interaction between failed bank material and turbulent flow near the bank. Near-bank turbulence is likely to influence initial bank failures and blocks of failed cohesive material that accumulate along the base of the bank may substantially alter turbulence near the bank, which should influence fluid forces acting on the bank and the capacity of the flow to remove accumulated material.

2.8 Turbulence in Meander Bends

Natural channel flows are typically fully-developed turbulent flows, and thus turbulent fluctuations (and turbulent stresses) are a primary means for redistributing momentum throughout the fluid (Nezu and Nakagawa 1993). Furthermore, fluid turbulence plays a critical role in the transport and dispersal of sediment, nutrients, and pollutants in the flow (Jamieson et al. 2010, Paiement-Paradis, Marquis and Roy 2011). Meanders produce highly three-dimensional mean flow characteristics due to curvature-induced secondary circulation, and therefore the structure and patterns of turbulence and momentum transfer should be different in meandering channels than in straight channels (Blanckaert and De Vriend 2005b).

In fully-developed turbulent straight channel flows, streamwise momentum dominates the generation of bed turbulence. The structure of turbulence in straight channels is characterized by 1) vertical profiles of turbulent kinetic energy ($k = 0.5[u'_{x}^{2} + u'_{n}^{2} + u'_{z}^{2}]$) and turbulent intensities ($u'_{i}$) that increase exponentially with depth, and 2) dominance of the streamwise turbulent stresses over the other stress components (Nezu and Nakagawa 1993, Blanckaert and Graf 2001). Experimental work in fully developed turbulent flow in straight, rectangular
channels has shown that $\overline{u'_5 u'_n, u'_n u'_z} \ll \overline{u'_z u'_z}$ and $\overline{u'^2_n/u'^2_s} = 0.51$ and $\overline{u'^2_z/u'^2_s} = 0.34$ respectively (Nezu and Nakagawa 1993). In contrast to straight channels, curvature-induced secondary circulation introduces a strong transverse shear component in meandering channels. The result of this added transverse advection of turbulent momentum is that typically all three shear stress components are of similar magnitude, and cross-stream turbulent intensities and normal stresses become the dominant contributor to the overall turbulent kinetic energy (Blanckaert and Graf 2001, Jamieson et al. 2010, van Balen, Blanckart and Uijttewaal 2010, Blanckaert et al. 2012a). Whereas in riffles, shear stress profiles may be linear over the entire flow depth, in pools vertical forcing of the flow and submergence of the high velocity core limit the region of linear shear stress profiles to the region between the bed and locus of highest velocities (Sukhodolov 2012). This finding is in general agreement with the experimental findings of Jamieson et al. (2010) and Blanckaert (2009). Whereas in the field study of Sukhodolov (2012) and in the flume experiment by Blanckaert and Graf (2001), streamwise-vertical shear stresses were the dominant contributor to the total stresses, the streamwise–cross-stream stresses were the dominant contributor at and downstream of the apex in Blanckaert (2009) and Jamieson et al. (2010). Vertical forcing of the flow by bed topography in natural meandering rivers with well-developed riffles and pools may strongly influence the structure of turbulence in bends, but further research in meandering rivers with varying width to depth ratios is needed to establish the validity of this hypothesis.

Our understanding of turbulence in the outer bank region of meander bends—where erosion of bank material by hydraulic action causes meander migration—is incomplete. The development of a comprehensive understanding of outer bank turbulence in bends is complicated by contradictory findings from experimental work. Some studies have shown that reduced
turbulence (as indicated by reduced turbulent kinetic energy, intensities, and absolute magnitudes of Reynolds stresses) at the outer bank relative to the adjacent thalweg flow are caused by the development of a weak outer bank circulation cell, having lower streamwise velocities than in the channel thalweg (Blanckaert and Graf 2001, Blanckaert et al. 2012a). In these studies, the outer bank cell acts as a buffer between the higher momentum flow in the main channel, and the lower momentum flow in the outer bank region, protecting the outer bank from impinging high momentum flow. Other experimental studies in curved channels have reported increased outer bank turbulence, in part due to the interaction of the mean flow with a developed bed morphology that topographically forced high momentum fluid into the outer bank region (Abad and Garcia 2009a, Abad and Garcia 2009b, Jamieson et al. 2010).

2.9 Summary and Relation to Conducted Research

The interactions among the flow structure—including the characteristics of turbulence, outer bank erosion, and planform migration in complex meander geometries like compound meander bends are not fully understood. Although flume experiments have advanced our understanding of the dynamics of complex meander geometries, due to their fixed banks these studies cannot extrapolate their findings beyond the time scales of bank erosion processes. Thus, examination of flow structure evolution over the timescale of planform migration processes is necessary to verify meander migration model assumptions. Chapter 3 examines the relative contribution of local curvature changes influences on mean flow structure to bank erosion in a compound bend over the timescale of planform evolution.

Chapter 4 investigates the influence of differing flow stages on the bed shear stress field and sediment entrainment potential in a compound meander bend. Patterns of the mean flow
structure and sediment entrainment potential are then related to short-term patterns of bed morphology change and bank erosion.

Very little is known about the structure of turbulence in the outer bank region of compound meander bends. Although a few studies have investigated outer bank turbulence in constant curvature flumes, it is unclear how these experimental findings translate to multilobed planform geometries with erodible banks. Moreover, no unified conceptual model of outer bank turbulence in meandering rivers exists to date. In Chapter 5, the structure of turbulence in the outer bank region of a compound meander bend is investigated, and a generalized conceptual model of outer bank turbulence is presented.
CHAPTER 3

INTERACTION AMONG MEAN FLOW, TURBULENCE, BED
MORPHOLOGY, BANK FAILURES AND CHANNEL PLANFORM IN AN
EVOLVING COMPOUND MEANDER BEND

3.1 Introduction

Meandering is a ubiquitous characteristic of rivers (Allen 1984, Howard 1992, Seminara 2006), yet the processes underlying dynamic changes in meandering rivers are not fully understood (Rhoads and Welford 1991, Abad and Garcia 2009a). The interaction among channel morphology, turbulent flow structure, and sediment transport frequently produces complex meander planforms that evolve through lateral and downstream channel migration (Hooke 1995, Seminara 1998, Seminara 2006). As meanders migrate, they often tend to increase in sinuosity and curvature, forming elongate bends with multiple maxima of curvature, otherwise known as compound loops (Frothingham and Rhoads 2003). Flow moving through simple meander bends is highly three dimensional (Bathurst et al. 1979, Dietrich et al. 1979, Rhoads and Welford 1991) as has been confirmed by numerous process-based field studies of time-averaged flow structure in simple bends with a single maximum of curvature and bed morphology consisting of a pool along the outer bank and point bar along the inner bank (Thorne and Hey 1979, Dietrich and Smith 1983, Thorne et al. 1985, Markham and Thorne 1992). In contrast, the relationship among 3-D turbulent flow structure, bank erosion, and planform evolution in

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compound loops, while likely more complex than in simple bends, is poorly understood. Studies focusing on flow in elongate, compound loops have been limited mainly to flume experiments (Whiting and Dietrich 1993b, Whiting and Dietrich 1993c, Whiting and Dietrich 1993a, Abad and Garcia 2009a, Abad and Garcia 2009b, Termini 2009). None of these investigations has included erodible banks, and only one (Abad and Garcia 2009a) has examined patterns of turbulence in this type of meander bend.

Bed morphology in curved channels with mobile substrates is strongly linked to patterns of flow through bends. As flow enters a bend, the outward directed centrifugal force generates superelevation of the water surface near the outer bank, which in turn creates an opposing inward directed pressure gradient force (Dietrich 1987). Although the pressure-gradient force is in balance with the depth-averaged centrifugal force, locally these two forces are imbalanced over depth. The result is secondary flow with near surface flow directed towards the outer bank, and near bed flow directed towards the inner bank. The strength of secondary flow is proportional to the changes in curvature through the bend; thus, sharp increases in curvature will lead to stronger secondary flow, though recent work has indicated existence of a saturation point at which secondary circulation no longer grows once a threshold curvature is reached (Blanckaert 2009). In three dimensions, the secondary flow is characterized by helical motion, redistributing downstream momentum such that the high velocity core is located near the outer bank, and submerged below the free surface downstream of the bend apex. This pattern of helical motion through bends has been documented both experimentally (Whiting and Dietrich 1993b, Whiting and Dietrich 1993c, Whiting and Dietrich 1993a, Peakall et al. 2007, Abad and Garcia 2009a, Abad and Garcia 2009b), as well as in field studies (Rozovskii 1957, Bathurst, Thorne and Hey 1977, Thorne and Hey 1979, Frothingham and Rhoads 2003). Differences in longitudinal water-
surface gradients along each bank created by superelevation also create spatial variations in the downstream boundary shear stress and corresponding bed-material fluxes. Sediment flux divergence (i.e., scour) along the concave bank creates a pool, while sediment flux convergence (i.e., deposition) along the convex bank creates a point bar (Nelson and Smith 1989). A topographic high near the bend inflection creates a riffle. Taken collectively, pools, point bars, and riffles form a linked morphology called a bar unit (Dietrich 1987), which is genetically linked to the planform geometry via curvature effects on turbulent flow structure. Whereas low to moderate amplitude bends exhibit only single bar unit forms, with the pool oriented along the concave bank (e.g., Dietrich 1987, Rhoads and Welford 1991), elongate and compound loops exhibit multiple bar units, having the same orientation, with pools located along the concave bank, and point bars located along the convex bank (i.e., shingle bars) (Kinoshita 1961, Hooke and Harvey 1983, Thompson 1986, Whiting and Dietrich 1993b, Whiting and Dietrich 1993c, Whiting and Dietrich 1993a, Frothingham and Rhoads 2003, Termini 2009). Bar-unit morphology accentuates secondary flow by topographically deflecting, or steering, flow laterally toward the concave bank (Dietrich and Smith 1983). This topographic steering leads to flow convergence in the pool, which results in flow acceleration and the potential for enhanced turbulence, bed shear stress and scour near the outer bank. In the case of elongate or compound bends with multiple bar forms, it may produce an additional feedback mechanism between planform evolution and channel curvature.

Attempts to connect near-bank fluid forces to lateral migration in meandering rivers have been relatively rudimentary. An underlying assumption of current mathematical models of planform evolution is that erosion of the outer banks occurs as a function of excess depth-averaged, near-bank velocity computed as a spatial convolution function of upstream channel
curvature (Ikeda et al. 1981, Parker et al. 1982, Blondeaux and Seminara 1985, Johannesson and Parker 1985) or, more recently, upstream and downstream curvature (Zolezzi and Seminara 2001). Bank erosion is assumed to be a simple linear function of near-bank velocity. This theoretical framework has been used to reasonably reproduce downstream bend translation, and asymmetry through time (Ikeda et al. 1981, Howard and Knutson 1984, Parker and Andrews 1986), as well as the development of compound loops (Zolezzi and Seminara 2001, Camporeale et al. 2007). Field studies provide some support for a relation between rates of bank erosion and magnitudes of near-bank velocities (Pizzuto and Meckelnburg 1989, Constantine, Dunne and Hanson 2009), but the amount of corroborating data is rather limited. Moreover, flow in rivers is turbulent and rates of bank erosion should be related to a metric of the turbulent stresses acting on the channel boundary. Current depth-averaged mathematical models of meander migration do not include turbulent stresses. Computational fluid dynamics (CFD) models and experimental studies of flow through bends are beginning to shed light on patterns of near-bank turbulence that could affect the bank toe and influence bank erosion, but such studies mainly have been restricted to channels with fixed boundaries (Abad and Garcia 2009a, Termini 2009). Field studies of turbulence in meander bends are limited and have not examined the relationship of near-bank turbulence to bank erosion (Anwar 1986).

Comprehensive field studies are needed to elucidate relationships between 3-D turbulent flow, planform, and morphology evolution in meandering rivers, especially in bends with complex geometries—a difficult task because most field studies only document flow in meandering rivers over a timescale much shorter than the scale of planform evolution. In the field, Frothingham and Rhoads (2003) examined mean flow structure at different stages within a compound meander loop and related this structure to short-term patterns of bank erosion in the
loop. Their study did not examine turbulence near the outer bank, nor did it examine interaction between turbulent flow structure and channel morphology over a timescale involving substantial planform change. This paper builds upon the study by Frothingham and Rhoads (2003) to examine the co-evolution among 3-D turbulent flow structure, bed morphology, bank failures, and channel planform in a compound meander loop over the timescale of planform change. To do so, the study relies on repeat surveys of channel morphology conducted over an 11-year period and detailed measurements of flow structure in the bend obtained 10 years apart. The study is novel in its approach of specifically investigating the feedback among flow structure, bed morphology, bank failures and planform migration within a complex meander bend. It also is one of the first to relate patterns of planform change to patterns of turbulence within a meandering river.
3.2 Study Reach and Channel Change

The study site is an elongated compound meander loop along the Embarras River in Champaign County, Illinois (Figure 3.1). The Embarras River originates on the Champaign moraine in the Champaign-Urbana metropolitan area and flows south between the West Ridge and Hildreth moraines. The drainage area upstream of the study site, located approximately 16 km downstream from the river’s origin on the Champaign moraine, is 57 km². Glacial moraines in the region formed about 18,000 years before present after the Wisconsin Glacial Maximum during retreat of the Lake Michigan lobe of the Laurentide ice sheet (Hansel and Johnson 1992,
Johnson et al. 1997). In the upper Embarras River valley, calcareous glacial till in the shallow subsurface is overlain by about 2-3 meters of modern alluvium.

To create suitable land for agriculture, extensive land drainage occurred throughout east central Illinois in the late nineteenth century and early twentieth century, resulting in channelization of meandering headwater streams (Urban and Rhoads 2003). Today, most first order streams in Illinois are channelized (Mattingly and Herricks 1990, Urban and Rhoads 2003). The upper Embarras River is no exception; much of the total length of the upper part of the river has been straightened and shaped into a trapezoidal channel geometry (Rhoads and Urban 1997, Urban 2000, Frothingham 2001). Only small sections of the headwater portions of this river currently are unchannelized.

The study bend is located within an approximately 800 m long meander train containing elongated bends and compound loops that has not been channelized since at least the 1930s. Comparative GIS analysis of georeferenced historical aerial photography indicates that the meander train, including the study bend, has evolved considerably over the past 60 years (Figure 3.1). Today the study bend has the form of an asymmetrical elongated compound loop (Frothingham and Rhoads 2003) with two distinct lobes of curvature – one upstream (lobe 1) and one downstream (lobe 2). Such bends have commonly been referred to as double-headed meanders (Hooke 1995).

The study reach is the location of an extensive investigation of flow structure conducted in 1998 and of patterns of short-term channel change conducted from 1997 to 2002 (Frothingham and Rhoads 2003). This paper builds on that work by documenting channel change in the reach over a longer period between 1997 and 2008, by examining details of turbulence for the 1998
data that were not described previously, and by presenting comparative data on flow structure collected in 2008 after the loop had evolved substantially.

Within the study reach, the bankfull channel of the Embarras River is 13 to 18 meters wide, 1.5 to 2.0 meters deep, and has an average gradient of 0.0008 m m$^{-1}$. Channel dimensions have remained relatively constant over the 11-year period of study. The reach exhibits well-developed pool-riffle sequences and point bars typical of natural meandering streams. Outer banks are nearly vertical and the strong cohesiveness of the bank material, along with shallow rooting depths of floodplain grasses, make these banks prone to frequent cantilever failures (Hooke 1995, Thorne et al. 1998). At any given time, numerous large blocks of failed bank material are present along the base of the outer bank. Bed material consists mainly of coarse sand and fine gravel with the coarsest material occurring on riffles and in the thalweg of pools (Frothingham and Rhoads 2003). In the deepest parts of pools, glacial till is exposed on the channel bed. Bank material is stratified alluvium that generally fines upward with substantial amounts of silt and clay in the upper part of the banks.

### 3.3 Field Data Collection and Analysis

Three dimensional velocity data were collected at several transects for two similar events in the study bend: 18 and 24 June 1998 (campaign 1); and 10 and 11 June 2008 (campaign 2). When collecting 3-D velocity data, the frame of reference of the measurements is an important consideration in relation to the objectives of the study (Rhoads and Kenworthy 1998). In most process-based field studies of meander bends, the channel path remains relatively constant over the time frame of measurement campaigns (i.e., these studies occur over the time scale of local erosion only). In such cases the convention of past field and modeling studies has been to align cross sections orthogonal to the local channel centerline (Dietrich and Smith 1983, Bridge 1992,
A specific aim of this study is to explore interactions between flow structure and channel form in an evolving meandering river. Given the amount of evolution of the study bend between measurement dates, two different sets of measurement transects were necessary: transects orthogonal to the channel path in 1998 (campaign 1) and transects orthogonal to the channel path in 2008 (campaign 2) (Figure 3.2). Transect endpoints were determined for both campaigns based on topographic surveys of the channel morphology. Detailed elevation data of the entire bend were collected in 1997 using a total station and in 2008 using a survey grade Real Time Kinematics (RTK) Global Positioning System. The elevation data were used to construct topographic maps of the study bend (Figure 3.2) and to define the inner and outer banks of the channel. Cross-sections in 1998 were established by fitting three arcs of curvature to the loop to represent the channel centerline and projecting cross sections orthogonal to the arcs (Frothingham and Rhoads 2003). Cross sections for 2008 were determined by identifying a set of midpoints between the channel banks, fitting a cubic spline to the midpoints to define the channel centerline (Güneralp and Rhoads 2008) and projecting cross sections orthogonal to the fitted centerline. In both cases, coordinates of the endpoints were located in the field using a total station and these endpoints were marked with sections of black iron pipe hammered into the ground.
Figure 3.2. Topographic maps of the study bend in 1998 (left), and 2008 (right). Note the two different sets of cross-sections for each date.
To quantify planform evolution in the loop, repeat surveys of channel morphology were conducted. The set of 14 transects established in 1997 was maintained throughout the eleven-year span of this study. Each of these cross sections was surveyed annually to document channel change over time.

Flow was measured at several transects during campaigns 1 and 2 using either one or two Acoustic Doppler Velocimeters (ADVs), which record instantaneous velocities in the streamwise ($u$), cross-stream ($v$), and vertical ($w$) directions by calculating the Doppler shift in sound waves as they reflect off suspended particles in the flow. A main advantage to employing ADVs is that the sensors remotely sample a volume of water approximately 0.25 cm$^3$ located 5–7 cm below the receiving transducer tips (Kraus, Lohrmann and Cabrera 1994), thus leaving the flow undisturbed. Measurements were obtained within the frame of reference defined by the set of cross sections on each date using a custom-built wading rod held steady in the flow by attaching it to a steel cable stretched taut between the black iron pipes. A rod operator sitting on a portable bridge spanning the channel immediately downstream of the wading rod was responsible for positioning the ADV within the flow for each measurement (Figure 3.1c). In this way, eight to nine vertical series of flow measurements were made at each transect, with each vertical containing 4–9 data points, producing a grid of 32–81 data points per cross section. Prior to measurement the wading rod was plumbed with a rod level to ensure proper vertical alignment. ADV data were obtained at a frequency of 25 Hz with a velocity accuracy of 0.01 cm s$^{-1}$ for an average of 60–90 seconds at each measurement location producing ~2,000–4,000 instantaneous 3-D velocity measurements per location. This spatial and temporal resolution provides information on mean (time-averaged) velocity components, patterns of secondary circulation, and turbulence characteristics of the flow.
Velocity measurements at each measurement location should be long enough to capture mean turbulence characteristics of the flow, while also being short enough to enable measurements at as many points as possible during each field campaign (two days). In this study, measurements were obtained over a sampling duration of 60–90s. Past work has indicated that time series of this length are long enough to accurately capture time-averaged turbulence characteristics, even in highly turbulent flows (Rhoads and Sukhodolov 2001, Buffin-Belanger and Roy 2005, Rhoads and Sukhodolov 2008). The ADV data were post-processed using an acceleration spike filtering method, which removed velocity spikes above a specified threshold on the premise that there is a physical upper limit to changes in velocity that can occur (Nikora and Goring 2000, McEwan 2002, Nikora and Goring 2002). The highly turbulent nature of the flow analyzed in this study made the spike filter a better choice over more typical filters (e.g., Signal to Noise, and/or correlation filtering), which do not perform as well where correlations scores are low due to turbulence. Time-averaged velocities in the downstream ($U$), cross-stream ($V$) and vertical ($W$) directions were used to develop plots of depth-averaged velocity vectors at each vertical profile as well as to produce contour plots of $U$ with superimposed cross-stream/vertical velocity vectors. Values of turbulence kinetic energy ($k$) were calculated as

$$k = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$

(3.1)

where $u'$, $v'$, $w'$ are velocity fluctuations in the downstream, cross-stream and vertical directions, respectively, and the overbars indicate time averaging.
3.4 Results

3.4.1 Channel Morphology and Migration Patterns

Repeat transect surveys along the study bend illustrate that patterns of erosion and deposition generally are highest near the lobe apices (cross-sections 6–8 and 11–14) (Figure 3.3). Average outer bank migration rates also confirm this trend (Table 3.1). The relatively high migration rates at the upstream end of the compound loop (cross section 1) correspond to translation of the compound loop upstream of the study loop downstream (Figure 3.1), resulting in a pronounced shift in the position of the thalweg at this location (Figure 3.3). Positions of the outer bank indicate that the upstream and downstream lobes have had different migration trajectories (Figure 3.4), a pattern typical of double-headed meanders (Hooke 1995). Lobe 1 (cross-sections 6–8) migrated predominantly laterally through extension, whereas Lobe 2 (cross-sections 12–14) migrated mainly downstream via translation, producing overall elongation of the loop and the development of straight sections of channel upstream of Lobe 1 and between Lobe 1 and Lobe 2 (Figure 3.2). In 1997, the loop was approximately 95 m in length; however, by 2008 the loop had elongated to 120 m, leading to an increase in sinuosity from 2.9 in 1997 to 3.5 in 2008 (Figure 3.2). The difference in migration trajectories of the two lobes also increased the planform asymmetry of the loop.
Table 3.1. Average migration rates at each of the 14 channel transects.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Mean Migration Rate (m yr$^{-1}$)</th>
<th>Transect</th>
<th>Mean Migration Rate (m yr$^{-1}$)</th>
</tr>
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<td>11</td>
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<tr>
<td>7</td>
<td>0.705</td>
<td>14</td>
<td>0.760</td>
</tr>
</tbody>
</table>

In lobe 1, erosion of the outer banks has resulted in nearly 8 m of lateral migration over the 11-year period. In 1997, the channel exhibited an asymmetric cross section with near vertical
outer banks throughout the lobe (cross-sections 5–8), a shape indicative of well-developed point bar, pool, and cut-bank morphology (Figure 3.3). Frothingham and Rhoads (2003) found that between 1997 and 1999 about 0.2 m of uniform lateral accretion occurred along the inner bank, which maintained the slope of the point-bar face. In contrast, the inner bank face at the upstream end of the lobe 1 (cross-sections 5 and 6) is much steeper in 2008 than in 1997, suggesting that bar growth over this period involved differential rates of accretion over the bar face. Steepening of the point-bar face has reduced asymmetry of the channel cross sections. Inner bank deposition and outer bank erosion appear to be roughly balanced, except perhaps near the lobe apex (cross-section 6), where the channel is slightly wider in 2008 than in 1997. Downstream of the apex (cross-sections 7–8), the cross-section is still asymmetrical, but the inner bank is slightly steeper in 2008 compared to 1997.

Figure 3.4. Locations of the outer bank derived from repeat topographic surveys during the eleven year study.
The riffle section between lobes 1 and 2 (cross-sections 9–11) has migrated laterally, but at a lower rate than the two lobes (Table 3.1). This section has also elongated because of the differential migration directions of the two lobes. Outer banks are still steep in this section, but over time failed material has begun to accumulate at the base of the banks and become vegetated with grasses. This material has shifted the thalweg toward the inner (west) bank, away from the cut bank, thereby reversing channel cross-section asymmetry in this section between 1997 and 2008.

In lobe 2, lateral migration of over 8 m occurred during the 11 year study period. The inner bank of the thalweg in 2008 has a slope similar to the lower slope of the point bar in 1997, but the upper part of the inner bank slope in 2008 has been modified by lateral accretion. Throughout the lobe (cross-sections 12–14), lateral accretion has produced an extended bench-like surface along the inner bank than lies below the level of the adjacent floodplain. Frothingham and Rhoads (2003) reported that between 1997–1999 lateral accretion in lobe 2 amounted to only 0.25–0.30 m compared to nearly 2 m of outer bank erosion; thus point bar accretion was not keeping pace with outer-bank erosion, leading to channel widening, especially downstream of the apex (cross-sections 13–14). The transects from 2008 indicate the pace of migration has necessitated development of a depositional surface at a much lower elevation than the height of the outer bank. Thus, lateral accretion has maintained the form of the lower part of the channel cross section, but has not been sufficient to build the point bar upward to the surface of the floodplain. Blocks of failed bank materials are numerous along the outer bank of Lobe 2 in 2008 (e.g., cross-sections 11 and 12).
3.4.2 Time-averaged Velocity Fields

Depth averaged 2-D vectors for the two measurement dates illustrate the general patterns of flow through the evolving bend (Figure 3.5), whereas contour plots of downstream velocities with superimposed cross-stream/vertical velocity vectors show details of three-dimensional fluid motion (Figure 3.6 and Figure 3.7). In campaign 1 the flow is strongly oriented outward upstream of lobe 1, whereas in campaign 2 flow entering lobe 1 converges along the inner portion of the channel cross section, resulting in high velocities at this location. Frothingham and Rhoads (2003) noted strong outward orientation of the flow in 1998, but did not specify a cause for this pattern. Shoaling of the flow by the point bar of lobe 1, which extends upstream along the inner bank of a gently curving thalweg within the compound loop, appears to be responsible for the net outward flux of fluid. In campaign 2, the channel upstream of lobe 1 has evolved into a fairly straight alignment, reducing the upstream extension of the point bar (Figure 2). Moreover, failed blocks of bank material along the north (outer) bank within this reach constrict the flow (Figure 3.8), producing the highest velocities in the lobe along the south (inner) bank at the bend entrance and a separated zone of recirculating fluid in the lee of the failed material along the north bank (cross-sections D and E). The core of maximum velocity is shifted toward the inner bank and the cross section here is fairly symmetrical, indicating a lack of point-bar development at this location.
As flow moves through lobe 1 on each date, velocity distributions reflect persistent extended effects of conditions at the bend entrance. In 1998, flow is directed toward the outer bank through the bend, leading to a pronounced discordance between the path of the flow and the path of the channel. In contrast, the path of the flow in 2008 conforms closely to the path of the channel. Channel curvature in lobe 1 actually is greater in 2008 than in 1998 (Table 3.2), suggesting that the magnitude of outward motion is not a simple lagged response of the flow to rapidly changing channel curvature. The cross-section plots of velocity components reveal the pronounced differences in flow through lobe 1 on the two dates (Figure 3.6 and Figure 3.7). Strong outward motion of fluid over the entire flow depth during campaign 1 results in a shift of the high-velocity core toward the outer bank. This core becomes submerged near the outer-bank toe, resulting in steep velocity gradients along the base of the outer bank. Toward the exit of the

Figure 3.5. Depth averaged flow vectors for the study bend during campaign 1 in 1998 (left) and campaign 2 in 2008 (right).
bend (cross-section 7), surface flow is still outward, but near-bed flow is markedly inward—a sign of helical motion. In campaign 2, flow decelerates into the pool in lobe 1 as it moves past the constriction associated with flow separation along the outer bank at the bend entrance. The high-velocity core remains centered within the channel cross section, perhaps shifting outward slightly toward the lobe exit (cross-section H), although this “shift” at least partly reflects expansion of the core as flow accelerates toward the transition from pool to riffle at the exit of the lobe. Helicity on this date is well-developed with clear outward motion at the surface and inward motion at the bed throughout the lobe (cross-sections E–H).
Table 3.2. Dimensionless radius of curvature values for the channel during both campaigns. Note that H is the mean hydraulic depth for each measurement date respectively.

<table>
<thead>
<tr>
<th>Transect</th>
<th>1998</th>
<th></th>
<th></th>
<th>2008</th>
<th></th>
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</tr>
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<tbody>
<tr>
<td></td>
<td>r/B</td>
<td>r/H</td>
<td></td>
<td>r/B</td>
<td>r/H</td>
<td></td>
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<tr>
<td>5</td>
<td>2.11</td>
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<tr>
<td>6</td>
<td>1.89</td>
<td>21.89</td>
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</tr>
<tr>
<td>7</td>
<td>1.21</td>
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<td>F</td>
<td>1.19</td>
<td>9.19</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>G</td>
<td>0.57</td>
<td>4.42</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>H</td>
<td>8.90</td>
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<td></td>
</tr>
<tr>
<td>12</td>
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<td>15.39</td>
<td>K</td>
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</tr>
<tr>
<td>13</td>
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<td>14</td>
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<td>65.25</td>
<td>O</td>
<td>1.54</td>
<td>17.06</td>
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</tr>
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</table>

In contrast to lobe 1, the basic pattern of flow through lobe 2 on the two dates is fairly similar, with depth-averaged vectors oriented toward the outer bank at the lobe entrance and apex (cross-sections 12 & 13 and K & M) (Figure 3.5). The high-velocity core is located toward the outer part of the channel throughout the lobe, becoming submerged beneath the surface toward the lobe exit (Figure 3.6 and Figure 3.7). Velocity gradients near the outer bank are strong on both dates, but especially in June 2008 when the high-velocity core is in immediate proximity to blocks of failed bank material along the outer bank. The most noticeable difference between the two sets of measurements is the contrast in the widths and cross-sectional areas of the flows. Despite approximately similar discharges, the width and area of flow in June 1998 are much greater than in June 2008, especially at and downstream of the lobe apex. This difference, although in part due to a slightly lower flow stage in June 2008 compared to June 1998, reflects development of the depositional bench along the inner bank over the 10-year period. The outward-directed flow in the lobe and widening of the channel lead to pronounced flow separation along the inner bank in campaign 1; no separation is evident in campaign 2 when the flow width is much less than in campaign 1. Net outward flow is also evident at the bend exit in
campaign 2 (cross-section O), but flow at the bend exit in campaign 1 is oriented slightly inward toward the region of flow separation. Overall the pattern of cross-stream and vertical fluid motion in campaign 2 is much more complicated than campaign 1. In both campaigns, flow is directed outward and downward toward the outer bank. Flow stagnation occurs near the apex of the lobe on both dates. Frictional resistance associated with blocks of failed bank material likely contributes to outer-bank stagnation. Moreover, the greater abundance of failed material during campaign 2 compared to campaign 1 probably accounts for the complicated pattern of cross-stream/vertical vectors in campaign 2. At and downstream of the apex, near-bed vectors are oriented inward indicating the development helical motion associated with flow curvature. Inward near-bed motion is especially pronounced at the lobe exit (cross-sections 14 and O), suggesting that helicity becomes well-developed downstream of the bend apex.
Figure 3.6. Three-dimensional perspective plot and cross-section plots for campaign 1 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical velocity vectors (arrows) for each transect where flow was measured in 1998.
Figure 3.7. Three-dimensional perspective plot and cross-section plots for campaign 2 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical velocity vectors (arrows) for each transect where flow was measured in 2008.
3.4.3 Patterns of Turbulent Kinetic Energy

In both campaigns, maximum values of $k$ in the set of cross sections correspond to portions of the flow with steep gradients in downstream velocity magnitudes (Figure 3.9 and Figure 3.10). As flow moves through lobe 1 on campaign 1, the locus of highest $k$ values is located near the bed through the thalweg and along the toe of the outer bank (cross-sections 5–7). This region of elevated $k$ lies between the high velocity core and the channel boundary where downstream momentum is being transferred outward and downward by secondary flow. As the high-velocity core moves close to the channel bank and becomes submerged (cross-sections 6 and 7), values of $k$ along and near the outer bank increase. High velocity fluid close to the channel boundaries intensifies velocity gradients, leading to increased turbulence generation (i.e., velocity

Figure 3.8. Bank blocks resting on the outer bank that constrict flow at the entrance to lobe 1 in campaign 2. Flow is from left to right.
fluctuations), and thus production of $k$. The pattern of $k$ appears to be influenced by the advective effects of helical motion of the flow, as evidenced by the inward projecting “tongue” of high $k$ toward the lobe exit (cross-section 7).

Figure 3.9. Three-dimensional perspective plot and cross-section plots for campaign 1 showing turbulent kinetic energy ($k$) magnitudes (contours) for each transect where flow was measured in 1998.
The pattern of $k$ in lobe 1 during campaign 2 is quite different from the pattern in campaign 1. Velocity gradients within the thalweg and near the outer bank are less intense than in campaign 1 because the high velocity core remains close to the inner bank or approximately centered within the channel. As a result, $k$ values (cross-sections D–E) at the lobe entrance are highest along the shear layer at the margin of the region of flow separation, immediately downstream from failed bank material resting on the north bank. A local peak of $k$ is evident

Figure 3.10. Three-dimensional perspective plot and cross-section plots for campaign 2 showing turbulent kinetic energy ($k$) magnitudes (contours) for each transect where flow was measured in 2008.
near the outer bank at the lobe apex, which may correspond to reattachment of the shear layer to the channel bank (cross-section F). Toward the exit to lobe 1 peak values still occur within the thalweg and near the base of the outer bank, but peak values of $k$ in this campaign are much lower than peak values in campaign 1.

Patterns of $k$ in lobe 2 are somewhat similar for both dates, but in contrast to lobe 1, values of $k$ are much higher for campaign 2 than for campaign 1. On both dates, the high velocity core is located near the outer bank, intensifying velocity gradients in this region and producing high values of $k$. The enhanced magnitudes of $k$ for campaign 2 are associated with failed bank blocks along the outer bank. These blocks increase fluid shear and turbulence production along the boundary by constricting the flow, thereby enhancing downstream velocity, and by serving as large roughness elements. Apparently these blocks of failed material generate a continuous shear layer along the outer bank that extends from the base of the pool to the water surface. During campaign 1, outer banks are less steep, and outer bank flow stagnation develops near the lobe apex. These effects limit peak values of $k$ to the base of the channel thalweg and turbulence production is less intense than in campaign 2. During campaign 1, flow expands and velocity magnitudes decrease as the channel width and area increase downstream of the apex (cross-sections 13–14), which results in diminished velocities and velocity gradients. Concordantly, peak values of $k$ decrease markedly.

3.5 Discussion

Results of the analysis of morphological change and flow structure over the study period demonstrate strong interconnections among spatial patterns of mean flow, turbulence, bed morphology, bank failures and channel migration in this evolving compound meander loop. The patterns of flow observed in campaign 1 create specific patterns of near-bank velocity and $k$
which have influenced subsequent erosion and deposition, and thus planform migration within the loop. Topographic deflection of the flow from extant bed morphology during campaign 1 seems to play a key role in patterns of $k$ and associated outer bank erosion. Longitudinal shoaling from upstream of and through the lobe 1 apex (cross-section 6) and just upstream of the apex in lobe 2 (cross-section 12) on the inner bank is pronounced (Figure 3.11). The effects of shoaling of the flow by a point bar are well-documented (Dietrich and Smith 1983, Dinehart and Burau 2005, Seminara 2006, Clayton and Pitlick 2007, Seminara 2010). Shoaling decreases the cross-stream water surface gradient, allowing the depth-averaged centrifugal force to dominate as the pressure-gradient force is diminished. The result is outward directed flow over the entire depth at the upstream end of the point bar, and net transfer of water outward, causing flow convergence in the thalweg. Net outward transfer of water is apparent from angles of deviation of the discharge vector from the path of the channel centerline ($\phi$) for each transect (Table 3.3). To maintain continuity under conditions of net cross-stream discharge, convective acceleration of downstream flow occurs in the thalweg. The result is rapid shifting of the high velocity core toward the outer bank near the bend apex (Dietrich and Smith 1983). Downstream of the apices of the lobes, shoaling diminishes (Figure 3.11) and typical helicoidal motion (surface outward and near bed inward directed secondary circulation) develops as the cross-stream pressure-gradient recovers (Figure 3.6). The patterns in both lobes during campaign 1 correspond well with the patterns Leopold and Wolman (1960) observed in Baldwin Creek, as well as the results in Muddy Creek (Dietrich and Smith 1983).
Table 3.3. Deviation angles of the flow to the channel centerline.

<table>
<thead>
<tr>
<th>Transect</th>
<th>$\phi$ (deg)</th>
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</tbody>
</table>
Figure 3.11. Longitudinal profiles of bed topography along and parallel to the channel centerline. The values of \( n \) correspond to the distance of the profile from the centerline in a left-handed curvilinear coordinate system after (Smith and McLean, 1984) (e.g., \( n = 1 \) is 1 m to the left of the centerline). The ADV transects are also indicated for reference.
By contrast, in campaign 2 longitudinal shoaling around lobe 1 is negligible. In fact, bed elevation decreases around the lobe along the inner bank (Figure 3.11). Instead, shoaling near the outer bank from failed bank material in the straight reach upstream of the lobe confines the high-velocity core to a position along the inner bank (Figure 3.7). Diminished topographic deflection by the point bar and constriction of the flow by failed bank blocks prevent strong outward advection of the high-velocity core toward the outer bank. Reduced shoaling by the point bar during campaign 2 may be related to inner-bank scour associated with flow constriction from the failed bank blocks or to changes in inherited flow structure associated with elongation and reduction in curvature of the reach upstream of lobe 1; more than likely it is a combination of both effects. In lobe 2, the pattern of bed morphology suggests weak shoaling by the point bar upstream of the apex (just upstream of cross-section K), but the topographic effect is not as pronounced as in campaign 1 (Figure 3.11). Shoaling along the outer bank caused by failed bank material constricts the flow and produces high levels of boundary resistance in campaign 2; thus, the high velocity core is located near the center of the flow cross section in lobe 2 (Figure 3.5 and Figure 3.7).

The results of this study also confirm that advection of high-momentum fluid toward the outer bank by secondary flow produces high levels of near-bank turbulence. Past work has shown that the value of $k$ near the channel boundaries can be related to boundary shear stress ($\tau_b$) using the linear relationship:

$$\tau_b \cong \alpha \rho k$$  \hspace{1cm} (3.2)

where ($\alpha$) is a proportionality constant equal to (0.19) and ($\rho$) is fluid density (Nezu and Nakagawa 1993, Biron et al. 2004). Thus, high values of $k$ near the channel boundaries presumably are related to enhanced sediment transport capacity and erosion of the channel bed.
and banks. At the study site, values of $k$ are highest in regions where velocity gradients are the strongest, i.e. near the base of the outer bank at and downstream of the lobe apices. In this curved channel, these regions of elevated $k$ are related to the position of the high-velocity core in relation to the channel boundaries. Curvature effects lead to development of helical motion and submergence of the high velocity core near the outer bank, whereas flow convergence from topographic effects promotes convective acceleration of flow within the pool. Both of these effects produce strong gradients in downstream velocity near the outer bank. The pattern of $k$ documented in this study differs from lab and modeling results reported by Blanckaert and Graf (2001) in a curved flume with fixed banks. In their study, values of $k$ were small near the outer bank result attributed to the development of an outer bank cell, which has been documented previously in field studies of flow in meander bends (Bathurst et al. 1977, Bathurst et al. 1979, Thorne and Hey 1979, Thorne et al. 1985), but which was not detected in this study. During campaign 2 flow separation occurs near the outer bank in lobe 1, resulting in diminished values of $k$ compared to campaign 1. Nevertheless, values of $k$ still are relatively high near the base of the outer bank compared to other parts of the flow. Also, Blanckaert (2001) found no evidence of a distinct shear layer characterized by high $k$ as is evident in the turbulence data for campaign 2 in lobe 1. Few field studies of turbulence in meander bends are available for comparison, but the high values of $k$ near the toe of the outer bank documented here correspond to the findings of Anwar (1986), who used two 2-D electromagnetic current meters to measure 3-D characteristics of turbulence in a small bend. The results also are consistent with high near-bank values of $k$ in a curved flow downstream of a small confluence (Rhoads and Sukhodolov 2008). Recent work has also shown that pronounced bank roughness and flow separation/stagnation along the margins of curved channels can produce strong velocity gradients, and the development of
distinct shear layers characterized by high values of $k$ (Rhoads and Massey 2011)—an effect documented in this study in conjunction with the influence of failed blocks of bank material on near-bank flow.

An interesting result of this study is that near-bank velocity and turbulence do not necessarily vary directly with bend curvature. Many mathematical models of meander migration assume that near-bank velocity, which can be related linearly to bend migration rate, increases with increasing bend curvature. Bend curvature in lobe 1 actually increases between campaigns 1 and 2, yet values of near-bank $k$ decrease markedly from campaign 1 to campaign 2 (Table 3.1). Instead, both near-bank $U$ and near-bank $k$ are strongly influenced by topographic deflection from the point bar and preserved blocks of failed bank material. This local effect apparently supersedes the planform-scale effect of increased curvature.

The documented patterns of planform evolution for the loop are entirely consistent with the patterns of mean flow and turbulence in the reach. The extension of lobe 1 through migration to the east and the downstream translation of lobe 2 through migration to the south conform to spatial patterns in the magnitudes of near-bank velocity and turbulence kinetic energy in the two lobes during campaign 1. This result suggests that rates of bank erosion indeed are governed by magnitudes of near-bank velocity and turbulence. High values of $k$ near the bed and bank in the channel thalweg, and along the outer bank face throughout lobe 1 and lobe 2 during campaign 1 are indicative of high shear stresses that are likely competent to erode material at the bank toe.

Differences in the directionality of lobe migration have led to the development of straight sections of channel upstream of each of the two lobes, resulting in increasing bend asymmetry over time. This increasing asymmetry coupled with the straightening entrance conditions appears to play an important role in the preservation of failed bank materials along the bank toe.
As the loop evolved from a continuous curving form in 1998 to the asymmetrical form in 2008, near-bank shear stresses in the developing straight reaches upstream of lobe 1 and between lobes 1 and 2 likely decreased at moderate to high flows. Decreases in channel curvature should reduce advection of momentum toward the outer bank by secondary flows, limiting the magnitude of streamwise velocities and turbulence near the bank face. This inference is supported by the low migration rates of the evolving straight sections of the loop compared to the lobes. Despite the development of the straight sections, outer banks in these portions of the loop are still nearly vertical and prone to cantilever failures (Thorne et al. 1998). As the loop has evolved, the potential for preservation of this failed material in the straight sections has increased because fluid forces to remove this material likely have decreased as curvature has decreased. Indeed, failed material at the upstream end of lobe 1 and between the two lobes has been stabilized by colonizing vegetation to the point where transported gravel is now accreting vertically onto the surface of the failed material. Between lobes 1 and 2 this failed material has initiated a reversal of channel sinuosity (Figure 3.12). Stabilized material in this section of the loop is now beginning to deflect flow toward the inner bank. Similarly, as mentioned in the discussion of flow through the lobes, stabilized bank failures resting on the outer bank are forcing flow entering lobe 1 toward the inner bank during campaign 2 (Figure 3.7). Submerged, unvegetated blocks resting along the bank toe through lobe 2 during campaign 2 are at least temporarily protecting the outer bank, i.e., basal endpoint control; however, the high magnitudes of $k$ generated near the bed in the thalweg and along the face of the bank blocks will likely remove the blocks, re-exposing the bank toe to high momentum fluid in the near future. The timescale of the removal of bank blocks is as of yet unknown, as is the potential of the blocks to interact with point bar dynamics (e.g., bar push-pull influences).
The patterns of near-bank velocity and turbulence in campaign 2 suggest that the lobes of the compound loop will continue to migrate in the near future along the same trajectories they have exhibited over the past ten years. The highest values of $k$ still are located immediately downstream of the lobe apices in each case, which should lead to eastward extension of lobe 1, and southward translation of lobe 2. Lobe 1 may migrate at a reduced rate relative to rates during the study period because of reductions in near-bank velocity and turbulence caused by diminished topographic deflection and by outer-bank flow separation. Lobe 2 will likely continue to translate downstream at similar rates, which will lead to continued elongation of the loop and increasing planform asymmetry. Stabilized bank failures in the straight section between the two lobes, coupled with elongation within the bend suggest that a third lobe of opposite curvature may develop in the near future, as flow becomes increasingly deflected into

Figure 3.12. Stabilized failed bank material on the outer bank between lobes 1 and 2. Notice colonization by vegetation, and vertical accretion of gravels. Flow is from top to bottom.
the inner (west) bank in this section. Previous theoretical perspectives on the development of high-amplitude meander loops suggested that loops might evolve to a stable condition (Parker et al. 1982); however, results from this study lend support to the hypothesis that meander loops, through complex feedbacks among flow, sediment transport, bed topography, bank configuration and channel planform, are continuously evolving features that do not obtain a permanent stable configuration (Parker, Diplas and Akiyama 1983, Parker and Andrews 1986, Seminara et al. 2001, Lanzoni and Seminara 2006).

The current study considers only a snapshot of two flows with similar discharges and the planform evolution of the loop between the two flows, but it begins to show how feedbacks among relevant processes operate over different temporal scales, resulting in morphological effects at different spatial scales (Figure 3.13). In the Embarras River system, hydrologic variability occurs at a high frequency (minutes to hours) with corresponding adjustments in reach-scale hydraulic conditions, including the 3-D structure and turbulence of the flow. At certain thresholds of flow, bed material is mobilized, creating the potential for morphological change. Bed material mobilization, if sustained over sufficient time periods, can produce point bar erosion or deposition (days to months). It also plays an important role in bank erosion through net removal of material at the base of the banks, which, in conjunction with wetting characteristics of the bank (hydrological variability), results in failure of bank blocks (days to months). Moreover, sustained bed-material transport ultimately is responsible for breakdown and removal of failed blocks, probably over a similar time period, but changes in channel planform, such as elongation and straightening, can produce changes in flow structure and sediment transport that may lead to preservation of bank blocks over the timescale of planform evolution. Point bar deposition and the production of bank blocks can strongly influence local patterns of
flow and sediment transport within the loop through topographic steering effects. “Push–pull” interaction between point bar and cut bank dynamics can occur via mutual feedbacks to flow and sediment transport. Ultimately, the combination of point bar deposition on the inner bank and production/removal of bank blocks on the eroding outer bank leads to progressive planform change over time spans of several years to decades. Localized effects, such as topographic steering of the flow by persistence of bank blocks in sections of the loop undergoing elongation and straightening, may also influence planform change as the locus of erosion is shifted to the opposite bank (e.g., reversal of curvature in the straight section). Changes in planform generate reach-scale changes in the pattern of three-dimensional flow through the evolving meander loop via feedback that operates over the timescale of planform adjustment. At any instant in time, 3-D flow, for a fixed flow discharge, will reflect the combined influences of point bar, bank block and planform effects (Figure 3.13). The complex interplay among processes acting over different temporal scales with corresponding manifestations of these interacting processes at different spatial scales has yet to be fully represented in models of meandering river dynamics.
Figure 3.13. Conceptual model of interplay among form and process at different temporal scales in a complex meander bend. Solid arrows are direct influences and dashed arrows are feedbacks.

3.6 Conclusion

This study has examined in detail the co-evolution of spatial patterns of mean flow, turbulence, bed morphology, bank failures and channel migration in an evolving compound meander loop. Results of this study suggest that bank erosion, and thus channel migration, is indeed governed by near-bank magnitudes of velocity and turbulence, but that local factors including deflection of the flow by point bars and failed bank blocks have a strong influence on near-bank flow characteristics. These factors can enhance or inhibit the development of high velocities and turbulent kinetic energy near the bank toe. Topographic deflection from longitudinal shoaling over the point bar upstream of lobe apices leads to flow convergence in the pool, resulting in convective acceleration of the streamwise flow. This effect, combined with curvature-induced secondary circulation, leads to the development of a submerged high-velocity
core along the bank toe, at or downstream of the lobe apex. Where the core is near the outer bank toe, velocity gradients increase markedly, generating high values of turbulence. Near-bank velocities and turbulence do not necessarily vary directly with channel curvature as assumed in models of meander migration because of the complicating effects of topographic steering by the point bar and disruption of lobe-entry flow by blocks of failed bank material. Stabilized blocks of failed material can protect the outer bank by topographically steering flow away from the bank, creating zones of flow separation along the bank in the lee of the blocks, and by protecting the bank toe from fluid forces.

Patterns of channel migration within the loop over the past 10 years conform to the patterns of near-bank velocity and turbulence documented at the beginning of this period, suggesting that spatial variation in these factors control the pattern of bank erosion. Differential patterns of lobe migration have resulted in elongation of the loop and increasing planform asymmetry. Moreover, stabilized and vegetated bank blocks in the straight reaches between meander lobes, where near-bank turbulence is low compared to the lobes, are now forcing the flow toward the inner banks, leading to scour and the possible beginnings of a reversal of channel sinuosity. Findings from this study support the hypothesis that compound loops (with double heading) tend towards increasing planform complexity, not toward a stable meander form.

A paucity of research has investigated the spatial structure of turbulence in the outer bank region of meandering rivers in the field. This study is one of the first to do so, but the effects of turbulence production in bends is just beginning to be understood through limited lab and modeling based research (Blanckaert and Graf 2004, Abad and Garcia 2009a, Termini 2009, van Balen et al. 2010). Field evaluations of findings derived from these experiments are crucial for
advancing knowledge of meandering river morphodynamics. Additional studies are needed that focus on the rates of preservation and/or destruction of bank blocks in relation to planform curvature, to near-bank flow characteristics, and to properties of failed materials. This study suggests that local effects on the flow from failed blocks of bank material can influence rates and patterns of bank erosion and possibly planform evolution. Mathematical models of meander migration do not consider these local effects and their influence on near-bank flow fields and bank erosion. Further research is required to understand the importance of local effects on flow, bank erosion and planform evolution within complex meander forms.


4.1 Introduction

Many lowland alluvial rivers exhibit meandering planforms characterized by a series of curves or bends. Over time, the planform of meandering rivers typically changes as bends migrate and evolve. The process of planform evolution involves interactions among extant channel morphology, hydrologic variability, turbulent flow structure, sediment transport, and bank erosion (Pizzuto 1994, Hooke 1995, Seminara 1998, Seminara 2006, Parker et al. 2011, Engel and Rhoads 2012).

Flow in bends is greatly influenced by centerline curvature, with the locus of maximum velocities located near the outer bank downstream of the region of greatest curvature (apex) and crossing to the opposite bank between successive bends (Dietrich and Smith 1983, Dietrich 1987). As flow enters a bend, channel curvature induces centrifugal acceleration and net movement of water toward the outer bank. The resulting superelevation of the water surface along the outer bank produces a counteracting centripetal acceleration associated with the inward-directed pressure-gradient force that balances the centrifugal acceleration of the bulk flow. The local imbalance of the inward and outward directed accelerations over depth gives rise to secondary circulation. Close to the water surface where velocities are high, the curvature induced centrifugal acceleration exceeds the pressure induced centripetal acceleration and flow is directed toward the outer bank. Near the bed, where boundary friction results in low velocities, the pressure-induced centripetal acceleration exceeds centrifugal acceleration and flow is
directed toward the inner bank. Opposing directions of fluid movement near the surface and near the bed result in large-scale three-dimensional spiraling of the flow, or helical motion (Rozovskii 1957). Helical motion has been well documented experimentally (Rozovskii 1957, Yen 1965, Whiting and Dietrich 1993b, Blanckaert and Graf 2001, Blanckaert and de Vriend 2004, Abad and Garcia 2009a, Termini 2009), as well as in the field (Bathurst et al. 1977, Bathurst et al. 1979, Dietrich et al. 1979, Frothingham and Rhoads 2003, Engel and Rhoads 2012). A small counter-rotating secondary cell often develops near the water surface along the outer bank (Bathurst et al. 1979, Thorne and Hey 1979, Blanckaert and de Vriend 2003). The development of this cell has been attributed to the combination of bank friction effects on the flow and the adverse streamwise pressure gradient that develops along the outer bank in conjunction with superelevation of the water surface. Formation of the outer bank cell is favored by rough, steep outer banks and intermediate to near-bankfull flow stages (Hey and Thorne 1975, Bathurst et al. 1977, Markham and Thorne 1992).

As the flow and deformable boundary in meanders interact, deposition along the inner bank and erosion along the outer bank move the channel across its floodplain over time. Increases in meander sinuosity and curvature from migration over decadal timescales can produce elongate bends with multiple curvature maxima known as compound bends or loops (Frothingham and Rhoads 2003). Fluvial processes in elongate, compound loops have mainly been studied in laboratory experiments (Whiting and Dietrich 1993b, Whiting and Dietrich 1993c, Whiting and Dietrich 1993a, Abad and Garcia 2009a, Abad and Garcia 2009b, Termini 2009). These studies focused primarily on fluid dynamics and none included erodible boundaries. Moreover, only a few field investigations have been conducted in compound loops to validate theoretical models or to determine whether results of laboratory experiments hold for
field prototypes. Field studies have shown that the near-bank position of the high velocity core corresponds closely to the locus of maximum bank erosion (Frothingham and Rhoads, 2003) and that local effects (e.g., failed blocks of bank material, pool-riffle morphology) can disrupt patterns of mean flow and turbulence produced by bend curvature (Engel and Rhoads, 2012; Sukhodolov, 2012). These local effects can also modify long-term patterns of bank erosion and planform evolution (Engel and Rhoads, 2012).

Past work has shown that separate lobes of compound loops often migrate with different trajectories and rates, increasing the planform complexity of these loops over time (Brice 1974, Hickin and Nanson 1975, Hooke and Redmond 1992, Engel and Rhoads 2012). As a compound loop evolves, often one or more of the lobes will increase in curvature, quantified as the ratio of centerline radius of curvature to channel width \((r/w)\). For a given width, as \((r/w)\) decreases, curvature \((\mathcal{C})\) increases because \(\mathcal{C} = r^{-1}\). The seminal work by Hickin (1974) identified \((r/w)\) as a dominant control on meander migration, with maximum rates occurring at a value of \((r/w = 2.5)\), and rates decreasing both for bends tighter \((r/w < 2.5)\) and gentler \((r/w > 2.5)\) than this value (Hickin 1974, Hickin and Nanson 1975, Hickin 1978, Nanson and Hickin 1983, Hickin and Nanson 1984, Nanson and Hickin 1986). Often, the individual lobes of a compound loop can meet or exceed the criteria for sharp bends at morphologically significant flow stages, and thus processes specific to sharp bends may play an important role in the fluvial dynamics of compound loops.

The hydrodynamics of sharp bends \((r/w \leq \sim 2.5)\) are more complex than simple bends with moderate or mild curvature (Hickin 1978, Nanson 2010), and include curvature-induced flow separation patterns at the inner and/or outer banks (Figure 4.1) (Ippen et al. 1962). Flow may separate along the inner bank at and downstream of the curvature maximum, forming a
“dead zone” where fluid recirculates around a vertical axis (Bagnold 1960, Leeder and Bridges 1975, Parsons 2002, Ferguson et al. 2003, Frothingham and Rhoads 2003, Blanckaert et al. 2012b). This “dead zone” can effectively reduce channel width and flow cross-sectional area (Blanckaert et al. 2012b), confining the region of helical motion to the thalweg (Ferguson et al. 2003). Flow may also stagnate along the outer bank in regions of increasing curvature (e.g., upstream of a curvature maximum), resulting in circulation horizontally about a vertical axis. This stagnation is generated by adverse pressure gradient associated with superelevation of the water surface as the bulk flow approaches the curvature maximum. A large adverse pressure gradient causes the flow to stall in the outer bank region (Rozovskii 1957). Recently, Blanckaert (2010) derived the condition required for sufficient adverse pressure gradients to exceed centrifugal forces—and thus promote outer bank flow stagnation—as \( r/w < \left[ 0.5C_f^{-1} h/w \right]^{1/2} \),

![Figure 4.1. Sketch of flow characteristics in high curvature bends showing location of flow separations zones. Shaded region indicates location of the point bar. After Dietrich (1987) schematic of flow in a meander with a well developed bar.](image)
where $C_f$ is the dimensionless Chézy coefficient, and $h$ is channel depth. The parameter $C_f^{-1} h/w$ characterizes the shape and roughness of the channel, and thus the onset of outer bank flow stagnation is favored in smooth, narrow channels (Blanckaert et al. 2012b).

Based on experimental work, Blanckaert (2009) reasoned that low migration rates in sharp bends are in part caused by saturation of curvature-induced secondary circulation, which limits the magnitude of the submerged high velocity core and bed shear stresses near the base of the outer bank, thereby limiting bank erosion. Later, Blanckaert et al. (2012b) also identified inner-bank flow separation and outer-bank flow stagnation as processes that contribute to the reduction of bank migration. In field settings, sedimentation in the stagnation zone may lead to the development of concave bank benches (Nanson and Page 1983, Hickin 1978).

Hydrologic variability (i.e., stage variation) can alter the structure of the flow, patterns of shear stress, sediment transport, and ultimately channel migration (Markham and Thorne 1992, Pizzuto 1994). Helical motion in bends strengthens, dependent on several factors, including decreases in $(r/w)$ (Hickin 1978) and increases in the ratio of channel depth to radius of curvature $(h/r)$ (Rozovskii 1957, Engelund 1974), in superelevation of the water surface, and in pool depth (Bathurst et al. 1979, Markham and Thorne 1992). All of these factors act to increase the centrifugal acceleration (and opposing centripetal acceleration) occurring in the bend (Dietrich 1987). Thus, for a given radius of curvature, increases in stage, or depth, will strengthen secondary circulation by increasing $(h/r)$. Increases in stage may also result in an increase in width, or decrease in $(r/w)$, making the bend effectively “sharper” for intermediate and higher stages than for lower stages. If these stage-related effects cause the flow to exceed a threshold for $(r/w \leq 2.5)$ for flow stagnation, forces acting on the outer bank will change, resulting in altered bank-erosion processes.
Clearly, high curvature bends exhibit more complex hydrodynamics than low to mild curvature bends. Until now, little effort has been made to relate the evolution of compound meander loops with the dynamics of high curvature bends. Furthermore, the influence of hydrologic variability on flow through compound loops and on loop evolution are as of yet not well understood. Thus, the objectives of this paper are to examine the influence of channel curvature and hydrologic variability (i.e., stage) on the three-dimensional structure of flow within a compound loop and to relate changes in bed morphology to flow structure at various flow stages. To fulfill these objectives, a three-year field experiment was conducted within a compound loop along a small meandering stream in Illinois.

4.2 Study Reach and Channel Evolution History

The study site is a compound meander loop along Sugar Creek in McLean County, Illinois (Figure 4.2). Sugar Creek has its origin in Bloomington-Normal metropolitan area and flows southwest toward the study site. The bend examined in the study is located approximately 41 km downstream from Bloomington-Normal, and has an upstream drainage area of 282 km$^2$. 
Figure 4.2. Location map of the study site showing the planform migration history within the reach. Flow is from right to left.

To provide land drainage for agriculture, and to efficiently drain urban areas, headwater streams have been extensively modified throughout central Illinois (Urban and Rhoads 2003). The total length of first order streams that has been straightened or channelized in many cases exceeds 90 percent (Mattingly, Herricks and Johnston 1993). The upper reaches of Sugar Creek are no exception. Sugar Creek forms the primary discharge outlet for the Bloomington-Normal Water Reclamation District, which has enlarged and straightened the channel to convey urban stormwater runoff. Downstream of the metropolitan area, long reaches of the creek have been straightened and converted into a trapezoidal cross-sectional shape to drain agricultural fields.
Only small sections of the upper reaches of Sugar Creek, including the study site, remain unchannelized.

The bend examined in this study is located within an approximately 1600 m long meander train containing elongated bends and compound loops that have not been channelized since at least the 1940s. Comparative GIS analysis of georeferenced historical aerial photography indicates that the meander train, including the study bend, has evolved considerably over the past 72 years (Figure 4.2). Currently, the study bend has the form of an asymmetrical elongated compound loop (Frothingham and Rhoads 2003) with three distinct lobes of maximum curvature: one upstream, and two downstream (hereafter labeled lobe 1 and lobe 2 for convenience). Although a third lobe exists upstream, flow measurements and analyses were conducted only in lobe 1, and lobe 2. The study bend has a bankfull channel width of 20–23 meters, a bankfull depth of 2–2.5 meters, and an average gradient of 0.001 m m\(^{-1}\).

The outer bank of the bend is nearly vertical, unvegetated (Figure 4.3), and consists mainly of basal lag gravels overlain by fine sands and silty loam soil. The floodplain of the creek is agricultural, with a riparian buffer of sedge grasses that varies in width from approximately 20 meters to as much as 200 meters (Figure 4.3). The inner bank of the study bend has a typical spatial succession of grasses, reeds, shrubs and trees with increasing distance from the channel.
Figure 4.3. Ground photo of the study bend. View is looking downstream at lobe 2 from approximately 1 channel width upstream of the apex (Near topographic transect B, Figure 4.5).

4.3 Field Data Collection and Analysis

To address the objectives of the paper, multiple quantitative data collection techniques have been employed.

4.3.1 Three-dimensional Time-averaged Flow

Three-dimensional, time-averaged velocity data were collected at the study site during three separate sampling campaigns [May 17, 2010 (campaign 1), May 26, 2011 (campaign 2), and September 7, 2012 (campaign 3)] corresponding to three different flow conditions (Table 4.1). An Acoustic Doppler Current Profiler (ADCP) was used to obtain these data along
sampling transects oriented perpendicular to the local channel direction (Figure 4.4). Two different ADCPs were employed: a broadband 1,200 kHz Workhorse Rio Grande ADCP (RG1200) manufactured by Teledyne RD Instruments (campaigns 1 and 2) and a variable frequency broadband M9 River Surveyor ADCP (M9) produced by Sontek (campaign 3). Both ADCPs operate on the principle of measuring the Doppler shift of acoustic pulses transmitted from divergent beams reflected by neutrally buoyant particles in the water column. Each ADCP uses four beams in a Janus configuration (i.e., beam pairs aimed in opposite directions) with a specified beam spread angle. The RG1200 has four 1,200 kHz beams with a beam angle of 20°, and the M9 has four 1,000 kHz or 3,000 kHz beams, depending on flow conditions, with a beam angle of 30°. ADCPs operate by transmitting acoustic pulses along each of the four active beams. Calculation of the Doppler shift between the transmitted frequency of the pulses and the reflection of those pulses off of suspended particles (scatterers) in the water column allows the ADCP to compute the along-beam velocities of the scatterers. By assuming that the flow movements can be considered homogenous at the sampling rate (typically 5-10 Hz), and that the movement of the particles represents the movement of the water, the ADCP can resolve the 3-D Cartesian magnitudes and directions of water velocities from the trigonometric relationship between the beam centers and beam angle. Data in the first 25 cm nearest to the probe are excluded to eliminate contamination of the velocity measurements from the draft of the probe and ringing of the transducer heads (i.e., so-called blanking distance) (Mueller et al. 2007). Additionally, data near the channel boundary are discarded to eliminate bins contaminated by side lobe interference. The amount of data screened is a function of water depth and beam angle, and can range from 6% (for the RG1200) to 13% (for the M9). In addition to determining water
velocities, both ADCPs also measure water depth and the spatial position of the probe relative to the bottom (i.e., bottom tracking).

Figure 4.4. Flow measurement cross sections for campaign 1 (red), campaign 2 (blue), and campaign 3 (green). Lettered topographic cross sections are also shown. Air photo taken from the 2010 National Agriculture Imagery Project (NAIP) dataset.
Table 4.1. Summary of hydraulic characteristics for the study bend.

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<th>ID</th>
<th>B (m)</th>
<th>H (m)</th>
<th>A (m²)</th>
<th>U (ms⁻¹)</th>
<th>Q (m³s⁻¹)</th>
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<td>9.65</td>
<td>1.04</td>
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</tr>
</tbody>
</table>

Cross-section No. (ID); width of the water surface (B); mean flow depth (H); cross-sectional area (A); bulk flow velocity (U); discharge (Q); percentage difference of the cross-section discharge from the mean discharge for each campaign (Q % diff)
To acquire data on time-averaged flow characteristics and mean water depths, operators on each bank pulled the ADCP, mounted on a catamaran, along the cross sections using a tag line. For each measurement transect, four passes across the channel were completed, ensuring that passes were in reciprocal pairs, where a pair consists of one pass starting on the left bank, and another starting on the right bank. Both the RG1200 and M9 sampled the flow at a similar rate (approximately 1 Hz), but that rate is not fixed, and varied slightly during the course of a measurement. The RG1200 sampled velocities in fixed 5 cm bins over the depth of flow, yielding 4–60 bins per ensemble, depending on flow depth. Measurements with the M9 varied in frequency and thus bin size across the channel. The sizes of bin ranged from 2–15 cm, which produced 10–63 bins per ensemble.

Due to limitations of the equipment setup, the use of GPS with the RG1200 probe in campaign 1 and campaign 2 was not possible. To locate the position of each measured ensemble within a transect, a method based on ADCP bottom track data that accounts for positional errors was developed. The positions of the ADCP probe at the beginning and end of a pass was determined relative to the surveyed endpoints of each cross section. The position of each ensemble along the transect was then computed by distributing the probe’s reported values of linear distance travelled (dead reckoning), or “distance made good” (DMG), between the beginning and ending locations of the pass. In high flows, an actively mobile bed may exist, producing error in the ADCP bottom track positions. In these cases, length scaling adjustments were made to ensemble locations by distributing the difference between the measured distance and probe-reported distance equally among all ensembles. Analysis of the differences, expressed as percentages, between the measured distance and probe-reported distance show that in campaign 1 the differences ranged from 5.4–27.3% with a mean of 14.8%. Differences in
campaign 2 ranged from 3.1–15.45% with a mean of 10.2%. Factors responsible for these differences include locational bias from mobile bed conditions and deviations of the tethered boat path (shiptrack) from the path of the transect as it was towed across the stream. The extent to which each of these factors contributed to differences between the measured distance and probe-reported distance is unknown. Given the rapid transit time of the probe across each transect, which minimized the effect of a mobile bed on locational bias, and visible deflection of the catamaran from the transect by the flow, it seems likely that deviations of the catamaran from the transect mostly accounted for the differences. In campaign 3, a GPS mounted to the M9 and tethered boat allowed ensemble positions reported by bottom tracking to be verified based on GPS data. In post processing, measured velocities for each of the four passes in a transect were averaged and mapped onto the transect using the Velocity Mapping Toolbox (VMT), a suite of Matlab® functions specifically designed to work with moving boat ADCP deployments (Parsons et al. 2012). Within VMT, the velocity data are rotated using a zero net secondary discharge condition, a frame of reference that is appropriate for meandering rivers (Markham and Thorne, 1998; Lane et al., 2000). VMT also includes a robust analysis and visualization platform for further exploring time- and space-averaged flow fields.

4.3.2 Channel Morphology and Planform Change

Detailed elevation data of the entire study bend were acquired for each campaign prior to the flow measurements using a robotic total station. Points were sampled along roughly equally spaced transects throughout the channel, point bar, and banks, yielding a total of 1,000–2,500 sampled elevations for each campaign. Locational precision of the surveys was +/- 0.5 cm horizontally, and +/- 0.5–1.0 cm vertically. Surveyed elevation data were used to construct topographic maps of the bend prior to measurement in each flow campaign. The positions of the
inner and outer banks derived from the elevation surveys were used to evaluate short term planform change within the study bend. In addition, the position of the top of the outer bank was surveyed prior to each campaign. Topographic channel cross sections were constructed by “slicing” the isosurface representing the total station surveys at 15 meter intervals along the mean position of the centerline of the channel for the study period. Though the transects where flow measurement were taken varied slightly from campaign to campaign, the topographic cross sections are extracted in the same locations for all campaigns.

Characterization of the sediment within the channel was based on bulk sampling of the bed in the field. Bed material was sampled at several transects through the entire bend. At each transect, a sample was collected at the thalweg, approximately one third channel width toward the inner bank from the thalweg, and if present, on the point bar. Channel samples were sieved in the lab, and grain size distributions by weight were computed for each sample. The resulting grain size distributions were used to calibrate the channel roughness at each cross section for use in computing boundary shear stresses.

To determine channel curvature, bank locations were digitized from georeferenced aerial photography at approximately channel width intervals at a fixed scale of 1:2,000. Using discrete bank measurements, a continuously differentiable channel centerline was fitted using piece-wise cubic splines (PCS) (Güneralp and Rhoads 2008). Channel centerline curvature, $C$, was then computed at regular intervals along each centerline as:

$$ C = \frac{x'y'' - y'x''}{(x''^2 + y''^2)^{3/2}} $$

(4.1)

where $x$ and $y$ are the Cartesian coordinates of the centerline, and the prime and double prime represent the first and second derivative accordingly. The radius of curvature ($r$) at each point along the centerline is the inverse of curvature ($r = 1/C$).
Bank erosion rates were computed by determining the change in orthogonal distance of the outer bank to the centerline for each campaign. An erosion rate was then determined by dividing the distance moved by the time between surveys, expressed as years.
4.3.3 Computation of Bed Shear Stress and Entrainment

Due to side lobe interference, ADCPs do not measure water velocities near the bed, therefore, computation of boundary shear stresses via direct measurement of near-bed velocity profiles is not possible. However, shear computation methods that use depth-averaged velocities, and channel roughness calibrated by grain size information provide reasonable estimates of boundary shear (Wilcock 1996, Sime, Ferguson and Church 2007). Boundary shear stress magnitude is commonly estimated as:

$$\tau_b = \rho C_f U^2$$  \hspace{1cm} (4.2)

where \( \rho \) is the fluid density, \( C_f \) is the coefficient of friction computed by:

$$C_f = \left[ \alpha_r \left( \frac{H}{k_s} \right)^{10} \right]^{-2}$$  \hspace{1cm} (4.3)

where \( \alpha_r \) is set equal to 8.1 (Parker 1991), and \( k_s \) equal to 2.95\( D_{b4} \) as specified by Whiting and Dietrich (1990). Equation (4.3) is commonly referred to as the Manning-Strickler law of bed resistance. By using both the grain size distributions and channel depths along each flow measurement cross section, Equation (4.3) allows the roughness to be varied spatially throughout the study bend. Equation (4.2) can be generalized to a two dimensional vector \( \mathbf{\tau}_b \) with streamwise \( (\tau_{bu}) \) and cross-stream \( (\tau_{bv}) \) bed shear stress component magnitudes of (a full derivation is given in Chapter 2):

$$\tau_{bu} = \rho C_f U \sqrt{U^2 + V^2}$$  \hspace{1cm} (4.4)

$$\tau_{bv} = \rho C_f V \sqrt{U^2 + V^2}$$

where \( V \) is the depth-averaged cross-stream velocity. The magnitude \( (\tau_{b(U,V)}) \) and direction \( (\theta_{b(U,V)}) \) of the two-dimensional vector \( \mathbf{\tau}_b \) can be found using the component magnitudes from Equation (4.4) by:
The magnitude of boundary shear stresses ($\tau_b$) computed by Equation (4.5) is made dimensionless ($\tau^*$) by the following relationship:

$$\tau^* = \frac{\tau_b}{\rho R g D}$$

where $R$ is the specific weight of submerged sediment ($R = 1.65$ for quartz), and $g$ is the acceleration due to gravity. The pioneering work of Shields (1936) determined the minimum, or critical, dimensionless shear stress ($\tau^*_c$)—also called the Shields parameter—necessary to initiate motion of (i.e., entrain) uniformly distributed grains of a given size. Quantities of dimensionless shear stress below the critical value represent stresses applied by the fluid on the bed that are expended on processes other than the transport of sediment (Buscombe and Conley 2012), therefore most approaches to modeling entrainment capability of the flow express sediment transport in a functional form as follows:

$$q^* = \alpha (\tau^* - \tau^*_c)^{3/2}$$

where $q^*$ is a dimensionless sediment transport rate, commonly called the Einstein parameter, $\alpha$ is a parameter modifying the effective rate of sediment transport, the value of which is dependent on the transport model, and the quantity in brackets is referred to as excess stress, or that stress which is assumed to be transporting sediment. The Shields parameter varies with properties of the fluid and grain size. It is common to express it as a function of grain Reynolds number:

$$Re_p = \frac{u_* D}{\nu}$$

where $\nu$ is the kinematic viscosity of the fluid, $u_*$ is shear velocity found as $\sqrt{\tau_b/\rho}$, $D$ is grain size. One such analytical expression for the Shields parameter is (Soulsby 1997):
where $D^*$ is dimensionless grain size given as:

$$D^* = \left(\frac{gR}{\nu}\right)^{1/3} \quad (4.10)$$

Shields’ experiments were conducted with homogenous sediments of uniform size. In cases of heterogeneous sediment mixtures of a range of grain sizes, individual grain size fractions in the mixture do not necessarily mobilize at the same shear stress as they would in a homogeneous mixture (Egiazaroff 1965, Wilcock 1988). Moreover, behavior of sediment mobilization in mixtures cannot be taken as a simple proportion of predicted critical shear stress at each size fraction. To account for the effects of grain to grain interactions in sediment mixtures, Equation (4.7) can be recast as:

$$q_i^* = \alpha \left[ (\tau_i^* - \tau_g^*)^{3/2} P_i \right] \quad (4.11)$$

where $q_i^*$ is the dimensionless sediment transport rate for the $i^{th}$ fraction of the grain size distribution described by $(\sum P_i = 1)$, and $\tau_g^*$ is the Shield parameter computed for the arithmetic mean grain size:

$$D_g = \sum_{i=1}^{L} D_i P_i \quad (4.12)$$

In Equation (4.11), $\tau_e^*$ is effective shear stress, and replaces the original critical Shields parameter $\tau_c^*$. This effective shear stress quantity represents the amount of shear necessary to initiate motion of grains at the $i^{th}$ size fraction in a mixture, and is computed by (Buscombe and Conley 2012):

$$\tau_e^* = \frac{0.3}{1 + 1.2D^*} + 0.055[1 - \exp(-0.02D^*)] \quad (4.9)$$
where the subscripts $i$, $g$, and $c$ are the $i^{th}$ fraction of a grain size distribution, arithmetic mean grain size, and critical value respectively, $u_*$ is shear velocity found as $\sqrt{\tau_b/\rho}$, $D$ is grain size, and $\sigma$ is the standard deviation of the grain size distribution found by

$$\sigma = \sqrt{\sum_{i=1}^{l} (D_i - D_g)^2 P_i}$$

(4.14)

Using Equation (4.13), the mobility of graded sediment at any given vertical location in the flow measurements can be determined by computing the excess dimensionless shear stress ($\tau_{e_i}^* - \tau_g^*$). Depth-averaged velocities and flow depths were provided by the ADCP measurements. The estimated values of bed shear stress (vector components and magnitudes) and excess shear were imported into ArcGIS® for each flow measurement campaign.
4.4 Results

4.4.1 Morphology of the Channel

4.4.1.1 Bed Morphology, Bed Material, and Channel Change

Bed morphology within the compound meander loop consists of multiple pool-riffle-point bar sequences—a common element of compound loops (Kinoshita 1961, Whiting and Dietrich 1993b, Abad and Garcia 2009a). The morphology of the portion of the loop examined in this study is similar amongst all three measurement campaigns, consisting of one pool and point bar (unit) sequence at each lobe (Figure 4.5). Channel substrate ranges from fine sand \(D_{84} = 0.18\) mm along the inner bank to very coarse pebbles \(D_{84} = 59.44\) mm) within the thalweg (Figure 4.4). Throughout the study bend, the channel consists of asymmetric cross sections with gently sloping inner banks, a deep thalweg located near the outer bank, and near vertical outer bank. This channel shape is associated with a well-developed pool, point bar, and cut bank (Figure 4.5, see also Figure 4.6).

During the period of study, erosion and deposition occurred near and/or downstream of the lobe apices, with lobe 2 being more active than lobe 1 (Figure 4.6, Table 4.2). Surveyed positions of the top of the outer bank illustrate that lobe 1 and lobe 2 have had different migration trajectories over the study period (Figure 4.7). Migration in lobe 1 (topographic cross-sections B–G) occurred primarily through downstream translation, whereas migration in lobe 2 (topographic cross-sections H–M) occurred through both lateral extension and downstream translation, causing the study bend to elongate. The compound loop was approximately 153 meters long in 2010. However, the observed patterns of bank migration increased the length of the loop to approximately 159 meters by 2012, causing an increase in sinuosity from 1.27 in May 2010 to 1.32 in September 2012. The total bank erosion distances orthogonal to the centerline for
each cross section were much greater for lobe 2 than for lobe 1 over the study period, with erosion rates (equivalent to migration rates in the lobes) approximately two to three times higher than in lobe 1 (Table 4.2).
Figure 4.5. Topographic map and $D_{84}$ particle size distributions of the study site on Sugar Creek, Illinois. Elevation isosurface derived from a total station survey on July 1, 2010. Sediment samples were taken March 24, 2010. Flow is from upper right to lower left. Contour interval is 20 cm, based on an arbitrary vertical datum.
Table 4.2. Mean bank erosion rates, and total erosion distances for each of the 13 topographic cross sections.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Mean bank erosion rate (m year$^{-1}$)</th>
<th>Total bank erosion (m)</th>
<th>Transect</th>
<th>Mean bank erosion rate (m year$^{-1}$)</th>
<th>Total bank erosion (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.09</td>
<td>0.10</td>
<td>H</td>
<td>1.20</td>
<td>2.88</td>
</tr>
<tr>
<td>B</td>
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<td>0.26</td>
<td>I</td>
<td>1.25</td>
<td>2.86</td>
</tr>
<tr>
<td>C</td>
<td>0.20</td>
<td>0.38</td>
<td>J</td>
<td>1.77</td>
<td>4.06</td>
</tr>
<tr>
<td>D</td>
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<td>K</td>
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<td>2.79</td>
</tr>
<tr>
<td>E</td>
<td>0.59</td>
<td>1.38</td>
<td>L</td>
<td>0.67</td>
<td>0.94</td>
</tr>
<tr>
<td>F</td>
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<td>M</td>
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<td>G</td>
<td>0.94</td>
<td>2.16</td>
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In lobe 1, erosion of the outer bank was greatest downstream of the apex (cross-section E–G), resulting in a maximum of 2.16 meters total migration (cross-section G) during the 3 year study period (Table 4.2, Figure 4.7). Changes in the channel cross-section morphology upstream (cross-section A) represent adjustments of the pool and scour hole upstream of the entrance to the study bend (Figure 4.6). Upstream and through the apex (cross-sections B–D), the elevation of the point bar initially increased, most likely due to the presence of large woody debris (LWD) which may have contributed to deposition by impeding flow and promoting accumulation of sediment upstream (Figure 4.5). The LWD was removed by the flow sometime between campaign 2 (May 2011) and campaign 3 (September 2012). By September 2012, two local zones of scour developed near the inner bank at the upstream and downstream ends of the LWD (cross-section B and cross-section D). Deposition was not uniform, with the largest deposition rates occurring immediately downstream of the LWD (cross-sections D–E), and smallest rates located farther downstream (cross-sections F–G). The outer bank of lobe 1 remained steep with nearly vertical banks (slopes ranging from 40–75°) throughout the study period.
In lobe 2, erosion of the outer bank was greatest immediately downstream of the apex (cross-section J), resulting in 4.06 meters of total migration during the 3 year study period (Table 4.2, Figure 4.7). The pool deepened near the apex, and moved laterally throughout the lobe. Deposition occurred on the point bar, though the elevation changes are near the measurement error of the topographic isosurface. Downstream of the apex, the thalweg is reoccupying a lower portion of the outer bank, likely a relict concave-bank bench which formed sometime between 1999–2003 (Figure 4.2).
4.4.1.2 Channel Curvature

Dimensionless radius of curvature values in the study bend vary both downstream and with differing flow stages (Table 4.3). Overall, channel curvature is highest (i.e., dimensionless radii of curvature are lowest) in the high flow event (campaign 1) due to increases in channel width and depth associated with increased flow stage. Note that the dimensionless radius of curvature of the lobe 1 apex (cross-section 1-3) during campaign 1 is below the threshold of 2.5 that Hickin (1974) found to be the curvature associated with maximum channel migration.

Table 4.3. Dimensionless radius of curvature values at flow measurement locations for each campaign. Transect locations are shown in Figure 4.4. Note that \( r \) is radius of curvature.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Campaign 1 (High)</th>
<th>Campaign 2 (Intermediate)</th>
<th>Campaign 3 (Low)</th>
</tr>
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<tr>
<td></td>
<td>( r/w )</td>
<td>( r/d )</td>
<td>( r/w )</td>
</tr>
<tr>
<td>1-1</td>
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<td>2-4</td>
</tr>
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<td>553.71</td>
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<td>262.68</td>
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</tr>
<tr>
<td>1-8</td>
<td>46.50</td>
<td>618.01</td>
<td>2-7</td>
</tr>
<tr>
<td>1-9</td>
<td>3.55</td>
<td>53.01</td>
<td>2-8</td>
</tr>
<tr>
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<td>3.22</td>
<td>49.51</td>
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</tr>
<tr>
<td>1-11</td>
<td>7.95</td>
<td>118.73</td>
<td></td>
</tr>
</tbody>
</table>

Radius of curvature (\( r \)), Channel top width according to edge of water (\( w \)), mean channel depth (\( d \))
Figure 4.6. Repeat topographic transects for each measurement campaign.
Figure 4.7. Surveyed locations of the outer bank during the three year study. Topographic transects are also shown.
4.4.2 Time-averaged velocity fields

4.4.2.1 Patterns of Depth-averaged Vectors

Depth-averaged 2-D vectors from the three measurement campaigns (May 2010, May 2011, and September 2012) illustrate the general flow patterns in the evolving study bend for three different hydrologic conditions (Figure 4.8). Patterns are similar for the high flow and intermediate events (campaigns 1 and 2). The cross-stream pattern of vectors is asymmetric upstream of the lobe 1 apex, with larger velocities over the point bar and smaller velocities in the thalweg (cross-sections 1-1, 1-2, and 2-1, 2-2). In campaign 1, the flow expands and is directed toward the outer bank just upstream of the apex (cross-section 1-2). However, in campaign 2, flow accelerates and diverges as it encounters LWD resting on the inner bank (cross-section 2-2). At the apex (cross-sections 1-3 and 2-3), the channel area increases by approximately 1.8 square meters (Table 4.1), flow decelerates throughout the entire cross-section, and near the outer bank velocities are greatly reduced compared to upstream. As flow exits the lobe, it accelerates, and the cross-stream pattern of vectors becomes more symmetric. Here the flow encounters a riffle (Figure 4.5) with a more uniform bed morphology. As flow enters lobe 2 (cross-sections 1-5–1-8, and 2-5–2-8), vectors are aligned with the orientation of the channel banks. Flow accelerates in the central channel and thalweg, but remains slower than flow over the point bar and inner bank, where it moves through grasses growing on the upper point bar. Vectors in the mid-channel region and thalweg just upstream of the lobe 2 apex (cross-section 1-9 and 2-7) are directed outward. In campaign 1 downstream of the apex and extending approximately 1 channel width downstream, a large block of failed bank material interacts with the flow near the outer bank (cross-sections 1-10 and 1-11), as evidenced by low velocities close to the bank.
The patterns of depth-averaged vectors in the low flow event (campaign 3) share some similarities with the intermediate and high flow events (campaigns 1 and 2), however there are significant differences. The nature of low flow events at this study site are unsteady—individual cross-section discharges varied as much as 43% from the campaign 3 mean discharge (Table 4.2). Vector magnitudes differ greatly between the two transects at the entrance of lobe 1 (cross-sections 3-1 and 3-2). Despite this unsteadiness, it is still useful to examine the characteristics of the depth-averaged vectors to understand how flow is directed through varied bed morphology. At low flow, the cross-stream patterns of depth-averaged vectors are highly asymmetrical. The locus of highest velocities is restricted to the thalweg throughout the bend. Moreover, vectors in the thalweg are directed toward the outer bank throughout lobe 1 (cross-sections 3-2–3-5). Vectors over the point bar are larger than in the thalweg, and are oriented toward mid-channel, especially downstream of the lobe 1 apex (cross-section 3-4)—a finding consistent with topographic steering of the flow around a shoaling bar (Dietrich and Smith 1983). Vectors in lobe 2 (cross-sections 3-6–3-9) are more in line with the orientation of the channel banks than in lobe 1, although vectors downstream of the lobe 2 apex (cross-section 3-8) are still directed outward. The bank block which strongly interacted with flow in campaign 1 is almost completely removed during campaign 3, but small roughness elements at the base of the outer bank reduce the velocity of the flow and deflect it inward during the low-flow event (cross-section 3-8).
Figure 4.8. Depth-averaged flow vectors for the study bend during campaign 1 in 2010 (A), campaign 2 in 2011 (B), and campaign 3 in 2012 (C).
4.4.2.2 Patterns of Three-dimensional Velocities

Contour plots of downstream velocities with superimposed cross-stream/vertical velocity vectors show the detailed three-dimensional fluid motion occurring in the study bend for each campaign (Figure 4.9–Figure 4.11). The general pattern of downstream velocities in all three campaigns is comprised of a core region of high velocities surrounded by diminishing velocities near the channel bed and banks. General patterns of cross-stream/vertical vectors indicate two circulation cells present throughout most of the study bend: 1) a large curvature-induced secondary circulation in the center channel region characterized by outward-directed near-surface flow and inward-directed near-bed flow, and 2) a small counter-rotating outer bank cell.

At the lobe 1 entrance, the high velocity core resides near the center of the channel and the magnitude of streamwise velocities diminishes greatly near the channel banks (cross-sections 1-1, 2-1, and 3-1). This inherited flow structure arises from flow converging around a mid-channel bar located upstream of the study bend. As flow enters the study bend, the high velocity core moves progressively closer to the outer bank, but specific patterns of downstream velocities are different for each campaign. During campaign 1, the high velocity core is located near the outer bank as it enters lobe 1 (cross-section 1-2). Immediately upstream of the apex (cross-section 1-3), overall downstream velocity magnitudes are reduced relative to those in the rest of lobe 1, and velocities within approximately 5 meters of the outer bank are much lower than velocities in the same region just upstream (cross-section 1-2). Downstream of the lobe 1 apex, velocity magnitudes increase, the high velocity core is located near the outer bank submerged below the free surface, and curvature induced secondary circulation is well defined (cross-sections 1-4–1-6). The high velocity core is displaced progressively outward as flow enters lobe 2 (cross-sections 1-7–1-9), becoming submerged below the surface at and just downstream of the
apex (cross-sections 1-9–1-11). The location of the submerged high velocity core corresponds well to where patterns of secondary vectors show downwelling of the flow. Reduced velocity magnitudes, and lack of well-defined secondary circulation near the inner bank throughout the study bend are a result of increased flow resistance due to grass growing on the lower portion of the inner bank floodplain.

In campaign 2, the high velocity core moved progressively closer to the outer bank, and the near outer bank velocities are lower than within the mid-channel region as flow traverses lobe 1 (cross-sections 2-2–2-5). As indicated by cross-stream/vertical vector magnitudes, curvature induced secondary circulation is strongest at, and downstream of, the apex (cross-section 2-3–2-5). Upstream of the apex, curvature-induced circulation is confined to mid-channel, and a counter-rotating circulation cell with slower downstream velocities than in the main channel is located near the outer bank. The high velocity core is closest to the outer bank downstream of the apex of lobe 1 (cross-section 2-5). The core moves progressively outward as flow enters lobe 2, but the secondary vectors display no discernible pattern near the outer bank, indicating that complex flow occurs in this region of failed bank material at and downstream of the apex (cross-sections 2-8–2-9).

In campaign 3, curvature induced secondary circulation is poorly defined, and instead local topographic effects dominate circulation patterns, with the locus of highest downstream velocities restricted to the thalweg throughout the bend. Secondary vectors near the inner bank in lobe 1 (cross-section 3-2 – 3-5) are directed outward as flow is deflected by the point bar, with the exception of cross-section 3-3, where approximately 2 meters from the inner bank, a topographic high causes flow to diverge locally toward the inner bank. At the downstream end of lobe 1, secondary vectors indicate a curvature-induced circulation cell within the thalweg.
Curvature-induced secondary circulation in lobe 2 is better defined than in lobe 1. Velocity magnitudes near the outer bank at the lobe 2 apex (cross-section 3-8) are greatly reduced relative to those in the middle of the channel, and outward-directed flow over the point bar is indicative of topographic steering of the flow. Downstream of the apex, curvature-induced secondary circulation is well defined within the thalweg.
Figure 4.9. Cross-section plots for campaign 1 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical vectors (arrows) for each transect where flow was measured in 2010. Thick black arrows indicate the inferred secondary circulation patterns.
Figure 4.10. Cross-section plots for campaign 2 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical vectors (arrows) for each transect where flow was measured in 2011. Thick black arrows indicate the inferred secondary circulation patterns.
Figure 4.11. Cross-section plots for campaign 3 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical vectors (arrows) for each transect where flow was measured in 2012. Thick black arrows indicate the inferred secondary circulation patterns.
4.4.3 Distribution of Bed Shear Stresses and Entrainment

Generally, patterns of bed shear stress vectors resemble patterns of depth-averaged velocities for all three measurement campaigns (Figure 4.12). High depth-averaged velocities are correlated with high bed shear stress magnitudes, whereas low depth-averaged velocities are correlated with low bed shear stress magnitudes. Additionally, bed shear stresses are low in the shallow regions of the flow such as over the point bar. In the high and intermediate flow events (campaigns 1 and 2), bed shear stress maxima are located in or near the thalweg upstream and at the lobe apices. Downstream of the lobe apices, shear stress maxima are located near the outer bank. The proximity of the locus of highest shear stress magnitudes to the outer bank correspond to the patterns of short-term bank erosion occurring during the study period (Table 4.2). In the low flow event (campaign 3), the locus of maximum bed shear stress is located in the thalweg throughout the bend.

Patterns of flow competence, expressed as the largest grain size that the flow is able to entrain (Figure 4.12), coupled with patterns of the largest percentile of the grain size distribution that can be entrained (Figure 4.13) indicate that the spatial distribution of bed mobility in the study bend is complex. Patterns of flow competence (Figure 4.12) in the high and intermediate flow events (campaigns 1 and 2), are similar, with the highest levels of competence corresponding closely with the location of maximum shear stresses in the bend. In general competence is highest in the thalweg and reaches a maximum at the transition between lobes 1 and 2. Patterns of percentiles mobilized exhibited are nearly opposite those of competence with the smallest percentiles of mobilization occurring in the thalweg, where sediment is coarsest, and the highest percentiles of mobilization occurring over the point bar, where the sediment is finest (Figure 4.5). This pattern also varies longitudinally along the reach. Upstream of the lobe 1
ape, as much as 80% of the grain size distribution can be entrained (Figure 4.13) corresponding to grain sizes less than 12 mm (Figure 4.12). Within lobe 1, the zone of highest competence remains centered in the channel, whereas the zone of high percentile entrainment shifts from near the outer bank upstream (cross-section 1-1) to near the inner bank at the apex (cross-section 1-3), and then back along the outer bank downstream of the apex (cross-section 1-4, Figure 4.12 and 4.13). Low competence and percentile of entrainment occur near the inner bank at cross-section 1-2—the location of the LWD (Figure 4.5). Downstream of lobe 1, flow competence increases with the increasing magnitude of bed shear stress, but the percentile entrainment decreases as the grain size of the bed material coarsens (Figure 4.5). Upstream of the lobe 2 apex, the flow has the potential to entrain up to 60% of the fine material along the inner bank in campaign 1 (cross-section 1-9). By comparison, only 20% of the grain size distribution can be entrained along the inner bank in campaign 2. Throughout the lobe 2 thalweg, the flow is competent to entrain particles as large as 20 mm, but less than 20% of the particle size distribution is capable of being entrained in both campaigns due to the coarse bed material within the thalweg Figure 4.13).

In the low flow event, zones of high competence (20 mm) are confined to the thalweg. Nevertheless, the pattern of percentiles of entrainment show that substantial bed material entrainment generally is confined to lobe 1 during this event, where as much as 50–60% of the grain size distribution can be mobilized. Downstream of lobe 1, the percentile of entrainment is 10% or less due to the coarse nature of the bed material distributions relative to the flow competence.

Estimates of flow competence and percentiles of entrainment (Figures 4.12 and 4.13) are for the bed only, and do not consider the mobility of material on the outer bank. Although inferences about the absolute magnitude of near-outer bank shear stress can be made by
considering bed shear stress vectors near the bank, the competence of the flow to erode the bank is not considered in the present study.
Figure 4.12. Bed shear stress vectors for the study bend during campaign 1 in 2010 (A), campaign 2 in 2011 (B), and campaign 3 in 2012 (C) superimposed on a color contour map indicating the largest sediment grain size that can be entrained at any given location for the flow conditions.
Figure 4.13. Bed shear stress vectors for the study bend during campaign 1 in 2010 (A), campaign 2 in 2011 (B), and campaign 3 in 2012 (C) superimposed on a color contour map indicating the largest percentile of sediment that can be entrained at any given location for the flow conditions.
4.5 Discussion

Results of the analysis of flow structure and morphological change in the study site on Sugar Creek provide insight into the linkages between the spatial patterns of the mean flow, roughness calibrated bed shear stress, bed morphology, and bank erosion in an evolving gravel bed compound meander loop. Patterns of flow in campaign 1—a near bank full flood representative of a morphologically significant event—are consistent with short-term bank erosion patterns in the loop over the 3 year study period. At high flow stages, curvature in lobe 1 is high enough (i.e., $r/w < 2.5$) to exhibit flow characteristics associated with sharp bends (Hickin 1974). Flow velocities at the outer bank are reduced relative to the rest of the lobe (Figure 4.8), with curvature-induced secondary circulation and the high velocity core restricted to the middle of the channel (Figure 4.9). This reduction in velocity near the outer bank at this location may reflect the development of an adverse pressure gradient in this region, but, if so, the effect of the gradient on the flow is not sufficient to produce flow stagnation and development of a zone of recirculating fluid. Overall, however, the spatial pattern of flow is generally consistent with conceptual models of flow in sharp bends (Parsons 2002, Blanckaert and de Vriend 2004, Kleinhans et al. 2010, Blanckaert 2011, Blanckaert et al. 2012b, Ottevanger, Blanckaert and Uijttewaal 2012). Little or no topographic steering of the flow by the point bar is evident in campaigns 1 & 2, as indicated by depth-averaged velocity vectors that are aligned parallel to the channel banks and that are not oriented toward the thalweg over the bar (Figure 4.8). Reduction of streamwise velocities near the outer bank during high flows at the lobe 1 apex (caused high planform curvature) also results in low shear stress magnitudes near the outer bank (Figure 4.12), relatively little change in the channel cross-sectional shape (Figure 4.6, cross-sections C–D), and relatively low bank erosion rates (Table 4.2). By contrast, in lobe 2 the high velocity core is near
to the outer bank and bed shear stress magnitudes and bank erosion rates are much higher than in lobe 1 during the study period.

Conceptually, meandering rivers develop via a range of planform evolution stages, or behaviors. Planform migration in meandering rivers can be related to centerline curvature (Hickin and Nanson 1975, Hickin and Nanson 1984). Within this framework, several stages of meander development are recognized for individual loops. Migration at low curvatures progresses to growth and extension, increasing planform complexity, potential double heading, and increases in curvature to an upper limit (Hooke 2003). A phase diagram of idealized individual meander bend trajectories by meander behavior, originally created by Hooke (2003) (Figure 4.14), provides the basis for an objective examination of planform change in the study bend. These idealized trajectories display a range of planform evolution behaviors including cutoff, active migration, and bend stabilization. Results from Sugar Creek for the 3 year study period, as well as for the migration history from 1998–2012 are plotted as points on this diagram. For the historical data, dimensionless curvature was determined as the average of curvature at discrete points spaced approximately 0.5 channel widths apart computed by piecewise cubic splines over the individual lobe (Güneralp and Rhoads 2008), divided by the bank full channel width estimated from aerial photography. Migration rates were computed as the distance the channel moved perpendicular to the centerline divided by the amount of time elapsed between repeat aerial photos.
Figure 4.14. Conceptual migration trajectory curves (from Hooke (2003)) plotted alongside data from Sugar Creek. The open diamond and square markers represent data computed from bank erosion and curvature changes during the study period, whereas filled diamonds and squares are derived from historical airphoto analysis of planform change over a 14 year period.

Planform migration behavior for each lobe based on historical air photo analysis indicates that the lobes occupy different regions of the phase diagram (Figure 4.14). Historical data from lobe 1 plot on the phase diagram within the trajectory associated with normal migration growth (curve C), whereas data from lobe 2 transcend many different curves, rather than following the pattern of any individual curve. Overall, however, the data for lobe 2 generally plot above the data for lobe 1. The clear distinction between the curvature-migration relations of lobes 1 and 2, which occur within the same compound loop, is a powerful indication of the complexity of lobe dynamics within these types of loops. The curvature-migration results for each lobe computed
from much more accurate total station surveys of the bank erosion over the study period, and measured wetted flow widths (for campaign 1, corresponding to a near bank-full event) are also plotted for comparison (Figure 4.14). The spatial patterns of mean flow structure, bed shear stress, and bed-material entrainment for campaign 1—a morphologically significant near bank-full flood event—are consistent with the spatial patterns of bank erosion during the period of field measurements. Again, data for lobe 1 plot below data for lobe 2 on the curvature-migration diagram. The lobe 1 position on the plot is located within the stabilizing meander trajectory (curve D), whereas lobe 2 is located within the actively migrating trajectory (curve C), indicating that the lobes within this compound loop exhibit different bend dynamics.

The analysis of 2-D and 3-D flow structure in campaign 1 shows that lobe 1 has flow characteristics associated with sharp bends. The position of lobe 1 in the “stabilizing” portion of the migration trajectory phase space (Figure 4.14) supports the hypothesis that a local reduction in velocity of the flow at the outer bank of sharp bends is a mechanism for decreasing bank erosion and migration of the channel. Lobe 1 will likely continue to stabilize in the short-term until upstream and/or downstream curvature readjusts the lobe behavior, tantamount to the “shifts” in bend dynamics referred to by Hooke (2003). Lobe 2, which plots within a more active portion of the migration trajectory phase space than lobe 1, will likely continue to migrate at a higher rate than lobe 1.

Sediment entrainment and transport rates in heterogeneous grain size mixtures in bends are the result of a balance between near-bed fluid forces (lift and drag), submerged weight of individual grains (body forces), and frictional resistance of the bed (Dietrich 1987). On a cross-stream sloping bed, body forces also have a cross-stream component that is proportional to the cube of the grain diameter, whereas lift and drag forces are proportional to the square of grain
diameter. Therefore, for the same bed shear stress, large grains will tend to move outward, and small grains inward (Odgaard 1981, Ikeda 1984, Parker and Andrews 1986, Dietrich 1987, Nelson and Smith 1989). In developed pool-riffle bed morphology, divergence of local bed shear stresses are balanced by this cross-stream component of sediment transport (via curvature-induced secondary circulation) and sediment caliber, resulting in a path of high bed load transport through the thalweg (Dietrich and Smith 1984, Dietrich and Whiting 1989, Lisle et al. 2000). In general, patterns of shear stress magnitudes (Figure 4.12) correlate with the spatial distribution of grain sizes in the study bend (Figure 4.5) with locations of highest shear stress magnitudes corresponding to locations with the coarsest bed material and locations with the lowest shear stress magnitudes corresponding to locations with the finest bed material. Thus, grain size sorting in the bend reflects patterns of bed shear stresses observed in all flow campaigns—near the outer bank bed material is finest upstream, coarsening in the downstream direction, with the path of coarsest sediment tracking along the thalweg through the pools of each lobe. Along the inner bank, bed material is coarsest upstream, fining in the downstream direction over the point bar, with the exception of the downstream end of lobe 1 (near topographic cross-section F), where bed material is coarser than the surrounding point bar.

Overall the general pattern of grain size sorting in the study bend is similar to expected patterns in simple meander bends (Dietrich and Whiting 1989), with the exception of the lobe 1 & 2 transition (i.e., cross-section F) where sediment on the point bar is coarse relative to upstream. Whereas simple meander bends have one pool and one point bar with a coarse bar head fining downstream, compound meander bends commonly have multiple point bars along the inner bank, termed “shingle bars” (Kinoshita 1961, Whiting and Dietrich 1993b, Frothingham and Rhoads 2003). Bowing of the bed elevation contours along the inner bank
toward the outer bank in lobes 1 and 2 indicates that well-developed bar forms exist at these locations (Figure 4.5). The extent of such bowing diminishes in the lobe 1-2 transition, indicating that bar morphology is less well-developed at this location. The coarsening of sediment between lobes 1 and 2 likely represents an intermediate sedimentary environment that marks the transition between the tail of the bar in the upstream lobe and the head of the bar in the downstream lobe.

The spatial variation of the bed material distribution and patterns of bed shear stresses and entrainment thresholds have important implications for patterns of bed material transport in the study bend and maintenance of point bar and pool topography. At the upstream end of lobe 1, the high and intermediate flows are competent to entrain grains as large as 16 mm in the thalweg (Figure 4.12)—a high proportion of the grain size distribution at that location (Figure 4.5); consequently, much of the bed material there is entrained at all flow stages (Figure 4.13). Bed shear stress and competence increase as flow moves downstream into the transition between lobes 1 and 2 (Figure 4.12), where bed material becomes coarser than upstream, and the proportion of the bed material distribution entrained decreases (Figure 4.13). The downstream increase in shear stress magnitudes suggests that fine material entrained upstream in lobe 1 is transported through the lobe 1 and 2 pools and transition, and is unable accumulate in the pools, even at low flow stages. Thus, pool development in the lobes is sustained throughout the flow hydrograph. Over the point bar that extends from lobe 1 to 2, decreasing grain sizes (Figure 4.5) and shear stress magnitudes (Figure 4.12) in the downstream direction indicate that coarse material entrained upstream cannot be transported downstream and will be deposited on the bed. Coarsening of the point bar sediment in the transition between lobes 1 & 2 (cross-section F), coincides with a local increase in shear stress magnitudes at this location at high stage (Figure
Although fining of bed material over the point bar in lobe 2 (cross-section H, Figure 4.5) leads to a relatively large proportion of the bed material distribution there being entrained at high flow, the reduction in shear stress from upstream to downstream over this bar indicates that any coarse sediment arriving from upstream will be deposited, thereby maintaining the bar. The pool and point bar maintenance described in the study bend via increasing shear stresses through the pools and decreasing shear stresses over the bars with associated downstream grain size sorting is in keeping with the theory of meander bend bed equilibrium advanced by Dietrich and Smith (1983, Dietrich and Smith (1984), and Dietrich and Whiting (1989). In this theory, downstream reductions or increases in shear stress magnitudes in gravel bed rivers, where much of the bed material is not mobilized except for at high flow stages, are a primary means sediment sorting in bends. Coarse material unable to transit the bar top in decreasing shear stresses should move outward toward the point bar “crest”, whereby it may avalanche into the pool to be transported downstream by higher shear stresses there. Equilibrium morphology is obtained when the point bar side slope allows just enough inward directed cross-stream transport to keep fine sediment from moving outward (Dietrich and Smith 1984). Although no measurements of sediment transport were made in this study, the overall patterns of flow competence, percentiles of entrainment, and bed shear stresses, when considered in the context of spatial variation of bed material size distributions in the bend, should maintain pool and point-bar topography.

Coarse sediment in the thalweg is highly compacted with few loose grains. Because this portion of channel bed is submerged at all flow stages, sediment was collected as bulk (surface and subsurface) samples and no formal evaluation of bed armoring was possible. Armoring may exist in this region of the channel and thus results of the entrainment analysis, which is based on the bulk samples, may not be fully representative of bed material conditions. Because armoring
will coarsen the bed-material size distribution, estimates of entrainment based on bulk samples, which will be finer than surface samples of armor layers, will overestimate the proportion of bed material that can be mobilized by the flow. Estimates of particle mobility based on the bulk samples indicate that all three events, including the intermediate and low flows (campaigns 2 & 3) are capable of mobilizing at least the finest fractions of the bed material at some locations within the thalweg. The effect of armoring may be to diminish mobility to nearly zero for virtually all bed material, especially for low flows.

Use of moving boat ADCP techniques to measure three-dimensional flow structure in large rivers is becoming more prevalent. Limitations of the present study include the inability to measure the mean flow structure close to the bed and outer bank (due to side lobe interference), and logistical considerations of deriving the ADCP location in the case of non-GPS deployments. Concurrent measurement of instantaneous flow velocities near the outer bank are needed to evaluate in detail velocity profiles and shear stresses near the outer bank. Only by looking at these outer bank quantities can patterns of bank erosion be linked directly to flow structure within the bend at various flow stages.

4.6 Conclusion

This study has examined interactions among three-dimensional time-averaged flow structure, bed shear stress, sediment entrainment patterns, and variation in flow stage in a compound meander bend and how these interactions are related to changes in channel morphology over a timescale of a few years. Analysis of the relationship between local curvature and variation in flow stage shows that local increases in centerline curvature (or decreases in dimensionless radius of curvature) within the upstream lobe of the bend examined here reduces outer bank velocities at morphologically significant flows. This reduction in outer bank
velocities creates a region that protects the bank from high momentum flow and corresponding high bed shear stresses. The upstream lobe of the compound loop, which has a dimensionless radius of curvature about one-third less than that of the downstream lobe, also has an average bank erosion rate less than half of the erosion rate for the downstream lobe. The relatively high rate of bank erosion within the downstream lobe corresponds to the shift in a core of high velocity and the zone of high bed shear stresses toward the outer bank as flow moves through the two lobes. This pattern of erosion provides a mechanism for continued migration of the downstream lobe in the near future. The differential bank erosion rates for the two lobes suggest that the compound bend will continue to elongate and grow in planform complexity in the near future—a finding that is in agreement with recent work on a compound meander loop along the Embarras River in East Central Illinois, which showed that loop elongation was occurring through differential migration rates and trajectories of separate lobes of the loop (Engel and Rhoads 2012). Together the results of this study and of the Embarras River investigation support the hypothesis that compound loops tend toward increasing planform complexity rather than stable bend forms, even if a single lobe of the loop begins to stabilize (Parker et al. 1983, Parker and Andrews 1986, Seminara et al. 2001, Lanzoni and Seminara 2006).

The distribution of bed material sizes within the multi-lobed bend corresponds to the spatial pattern of bed shear stress magnitudes, indicating that bed material sorting within the bend is governed by bed shear stress. Within the thalweg, which extends along the outer bank through two distinct lobes of the bend, bed shear stresses and particle sizes increase in the downstream direction. The proportion of bed material entrained in the upstream part of the loop exceeds that entrained downstream, but because the bed shear stress increases in the downstream direction, fine bed material arriving from upstream is transported through the thalweg, sustaining
pools near the outer bank. Along the point bar, bed shear stresses and particle sizes generally decrease downstream, except in the transition between the lobes where particle size and bed shear stresses locally increase, indicating that a discontinuity in point-bar sediment characteristics exists between the lobes of this multi-lobed bend. The percentage of bed material entrained by high flow is locally high over downstream portions of the point bar where sediment is fine; however, the general decrease in bed shear stress from upstream to downstream along the inner bank implies that any coarse sediment entrained upstream will be deposited before reaching the downstream end of the point bar.

Although bed shear stresses and near-bank velocities are related to patterns of bank erosion, shear stresses acting on the outer bank were not quantified in this study. Detailed studies are needed to connect fluid forces acting on stream banks throughout compound bends to mechanisms and spatial patterns of bank erosion. Future work should examine the spatial variation of turbulent shear stresses in the near-bank region of compound bends. Characteristics of outer bank turbulence in curved channels are as of yet not fully understood. Moreover, the effects of changes in local curvature—like those that often occur in multilobe planforms—on the distribution of turbulent stresses near the banks are unknown. The processes of turbulence generation and the relationship of turbulence characteristics to bed and bank morphology are just now beginning to be understood through lab and modeling experiments (Blanckaert and Graf 2001, Abad and Garcia 2009a, Abad and Garcia 2009b, Jamieson et al. 2010, Blanckaert et al. 2012a). Field experiments are a crucial part of verification of theoretical findings from these experiments, and are necessary for improving knowledge of river morphodynamics (Engel and Rhoads, 2012).
CHAPTER 5

VELOCITY PROFILES AND THE STRUCTURE OF TURBULENCE AT THE OUTER BANK OF A COMPOUND MEANDER BEND

5.1 Introduction

Lowland alluvial rivers tend to meander within their floodplains, eroding the outer bank of successive bends (Parker et al. 2011, Engel and Rhoads 2012). Over the past 3 decades, the fluvial dynamics of meander bends, including processes related to outer bank erosion, have been the focus of numerous scientific investigations. Despite this effort, a comprehensive understanding of the hydraulic processes of outer bank erosion—especially the role of flow turbulence—remains elusive. Because natural river flows are fully turbulent, the erosive stresses acting on the banks of meandering rivers should be related to turbulent stresses. Current models of outer bank erosion, however, rely on simple parameterization of the flow via excess velocity, excess shear stress at the bank toe, or excess flow depth (Darby and Thorne 1996, Simon et al. 2000, Langendoen and Simon 2008, Blanckaert et al. 2012a). These simplified models do not account directly for the effects of turbulence, which impact bank erosion through both bed-material transport at the toe of the bank and through direct shear forces acting on the face of the bank. Although bank geotechnical models predict mass wasting of the outer banks reasonable well (Simon et al. 2000, Wood et al. 2001, Langendoen and Simon 2008), these models still rely on simplifications of the near-bank velocity and/or shear stress magnitudes. An enhanced understanding of the nature of turbulence near outer banks should lead to improvements in the representation of shear stresses and mechanisms of bank erosion in morphodynamic models of
meandering rivers. Such understanding requires detailed measurements in the outer bank region of natural rivers.

An improved understanding of the near-bank flow processes and bank erosion is also of practical importance. Between 1990 and 2003, over 4,000 bank stabilization projects occurred in the United States at a cost of over 0.5 billion dollars (Bernhardt et al. 2005). Motivations for bank stabilization projects include maintaining a navigable channel, protection of property, reduction of fertile soil loss, and increasing flood capacity (Odgaard 1984, Lave, Doyle and Robertson 2010).

This paper uses field data to analyze the characteristics of turbulence near the outer bank of a compound meander loop along a small meandering river and, based on this analysis, develops a conceptual framework of the structure of turbulence in the near outer bank region of meander bends. The specific objectives of this paper are to i) to determine the structure of turbulence at the outer bank of an actively migrating meander bend, ii) evaluate the spatial variability of turbulence characteristics in relationship to the curvature-induced mean flow field, and iii) develop a conceptual model of the nature of turbulence at the outer banks of meander bends synthesizing the present field measurements and findings from relevant experimental studies. Currently, a coherent conceptual framework describing the structure of outer bank turbulence in bends does not exist.

5.2 Turbulence in Meandering Rivers: Implications for Bank Erosion

Natural channel flows are typically fully-developed turbulent flows, and thus turbulent fluctuations (and turbulent stresses) are a primary means for redistributing momentum throughout the fluid (Nezu and Nakagawa 1993). Furthermore, fluid turbulence plays a critical role in the transport and dispersal of sediment, nutrients, and pollutants in the flow (Jamieson et
Meanders produce highly three-dimensional mean flow characteristics due to curvature-induced secondary circulation, and therefore the structure and patterns of turbulence and momentum transfer should be different in meandering channels than in straight channels (Blanckaert and De Vriend 2005b).

**Figure 5.1. Coordinate system definition sketch.**

A curved channel can be described by an intrinsic coordinate system with streamwise ($s$), cross-stream ($n$), and vertical ($z$) axes (Figure 5.1). Whereas in straight channels, the streamwise component of flow dominates the transfer of momentum in the fluid (and by extension, the turbulent stresses), curvature-induced secondary circulation in bends leads to significant advection of momentum within the cross-stream-vertical plane. This added advection can reduce the dominance of the streamwise turbulent stress component, and likewise make cross-stream and vertical stress components more important to the overall turbulent fluctuation of the fluid—including near the channel bed and outer banks where material can be eroded.

Numerous studies have examined the mean characteristics of bend flow in the laboratory, and have contributed significantly to our understanding of the effects of curvature on the mean
flow field and channel morphology of bends (Rozovskii 1957, Engelund 1974, Devriend and Geldof 1983, Seminara and Tubino 1989), including large amplitude loops (Whiting and Dietrich 1993b, Whiting and Dietrich 1993c, Whiting and Dietrich 1993a, Termini 2009), and asymmetrical planforms (Abad and Garcia 2009a, Abad and Garcia 2009b). Findings from these experimental studies have also been verified with detailed process-based field studies (Dietrich et al. 1979, Dietrich and Smith 1984, Dietrich and Whiting 1989, Frothingham and Rhoads 2003, Engel and Rhoads 2012). However, there are fewer studies that have examined bend turbulence in detail experimentally. Table 5.1 briefly summarizes the findings in relevant existing laboratory and field experiments that have measured turbulence characteristics in the outer-bank region of curved channels. Existing approaches have used constant curvature flumes, with both flat-bed configurations of varying fixed channel and bank roughness, and sand beds at equilibrium with steady flow conditions to examine turbulence characteristics of the flow (Blanckaert and Graf 2001, Abad and Garcia 2009a, Jamieson et al. 2010, Blanckaert et al. 2012a). Of these studies, only Blanckaert and Graf (2001) and Blanckaert et al. (2012a) focused their efforts on the turbulent characteristics occurring at the outer bank. Although, Abad and Garcia (2009a) and Jamieson et al. (2010) do make some inference of processes occurring at the outer bank, it was not the focus of their research.
Table 5.1. Summary of existing literature on outer bank turbulence in meandering channels.

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<th>Author(s)</th>
<th>Experimental Setup</th>
<th>Outer Bank Turbulence Findings</th>
<th>Notes and Limitations</th>
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| Blanckaert & Graf (2001) | Lab: 120° const. curvature flume with sand                                         | 1. Shear stresses are reduced in the outer bank region relative to main channel  
2. $\tau_{nz}$ stresses are correlated with circulation cells, and are of the same order of magnitude as the other shear stresses; near-bed $\tau_{nz}$ is associated with the transversal component of the bed stress  
3. $\tau_{sn}$ stresses near 0 at the water surface near-bank, increasing linearly to the bed | 1. measured at only 1 cross section, at 60°  
2. artificially sharp outer bank/bank toe interface  
3. extrapolated velocities and turbulence quantities to the bed due to limitations with measuring near the boundaries |
| Abad & Garcia (2008a)    | Lab: 200° asymmetric compound bend (Kinoshita) flume, rectangular smooth channel upstream & downstream skewed experiments | 1. The core of high velocities hugs the inner bank, and in general turbulent metrics find their maxima here  
2. $k$ is perfectly correlated with local curvature  
3. $\tau_{ss}$ stresses are the major contributor to $k$, except just downstream of apex, where $\tau_{nn}$ is dominant  
4. $\tau_{sn}$ are the largest shear stress component, with local maxima at the inner and outer banks | The channel is rectangular, thus flow patterns are not necessarily representative of self-formed channels (with developed pool and point-bar topography) |
| Jamieson, Post & Rennie (2010) | Lab: 135° const. curvature flume with sand. 2 experiments, on developing and equilibrium beds | 1. $\tau_{sz}$ stresses near-bank become less dominant as flow moves through the bend as $\tau_{sn}$, and $\tau_{nz}$ magnitudes increase  
2. Magnitudes of $\tau_{sn}$ at the outer bank are high relative to other stresses, and fluctuations are directed into the bank  
3. $\tau_{nz}$ stresses are correlated with circulation cells (see their Figs. 6 and 9c) | Artificially sharp outer bank/bank toe interface. Only Reynolds stresses and $k$ evaluated near the bed are presented rather than profiles of quantities over depth |
| Blanckaert et al. (2012) | Lab: 193° curved flume. Rectangular channel, with varied outer bank roughness (smooth, sand, gravel) | 1. Outer bank velocities and $k$ are lower than in the main channel. Although $\tau_{nz}$ magnitudes increase slightly near the bank, they are much lower than in the main channel  
2. $\tau_{nn}$ stresses are the main contributor to peak values of $k$  
3. $\tau_{nz}$ stresses are related to circulation cells, however correlation in the near-bank region is not good as in the main channel | This study doesn’t present all turbulent stress results, and instead focuses on computing advection and vorticity terms for model verification of the SOC. Also, as a rectangular channel, flow patterns may not be fully representative of those found in self-formed channels. |
### Table 5.1. (continued)

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</tr>
</thead>
</table>
| Anwar (1986)         | Field: Sand-bedded 35° simple meander bend | 1. Normal stresses have their maxima near the water surface at the outer bank, with the highest values at the bend apex  
2. Shear stresses have their maxima at the outer bank near the apex, decreasing downstream  
3. Maximum outward directed values of $\tau_{sn}$ stresses occur at the outer bank near the water surface | Anwar uses different sign conventions. Thus, $\tau_{sn}$ stresses are positive when directed outward (streamwise and lateral contributions having the same sign) |
| Sukhodolov (2012)    | Field: Sand-bedded 150° compound meander bend | 1. Shear stress components are of the same magnitude near the outer bank  
2. Generally, shear stress magnitudes increase with curvature, with maxima at or near the apices  
3. $\tau_{nz}$ stresses are directed outward strongest at the bend apices (see cross-section 5-5 & 7-7, Fig. 10). Outward directed $\tau_{nz}$ in cross-section 5-5 occurs near the bed. At the water surface $\tau_{nz}$ is directed inward, perhaps associated with an outer bank cell | Sukhodolov does not discuss outer bank turbulence characteristics. All interpretation of outer bank stresses have been derived considering the contour plots of turbulent quantities in the paper |
2 different measurements in the bend 10 years apart | 1. Submergence of high velocity fluid below the water surface at bend apices increases velocity gradients near the outer bank and bed  
2. $k$ magnitudes are greatest near the bank toe, downstream of apices | Only $k$ is quantified, and an empirical relationship between $k$ and boundary shear is used to qualitatively evaluate near-bank erosion patterns |
Field experiments focusing on the turbulent characteristics of flow in meander bends, especially turbulence near the outer bank, are scarce. Anwar (1986) used electro-magnetic current meters (ECMs) to investigate turbulence through a simple bend in the United Kingdom. Additionally, Engel and Rhoads (2012) investigated the patterns of turbulent kinetic energy and planform evolution in a small compound meander loop, but included only a qualitative analysis of near bank shear stresses and outer bank erosion. Recently, Sukhodolov (2012) examined the turbulent structure in a lowland meander bend, however analysis was restricted to the central region of the channel.

The development of a comprehensive understanding of outer bank turbulence in bends is complicated by contradictory findings from experimental studies. On the one hand, some work has shown that that turbulent kinetic energy, turbulence intensities, and absolute magnitudes of Reynolds stresses at the outer bank are low relative to magnitudes of these metrics within the adjacent thalweg flow (Blanckaert and Graf 2001, Blanckaert et al. 2012a). Low levels of turbulence near the outer bank have been attributed to the development of a weak outer bank cell of secondary circulation, referred to as a secondary outer bank cell (SOC). This cell, which rotates counter to the main curvature-induced helical cell, develops in a near-bank region with lower streamwise velocities than in the channel thalweg. Formation of the cell is induced by the effects of roughness of a near-vertical bank on the adjacent flow, which produces reversals in the gradient of streamwise velocity near the water surface along the outer bank. Increases in bank roughness result in expansion of the SOC, which acts as a buffer between the high momentum flow in the main channel, and the low momentum flow in the outer bank region, protecting the outer bank from impinging high momentum flow. Although, Blanckaert et al. (2012a) noted that the SOC advects high-momentum near-surface fluid downward toward the base of the outer
bank, the net effect of cell development is a reduction in the magnitude of turbulence in the outer bank region. The development of SOCs is especially pronounced in sharp bends and may contribute to the low migration rates of such bends by protecting the outer bank from erosion (Blanckaert, 2012). Other experimental work in curved channels with mobile beds have reported increased outer bank turbulence, in part due to the interaction of the mean flow with a fully developed bed morphology that topographically forces high momentum fluid into the outer bank region (Abad and Garcia 2009a, Abad and Garcia 2009b, Jamieson et al. 2010). The few existing field studies of turbulence in meandering rivers indicate that levels of $k$ near the outer bank are relatively high due to displacement of the high-velocity core toward the base of the outer bank through advective transport of momentum by helical motion, producing strong velocity gradients near the channel boundary (Anwar 1986, Engel and Rhoads 2012, Sukhodolov 2012). Sukhodolov (2012) reported the presence of an SOC in at least one of his measurement transects while also reporting increased turbulent kinetic energy magnitudes at the bank toe relative to the thalweg. This finding suggest that, contrary to assertions by Blanckaert et al. (2012a), high levels of near-bank turbulence can occur even when SOCs develop. Other factors may impact the strength and structure of turbulence at the outer bank besides the presence or absence of an outer bank cell.

5.3 Study Reach and Channel Evolution History

The study site is a compound meander loop, composed of multiple centerline curvature maxima (Brice 1974, Frothingham and Rhoads 2003), and is located in the upper portion of the Sugar Creek watershed in McLean County Illinois (Figure 5.2). Sugar Creek is part of the Lower Illinois River watershed and has its origin in the Bloomington-Normal metropolitan area and
flows southwest. The bend examined in the study is located approximately 41 km downstream from Bloomington-Normal, and has an upstream drainage area of 282 km$^2$.

Figure 5.2. Location map of the study site showing the planform migration history within the reach. Flow is from right to left.

To provide land drainage for agriculture, and to efficiently drain urban areas, headwater streams have been extensively modified throughout central Illinois (Urban and Rhoads 2003). The total length of first order streams that have been straightened or channelized in many cases exceeds 90 percent (Mattingly et al. 1993). The upper reaches of Sugar Creek are no exception. Sugar Creek forms the primary discharge outlet for the Bloomington-Normal Water Reclamation District, which has enlarged and straightened the channel to convey urban stormwater runoff. Downstream of the metropolitan area, long reaches of the creek have been straightened and
converted into a trapezoidal cross-sectional shape to drain agricultural fields. Only small sections of the upper reaches of Sugar Creek, including the study site, remain unchannelized.

The bend examined in this study is located within an approximately 1,600 m long meander train containing elongated bends and compound loops that have not been channelized since at least the 1940s. Comparative GIS analysis of georeferenced historical aerial photography indicates that the meander train, including the study bend, has evolved considerably over the past 72 years (Figure 5.2). Currently, the study bend has the form of an asymmetrical elongated compound loop with three distinct lobes of maximum curvature: one upstream, and two downstream (hereafter labeled lobe 1 and lobe 2 for convenience, Figure 5.3). Although a third lobe exists upstream, flow measurements and analyses were conducted only in the downstream portion of lobe 1, and lobe 2. The study bend has a bank full channel width of 20–23 meters, a bank full depth of 2–2.5 meters, and an average gradient of 0.001 m m\(^{-1}\).

![Figure 5.3. Curvature in the study bend. Measurement cross-sections are identified with black squares.](image-url)
Bed morphology within the compound meander loop consists of multiple pool-riffle-point bar sequences—a common element of compound loops (Kinoshita 1961, Whiting and Dietrich 1993b, Whiting and Dietrich 1993c, Abad and Garcia 2009a, Abad and Garcia 2009b). Channel substrate ranges from coarse sand ($D_{50} = 1.79$ mm) to very coarse gravel ($D_{50} = 35.11$ mm), with the coarsest sediment located in the thalweg (Figure 5.4). The outer bank of the bend is nearly vertical, unvegetated, and consists mainly of basal lag gravels overlain by fine sands and loam soil textures. The floodplain of the creek is agricultural, with a riparian buffer of sedge grasses that varies in width from approximately 20 m to as much as 200 m (Figure 5.5). The inner bank of the study bend has a typical spatial succession of grasses, reeds, shrubs and trees with increasing distance from the channel.
Figure 5.4. Topographic map and $D_{94}$ particle size distributions of the study site on Sugar Creek, Illinois. Elevation isosurface derived from a total station survey on July 1, 2010. Sediment samples were taken March 24, 2010. Flow is from upper right to lower left. Contour interval is 20 cm, based on an arbitrary vertical datum.
Characterization of the sediment within the channel bed and banks was based on bulk sampling of exposed surfaces in the field. Two separate sediment sampling campaigns were completed. In the first, bed material was sampled at several transects through the entire bend. At each transect, a sample was collected at the thalweg, approximately one third channel width toward the inner bank from the thalweg, and if present, on the point bar (Figure 5.4). In the second campaign, bulk samples were collected in the vertical cut-banks at several locations throughout the study bend. The sampling strategy for the banks was to obtain a representative sample at each of the main stratigraphic layers in the cut bank. Channel samples were dry-sieved in the lab, and grain size distributions by weight were computed for each sample (Figure 5.4).
Grain size distributions of bank materials finer than 0.063 mm were determined through pipette analysis. The resulting analysis yielded the percent sand, silt, and clay within each bank sediment sample.

5.4.1 Time-averaged Velocity Field

The present study is part of a larger research effort at this study bend, in which both the short-term bank erosion and time-averaged flow field patterns are analyzed at three different flow stages (see Chapter 4 of this dissertation). For this study, only the data corresponding to campaign 2 (May 26, 2011 moderate flood event) are considered. A broadband 1,200 kHz Workhorse Rio Grande acoustic Doppler current profiler (ADCP), with a sampling frequency of ~1 Hz, manufactured by Teledyne RD Instruments was employed to measure the time-averaged flow structure along sampling transects oriented perpendicular to the local channel direction (Figure 5.4). An ADCP operates on the principle of measuring the Doppler shift of acoustic pulses transmitted from divergent beams reflected by neutrally buoyant particles in the water column. The ADCP transmits acoustic pulses along each of four active beams. Calculation of the Doppler shift between the transmitted frequency of the pulses and the reflection of those pulses off of suspended particles (scatterers) in the water column allows the ADCP to compute the along-beam velocities of the scatterers. By assuming that the flow movements can be considered homogenous at the sampling rate (typically 5-10 Hz), and that the movement of the particles represents the movement of the water, the ADCP can resolve the 3-D Cartesian magnitudes and directions of water velocities from the trigonometric relationship between the beam centers and beam angle. Data in the first 25 cm nearest to the probe are excluded to eliminate contamination of the velocity measurements from the draft of the probe and ringing of the transducer heads (i.e., so-called blanking distance) (Mueller et al. 2007). Additionally, data within the first 6% of
the water depth near the channel boundary are discarded to eliminate bins contaminated by side lobe interference. In addition to determining water velocities, the ADCP also measures water depth and the spatial position of the probe relative to the bottom (i.e., bottom tracking). To acquire data on time-averaged flow characteristics and mean water depths, operators on each bank pulled the ADCP, mounted on a catamaran, along the cross-sections using a tag line. For each measurement transect, four passes across the channel were completed, ensuring that passes were in reciprocal pairs, where a pair consists of one pass starting on the left bank, and another starting on the right bank. Measured velocities were post-processed using the Velocity Mapping Toolbox (Parsons et al. 2012) to visualize the 3-D time- and space-averaged flow field at each channel cross-section. See Chapter 4 of this dissertation for complete details of the experimental setup and instrumentation.

5.4.2 Outer Bank Instantaneous Velocities

In this study, detailed measurements of instantaneous flow field at the outer bank of an actively migrating meandering river during a moderate flood flow event were made using Acoustic Doppler Profilers (ADVs). Measurements of the instantaneous velocities made it possible to resolve both the mean \( \overline{u}_i \) \((i = s, n, z)\) and turbulent fluctuations \( u'_i \) \((i = s, n, z)\), along with the complete stress tensor \( \tau_{ij} = -\rho \overline{u}_i' u'_j \) \((i, j = s, n, z)\) occurring at different spatial locations along the outer bank (Figure 5.4).

Measurement of 3-D instantaneous velocities \( u_i \) \((i = s, n, z)\) (Figure 5.1) near the outer bank were obtained using an Acoustic Doppler Velocimeter (ADV) deployed within the plane of each ADCP transect (Figure 5.4) using a custom mount and scaffold system (Figure 5.6). The ADV mount consists of a metal frame with leveling screws that holds a wading rod to which the ADV sensor is attached. Scaffolds are placed on each side of the mount to allow access to it by
an operator. For each set of measurements, ADV data were obtained at a sampling frequency of 25 Hz in an irregular grid consisting of 2 verticals of 3–10 points spaced approximately 1–2 meters apart within 1–3 meters of the outer bank, producing a grid of 12–40 points. ADV sampling was performed for a minimum of 60 seconds at each grid point, with an average sampling time of 81 seconds. Near-bed points were sampled for an average of 99 seconds at each location. Statistical analysis of ADV sampling times in rivers shows that 60–90 seconds is the optimum sampling length to resolve the mean flow velocities, turbulent intensities and shear stresses while minimizing the standard error of the measurement (Buffin-Belanger and Roy 2005). Each vertical sampling position was geolocated using a robotic total station with centimetric accuracy. ADV data were post processed and filtered using a phase-space threshold despiking method (Goring and Nikora 2002, Wahl 2003). The highly turbulent nature of the flow

Figure 5.6. ADV custom mount system being used to measure instantaneous velocity near the outer bank.
in the outer bank region made the choice of a phase-space filter preferable over more typical filtering methods (e.g., signal to noise ratio, or correlation thresholds), which tend to exclude more data than necessary in low correlation environments. Instantaneous velocities \( u_i (i = s, n, z) \) were Reynolds decomposed into mean \( \bar{u}_i (i = s, n, z) \) and turbulent \( u'_i (i = s, n, z) \) components. Using this decomposition, the turbulent kinetic energy \( \langle k \rangle \):

\[
k = \frac{1}{2} \left( u'^2_s + u'^2_n + u'^2_z \right)
\]

and Reynolds stresses \( \tau_{ij} \):

\[
\tau_{ij} = -\rho u'_i u'_j \quad i, j = s, n, z
\]

where \( i, j \) are index variables indicating the direction component of the velocities (i.e., \( s, n, \) or \( z \), Figure 5.1) where determined for each sample location.

### 5.5 Results

#### 5.5.1 Time-averaged Velocity Field

Patterns of mean flow through the reach, as defined by time-averaged streamwise, cross-stream, and vertical velocity components measured at cross-sections 2-5 through 2-9 for campaign 2 using an ADCP, provide a context for interpreting patterns of near-bank turbulence derived from the ADV measurements. Contour plots of streamwise velocities with superimposed cross-stream/vertical velocity vectors show the detailed three-dimensional fluid motion occurring in the study bend (Figure 5.7). The general pattern of streamwise velocities is comprised of a core region of high velocities surrounded by diminishing velocities near the channel bed and banks. General patterns of cross-stream/vertical vectors indicate two circulation cells present throughout most of the study bend: 1) a large curvature-induced secondary circulation in the
center channel region characterized by outward-directed near-surface flow and inward-directed near-bed flow, and 2) a small counter-rotating outer-bank cell.

As distance increases downstream, the high velocity core is advected toward the outer bank and accelerates as flow traverses the lobe 1 exit (cross-sections 2-5–2-7) into lobe 2 (cross-sections 2-8–2-9). As indicated by secondary velocity vector magnitudes, curvature-induced secondary circulation—with outward-directed near-surface flow, and inward-directed near-bed flow—is strongest upstream (cross-section 2-7) and immediately downstream (cross-section 2-9) of the lobe 2 apex. Upstream of the lobe 2 apex, curvature-induced circulation is confined to the mid-channel region, with slower streamwise velocities located near the outer-bank relative to the thalweg (cross-section 2-5). As the high velocity core moves progressively outward as flow moves downstream toward the lobe 2 apex, near outer bank velocity magnitudes increase. A small secondary circulation cell near the water surface in the outer bank region rotating with opposite orientation to the main curvature-induced cell is inferred from the secondary velocity vectors in cross-sections 2-6, and possibly 2-8. Throughout the study bend, the main curvature-induced secondary cell shifts progressively outward through the bend; however, it does not appear to impinge upon the outer bank at any cross section. Flow near the outer bank is directed toward this bank over the entire depth upstream of the apex (cross-sections 2-5, 2-7–2-8). Just upstream of the lobe 2 apex at cross-section 2-8, a large block of failed bank material rests on the outer bank toe. Interaction between the flow and the bank block results in reduced flow velocities in the outer bank region both at the location of the bank block (cross-section 2-8), and downstream in the lee of the block (cross-section 2-9). Secondary velocity vectors display no discernible pattern near the outer bank, likely due to reduced spatial resolution of velocity data in
the shallow depths around the bank block. Complex flow occurs in this region of failed bank material at and downstream of the lobe 2 apex (cross-sections 2-8–2-9).

![Cross-section plots for campaign 2 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical vectors (arrows) for each transect where flow was measured in 2011. Thick black arrows indicate the inferred secondary circulation patterns.](image)

**Figure 5.7.** Cross-section plots for campaign 2 showing downstream velocity magnitudes (contours) with superimposed cross-stream/vertical vectors (arrows) for each transect where flow was measured in 2011. Thick black arrows indicate the inferred secondary circulation patterns.

5.5.2 Profiles of Mean Velocity and Turbulence Near the Outer Bank

To examine in detail the relation between mean flow and turbulence near the outer bank, vertical profiles of time-averaged streamwise, cross-stream and vertical velocities, Reynolds stresses, and turbulent kinetic energy in the outer bank region were derived from the ADV measurements at each cross section where instantaneous velocity data were collected (Figure 5.8–12).
5.5.2.1 Time-averaged Velocity

In general, time-averaged velocities profiles throughout the outer bank of the study bend indicate that the maximum streamwise velocities ($\overline{u_z}$) occur below the free surface, and are greatest toward the channel thalweg and reduce in magnitude in proximity to the outer bank (Figure 5.8–12). Patterns of secondary circulation, as indicated by cross-stream ($\overline{u_n}$) and vertical ($\overline{u_z}$) profiles and vectors, vary spatially both with proximity to the outer bank and downstream through the study bend. At the exit to lobe 1, near-bank flow is weakly directed outward ($\overline{u_n}$) and velocity magnitudes are about 8% of the $\overline{u_z}$ velocity magnitudes with more distal flow showing curvature-induced secondary circulation (cross-sections 2-5 and 2-6, Figure 5.8 and 5.9). Measurements above approximately 8.45 m (0.6 $z/h$) for the near-bank profile at cross-section 2-5 were not possible due to a local protrusion of the bank that interfered with operation of the ADV at this location. At the entrance to lobe 2 (cross-section 2-7, Figure 5.10), flow is directed toward the outer bank over the entire profile and $\overline{u_n}$ velocity magnitudes are about 17% of the $\overline{u_z}$ velocity magnitudes. Upwelling proximate to the outer bank near the water surface may indicate evidence of an SOC in the lobe 1 exit and entrance to lobe 2 (cross-sections 2-5–2-7, Figure 5.8–10), but the sampling density of ADV measurements is not sufficient to resolve an SOC in the near-bank region.
Figure 5.8. Vertical profiles of velocity and turbulence components with estimated outer bank profile (left plots) along with profiles of velocity and turbulence components expressed in terms of dimensionless depth (right plots). Time-averaged streamwise ($\overline{u}$), cross-stream ($\overline{v}$), and vertical ($\overline{w}$) velocity components with cross-stream/vertical vectors (top); Reynolds shear stress components ($\tau_{xz}$, $\tau_{xn}$, $\tau_{nz}$, in kinematic units) (middle); and Reynolds normal stress components with turbulent kinetic energy ($\tau_{xx}$, $\tau_{nn}$, $\tau_{zz}$, in kinematic units) (bottom) for cross-section 2-5. Vertical black lines denote zero magnitudes for each measured quantity, dark blue lines denote the water surface elevation, and the shaded area denotes estimated bank geometry.
Figure 5.9. Vertical profiles of velocity and turbulence components with estimated outer bank profile (left plots) along with profiles of velocity and turbulence components expressed in terms of dimensionless depth (right plots). Time-averaged streamwise ($\bar{u}_x$), cross-stream ($\bar{u}_n$), and vertical ($\bar{u}_z$) velocity components with cross-stream/vertical vectors (top); Reynolds shear stress components ($\tau_{sx}$, $\tau_{sn}$, $\tau_{nz}$, in kinematic units) (middle); and Reynolds normal stress components with turbulent kinetic energy ($\tau_{ss}$, $\tau_{nn}$, $\tau_{zz}$, in kinematic units) (bottom) for cross-section 2-6. Vertical black lines denote zero magnitudes for each measured quantity, dark blue lines denote the water surface elevation, and the shaded area denotes estimated bank geometry.
Figure 5.10. Vertical profiles of velocity and turbulence components with estimated outer bank profile (left plots) along with profiles of velocity and turbulence components expressed in terms of dimensionless depth (right plots). Time-averaged streamwise ($\overline{u}$), cross-stream ($\overline{u}_n$), and vertical ($\overline{u}_z$) velocity components with cross-stream/vertical vectors (top); Reynolds shear stress components ($\tau_{sz}$, $\tau_{sn}$, $\tau_{nz}$, in kinematic units) (middle); and Reynolds normal stress components with turbulent kinetic energy ($\tau_{ss}$, $\tau_{nn}$, $\tau_{zz}$, in kinematic units) (bottom) for cross-section 2-7. Vertical black lines denote zero magnitudes for each measured quantity, dark blue lines denote the water surface elevation, and the shaded area denotes estimated bank geometry.
Figure 5.11. Vertical profiles of velocity and turbulence components with estimated outer bank profile (left plots) along with profiles of velocity and turbulence components expressed in terms of dimensionless depth (right plots). Time-averaged streamwise ($\overline{u}_x$), cross-stream ($\overline{u}_n$), and vertical ($\overline{u}_z$) velocity components with cross-stream/vertical vectors (top); Reynolds shear stress components ($\tau_{xz}$, $\tau_{zn}$, $\tau_{nz}$, in kinematic units) (middle); and Reynolds normal stress components with turbulent kinetic energy ($\tau_{xx}$, $\tau_{nn}$, $\tau_{zz}$, in kinematic units) (bottom) for cross-section 2-8. Vertical black lines denote zero magnitudes for each measured quantity, dark blue lines denote the water surface elevation, and the shaded area denotes estimated bank geometry.
Figure 5.12. Vertical profiles of velocity and turbulence components with estimated outer bank profile (left plots) along with profiles of velocity and turbulence components expressed in terms of dimensionless depth (right plots). Time-averaged streamwise ($\overline{u_x}$), cross-stream ($\overline{u_n}$), and vertical ($\overline{u_z}$) velocity components with cross-stream/vertical vectors (top); Reynolds shear stress components ($\tau_{xz}$, $\tau_{xn}$, $\tau_{nz}$, in kinematic units) (middle); and Reynolds normal stress components with turbulent kinetic energy ($\tau_{xx}$, $\tau_{nn}$, $\tau_{zz}$, in kinematic units) (bottom) for cross-section 2-9. Vertical black lines denote zero magnitudes for each measured quantity, dark blue lines denote the water surface elevation, and the shaded area denotes estimated bank geometry.
Immediately upstream of the lobe 2 apex, where a large block of failed bank material rested on the outer bank toe (cross-section 2-8, Figure 5.11), the velocity data exhibit a much different pattern than elsewhere in the study bend. This difference reflects interaction of the flow with the submerged bank block. Although two velocity profiles were obtained at this location, difficult measurement conditions compromised the quality of data for the second profile, therefore it has been excluded from the analysis. Streamwise flow ($\bar{u}_x$) in the region of the bank block approximates a logarithmic profile with the highest velocities at the water surface. Data for $\bar{u}_n$ and $\bar{u}_z$ provide no evidence for secondary circulation. Downstream of the apex (cross-section 2-9, Figure 5.12), the high velocity core is again submerged, and patterns of $\bar{u}_n$ and $\bar{u}_z$ velocities indicate the secondary circulation, with near-surface flow directed outward, and near-bed flow directed inward, is present in both velocity profiles.

5.5.2.2 Reynolds Shear Stresses

Profiles of Reynolds shear stresses provide insight into the fluxes of momentum produced by turbulent fluctuations (Figure 5.8–12). Patterns of streamwise-vertical shear stresses $\tau_{sz}$ through the exit of lobe 1 (cross-sections 2-5 through 2-7) are complex. Generally, $\tau_{sz}$ increases with depth in the range $1 \geq z/h \geq 0.2$, then decreases with proximity to the bed ($z/h < 0.2$). Maximum values of $\tau_{sz}$ for profiles nearest to the outer bank occur at $z/h$ of about 0.15–0.2, whereas maxima occur higher in the water column ($z/h \approx 0.20–0.25$) for profiles close to the thalweg. Moreover, for near-bank profiles, $\tau_{sz}$ is negative for about the first 20 cm below the surface, or $1 \geq z/h \geq 0.4$ (i.e., the cross-product of streamwise $u_s$ and vertical $u_z$ fluctuations average to a positive value, with downstream and upward directions being positive). In cross-section 2-7, $\tau_{sz}$ is also negative from the surface to a depth of 25 cm ($1 \geq z/h \geq 0.65$). At cross-section 2-8 and 2-9, where flow is interacting with the failed bank block, the pattern of $\tau_{sz}$
differs from upstream. Instead of increasing with flow depth, profiles of $\tau_{sz}$ at these locations have local minima near the water surface and bed, with local maxima at approximately 50% of the flow depth, creating a roughly parabolic distribution of stresses over depth.

Overall, profiles of streamwise-cross-stream shear stresses $\tau_{sn}$ at the exit of lobe 1 (cross-sections 2-5–2-7) are similar. Values of $\tau_{sn}$ are negative over the entire depth (i.e., time-averaged values of $u'_s$ and $u'_n$ have the same sign, where $n$ is positive toward the outer bank), decreasing to local absolute maxima that corresponds to the location of the $\tau_{sz}$ maxima. However, in the vertical farthest from the bank in cross-section 2-6, the absolute highest magnitude of $\tau_{sn}$ occurs 7 cm below the water surface at $z/h = 0.91$, with magnitudes decreasing toward zero with depth. In cross-section 2-8 $\tau_{sn}$ is negative over the entire depth, with magnitudes similar to those of $\tau_{sz}$, in essence mirroring the quasi-parabolic distribution of $\tau_{sz}$ stresses. Farther downstream (cross-section 2-9), the distribution of $\tau_{sn}$ is similar to that of cross section 2-6. The largest magnitudes of $\tau_{sn}$ are located around 5 cm below the water surface ($z/h = 0.9$), and decrease linearly toward zero with depth. The point at which $\tau_{sn}$ reaches near-zero corresponds roughly with the point at which $\overline{u'_n}$ changes from positive (i.e., directed outward) to negative (i.e., directed inward). Thus patterns of secondary circulation, which redistribute high streamwise momentum outward near the surface, may also have an impact on the strength and distribution of $\tau_{sn}$ in the upper portion of the water column. In the ADV vertical farthest from the outer bank, a secondary peak in $\tau_{sn}$ occurs near the bed (elevation around 7.6 m) at $z/h$ from about 0.10 to 0.15 that corresponds to the steepest portion of the of the $\overline{u'_s}$ velocity profile.

The magnitudes of $\tau_{nz}$ are generally less than the other two shear stress components throughout the bend, constituting only 4–36% of the total shear stress. With the exception of the
near bank ADV profile at cross section 2-5, the profiles of $\tau_{nz}$ displays a consistent pattern. Values of $\tau_{nz}$ are positive in the upper 50% of the water column throughout the study bend, with local maxima occurring just below the water surface. In the intermediate region of the flow ($0.6 \geq z/h \geq 0.35$), $\tau_{nz}$ decreases with increasing depth, becoming negative at the low end of this range of dimensionless depth. Near the bed ($0.25 \geq z/h \geq 0.1$), values of $\tau_{nz}$ reach a local maximum similar to patterns observed in both $\tau_{sz}$ and $\tau_{sn}$, especially in the lobe 1 exit and upstream of the failed bank material (cross-sections 2-5 – 2-7). Downstream of the apex of lobe 2 where patterns of $\vec{u}_n$ and $\vec{u}_z$ vectors indicate strong secondary circulation in the plane of the cross section, maximum values of $\tau_{nz}$ are found lower in the water column ($z/h \approx 0.6 – 0.7$) than in the profiles upstream.

The structure of Reynolds shear stresses occurring in the near-bank region of the study bend has several important characteristics: 1) absolute magnitudes of Reynolds shear stresses upstream of the failed bank block (cross sections 2-5 – 2-7) are of similar order, although $\tau_{nz}$ stresses are the smallest component of the total stress, 2) with the exception of cross-sections 2-8 & 2-9, which are in the lee of a failed bank block, $\tau_{sn}$ shear stresses are directed toward the outer bank, 3) $\tau_{sn}$ shear stresses increase as the high-velocity core moves close the outer bank (Figure 5.3), and 4) the patterns of shear stresses in flow interacting with the failed bank block are markedly different than for flow upstream, which is not influenced by large bank roughness elements.

5.5.2.3 Reynolds Normal Stresses and Turbulent Kinetic Energy

The patterns of Reynolds normal stresses indicate how various components of turbulent kinetic energy ($k$) contribute to the turbulent transport of momentum (Figure 5.8–12). In general, the patterns of normal stresses and turbulent kinetic energy are similar throughout the
bend. As flow exits lobe 1 and approaches the lobe 2 apex (cross-sections 2-5–2-7), local maxima of the normal stresses and turbulent kinetic energy are found near the bed in the bottom 20% of the flow (approximately 10–15 cm above the bed). This region corresponds to the portion of the velocity profiles where velocity gradients over depth are the largest. As the mean flow accelerates into lobe 2, and curvature-induced secondary circulation moves progressively closer to the outer bank, velocity gradients steepen, leading to enhanced absolute magnitudes of the normal stresses and $k$. Just upstream of the apex (cross-section 2-8), the failed bank block resting on the outer bank toe disrupts the pattern of normal stresses and $k$. Here, the maximum is located at approximately 60% of the flow depth (elevation of 8.2 m), and represents the influence of the bank block on the flow structure. The nearly constant magnitude of $k$ over depth near the mid-section of the channel suggests the time-averaged structure of turbulence in the wake of the failed bank block is fairly uniform over the entire water column. Downstream of the apex, in the lee of the block (cross-section 2-9), the pattern of normal stresses and $k$ is still nearly constant over depth, although considerably noisier than upstream (cross-section 2-8), presumably due to dissipation coherent turbulence associated with wake flow around the block.

The contribution of fluctuations of each velocity component to the total $k$ can be quantified from Equation (5.2) as $0.5 \overline{u'^2}/k$, and is useful for identifying the relative proportion of each fluctuation component to the time-averaged turbulence characteristics (Figure 5.13). Although contributions of each fluctuation component are not significantly different when averaged over depth anywhere in the study bend (Table 5.2), profiles of relative contributions vary upstream and downstream of the failed bank material (Figure 5.14). Upstream of the bank block in the lobe 1 exit (cross-section 2-5 – 2-7), $u'_s$ fluctuations account for as much as 80% of the total $k$ in a region just above the bed ($0.3 \geq z/h \geq 0.15$). Closer to the bed ($z/h < 0.15$),
$u'_n$ fluctuations become more significant to the overall $k$, but remain less important than streamwise fluctuations. In the upper 50% of the water column, $u'_n$ and $u'_z$ contribute nearly the same proportion to the total $k$ (~25% each). At and downstream of the failed bank block (cross-sections 2-8 & 2-9), total contributions by $u'_s$ and $u'_n$ for $0.5 \geq z/h \geq 0.1$ are similar ($u'_s = 33 - 53\%$, and $u'_n = 25 - 45\%$), whereas in the upper 50% of the flow depth contributions of each fluctuation component are different, with $u'_s$ contributing the most, followed by $u'_n$ and then $u'_z$. 
Figure 5.13. Vertical profiles of the contribution of each fluctuation component to the total $k$ upstream (A) and downstream (B) of the failed bank material.
### Table 5.2. Depth-averaged contributions of each fluctuation component to the total $k$.

<table>
<thead>
<tr>
<th>All cross sections</th>
<th>$0.5(u_s^2)/k$</th>
<th>$0.5(u_n^2)/k$</th>
<th>$0.5(u_z^2)/k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.33</td>
<td>0.16</td>
<td>0.02</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.82</td>
<td>0.64</td>
<td>0.31</td>
</tr>
<tr>
<td>Average</td>
<td>0.51</td>
<td>0.32</td>
<td>0.16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Upstream of Bank Block</th>
<th>$0.5(u_s^2)/k$</th>
<th>$0.5(u_n^2)/k$</th>
<th>$0.5(u_z^2)/k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.33</td>
<td>0.16</td>
<td>0.02</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.82</td>
<td>0.64</td>
<td>0.31</td>
</tr>
<tr>
<td>Average</td>
<td>0.52</td>
<td>0.31</td>
<td>0.17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Downstream of Bank Block</th>
<th>$0.5(u_s^2)/k$</th>
<th>$0.5(u_n^2)/k$</th>
<th>$0.5(u_z^2)/k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.33</td>
<td>0.23</td>
<td>0.02</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.66</td>
<td>0.52</td>
<td>0.23</td>
</tr>
<tr>
<td>Average</td>
<td>0.49</td>
<td>0.35</td>
<td>0.16</td>
</tr>
</tbody>
</table>

5.5.3 Outer Bank Material Properties, Turbulent Stresses, and Bank Erosion

Bank material within the two lobes of the study reach consists of three main stratigraphic layers: an upper cohesive layer about 1.75 m thick containing abundant roots, about 25–30% clay, and 45–50% silt; an underlying sandy layer about 0.5 m thick containing about 90 percent sand; and a basal sand and gravel layer about 0.5 m thick that is similar in size characteristics to bed material in the channel thalweg (Figure 5.14, A & B). The sandy layer below the cohesive material is noncohesive and highly susceptible to erosion by hydraulic action. Velocity data obtained at the lobe 1 exit provides information on the structure of near-bank turbulence within the reach for clean, nearly vertical banks. Values of shear stress and turbulent kinetic energy at this location are highest on the lower part of the outer bank consisting of erodible sand (Figure 5.14C). Erosion of the sand removes material from the bottom part of the outer bank, which
destabilizes the upper portion of this bank. Once the weight of material in the upper part of the
bank exceeds the tensile strength of cohesion, the overlying material will fail (Thorne 1998),
resulting in the production of bank blocks (Figure 5.14D). The production of such blocks
temporarily protects the base of the bank from turbulent stresses. Downstream of the bank block
at cross-section 2-9, near-bank shear stresses are highest in the upper 50% of the profile near the
outer bank, corresponding to the cohesive portion of the bank.
Figure 5.14. Annotated photographs of the outer bank of the study bend showing characteristic bank material profiles in lobe 2 (A), and lobe 1 (B). Example of hydraulic erosion of sands in lobe 2 (C). Failed bank material with intact grasses resting along the outer bank of lobe 2 (D).

5.6 Discussion

Results of the analysis of time-averaged velocity field show that flow structure through the two lobes of the compound bend is dominated by curvature-induced secondary circulation in the mid-channel region, convective acceleration of flow in the downstream direction, and
shifting of the locus of the core of highest velocities progressively outward over distance downstream. Mean flow characteristics near the outer bank include increases in the flow magnitudes with increasing curvature, and an inferred counter-rotating outer bank cell near the water surface upstream of the lobe 2 apex (Figure 5.7).

Patterns of Reynolds stresses deviate significantly from those expected in straight, fully-developed open channel flows (Figure 5.8–12). In straight channels, bed-generated turbulence is dominated by turbulent fluctuations of streamwise fluid. Nezu and Nakagawa (1993) generalized the structure of 2-D, straight-channel fully developed flows, finding that the root mean square of the fluctuations (i.e., turbulent intensities) and turbulent kinetic energy, varies exponentially from a maximum at the bed toward zero near the water surface:

\[
\sqrt{\frac{u_i'^2}{u_*}} = D_i \exp \left(-C_k \frac{z}{h}\right) \quad i = s, n, z
\]

\[
\frac{k}{u_*^2} = D_k \exp \left(-2C_k \frac{z}{h}\right)
\]

where \(u_*\) is shear velocity, and \(C_k\) is a constant equal to 1, \(D_i\) is 2.30, 1.63, and 1.27 for \(s, n, z\) respectively, and \(D_k = 4.72\). Equations (5.3) & (5.4) describe flow turbulence in the mid-channel region of smooth beds and are applicable even over rough beds for \(0.2 \geq z/h \geq 0.8\) (Nezu and Nakagawa 1993). The relationship between depth-averaged (denoted by \(\langle \cdot \rangle\)) streamwise, cross-stream, and vertical turbulent fluctuations in straight channels is also well established:

\[
\frac{\langle u_{s}'^2 \rangle / \langle u_{s}^2 \rangle}{\langle u_{n}'^2 \rangle / \langle u_{n}^2 \rangle} = 0.51
\]

\[
\frac{\langle u_{n}'^2 \rangle / \langle u_{n}^2 \rangle}{\langle u_{z}'^2 \rangle / \langle u_{z}^2 \rangle} = 0.31
\]

Recalling that the cross-products of the components of turbulent fluctuations \((u'_s, u'_n, u'_z)\) determine the magnitudes of the Reynolds stresses, it is evident from Equation (5.5) that in
straight channels, streamwise turbulent fluctuations dominate Reynolds stresses. Data on Reynolds stresses for most straight open-channel flows show that the streamwise-vertical Reynolds stress ($\tau_{sz}$) is the largest component of the stress tensor. However, in a meander bend with well-developed curvature-induced secondary circulation (i.e., outward directed near-surface flow and inward directed near-bed flow), turbulent fluctuations in the cross-stream and vertical planes may become major contributors to the total turbulent flux of momentum. Blanckaert and Graf (2001) found that streamwise fluctuations were the dominant contributor to the total turbulent momentum flux in their experimental bend. On the other hand, Jamieson et al. (2010) reported that $\tau_{sz}$ stresses in the straight channel entrance of their flume were double the values of $\tau_{sn}$ and four times the values of $\tau_{nz}$, whereas in the fully-developed curved flow $\tau_{sn}$ and $\tau_{nz}$ actually exceeded values of $\tau_{sz}$. In the study bend, the contribution of cross-stream and vertical normal stresses to the turbulent kinetic energy increases as the high velocity core moves outward progressively downstream through the bend (Table 5.3). Relatively equal contributions of cross-stream and vertical normal stresses to the turbulent kinetic energy (Table 5.2) are indicative of the likely presence of a vertically-oriented shear layer in the lee of the bank block (cross-sections 2-8 & 2-9) (Sukhodolov and Rhoads 2001).

**Table 5.3. Relative proportion of ensemble-averaged turbulent normal stresses for each cross section.**

<table>
<thead>
<tr>
<th>XS</th>
<th>$\langle \bar{u}<em>{sz}^2 \rangle / \langle \bar{u}</em>{sn}^2 \rangle$</th>
<th>$\langle \bar{u}<em>{sz}^2 \rangle / \langle \bar{u}</em>{sz}^2 \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-5</td>
<td>0.53</td>
<td>0.24</td>
</tr>
<tr>
<td>2-6</td>
<td>0.61</td>
<td>0.35</td>
</tr>
<tr>
<td>2-7</td>
<td>0.72</td>
<td>0.35</td>
</tr>
<tr>
<td>2-8</td>
<td>0.51</td>
<td>0.33</td>
</tr>
<tr>
<td>2-9</td>
<td>0.81</td>
<td>0.34</td>
</tr>
</tbody>
</table>

When evaluated close to the face of nearly vertical outer banks, $\tau_{sn}$ represents the shear stress responsible for hydraulic erosion of these banks. Throughout the study bend, $\tau_{sn}$ is
directed toward the outer bank (excluding flow influenced by the bank block), and \( \tau_{sn} \) magnitudes are closely related to the structure of the mean flow. As the core of high momentum fluid moves outward and becomes submerged below the free surface in the downstream direction due to curvature effects on the flow, turbulence generated from the bed and banks, and thus the Reynolds shear stresses, increase near the bed. Most of the increase in Reynolds shear stresses is due to increases in \( u'_s \) and \( u'_n \). High values of \( \tau_{sn} \) at the level of sandy layers near the base of the outer bank (Figure 5.14) suggest that erosion of these layers, along with subsequent failure of cohesive material into the channel, is the primary mechanism of bank erosion within the study bend. This result is supported by field observations of bank failures resting on the bank toe (Figure 5.14D) along much of the reach (Figure 5.3).

Conceptually, the structure of turbulence along the outer bank region in the study bend can be separated into: 1) turbulence associated with interaction between curvature-induced flow paths and the channel boundary (Figure 5.15, A–C), and 2) turbulence associated with interaction between near-bank flow and bank blocks resting along the toe of the bank (Figure 5.15, C2). As curvature effects on the flow act to redistribute high momentum outward progressively through a meander bend, the contributions of cross-stream and vertical velocity fluctuations to turbulent kinetic energy increase. Sharp channel curvature within a lobe, such as in lobe 1 of the study bend, can limit the magnitude of near-bank streamwise velocities, restricting the locus of the high-velocity core and helical motion to the middle of the channel. This situation is exemplified by conditions at the exit to lobe 1 in the study bend (section 2-5) where the highest velocities are located near the center of the channel and the profile of near-bank transverse velocities indicates that helical motion does not penetrate close to the bank at this location. Turbulence is generated as the flow encounters resistance arising from the boundary, with the highest values of turbulent
shear stress and kinetic energy corresponding to the near-bed and bank toe region. Although shear and normal stresses here are likely to be dominated by streamwise velocity fluctuations, proximity of the near vertical banks produces non-linear variation of stress profiles over depth (Figure 5.15A). At the apex of the downstream lobe (Figure 5.15B), curvature-induced helical motion begins to enhance the contributions of cross-stream and vertical velocity fluctuations to the shear stresses and turbulent kinetic energy as high momentum fluid moves close to the outer bank. In the study bend, the high velocity core moves outward through the entrance to lobe 2 (Figure 5.7, cross-sections 2-6 & 2-7) and near-bank shear stresses and turbulent kinetic energy increase as high momentum fluid is advected toward the bank (Figure 5.9 & Figure 5.11). Downstream of the apex (Figure 5.15C), the core of high velocity is fully submerged, and proximate to the outer bank. Turbulent fluctuations of cross-stream, and to a lesser degree, vertical velocities contribute substantially to the overall stresses and turbulent kinetic energy. This location should, in the case of clean, near-vertical banks, comprise the highest near-bed and near-bank toe turbulent stresses in the bend as high momentum fluid directly impinges the outer bank. Helical motion of the time-averaged flow submerges the high velocity core, steepening velocity gradients, and enhancing turbulent kinetic energy near the bed and bank toe, creating a mechanism for hydraulic erosion of noncohesive material at the base of the outer bank. If bank material above the toe is cohesive, it will be prone to failure (Thorne et al. 1998). Flow encountering large roughness elements along the outer bank—like blocks of failed bank material—can disrupt curvature-induced turbulence structure near the bank (Figure 5.15C2).

The frictional effects of large bank blocks may shift the submerged high velocity core away from the outer bank (Engel and Rhoads 2012). In the study bend, such effects created large velocity gradients between the free stream flow and the portion of the outer bank above the bank
block, leading to the formation of a shear layer, characterized by moderate to high levels of turbulent kinetic energy and turbulence structure that is quasi-2-D over depth. The bank block resting near the lobe 2 apex (cross-section 2-8) represents an obstacle to flow that results in reduced near-bank velocities compared to upstream, and relatively small Reynolds stresses. Additionally, nearly equal values of $\tau_{ss}$ and $\tau_{nn}$ along with relatively low values of $\tau_{zz}$ suggest that turbulence near the outer bank is essentially quasi-two-dimensional and represents a shear layer between slow flow in the lee of the block and fast flow in the thalweg. The zone of reduced velocities acts as a buffer that protects the vertical bank above the bank block from high momentum fluid and shear stresses. The dimensions of the zone of reduced velocities above the bank blocks is likely dependent on i) flow stage, and ii) the dimensions of the bank block. This study examined near-bank turbulence at an intermediate flow stage and it is unclear whether the zone of reduced velocities would extend to water surface at stages approaching bank-full flow. Farther downstream from the bank block (cross-section 2-9), the high velocity core again becomes submerged near the outer bank, and strong secondary circulation advected momentum toward the outer bank toe, as reflected in the increase in Reynolds stresses and turbulent kinetic energy at this location compared to upstream (cross-section 2-8).
Figure 5.15. Conceptual model of turbulence at the outer bank of a meander bend upstream of the apex (A), at the apex (B), and downstream of the apex (C). Also shown in the effect of a bank block on the flow turbulence downstream of the apex (C2). Graphs on the right represent idealized vertical profiles of Reynolds shear stresses and turbulent kinetic energy.
The findings in this study support the assertion by Engel and Rhoads (2012) that local influences on flow in bends, such as persistent bank blocks, may impact patterns of bank erosion in compound bends. Although the curvature-induced structure of the outer bank turbulence can serve as a mechanism to enhance bed and bank shear stresses by increasing the turbulent momentum flux toward the bed and bank, the production of large roughness elements through bank erosion, such as bank blocks, can locally attenuate the influence of curvature on near-bank turbulence.

Measurement of turbulence quantities in the outer bank region of an actively migrating meander bend is difficult, requiring instrumentation capable of measuring instantaneous velocities with a high degree of accuracy. Normally, ADVs are employed in labs or wadeable streams. In this study, ADVs were used in adverse flow conditions, under a changing hydrograph, requiring a fast-paced measurement campaign. As such, the tradeoff between collecting data at many points within a bend over short sampling durations versus at a few points for long sampling durations is a delicate one. To capture adequately the characteristics of turbulence structure, the number of sampling locations in this study is much less than the density normally obtained in a wadeable stream and/or lab situation. Moreover, obtaining measurements near the complex outer bank topography was difficult, especially when submerged obstacles, such as bank blocks, were present. Despite these limitations, the measurements and analysis presented herein shed important light on the characteristics of turbulence near the outer banks of meander bends and the possible relation of these characteristics to bank erosion.

5.7 Conclusion

In this study, the structure of the turbulence in the outer bank region of a compound meander loop was examined in detail within the context of the general pattern of mean flow
through the loop. Results show that the structure of turbulence is linked to curvature-induced effects through the progressive advection of high momentum fluid toward the outer bank as flow moves through successive lobes of the loop. Contrary to straight-channel bed-generated turbulence, where streamwise turbulent fluctuations are the predominant contributor to Reynolds stresses, curvature-induced secondary circulation in the study bend enhances the strength of cross-stream and vertical turbulent fluctuations leading to increased contribution to the Reynolds stresses from these components. The study has also shown that large roughness elements, such as failed bank material, can disrupt the curvature-induced pattern of turbulence. Bank blocks reduce flow velocities and turbulent stress in the immediate lee of the block. Here turbulence becomes quasi-two-dimensional, and magnitudes of the Reynolds stresses are relatively small compared to locations unaffected by bank blocks. Results of this study support the bank-toe protection hypothesis that large roughness elements can protect the outer bank from fluid forces and reduce bank erosion rates (Carson and Kirkby 1972). Furthermore, the findings support the assertion that the effects of local topographic features on erosion and deposition within compound bends can be more important than reach-scale effects associated with channel curvature (Engel and Rhoads 2012).

This study improves our understanding of outer bank turbulence in an actively migrating alluvial meander bend. Previous work concerning outer bank turbulence has been limited to lab and modeling experiments. The findings of this study generally confirm the hypothesis that curvature enhances the strength of turbulence at the outer bank (Abad and Garcia 2009a, Jamieson et al. 2010, Sukhodolov 2012). Some researchers have suggested that the presence of an outer bank circulation cell (SOC) has a protective effect on outer bank turbulent stresses, reducing the overall turbulence at the outer bank (Blanckaert and Graf 2001, Blanckaert et al.
Although patterns of time-averaged velocities near the outer bank measured by an ADCP in this study bend show the possible signature of a SOC, the measurement grid of ADV verticals was not dense enough to resolve SOCs in the outer-bank region. Based on the results of this study, it is not possible to evaluate the role of SOCs on near-bank turbulence structure. Logistical difficulties associated with the relatively flashy hydrological regime at the study site, with setup times for ADV measurements, and with the complex topography of the outer bank, limited both the number of locations within the flow near the outer bank at which measurements could be obtained and the proximity of the measurements to the outer bank. More extensive sets of near-bank turbulence measurements may be possible in meandering streams with uniform outer banks and sustained, relatively constant flows. Future work examining the turbulent structure in the outer bank of meander bends should focus on accurate determination of the fluid stresses proximate to the boundary. Also, more research is needed to explore the structure of turbulence around failed blocks of bank material, how curvature-induced turbulence is enhanced or attenuated by the development of bank blocks, and how modification of turbulence by bank blocks influences the persistence of these roughness elements.
CHAPTER 6
CONCLUSION

6.1 Summary of Findings

The primary goal of this research was to examine the effects of varying curvature, stage, local topography, and flow turbulence on the planform evolution and fluvial dynamics of compound meander bends. Successful research toward this goal contributes to the discipline of fluvial geomorphology by improving our understanding of the process interrelationships occurring over a range of spatial and temporal timescales that culminate in the formation of complex river planforms. The research consisted of three separate field studies in two actively migrating compound loops in central Illinois. In the first study, patterns of planform evolution occurring in a compound loop over an 11 year timeframe were related to the patterns of time-averaged three-dimensional flow and turbulent kinetic energy during two similar discharge, high flow events bracketing that timespan. In the second study, the effects of local planform curvature, topography, and stage on the time-averaged flow structure were related to patterns of bed shear stress and short-term bank erosion in a compound meander bend. In the last study, the structure of outer bank turbulence was documented and related to the time-averaged flow structure and interactions with large roughness elements in a compound loop. The conclusions of this research suggest that patterns of flow, sediment entrainment, and planform evolution in compound meander bends are more complex than in simple meander bends. Moreover, interactions among local influences on the flow such as outer bank blocks, local topographic steering, and locally high curvature, tend to cause compound loops to evolve toward increasing planform complexity over time rather than stable configurations.
The research was guided by questions described in Chapter 1. Each of these questions is restated below along with summary of the main findings of the research. Research questions 2 and 3 are linked, and thus are discussed together below.

1. How do the 3-D turbulent flow structure, bed morphology, bank failures, and channel planform in a compound meander bend co-evolve over the timescale of planform change?

2. What is the relationship between near outer-bank flow turbulence, and long-term planform evolution in a compound meander bend?

The dynamic evolution of the planform of meandering rivers often leads to the development of compound meander bends with multiple lobes of maximum curvature. Time-averaged flow structure and turbulent kinetic energy were measured in the Embarras River during two similar high flow events spaced 11 years apart (see Chapter 3). Patterns of bed evolution and planform migration in the bend over the study timeframe were also analyzed. Results suggest that bank erosion, and thus planform evolution, while governed by near-bank magnitudes of velocity and turbulence, can be influenced by local factors including deflection of the flow by point bars and failed bank blocks. These factors can enhance or inhibit the development of high velocities and turbulence kinetic energy near the bank toe. Longitudinal shoaling over the point bar upstream of lobe apices leads to topographically-induced flow convergence in the pool, resulting in convective acceleration of the streamwise flow. The core of high velocity becomes submerged at, or downstream of, the lobe apex along the outer bank toe due to a combination of curvature-induced secondary circulation and convective acceleration into the pool. Velocity gradients increase where the high velocity core is near the toe of the outer bank, generating high values of turbulent kinetic energy. An important assumption in
models of meander migration is that near-bank excess velocities vary directly as a spatial convolution function of the upstream and/or downstream curvature (Ikeda et al. 1981, Seminara et al. 2001, Zolezzi and Seminara 2001, Hooke, Gautier and Zolezzi 2011). However, findings of this research show near-bank velocities and turbulence do not necessarily vary directly with channel curvature because of the complicating effects of topographic steering by the point bar and disruption of lobe-entry flow by blocks of failed bank material. Stabilized blocks of failed material can protect the outer bank by topographically steering flow away from the bank, creating zones of flow separation along the bank in the lee of the blocks, and by protecting the bank toe from fluid forces. Ultimately, long-term deflection of flow around stabilized blocks protected from erosion by rooted vegetation may cause a reversal in centerline curvature over the timescale of planform migration processes.

3. What is the effect of stage variation on the patterns of sediment entrainment, development of channel morphology and patterns of bank erosion in a compound bend?

Examination of the flow structure, bed material size distributions, bed morphology, and bed shear stress for three events with different flow stages at the study bend on Sugar Creek, Illinois, elucidate how sediment entrainment, erosion and deposition on the channel bed, and patterns of bank erosion are influenced by variations in flow stage (see Chapter 4). The distribution of bed material sizes within the multi-lobed bend corresponds to the spatial pattern of bed shear stress magnitudes, indicating that bed material sorting within the bend is governed by bed shear stress. Bed shear stresses and particle sizes increase in the downstream direction along the outer bank through two distinct lobes of the bend. The proportion of bed material entrained in the upstream part of the loop exceeds that entrained downstream, but because the
bed shear stress increases in the downstream direction, fine bed material arriving from upstream is transported through the thalweg, sustaining pools near the outer bank. Along the point bar, bed shear stresses and particle sizes generally decrease downstream, except in the transition between the lobes where particle size and bed shear stresses locally increase, indicating that a discontinuity in point-bar sediment characteristics exists between the lobes of this multi-lobed bend. The percentage of bed material entrained by high flow is locally high over downstream portions of the point bar where sediment is fine; however, the general decrease in bed shear stress from upstream to downstream along the inner bank implies that any coarse sediment entrained upstream will be deposited before reaching the downstream end of the point bar.

Analysis of the relationship between local curvature and variation in flow stage shows that local increases in centerline curvature (or decreases in dimensionless radius of curvature) within the upstream lobe of the bend examined here reduces outer bank velocities at morphologically significant flows. This reduction in outer bank velocities creates a region that protects the bank from high momentum flow and corresponding high bed shear stresses. The upstream lobe of the compound loop, which has a dimensionless radius of curvature about one-third less than that of the downstream lobe, also has an average bank erosion rate less than half of the erosion rate for the downstream lobe. The relatively high rate of bank erosion within the downstream lobe corresponds to the shift in a core of high velocity and the zone of high bed shear stresses toward the outer bank as flow moves through the two lobes. This pattern of erosion provides a mechanism for continued migration of the downstream lobe in the near future.
4. What is the spatial structure of turbulence near the outer bank of a compound meander bend, and how does this structure vary spatially in relation to the evolving pattern of the three-dimensional flow (time-averaged velocities) as water moves through the bend?

In Chapter 5, the structure of the turbulence in the outer bank region of a compound meander loop was examined in the context of the structure of mean flow within the loop. Results show that the structure of turbulence is linked with the progressive advection of high momentum fluid toward the outer bank as flow encounters increasing curvature. However, large roughness elements, such as failed bank material, can disrupt the curvature-induced pattern of turbulence near the bank. Contrary to straight-channel bed generated turbulence where streamwise turbulent fluctuations are the predominant contributor to Reynolds stresses, curvature-induced secondary circulation in the study bend enhances the strength of cross-stream and vertical turbulent fluctuations leading to increased contributions to the Reynolds stresses from these components. As high momentum fluid nears the outer bank and becomes submerged below the water surface as flow moves through the bend, velocity gradients steepen locally near the base of the bank producing peaks in Reynolds stresses and turbulent kinetic energy there. In the study bend, this location also corresponds to the highly erodible sandy sediment layer just above the basal lag gravels in the outer bank.

6.2 Future Work

This research has examined the interactions among three-dimensional time-averaged flow structure, bed morphology evolution, outer bank erosion, and planform change in compound meander bends over both short- and long-term timescales. A primary finding of the research is that compound meander loops tend to increase in complexity over time through processes acting at local and short-term timescales that influence, and are influenced by, long timescale dynamics.
in the system. Additional work is needed to elucidate how specific short-term processes relate to evolving complexity in multilobe planforms. The presence of failed bank material along the outer bank in both study bends affected the structure of the turbulent flow, acting to disrupt curvature-induced advection of high momentum fluid into the toe of the bank. The characteristic residence time of bank blocks should be a function of the geotechnical properties of the blocks, local variations in curvature, and the hydrologic regime of the river system. Results in the Embarras River show that the stabilization of a previously deposited bank block within the elongating low-curvature transition between the two lobes deflected flow for a sufficient time period to increase the sinuosity of the transition. This change in planform, coupled with differing migration trajectories of the two lobes, suggests that bank block residence time is an important factor in the developing complexity of compound loops. Therefore, future work should examine the relationship between the formation and destruction of large outer bank roughness elements and local curvature-induced flow structure.

Analysis of spatial variation of bed material size and entrainment potential in the Sugar Creek compound bend shows that sediment sorting within the bend is governed by spatial variations of shear stress magnitude. Along the thalweg, which extends along the outer bank through two distinct lobes of the bend, sediment coarsens and shear stresses increase in the downstream direction. Bed material becomes finer and shear stress generally decreases along the inner bank in the downstream direction, except for the transition between the lobes where locally coarse sediment and higher shear stresses exist. The coarsening of sediment between the two lobes in Sugar Creek likely represents an intermediate sedimentary environment that marks the transition between the tail of the bar in the upstream lobe and the head of the bar in the downstream lobe. In the classification of the bar-unit, a topographic high comprising the bar is
genetically linked to the topographic low which forms the pool (Dietrich 1987). Successive alternating bar units adequately describe the typical morphology in meandering channels. However, it is unclear whether multiple bars, pools and riffles in compound bends represent successive individual bar units similar to those that form in a uniformly curving elongated bend, so-called shingle bars (Whiting and Dietrich 1993b), or an integrated bar complex consisting of the amalgamation of bars that develop in response to spatial variations in curvature associated with individual lobes of a compound loop. In both the bends studied in the Embarras River (Chapter 3) and Sugar Creek (Chapters 4 & 5), bar complexes extend around the entire loop, similar to bar complexes observed at compound loops on large meandering rivers (Jackson 1976), but the morphological and sedimentological expressions of these bars is greatest at, or downstream of, local curvature maxima, and least in the inter-lobe transitions. Whereas classical shingle bars (Kinoshita 1961) appear in elongate bends that lack separate lobes defined by spatially-varying curvature (Whiting and Dietrich 1993b, Abad and Garcia 2009b), the locus of maximum bar expression at distinct lobes within both the Sugar-Creek and the Embarras-River study bends seems to indicate that the bar forms within the loop differ from shingle bars and are indeed curvature dependent. Future work is needed to evaluate the transition zones marking gradation between the bars at a range of flow stages, and in varying multilobe configurations to determine the validity of bar unit classification for compound channel planforms.

Work undertaken in Chapter 5 relating turbulence to changing curvature in a compound meander bend represents one of the first attempts to quantify the structure of turbulence in the outer bank region of a meander outside of the lab or through modeling approaches. Findings generally support the hypothesis that turbulence is enhanced near the outer bank as curvature-induced advection moves the core of high velocity flow below the water surface and outward
progressively through a bend. A limitation of the current research is that although fluid turbulence was quantified near the outer bank, no measurements were made immediately proximate to the bank face, and therefore computation of the fluid shear acting on the boundary was not possible. Future work is required to relate hydraulic stresses on the bank face to the time-averaged flow structure and turbulence occurring in the near-bank region. Although some lab and field experiments have investigated the formation and role of secondary outer bank circulation (SOC) cells in bank shear stresses and their morphological implications (Blanckaert and Graf 2001, Kleinhans et al. 2010, Blanckaert et al. 2012a), no field studies have directly examined the impacts of these cells on bank shear stresses. Related to the need to determine failed block residence time, additional work is required to evaluate the modifications of curvature-induced flow structure on the interaction of flow deflection and turbulent structure around bank blocks. In straight channel flow, deflection around a fixed object creates flow separation and a shear layer/mixing interface that exchanges low momentum fluid in the lee of the object with high momentum fluid in the free stream adjacent to the object. In meander bends, lateral and vertical advection of momentum caused by curvature of flow streamlines should influence the structure of turbulence created by deflection of flow locally around bank blocks. Future work should examine how the effects of flow curvature inhibit or enhance the structure of turbulence around large roughness elements, how turbulent stresses generated by bank blocks affect the residence time of these blocks, and how residence times of bank blocks, particularly the long-term persistence of these blocks, influences planform dynamics.


