Chapter 1

Introduction

3.1. Motivation and Objectives

River science is defined by contributions from interdisciplinary fields including hydrology, geomorphology, and ecology. Seminal work in river science has sought to describe the linked nature of these systems through the connectivity of systems [*Junk et al.*, 1989; *Ward*, 1989; *Tockner et al.*, 2000; *Amoros and Bornette*, 2002; *Opperman et al.*, 2010; *Covino*, 2017], quantification of processes often for the purpose of river restoration [*Palmer et al.*, 2005; *Kondolf et al.*, 2006; *Beechie et al.*, 2010; *Wohl et al.*, 2015], and the economic importance of natural processes through the understanding of ecosystem services [*Costanza et al.*, 1997; *Brauman et al.*, 2007; *Costanza et al.*, 2014]. These topics in river science are inherently linked. Human needs have been at the forefront of river management for centuries and only relatively recently have efforts been made to understand ecological demands. Therefore, many river systems have been subjected to substantial alteration of connectivity and process leading to decreased ecosystem services. Quantification of river processes in the context of altered river hydrology, geomorphology, and ecology can provide context for historical and contemporary conditions and inform integrated anthropogenic- and ecologic-influenced river management strategies.

Lateral channel-floodplain connectivity drives exchange of water and associated hydrodynamic processes. While qualitative assessment of connectivity and associated processes has been described and refined for decades, quantification of these connectivity processes has typically been in the form of intense feature and reach field efforts [*Lane and Richards*, 1997; *Babaeyan-Koopaei et al.*, 2002; *Jones et al.*, 2014; *Scott et al.*, 2014], laboratory description of process [*Shiono and Knight*, 1991; *Myers et al.*, 2001; *Yang et al.*, 2007; *Vermaas et al.*, 2011], or modeling efforts with simplified river morphology [*Bousmar and Zech*, 1999; *Cao et al.*, 2006]. The combination of continued improvement in computational power, hydrodynamic models, and improved resources for topographic and vegetation data acquisition improves modeling capabilities to describe both local feature and reach length processes. The applicability of two-dimensional hydrodynamics has been expressed in a number of ecological scenarios usually under steady flow conditions or time-series analysis [*Crowder and Diplas*, 2000; *Lacey and Millar*, 2004; *Crowder and Diplas*, 2006; *Jacobson and Galat*, 2006; *Daraio et al.*, 2010; *Carnie et al.*, 2016; *Stone et al.*, 2017]. While unsteady modeling further increases computational demands, there is compelling relevance to contemporary ecological strategies such as short term environmental flows and biogeochemical flood processes. Unsteady flow dynamics within modeled rivers are often ignored in favor of simpler, steady flow conditions. However, the dynamics with which floods interact with the floodplain geomorphology and ecology are of critical importance.

Incorporation of improved channel-floodplain dynamics is often the focus of contemporary integrated river management with the idea that floodplain storage of flood flows is an integral part of the attenuation process and essential to floodplain ecology [*Hudson and Middelkoop*, 2015]. Flood wave attenuation, an ecosystem service [*Brauman et al.*, 2007], is a reach scale process that accrues as a flood wave travels downstream. Previous research indicates the strong influence of water storage on the process of attenuation, but research is dominated by simplified conditions and one-dimensional modeling strategies [*Wolff and Burges*, 1994; *Woltemade and Potter*, 1994; *Jaffe and Sanders*, 2001; *Acreman et al.*, 2003; *Sanders et al.*, 2006; *Sholtes and Doyle*, 2010; *Fong et al.*, 2016]. New research indicates that floodplain connectivity has a substantial impact on flood wave shape [*Fleischmann et al.*, 2016]. This finding from gage analysis in combination with the call from previous work for two-dimensional hydrodynamic modeling in the process of flood wave attenuation displays a scientific need [*Wolff and Burges*, 1994; *Ghavasieh et al.*, 2006; *Sholtes and Doyle*, 2010]. Further, with high-resolution two-dimensional modeling now accessible, local feature scale processes which contribute to reach and basin scale attenuation can be analyzed as well.

Due to the applicability of attenuation and connectivity processes research in contemporary river management strategies, the goal within this dissertation was to quantify the hydrodynamics associated with short duration flood waves with a focus on how processes have changed through time due to both anthropogenic and climatic alterations. Therefore, three specific objectives were set for each of the following three chapters:

1. Evaluate how the ecosystem service of flood wave attenuation has changed with the implementation of river engineering practices in the name of flood protection and water use as well as contemporary river restoration efforts
2. Describe the sensitivities of flood wave attenuation to contemporary and altered conditions representative of historical river manipulation
3. Characterize channel-floodplain connectivity through lateral connectivity metrics important in the consideration of biogeochemical processes

The following three chapters describe the research conducted to address each of the specific objectives. Each chapter was written as a standalone paper to be submitted to a scientific journal for publication. All chapter objectives were achieved using two-dimensional hydrodynamic modeling methods. Chapter 2 describes the impact of river engineering and restoration strategies on flood wave attenuation with a focus on three representative time periods within the Middle Rio Grande: a pre-engineered historical system, an engineered pre-restoration system, and a contemporary system including recent river restoration strategies. Chapter 3 focuses on statistically describing flood wave attenuation sensitivities to contemporary channel-floodplain conditions and understanding how specific alterations to the Rio Grande have impacted hydrodynamic processes. Chapter 4 switches focus from attenuation to local hydrodynamic processes to quantify mass and momentum flux at the channel-floodplain interface, and to compare lateral and longitudinal flow characteristics in a contemporary setting.

3.2. Broad Contribution of Research

With motivation for this research driven by fields of river science which focus on channel-floodplain connectivity, process-based understanding of river hydrodynamics, and ecosystem services important to anthropogenic river management strategies; the research presented here addresses each of these topics and extends the body of knowledge in each respective field. The contributions of the following three chapters are in the form of modeling methodologies, quantifiable hydrodynamic metrics, and new strategies for incorporating large-scale spatial and temporal analysis of processes.

The methods used were chosen to both inform river science within the Middle Rio Grande and improve methods for further study in other rivers as well. All portions of the dissertation were completed using two-dimensional hydrodynamic modeling techniques. Methodologies were implemented to create high-resolution computational meshes to represent the complexities of channel-floodplain connectivity and floodplain topography. With continually improving computational power, these types of hydrodynamic models have the ability to inform process on a local scale, but can now be run over considerably larger distances than in the past. Linking local feature dynamics with watershed and regional dynamics is critical to linking scientific understanding of hydrologic processes [*Harvey and Gooseff*, 2015], so the ability to model large areas, yet retain feature resolution, can drive this science forward and is displayed within this research.

While no model will ever completely replicate natural processes, the measurement of hydrodynamics along rivers in both time and space is extremely difficult at small spatiotemporal scales. Numerical simulation can complement empirical river science to a great degree [*Covino*, 2017]. Therefore, improvement and advancement of computational techniques must continue. Specific to this research, the implementation of scripting techniques to extract information at key locations of interests can help solve some problems arising from computational storage demands and thus inform specific questions of interest. In addition, this research displays the ability of high-resolution, two-dimensional modeling to capture hydrodynamic channel-floodplain processes that are not expressed in lower-resolution, two-dimensional models or one-dimensional, hydrodynamic models. While other modeling strategies are suitable for other topics such as flood mapping, quantifying hydrodynamics appropriately should use the more data-intensive techniques displayed here.

The research within this dissertation also presents metrics novel to flood wave attenuation. The attenuation metrics are complementary in that they help explain the processes which cause attenuation through the context of historical modeling (Chapter 2) and modeling of alterations to contemporary conditions (Chapter 3). Comparison of attenuation ratios and statistical analyses conducted within the attenuation chapters indicate the same processes occurring but from different quantification approaches. Therefore, the ratio metrics are valuable in the future application to other river systems which will provide further context for flood wave management. Understanding of attenuation processes may be critical as integrated floodplain management and environmental flow implementation continue to be pursued. Unsteady flows are critically important to rivers, thus understanding of the processes impacting flood waves should be pursued for these interdisciplinary reasons.

Finally, the research informs hydrodynamic processes key to floodplain connectivity science. The novel approaches for both local and integrated mass and momentum flux represent new approaches for quantifying lateral channel-floodplain connectivity (Chapter 4). These flux metrics have been expanded in one approach to analyze lateral and longitudinal discharge relationships, however, the metrics have applicability to countless hydrologic, geomorphic, and ecologic studies. For example, quantification of lateral sediment and nutrient fluxes are critical to floodplain ecosystems, thus the addition of focused channel-floodplain flux quantities could prove to be extremely helpful in other fields.

3.2.1. Conceptual Model of Linked Nature of Dissertation

The three chapters of research presented here quantify hydrodynamic processes occurring along various scales during unsteady flow events. Along reach-scales, flood wave attenuation is dependent on the transfer of water and the dissipation of momentum as the unsteady pulse moves downstream. These reach-scale hydrodynamic processes are the result of the integrated local and feature-scale flux of mass and momentum. Figure 1.1 displays the topics of each chapter in relation to greater fields within river science. Flood wave attenuation and mass and momentum fluxes are dependent on lateral floodplain connectivity, which stems from hydrologic, geomorphologic, and ecological processes. In addition, attenuation and fluxes are influenced by the way in which rivers are managed, both historically and at present. In the context of broader fields of river science, flood wave attenuation is considered an ecosystem service in that natural mechanisms provide flood control for downstream locations. While mass and momentum flux accrue to create flood wave attenuation, upstream flood wave attenuation will also likely decrease downstream lateral fluxes. These hydrodynamic fluxes are important to biogeochemical processes occurring in the channel-floodplain system. Thus, each chapter has applicability to, and improves understanding of, other fields of river science beyond the specific application. In addition, the techniques used for quantification of hydrodynamic processes within my dissertation advance computational methodologies in river science.

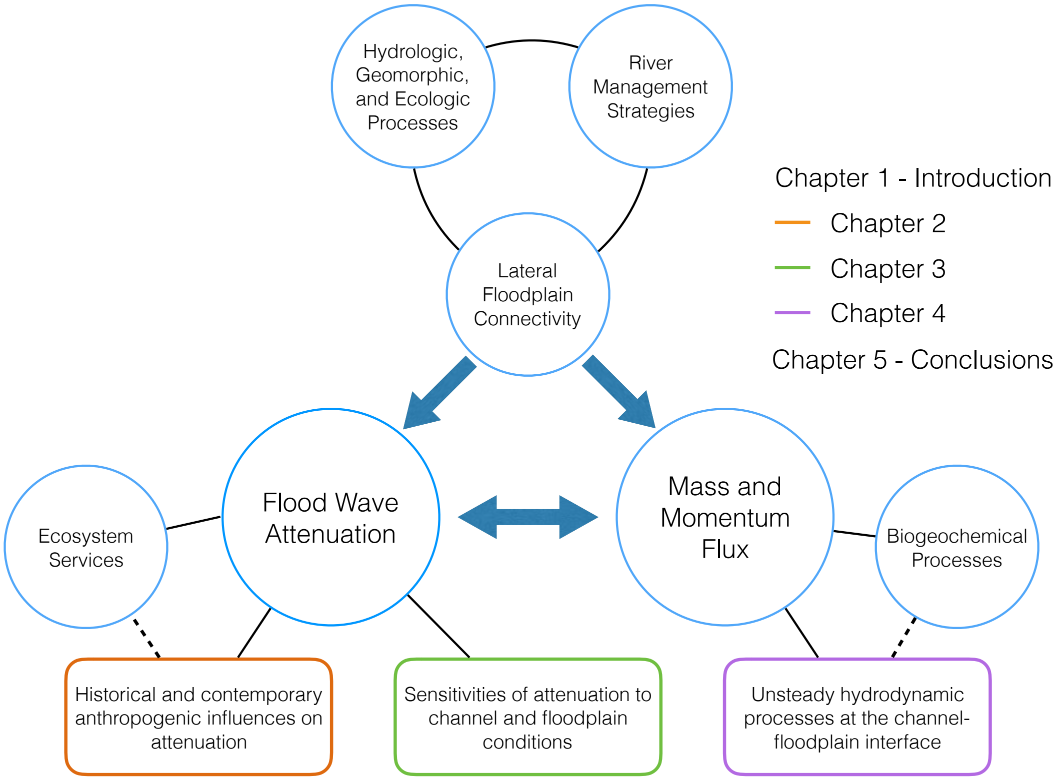

Figure 1.1. Conceptual model of dissertation research.

3.3. Modeling Environment

3.3.1. Deltares' D-Flow Flexible Mesh

All two-dimensional hydrodynamic modeling was conducted using the Netherlands-based Deltares' new D-Flow Flexible Mesh (D-Flow FM) [*Deltares*, 2015]. While several fully two-dimensional models now exist, D-Flow FM was chosen for a few reasons. First, the model has been verified as using appropriate and highly efficient numerical techniques to compute water depths and velocities. At the time this research began, we became beta testers in agreement with Deltares and were given access to both a Windows graphical user interface (GUI) and Linux source code. The Windows GUI was used for mesh and boundary fabrication as well as runs of smaller models while the Linux source code was built on a supercomputer at the University of New Mexico's Center for Advanced Research Computing (CARC).

The availability of the source code was another reason D-Flow FM was chosen. While no alterations were ultimately made to the code, we were interested in the possibility that we could manipulate the code to only give model outputs in areas of interest, thus saving on computational storage with the large datasets produced by hydrodynamic models with high spatial and temporal resolution. While the source code was not manipulated, the availability of the source code allowed for improved understanding of how the model calculates hydrodynamics and the building of the model on university supercomputers.

The ability to partition a mesh and use parallel computing resources was the final reason that D-Flow FM was chosen over other available two-dimensional models. The goal of the modeling methodology was to implement modeling techniques in the fields of attenuation research and connectivity processes that captured large spatial and temporal scales. Therefore, high-resolution models were created which averaged 25 m^2 in element area. This produced contemporary models with nearly 800,000 computational elements and a historical model with nearly 3,900,000 computational elements. Main channel elements were curvilinear in form to promote efficient calculation of longitudinal discharge, and floodplain elements were predominantly triangular in shape to describe the complex topography of the floodplain. Main channel elements were curvilinear in form to promote efficient calculation of longitudinal discharge, and floodplain elements were predominantly triangular in shape to describe the complex topography of the floodplain and improve complex inundation dynamics.

The D-Flow FM solver techniques are driven by the fundamental shallow-water equations based upon conservation of mass and momentum. These equations are depth-averaged as the spatial and temporal horizontal scales are much larger than vertical scales and hydrostatic pressure distribution is assumed within D-Flow FM [*Deltares*, 2015]. The continuity equation, or conservation of mass, is defined by Equation 1.1, while Equations 1.2 and 1.3 represent the conservation of momentum in the x- and y-directions

[*Chaudhry*, 2007]. Within these equations *h* represents water depth, *t* is time, *u* is depth-averaged velocity in the *x*-direction, and *v* is depth-averaged velocity in the *y*-direction, *g* is the gravitational constant, S_{Ox} and S_{Oy} are the channel bottom slope in the x- and y-directions, respectively, and S_{fx} and S_{fy} are the friction slope in the x- and y-directions, respectively.

$$\frac{\partial h}{\partial t}+\frac{\partial(uh)}{\partial x}+\frac{\partial(vh)}{dy}=0 \tag{1.1}$$

$$\frac{\partial u}{\partial t}+\frac{1}{2}\frac{\partial u^2}{\partial x}+\frac{\partial uv}{\partial y}=-g\frac{\partial h}{\partial x}+g\left[S_{Ox}\text{-}S_{fx}\right] \tag{1.2}$$

$$\frac{\partial v}{\partial t}+\frac{\partial uv}{\partial x}+\frac{1}{2}\frac{\partial v^2}{\partial y}=-g\frac{\partial h}{\partial y}+g\left[S_{Oy}\text{-}S_{fy}\right] \tag{1.3}$$

Within D-Flow FM, these equations are solved using finite-volume techniques implementing established k-ε turbulence closure methodology [*Deltares*, 2015]. With latitude, longitude, elevation, and roughness defined by the user, output data at each element includes *h*, *u*, and *v*. For calculation of friction losses, Manning's roughness coefficients were chosen for bed and vegetation roughness description with vegetation mapping and hypothetical conditions defining the spatial extents. One-meter topographic digital elevation models were interpolated to D-Flow FM mesh nodes using values nearest to mesh nodes. The mass and momentum equations were solved using a time-step dependent on a maximum Courant number of 0.7 (Eqn. 1.4), which allows for time-steps to vary based upon flow conditions. More specific description of mesh smoothing and orthogonalization methods and finite-volume mathematical techniques can be found in the D-Flow FM User Manual [*Deltares*, 2015].

$$0.7 \geq u\Delta t/\Delta x \tag{1.4}$$

3.3.2. Parallel Computing at CARC

The benefits of D-Flow FM would not have been achievable without collaboration from CARC. The supercomputers at CARC allow for research across all disciplines with a support staff that helps facilitate computational techniques. The staff at CARC built D-Flow FM allowing me to focus on the modeling methodologies. The D-Flow FM model was built on Ulam, a supercomputer at CARC which allows for tightly-coupled parallel computing. The parallel computing of a D-Flow model involves the partitioning of the entire model domain into smaller domains. These domains then simultaneously solve the defining physical equations while overlapping in small areas to produce contiguous results.

The D-Flow FM GUI interface allows for the partitioning of a model into any number of domains. At the beginning of the modeling enterprise, a benchmarking study was implemented to determine the number of domains at which the models ran most efficiently. That is, at some point, small gains in computational speed may not support increased computational resources in the further partitioning of the models. Additionally, users on Ulam are limited to the number of computational nodes. Each node on Ulam has 8 individual processors. Substantial decreases in computational time were found by using up to 8 nodes (64 processors or model partitions). To most efficiently use Ulam nodes in addition to considerations about queue time in regard to node limitations, the majority of models were run on 4 nodes or 32 partitions. The exception was the historical model in Chapter 2 which was run on 8 nodes (64 partitions) due to the substantially greater number of elements in that model compared to contemporary models because of much greater lateral extents.

1.3.3. Model Validation and Uncertainty

To determine if the contemporary model used in Chapters 2 through 4 was appropriate for unsteady conditions within the reach of study, an unsteady hydrograph from September 13 – 18, 2013 was modeled. In addition, 1, 1.5, and 3-day segments of model results starting on September 13th were used to investigate the appropriateness of the contemporary topographic and roughness conditions on similar time-scales to those investigated in this research (Fig. 1.2). Topographic data was defined with 2010 and 2012 light detection and ranging data. Vegetation and Manning's roughness relationships from prior studies involving hydrodynamic modeling were utilized on the floodplain [*Mussetter Engineering*, 2002; *Adair*, 2016], while a channel roughness of 0.025 was defined. More specific contemporary model methodology is defined in Chapter 2 and topographic methods included in Appendix B. Using the Nash-Sutcliffe Efficiency (NSE), percent bias (PBIAS), and root mean square error-standard deviation ratio tests (RSR) [*Moriasi et al.*, 2007], the model returned satisfactory results for stage when compared to data recorded 14 river kilometers downstream at USGS 08330000

(Albuquerque gage) under all durations (Table 1.1). These results provided confidence for the modeling of short duration flow events within this dissertation. While having more events to validate the model would have been beneficial, events such as the September 2013 storm are rare, thus other storms were not of the same magnitude and less appropriate for validation.

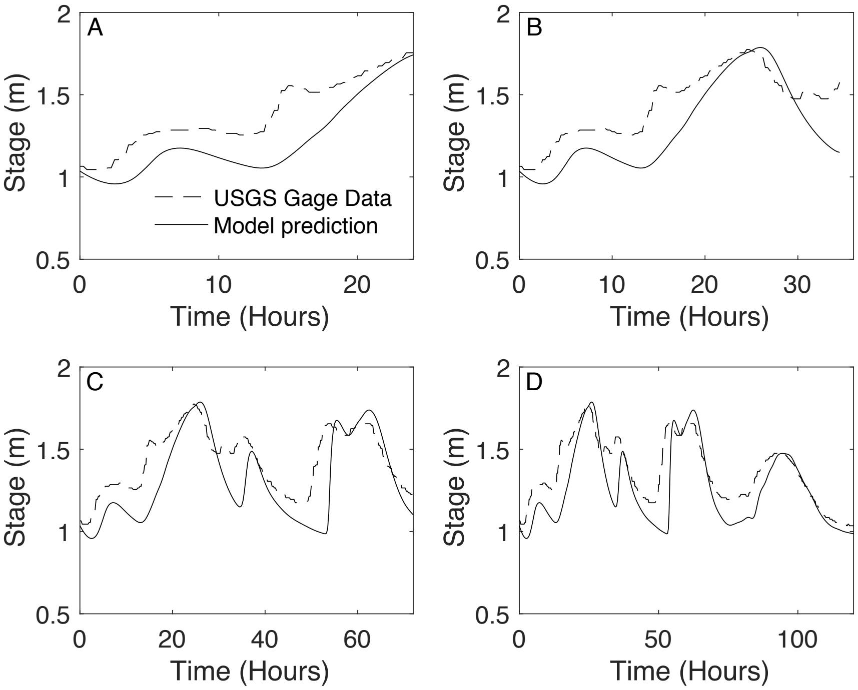

Figure 1.2. Unsteady flow validation of contemporary model for (A) 1-day, (B) 1.5-day, (C) 3-day, and (D) 5-day durations.

Table 1.1. Statistical results of contemporary model validation for four durations beginning on September 13, 2013.

	1-day	1.5-day	3-day	5-day
NSE	0.53	0.59	0.52	0.65
PBIAS	11.85	9.64	8.13	6.62
RSR	0.69	0.64	0.70	0.59

The validation of this contemporary model was deemed an acceptable level of performance for two reasons: (1) the gage data used for the upstream discharge boundary and downstream for statistical evaluation are subject to the uncertainty discussed in sand-bed river gaging strategies [*Isaacson and Coonrod*, 2011], and (2) the modeling conducted in this research is predominantly theoretical in its application to river science, as opposed to a specific practical event. While any method of data collection is prone to error, the uncertainties associated with the computational modeling method must be addressed. Topographic uncertainty is likely highest within the main channel where one-dimensional cross-section elevation data were used to interpolate two-dimensional elevation data. Roughness uncertainty is inherent to two-dimensional, hydrodynamic modeling as roughness becomes an all-encompassing momentum dissipation mechanism due to the direct interpolation of latitude, longitude, and elevation information [*Lane and Richards*, 1998; *Morvan et al.*, 2008]. However, validation suggests methodology used within this dissertation creates topographic and roughness conditions suitable for addressing unsteady processes within the reach.

Uncertainties and sources of error were minimized as best as possible by utilizing the most detailed data available. With the contemporary model performing appropriately, historical and altered model scenarios were created with the same methodology where possible. No validation data were available for these events, however, the similarity in mesh creation techniques should provide appropriate results for era and alteration comparisons conducted within Chapters 2 through 4. A sensitivity analysis of the relationship between microtopography and roughness was conducted in Appendix A to better understand the relationship these factors have with unsteady flow modeling.

1.4. The Middle Rio Grande

The work presented in this dissertation focuses on a 32-km stretch of the Middle Rio Grande (MRG) which runs through Albuquerque, NM, and is known as the Albuquerque Reach. The Albuquerque Reach provides an excellent setting for research dealing with historical and contemporary influences on hydrodynamic processes as the river has been subjected to substantial alterations during the past century under the name of flood control, water use, and river restoration. As each chapter of the dissertation was written as a standalone scientific paper for publication, each includes a section with relevant facts about the MRG to place the chapter research into context.

While specific findings presented within this research will be most applicable to semi-arid, snowmelt driven river systems, the methods presented within the dissertation are highly applicable to all river systems. Further, the quantification of the presented attenuation and flux metrics in other systems will be beneficial to the further understanding of how processes are both similar and different in various other types of systems.