CHANNEL CHANGE OF THE UPPER UMATILLA RIVER DURING AND BETWEEN FLOOD PERIODS: VARIABILITY AND ECOLOGICAL IMPLICATIONS

by

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Title: CHANNEL CHANGE OF THE UPPER UMATILLA RIVER DURING AND BETWEEN FLOOD PERIODS: VARIABILITY AND ECOLOGICAL IMPLICATIONS

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This study examines the role of floods in shaping the geomorphology of the multi-channel, gravel-bed upper Umatilla River, northeastern Oregon, USA. Three parts are presented: (1) the development and application of an error-sensitive aerial photo-based planform channel-change detection and measurement methodology, (2) an examination of the occurrence, variability, and landform impacts of channel widening, straightening, and lateral movement during two mid-to-late 20th century flood periods, (3) an investigation of the effects of these floods on channel complexity, a proxy of habitat quality and indicator of ecological health in multi-channel rivers. Floods in 1964-5 (17- to 37-year recurrence interval) scoured, widened, and straightened the active channel in conjunction with large lateral movements, bar accretion, and capture of marginal vegetated areas by lateral scour. Following the flood, lateral movements were smaller, the channel narrowed, and bars, scoured areas, and vegetation lapsed from the channel. A similar flood in 1975 also scoured, widened, and straightened the channel; however, lateral channel movement and changes in channel landforms were less in 1975 due to latent adjustment of the channel to the first flood. Migratory straightening, meander cutoffs, and avulsions dominated lateral movements during flood periods, whereas episodes of migratory (lateral) extension and (downstream) translation of meanders dominated lateral movement between flood periods. Channel changes were spatially variable and generally greater in reaches with wide floodplains. Floods reduced the overall complexity of the river channel, although the magnitude of change was highly variable and some areas increased in complexity in response to flooding. By contrast, channel complexity increased in the period between floods, particularly in laterally confined areas where complexity loss was high during the first flood period. Two key processes appear to most affect channel complexity: (a) lateral scour and avulsions, which capture vegetation into the channel, and (2) migrations of the main channel, which reflect bar accretion and dissection. Results of this study are broadly congruent with theories (and their corollaries) emphasizing adjustment of channel dimensions, increased rates of change, and reduced complexity in response to flood disturbance, but only partially consistent with theories emphasizing large geomorphic changes in structurally confined settings.

This dissertation includes both previously published and co-authored material.

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To my Father

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CHAPTER I

INTRODUCTION

Rivers are complex open systems that display remarkable variability in processes and landforms. As open systems, rivers experience variable inputs of energy and material. River floods are caused by large inputs of water (in the form of precipitation) and are often accompanied by similarly large inputs of sediment and organic materials from hillslopes and the channel network. Consequently, floods have the potential to generate extreme processes and to cause large, and potentially unique, changes in channel landforms. Understanding relations between river processes and landforms forms generally requires a better understanding of the role of floods in driving the evolution of channel and floodplain systems. Whereas developing a better understanding of flood impacts has been a major objective in fluvial geomorphology (Baker et al, 1988), few studies have addressed the impacts of floods in terms of variability of process-form interactions. Because of their significance to the assemblage and diversity of channel landforms, these interactions have become an increasingly important focus in river management and restoration; however, because river process and landforms are space- , time-, scale-, and threshold-dependent, their interactions are often nonlinear and complex (Murray and Fonstad, 2007). These characteristics have complicated efforts to develop operational models of river process-form interactions and have hindered practical application of fluvial geomorphology to ecological river management and restoration.

This study examines the role of large flood events in driving variability in the planform composition and complexity of the mixed pattern gravel-bedded upper Umatilla River, northeastern Oregon, USA. Large floods in rivers of this semi-arid mountainous region originate from rain-on-snow events, generate unusually large volumes of runoff (Harris and Hubbard, 1983), and significantly rework river channels and floodplains (Waananen et al., 1971). Floods in December 1964 and January 1965 were among the largest recorded at the time of their occurrence, and the 1975 flood was similar in magnitude. Channel widening, straightening, and increased lateral movement are common flood effects in arid and semi-arid regions, and preliminary assessment of flood impacts on the Umatilla River reflected these impacts; however, relatively little is known about how these processes affect river characteristics such as the compositional structure or complexity of the channel. Because these characteristics act as physical controls in riverine ecosystems, they are important regulators of river health and quality. Developing a better understanding of flood disturbance, its influence on the evolution of mountain river systems, and its role in shaping riverine habitats of the Interior Pacific Northwest is a major research priority in regional river management and restoration (NRC, 1996; Beschta, 1997). The 1964-65 and 1975 floods on the Umatilla River, coupled with the availability of aerial photos and streamflow records during and between flood periods, provide an excellent opportunity to examine the nature and variability of flood-driven geomorphic processes and landform changes in a mixed multi-channel river system.

In this three-part dissertation I present: (1) the development and application of an error-sensitive aerial photo-based planform channel-change detection and measurement methodology, (2) an examination of the occurrence, variability, and landform impacts of channel widening, straightening, and lateral movement during two mid-to-late 20th century flood periods, (3) an investigation of the effects of these floods on channel complexity, a proxy of habitat quality and indicator of ecological health in multi-channel rivers. The theoretical contexts, problem statements, and research questions for each of these chapters are outlined in the sections below.

Chapter II: Accuracy assessment of georectified aerial photographs: implications for measuring lateral channel movement in a GIS

This chapter includes both previously published and co-authored material.

Aerial photographs are rich sources of information on historical river conditions (Trimble, 1991; Lawler, 1993) and have been widely used to track the historical planform evolution of river systems (e.g., Lewin and Weir, 1977; Petts, 1989; Gurnell, 1997; Surian, 1999; Graf, 2000; Winterbottom and Gilvear, 2000; O'Connor et al., 2003; plus many others). Historical planform channel analysis typically involves the co-registration of aerial photos and maps from different years so channel positions can be analyzed in overlay. Since the 1980s, the development of desktop GIS software and improvements in remote sensing and digital scanning technology have enabled users to more efficiently scan and co-register aerial photos; however, spatial error in digital imagery (including scanned aerial photos) is inevitable and can impart inaccuracies in measurements of lateral channel movement.

While there has been widespread recognition in the GIScience community of the sources, types, and implications of locational error in geospatial data sets (Chrisman, 1982, 1992; Goodchild and Gopal, 1989; Unwin, 1995; Leung and Yan, 1998), fluvial geomorphologists have generally ignored the magnitude of geospatial error in relation to geomorphic change or have used only Root Mean Square Error (RMSE) as a measure of this error (e.g., Urban and Rhoads, 2004). Only recently have fluvial geomorphologists begun to embrace geospatial error as an independent research topic (e.g., Mount and Louis, 2005). Consequently, despite the development of approaches for measuring positional accuracy of linear features (e.g., Goodchild and Hunter, 1997; Leung and Yan, 1998) and recognition of the inherent problems of positional error on maps of rivers (Hooke and Redmond, 1989; Locke and Wyckoff, 1993) and lakes (Butler, 1989), there is no widely supported conceptual framework for evaluating and treating positional error on digital imagery in the measurement of lateral channel movement.

In this chapter, I seek to identify the magnitude and controls of geospatial error in georectified aerial photos and to address the implications of this error for measuring lateral channel movement. Accordingly, I raise the following questions:

- How is the locational accuracy of georectified aerial photos affected by the number and type of ground control points (GCPs) and the order of polynomial transformation used in georectification?
- Is root-mean-square error (RMSE) a good proxy of overall georectification error?
- What are the implications of georectifcation error for quantifying lateral channel movement and how can such error be minimized?

Chapter III: Planform channel change during and between flood periods on the upper Umatilla River, northeastern Oregon, USA

Floods are notorious geomorphic agents, but they greatly vary in their ability to alter channel-floodplain systems. Floods are more effective in generating large channel adjustments in arid or semi-arid climates (Wolman and Gerson, 1978; Baker 1977) and in small, steep basins with flashy hydrographs, high bedload, low bank cohesion, and deep, narrow valley cross-sections (Kochel 1988). These characteristics promote a combination of relatively high sensitivity and high unit stream power, which can drive high-magnitude channel adjustments during floods. Channel widening, increased lateral movement, and loss of sinuosity are common planform channel adjustments during floods (Bridge, 1993; Knighton, 1998; Wohl, 2000); however, the occurrence and magnitude of these effects can vary within rivers during floods. Channel response to floods generally depends on the magnitude, frequency, and duration of flood flows and the make-up and dimensions of the valley floor. These two factors interact to determine the occurrence, magnitude, and effectiveness of different channel-change processes. Differences in valley morphology in relation to lateral confinement of the channel can affect the unit stream power and relative sensitivity of the channel to change forced by flood flows (Newson, 1980; Patton, 1988).

Several different processes can cause channel change during floods. Building on the work of Nanson and Beach (1977) and O'Connor et al. (2003), Beechie et al., 2006 recognized migration, avulsion, meander cutoffs, and "channel switching" as the dominant processes responsible for lateral movement, bank erosion, and sediment deposition in mountain river systems of the Pacific Northwestern U.S. Whereas the importance of these processes in creating heterogeneity in channel landforms has been increasingly recognized by river ecologists (Ward et al., 2001, 2002), questions related to controls on the occurrence, frequency, and magnitude of these processes, as well as their effects on channel landforms, remain largely unresolved. These questions represent an ongoing challenge for geomorphologists working in multi-channel systems wherein lateral movement and its impacts on channel landforms are often complex and poorly understood. Floods often play a significant role in multi-channel patterns because they promote the erosion, abandonment, and reoccupation of secondary channels. These processes are particularly important in laterally active anabranching rivers, which have islands that are excised from floodplains by avulsion during floods and other high-flow events (Nanson and Knighton, 1996). Lateral migration and meander cutoffs are also evident in anabranching rivers, and likely play an equally significant role in the evolution of these rivers by way of construction and conversion of bars to islands within the channel (Knighton, 1998). A better understanding of the relative occurrence, variability, and controls on lateral movement processes in anabranching mountain river systems, the influence of floods on these processes, and the impacts of these processes on channel landforms and habitat quality is currently needed for improved river management and restoration.

The Umatilla River is a semi-arid, gravel-bed channel system with laterally active multi-channel pattern. Examination of pre- and post-flood aerial photos of the Umatilla River revealed large lateral movements, channel widening, widespread scour of channel and floodplain surfaces, removal of channel vegetation, and complex bar construction in response to floods in 1964-5 and 1975. Aerial photos between these events showed channel narrowing and revegetation, suggesting that floods play a special role in driving channel-floodplain processes and landform changes that control the pattern and evolution of the Umatilla River and similar mountain rivers.

The goals of this study are: (1) to identify flood-driven geomorphic processes and landform changes, (2) to characterize the variability and explore the controls of these processes and landform changes, and (3) to investigate potential linkages between channel processes and landform changes. The following research questions are addressed:

- what processes and landform changes characterize floods?
- how do these processes vary over space and time, and what are their controls?

- how do flood processes and impacts differ from those of the post-flood recovery period?
- how do channel processes and landforms interact to define the channel pattern and how do floods affect these interactions?
- how do floods affect the overall evolution of the channel-floodplain system?

Chapter IV: The effects of floods on planform complexity of the upper Umatilla River, northeastern Oregon, USA

River channel patterns reflect complex interactions between processes and forms in channel-floodplain systems. In multi-channel gravel-bed rivers these interactions can result in variable arrangements of channels, bars and islands. In many mountain regions channel patterns of gravel-bed rivers have been simplified by dams, channelization, wetland drainage and filling, levee and revetment building, and deforestation (Wohl, 2006). These activities have destroyed or diminished habitat for many aquatic and riparian species (National Research Council, 1992). In their promotion of an ecological perspective for aquatic and riparian restoration practices, Kaufman et al. (1997) cite an unprecedented need for the preservation and restoration of biological diversity, including restoration of the fluvial processes and landforms that underpin important linkages between native organisms and their environment.

Ecological disturbance and biodiversity have been linked through the Intermediate Disturbance Hypothesis (IDH), which states that biodiversity is greatest when and where disturbance is neither too large and frequent, nor too small and infrequent (Connell, 1978; Resh et al, 1988; Petraitis et al., 1989). Biodiversity, commonly defined as species richness, is therefore maximized under conditions of intermediate disturbance. A concept in fluvial geomorphology that is somewhat parallel to biodiversity is physical complexity, defined by Graf (2006) as the number of geomorphic surfaces per unit length of channel. Riverine geomorphic surfaces are created by disturbance and post-disturbance recovery, similar to the ways in which processes determining biodiversity are influenced by disturbance. In the case of rivers, the main disturbance process is floods, but various forms of disturbance may be important in ecosystems. Multi-channel gravel-bed rivers typically go through disturbance-driven cycles of creation and abandonment of side channels (Burge and Lapointe, 2005). As in the IDH in ecology, the magnitude and frequency of disturbance events is a key concept used in fluvial geomorphology to explain development of and changes in landforms.

The fundamental thesis of this paper is that fluvial landform systems are like biological communities in that their diversity (physical complexity) is dependent on the magnitude and frequency of disturbance. If so, then the intermediate disturbance hypothesis will apply to fluvial landforms and can be used to predict the response of channel systems to flood disturbance. If floods are too large and/or frequent, or to small and/or infrequent, then according the IDH, multi-channel rivers would lose some physical complexity. Only a few studies to date have explored the link between magnitude and frequency of disturbance and physical complexity of channel systems, but their results are supportive of the applicability of the IDH to physical complexity in fluvial systems. Graf (2006) found that the reduction in flooding downstream of large dams reduced physical complexity 14-56% across 36 rivers in seven regions of the U.S. Sheldon and Thoms (2006) found a similar loss of physical channel complexity in response to flow regulation on the Barwon-Darling River in Australia and cited the loss as a potential contributing factor to low retention of organic matter within the river system.

Physical complexity of fluvial systems as used here is distinct from geomorphic complexity in the broader sense – what might be termed system complexity. In recent years geomorphologists have become increasingly interested in system complexity (Malanson, 1999; Phillips, 1999b, 2007; Schumm, 2005; Sheldon and Thoms, 2006; Thoms, 2006; Murray and Fonstad, 2007). Werner (1999) stated that complexity in natural landform patterns is a manifestation of [complex] nonlinear interacting processes that operate in open systems to both modify and respond to the environment in which they operate, implying that physical complexity results from complex interactions between processes and landforms. While the sources and manifestations of complexity in geomorphic systems continue to be modeled and debated (Murray and Fonstad, 2007), empirical studies of complexity are scarce. Because physical complexity (defined as number of surfaces per length of river channel) is an observable property, it is a logical starting point in the quest to develop a better understanding of behavioral complexity in geomorphic systems.

In a test of the IDH applied to a fluvial system, this study evaluates of the effects of the 1964-5 and 1975 floods on planform complexity of the upper Umatilla River of northeastern Oregon. In this study channel complexity is defined as the spatial density of distinguishable channel surfaces (see Graf, 2006), expressed as the number of surfaces within the active channel per length of floodplain. Channel landforms were classified and mapped from a series of pre-, post-, and inter-flood aerial photographs (Table 2). The following questions are addressed:

- How much does channel complexity vary over space and time?
- How and to what degree do moderate-to-large floods affect channel complexity?
- What factors affect the spatial variability of channel complexity?
- Can the intermediate disturbance hypothesis be adapted to explain changes in channel complexity in response to floods?

Study Area

The Umatilla River is a gravel-bed river that originates in the Blue Mountains of northeastern Oregon and flows west to the Columbia River (Figure 1). This study focuses on a segment of the upper Umatilla River between the confluences of Meacham and Wildhorse Creeks. This segment flows through a bedrock canyon that drains approximately 1,650 km^2 at its downstream end near the City of Pendleton. The geology of the watershed is dominated by the Columbia River Basalts, which originated from Miocene-age lava flows and form the uplands and canyons of the Umatilla River watershed. Quaternary alluvium forms the valley floor, averages 12 feet in thickness (Gonthier and Harris, 1977) and varies in width from approximately 500 to 2000 meters. The channel bed is composed of basalt gravel ($D_{50} \sim 6$ cm, $D_{84} \sim 15$ cm) that fines downstream. The river has a mixed multi-channel pattern typical of the wandering pattern described by Church (1983) for the Bella Coola River in British Columbia. This pattern is similar to the Type 5 (gravel-dominated, laterally active) anabranching pattern described by Nanson and Knighton (1996) and the island-braided pattern described by Beechie et al. (2006). Some reaches primarily flow in a single meandering channel and others flow in braided or anabranching channels that are separated by bars or vegetated islands and share full (connected at the upstream and downstream ends) or partial connection (connected at the upstream or downstream end) to the main channel at low flow. Chutes and abandoned channels typically operate as secondary channels. Floodplains and islands have cottonwood-willow forests on their upper surfaces, and shrubby or herbacious vegetation on their lower surfaces, including some bars. Land use includes forestry and dryland farming on the uplands, and ranching, irrigated farming, and residential development on the terraces and floodplains.

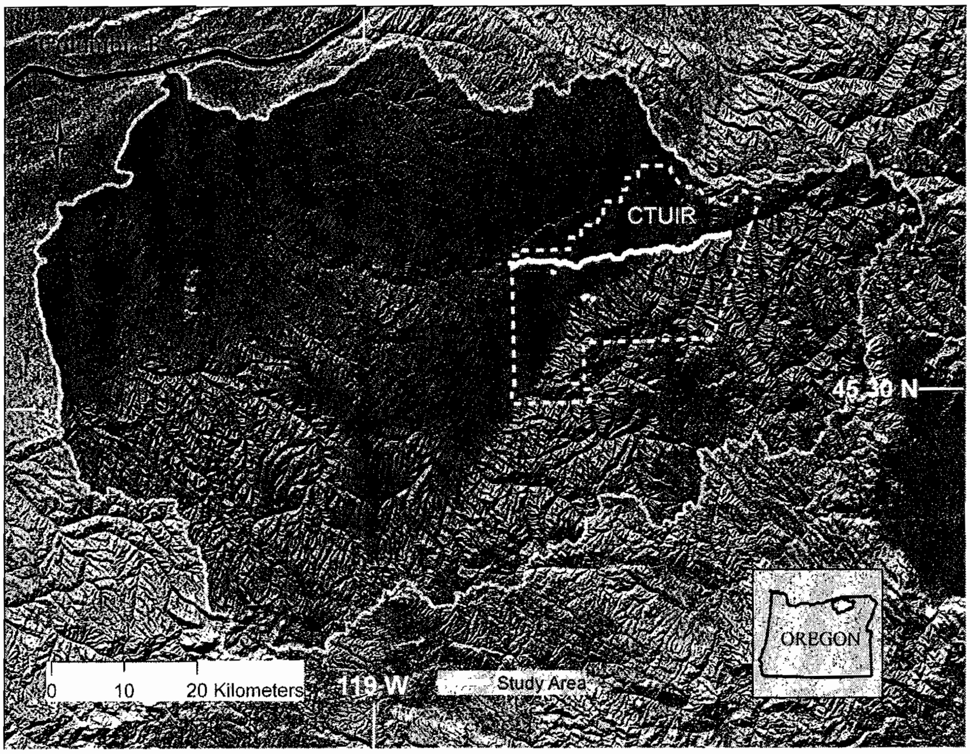


Figure 1. The Umatilla River watershed, with the upper Umatilla River and tribal reservation of the Confederated Tribes of the Umatilla Indian Reservation (CTUIR) highlighted in white.

CHAPTER II

ACCURACY ASSESSMENT OF GEORECTIFIED AERIAL PHOTOGRAPHS: IMPLICATIONS FOR MEASURING LATERAL CHANNEL MOVEMENT IN A GIS

This chapter includes both previously published and co-authored material. M.L. Hughes designed the study, conducted the analysis, created the figures, provided initial interpretations of the data, and wrote the initial draft of the text. P.F. McDowell and W.A. Marcus provided additional interpretations of the data, revisions of the text, and suggestions concerning publication of the article cited in this chapter as Hughes et al., 2006.

1. Introduction

Aerial photographs are rich sources of information on historical river conditions (Trimble, 1991; Lawler, 1993) and have been widely used to track the historical planform evolution of river systems (e.g., Lewin and Weir, 1977; Petts, 1989; Gurnell, 1997; Surian, 1999; Graf, 2000; Winterbottom and Gilvear, 2000; O'Connor et al., 2003; plus many others). Historical planform channel analysis typically involves the co-registration of aerial photos and maps from different years so channel positions can be analyzed in overlay. Since the 1980s, the development of desktop GIS software and improvements in remote sensing and digital scanning technology have enabled users to more efficiently scan and co-register aerial photos; however, spatial error in digital imagery (including scanned aerial photos) is inevitable and can impart inaccuracies in measurements of lateral channel movement.

While there is widespread recognition in the GIScience community of the sources, types, and implications of locational error in geospatial data sets (Chrisman, 1982, 1992; Goodchild and Gopal, 1989; Unwin, 1995; Leung and Yan, 1998), fluvial geomorphologists have generally ignored the magnitude of geospatial error in relation to geomorphic change or have used only Root Mean Square Error (RMSE) as a measure of this error (e.g., Urban and Rhoads, 2004). Only recently have fluvial geomorphologists begun to embrace geospatial error as an independent research topic (e.g., Mount and Louis, 2005). Consequently, despite the development of approaches for measuring positional accuracy of linear features (e.g., Goodchild and Hunter, 1997; Leung and Yan, 1998) and recognition of the inherent problems of positional error on maps of rivers (Hooke and Redmond, 1989; Locke and Wyckoff, 1993) and lakes (Butler, 1989), there is no widely supported conceptual framework for evaluating and treating positional error on digital imagery in the measurement of lateral channel movement.

In this article, we seek to identify the magnitude and controls of geospatial error in georectified aerial photos and to address the implications of this error for measuring lateral channel movement. Accordingly, we raise the following questions:

(i) How is the locational accuracy of georectified aerial photos affected by the number and type of ground control points (GCPs) and the order of polynomial transformation used in georectification?

(ii) Is root-mean-square error (RMSE) a good proxy of overall georectification error?

(iii) What are the implications of georectifcation error for quantifying lateral channel movement and how can such error be minimized?

We address these questions using repeated georectification of an aerial photo showing the Umatilla River in northeastern Oregon. The quality and scale of this imagery is typical of those used throughout North America and many other parts of the world to reconstruct river histories. This article is the first phase of a broader study to evaluate channel and floodplain change resulting from large floods in selected rivers of the U.S. Pacific Northwest.

2. Background

GIScience and remote sensing play an increasingly significant role in geomorphological studies. Some recent examples of topics that have benefited from advances in the generation and handling of digital geospatial data include (but are not limited to) mapping and modeling of: fluvial erosion (Finlayson and Montgomery, 2003), complex terrain (Wilson and Gallant, 2002), mass wasting (Roering et al., 2005); mountain topography (Schroder, Jr., and Bishop, 2004), historical channel change (Leys and Werrity, 1999; Collins et al., 2003), and river habitats (Marcus et al., 2003) and depths (Fonstad and Marcus, 2005). While many studies have developed methods for using digital data (e.g., aerial photos, satellite images, historical maps, and digital elevation models) to address traditional research topics, relatively few studies have rigorously addressed the effects of geospatial data quality on the results of geomorphic analyses (although see Holmes et al., 2000; Mount et. al., 2003; Mount and Louis, 2005). Therefore, geomorphologists using geospatial data need to better understand how the quality of such data may affect analyses of digital data sets and to understand what factors control geospatial data quality. Development of error-sensitive change detection methods depends on this knowledge. As GIScience continues to better establish a theoretical basis in geography, opportunities are emerging for geomorphologists to undertake GIScience studies aimed at better understanding the applicability and limitations of digital geospatial data in their research.

2.1. General notes and terminology

Before aerial photos can be overlaid to map channel change in a GIS, they must be scanned and co-registered. Aerial photo co-registration refers to the conversion of digitally scanned photos to a common projection and coordinate system. Co-registration is usually achieved by georegistering individual photos to the same base layer. Digital orthophotographs (DOQs) and topographic maps (digital raster graphics or DRGs) are typically used as base layers.

Several techniques are available for co-registration of digital aerial photographs in a GIS, including aerotriangulation, orthorectification, and polynomial transformation. Each of these techniques has advantages and disadvantages that make it appropriate for specific applications. Aerotriangulation and orthorectification are typically used only when polynomial georectification fails to yield acceptable results. During aerotriangulation, GCPs are forced to have identical coordinates on the target (unregistered) layer and (georeferenced) base layer, thereby causing the image to be warped along triangulated edges rather than at point locations. This process requires a large number of GCPs for high accuracy and can therefore be difficult to apply in river change analysis because the number and distribution of GCPs are often limited. Moreover, error on triangulated photos varies in a nonsystematic fashion, complicating error analysis and application of buffers for reducing error and uncertainty during change detection. By contrast, orthorectification can provide high degrees of geospatial accuracy, but is less commonly employed by geomorphologists because it requires sophisticated software and is generally more labor- and data-intensive.

In this article, we evaluate polynomial georectification, which is readily applied to large sets of aerial photos (e.g., photos from flight lines along a river), can be performed with most commercially available GIS software packages, and is widely used for co-registration of aerial photos. When coupled with pixel resampling to correct for image warping during transformation, the process is called polynomial georectification. After scanning the original paper photo to create a digital file, polynomial georectification is performed in three steps: (i) matching of ground-control points (GCPs) on the scanned photo image and base layer, (ii) transformation of the GCP coordinates on the scanned image from a generic raster set to a geographical projection and coordinate system, and (iii) pixel resampling.

2.2. Aerial photo scanning

During the scanning procedure, the user defines the type (color versus gray scale) and resolution (dots per inch or d.p.i.) of the scan. Color and gray scale photos are customarily scanned into color and gray scale digital images, respectively. Because some data are "lost" in this digital conversion, users tend to maximize the resolution of the scan to improve image quality; however, users should consider the resolution of the base layer to which the digital photo will be registered before selecting a scan resolution. Scanning to a pixel resolution of 0.1 m, for example, makes little sense if the base-layer resolution is 2.0 m. Data loss during photo georectification, which includes pixel resampling (discussed below), may be minimized if the resolution of the scanned photo and georeferenced base layer are similar.

2.3. GCP selection for channel change analysis

The number, distribution, and type of GCPs can affect the accuracy of polynomial georectification, and researchers investigating river channel change have offered different guidelines for GCP selection. In examining historical planform change using scanned maps, Leys and Werrity (1999) noted that GCPs should be widely distributed across the image to provide a "stable warp," while Richards (1986) and Campbell (2002) advised that the majority of control points should be located around the edge of the image with several uniformly spaced points in its central portion. While these suggestions may be appropriate for satellite images that have relatively little error due to topographic variations, or for scanned maps with constant scale variations across their projections, they are not necessarily well suited for historical aerial photos, which usually have GCPs and areas of analytical interest that are unevenly distributed across the image over space and time, particularly in rural or forested settings. Moreover, better accuracy may be obtained by concentrating GCPs near the features of interest rather than across the entire aerial photo. This is particularly true with river channels, which tend to flow through floodplains of low relief and may be surrounded by valley walls of relatively high relief. Selecting GCPs that are far removed from the river channel may unnecessarily skew the transformation toward topographically complex areas not representative of the river channel and floodplain.

In addition to GCP distribution, GCP type can affect georectification accuracy. For the purposes of this study, we define two types of GCPs: hard and soft points. Hard points are features that have a sharp edge or corner, so their locations can be pinpointed. Hard points may include features such as building corners, road intersections, fences, and sidewalks. Soft points are features with irregular or fuzzy edges, such as rock outcrops and the centers of individual trees and shrub clusters. Because it is more difficult to pinpoint a soft point and because soft points may change over time (e.g., as when a tree grows larger), the choice of soft rather than hard points can affect overall georectification accuracy. However, in order to have enough GCPs for polynomial georectification, particularly in riverine environmentss, it is sometimes necessary to intermix hard and soft GCPs; therefore, soft points often cannot be categorically excluded.

Another challenging aspect of locating GCPs on historical aerial photos is that the correspondence between features on photos collected years or decades apart is sometimes poor. Buildings, roads, fences, trees, and other similar features can be moved, obliterated, or altered over time. Even in developed areas, GCPs may be difficult to locate and users are often faced with using a sub-optimal number, type, or spatial distribution of GCPs.

2.4. Polynomial georectification, transformation order, and RMSE

Polynomial transformation is applied to unregistered raster images (including scanned aerial photos) using linear and nonlinear functions. Polynomial transformations are named by their order, or the numerical value of the highest exponent used in the polynomial function. Therefore, first-order, second-order, and third-order transformations are linear, quadratic, and cubic transformations, respectively. When curvilinear (i.e., quadratic or higher) functions are used, the term “rubbersheeting” is sometimes applied, although this term may also be applied to aerotriangulation. Transformations using curvilinear functions are popular for aerial photos of the scale and terrain of this study because they can correct for some of the effects of both radial error (related to curvature of the earth) and geometric error (related to topography and camera lens distortion) and can therefore lend map-like qualities to a georectified photo without orthorectification. Remote sensing textbooks and photogrammetry manuals tend to emphasize the use of first-order and second-order transformations (e.g., Campbell, 2003; Leica Geosystems, 2003), because third- and higher order transformations tend to excessively warp digital images.

During polynomial transformation, a least-squares function is fit between GCP coordinates on the scanned image and base layer. This function is then used to assign coordinates to the entire photo. After transformation, GCPs on the photo and base layer will have slightly different coordinates, depending on the degree to which the overall transformation affects the proximal area of each GCP. The difference in location between the GCPs on the transformed layer and base layer is often represented by the total root-mean-square error (RMSE), a metric based on the Pythagorean Theorem and calculated for a coordinate pair by the equation (Slama et al., 1980)

$$\mathrm{RMSE} = [(x_s - x_r)^2 + (y_s - y_r)^2]^{1/2} \tag{1}$$

where x_s and y_s are geospatial coordinates of the point on the source image; and x_r and y_r are coordinates of the same point on the transformed aerial photo. The RMSE for the whole image is the sum of the RMSE for each coordinate divided by the square root of the number of coordinate pairs.

2.5. Pixel resampling

Spatial transformations typically generate a different number of pixels in the transformed image than in the original image. Moreover second-order or higher transformations can create pixels of variable size across the transformed image. A resampling step is necessary to equalize pixel size throughout the image and to assign values from the original image to the transformed image. There are a number of resampling approaches; nearest neighbor, bilinear, and cubic convolution (Campbell, 2002) resampling schemes are most common and are included in almost all GIS programs. We found that cubic convolution produced output photos best suited for interpretation of fluvial features because it smoothes jagged edges along linear boundaries (e.g., river banks). Nearest neighbor resampling can create jagged feature boundaries, but does not alter the original pixel values, a critical element if spectral analysis of the image is planned. Bilinear resampling provides intermediate results in comparison to the other two techniques. If the reference and transformed images are approximately the same resolution, variations in resampling methods should not alter spatial location by more than approximately ± 0.5 pixels; however, because resampling methods affect image interpretation, we recommend experimentation with different resampling methods to select a method that works best for specific photo sets and research applications.

3. Study area

The Umatilla River is a gravel-bed river originating in the Blue Mountains of northeastern Oregon and flowing into the Columbia River at Umatilla, OR (Fig. 1). Its channel pattern ranges from meandering to anabranching, making it laterally mobile, particularly in reaches that are naturally unconfined or that have not been channelized. Because of ongoing efforts to improve water quality and restore native fisheries, the Umatilla River has been the focus of several completed and ongoing geohydrologic investigations, including a thermal TMDL study (ODEQ, 2001) and a hydrogeomorphic classification of riverine wetlands (Adamus, 2002). These studies have identified a need to better understand the river's historical fluvial processes, how these processes have influenced contemporary fluvial landforms, and how river process-form relationships affect aquatic and wetland habitats important to native species. Channel modifications, including levees and revetments, are believed to degrade physical habitats and water quality by physically constraining the river channel and hampering lateral channel movements that may otherwise benefit habitat quality. Therefore, a detailed understanding of lateral channel movement serves a variety of river science and management needs.

4. Study design and methods

We hypothesized that georectification accuracy would improve when larger numbers of GCPs are used, when hard rather than soft GCPs are selected, and when a second-order polynomial is applied for spatial transformation. To test these hypotheses, we repeatedly georectified a 1964, 1:20,000 black-and-white aerial photo of the

Umatilla River at Pendleton, OR (ASCS, 1964), varying the hypothesized controls to evaluate their relative effects. The quality and scale of this photo was typical of historical aerial photos used for analysis of channel change. The photo was scanned at a resolution of 600 dots per inch (DPI) and saved as a JPEG file (Fig. 2). Although TIFF format is best for complete data preservation, the .JPEG file format generated much smaller file sizes and did not compromise the ability to precisely locate GCPs at normal compression ratios (Zhilin et al., 2002). The 600 DPI scan resolution was chosen because it produced pixels of about 1 m, the same resolution as the base DOQ.

During each experiment, the image was georectified to the USGS 7.5-minute Digital Orthophoto Quad (DOQ) of Pendleton, OR using the georeferencing toolbar in ESRI's ArcGIS 8.2 ArcMap software. For each experiment, we conducted trials whereby one of the three variables (number of GCPs, type of GCP, or polynomial order) was changed and the other two were held constant (Table 1). All images were rectified using cubic convolution resampling. After each trial, we used ArcMap's field calculation utility to measure the distance between 31 corresponding test-points (Fig. 3H) on the georectified photo and DOQ. The distance between the corresponding test-points on the photos and DOQ represented locational error; a zero distance between points would indicate perfect co-registration (although we never experienced this result in practice). Only hard points were used for the 31 test-points. GCPs and test-points were located on or immediately adjacent to the river's floodplain, according to availability, and within approximately 0.75 km of the river channel.

4.1. Experiment 1: Number of GCPs

Experiment 1 evaluated the degree to which the number of GCPs affected the overall georectification accuracy (Table 1). Trials with 6, 8, 10, 12, 14, 20, and 30 GCPs were conducted (Figs. 3A - G). The number and locations of GCPs used for the experiments approximately corresponds to the number and locations of GCPs that are typically available for this type of application. During these trials, only hard GCPs were used and the images were transformed using a second-order polynomial function, which yielded the best results during pilot trials. We plotted five indicators to evaluate the magnitude of and controls on georectification error: the RMSE of GCPs and the mean, median, 90th percentile cumulative error value, and maximum distances between the 31 test-points on the georectified image and DOQ. The degree of correspondence between the reported RMSE and the summary statistics for the 31 test-points provided the basis for evaluating georectification accuracy.

4.2. Experiment 2: GCP type

Experiment 2 tested how using hard- versus soft-edged GCPs affected georectification accuracy. Hard-edged GCPs were defined as landscape features with permanent, easily identified corners or edges and mainly included building corners, but also included fence corners and street and sidewalk intersections. Soft-edged GCPs were defined as features with "soft" or fuzzy edges; in this study we used only isolated tree canopies for soft-edged GCPs. Trials were conducted to compare test-point error resulting from transformations based on 10, 20, and 30 hard or soft point GCPs (Table 1). A second-order polynomial transformation was used for all the experimental trials.

Differences in median and range of test-point values from trial to trial provided the basis for evaluating the effects of test-point type on georectification accuracy.

4.3. Experiment 3: Polynomial order

Experiment 3 tested how polynomial order affected georectification accuracy. Aerial photos were georectified with 14 identical GCPs using a first-, second-, and third-order polynomial transformation function. We chose 14 GCPs based on the results of Experiment 1, which showed that RMSE did not substantially improve when more than eight GCPs were used. Therefore, we believed that 14 GCPs would be more than sufficient to limit the number of GCPs as a factor affecting comparisons of photos georectified with different polynomial functions. Differences in the median and range of test-point values from trial to trial provided the basis for evaluating the effects polynomial order on georectification accuracy.

5. Results

5.1. Number of GCPs

Figure 4 displays the results of Experiment 1. RMSE initially increased from < 1.0 to ~ 4.0 m as the number of GCPs increased from six to eight, while the independent test-point mean, median, and 90th percentile cumulative error value decreased. With eight or more GCPs, the RMSE and the mean and median test-point errors showed little change, remaining at ~ 4.0 ± 0.75 m; however, the 90th percentile cumulative frequency value of test-point errors continued to improve as GCP number increased to 30. When

30 GCPs were used the RMSE converged with the mean, median, and 90th percentile error values of test-points to 4.0 ± 1.0 m.

5.2. GCP type

Comparison of test-point distributions shows that GCP type has little effect on the median value of test-point error; however, soft-point transformations displayed a greater range of error with higher outliers (i.e., larger errors) than the hard-point transformations (Fig. 5). For soft-point transformations, the median and upper range of test-point values increased from 10 to 20 GCPs, but then decreased from 20 to 30 GCPs. In contrast, the median and upper range of test-point values from hard point transformations consistently decreased as more GCPs were added.

5.3. Polynomial order

Figure 6 shows the effect of polynomial order on test-point error. The second-order transformation yielded the best results with the lowest overall values and the smallest inner quartile range, although the median error was similar to that of the first-order transformation. The third-order transformation displayed much higher error values than either the first- or second-order transformations.

6. Discussion

6.1. Experimental results

Results of this study support the hypotheses that georectification accuracy improves when larger numbers of GCPs are concentrated within an area of interest (although this effect is not reflected by the RMSE values), when hard rather than soft GCPs are selected, and when a second-order transformation is used. While these hypotheses may be intuitive, results of this study reflect the relative sensitivity of georectification accuracy to its user-defined controls.

With respect to the number of GCPs, RMSE remained approximately the same when 8 or more GCPs were used (Fig. 4) and displayed little variability when 12 or more GCPs were used. The lack of significant improvement in the RMSE with additional GCPs is not surprising in the riverine landscape of the Pendleton area (Fig. 2). RMSE will improve with more GCPs only if the additional GCPs improve the fit of the polynomial function. In our low lying, relatively flat river landscape, adding more than 8 GCPs provided little additional information necessary to correct for average image displacement and topography across the photo. In fact, adding more GCPs can increase the RMSE, because the polynomial must be fit through a larger scatter of points, potentially creating larger residuals (e.g., note the ~ 1 m increase in RMSE moving from 10 to 12 GCPs in Fig. 4). This increase in RMSE may arise from displacement error due to greater topographic variability or from the use of additional GCPs that are imprecisely located.

As with the RMSE, the mean and median errors associated with the 31 test-points remained approximately constant when 12 or more GCPs were used (Fig. 4). In contrast, the 90th percentile value for the test-points continued to improve as more GCPs were added. This result is consistent with Unwin's (1995, p. 552) statement that RMSE does not capture spatial variations in error. This phenomenon is reflected in the 90th percentile values of test-points, which continued to improve as more GCPs were used and local topography was better represented in the transformation. Also, the 31 test-points were concentrated in one side of the photo (Fig. 4H) because of the clustering of hard points in that area; as more GCPs in this area were used, the error improved (note the locations of the GCPs in Figs. 4A - G relative to the test-point locations in Fig. 4H). Thus, the RMSE provided a reasonable estimate of the central tendencies of the error for the 31 independent test-points when 12 or more GCPs were used (Fig. 4), but was a poor indicator of the upper range of test-point error, which is driven by topographic variability in relation to GCP locations.

Like the number of GCPs, the order of the transformation polynomial exerted a clear influence on test-point error. The second-order transformation yielded the best results, probably because it was best able to capture spatial variations resulting from GCPs located both on and adjacent to the floodplain. A first-order transformation might work as well in areas where all GCPs could be located on the floodplain; but limiting GCPs to the immediate river area may not be an option with historical imagery and users are often faced with placing GCPs on terraces and hillslopes.

The third-order transformation generated poor results because of the excessive warping near the outer boundary of GCP locations, a classic problem with higher order transformations. Third and higher order transformations require GCPs far removed from the key features of interest in order to avoid boundary effects. Use of outlying points for GCPs would contradict our finding above that river studies should constrain GCPs to the area of the interest near the river. In general, it is hard to imagine a scenario where third or higher order transformations would be appropriate for studies of areas with similar topography.

In comparison to the number of GCPs and transformation order, GCP type exerted a less consistent influence on georectification accuracy. The median values of test-points derived from hard- and soft-point transformations were generally similar. However, the quartile ranges and outlying values were greater for the soft-point transformations when 20 or 30 GCPs were used. In contrast, with 10 GCPs both the median and inner quartile range were lower for the soft-point transformation, probably because the distribution of soft points was more favorable with respect to the 31 independent test-points. Results suggest that hard points should ideally serve as the basis for polynomial georectification, but that some soft points may be used without significantly changing the average transformation error or overall georectification accuracy.

These results have significant implications for understanding the positional accuracy of rivers and other landscape features on georectified aerial photos. First, GCPs on historical aerial photos are typically limited in number, so transformations are often generated from a limited number of GCPs that may or may not be representative of key areas of interest. The "average" positional accuracy in such cases may therefore be acceptable, but local errors, perhaps critical to the measurements, may be missed.

Second, users tend to remove “rogue” points to improve RMSE. Our results suggest that, contrary to intuition, this practice may actually diminish georectification accuracy in key areas where the additional GCP(s) may otherwise improve accuracy. Third, tracking the relation between RMSE and number of GCPs may be misleading because using more GCPs can result in better transformations, even when the RMSE appears to have stabilized. In general, increasing the spatial density of GCPs within an area of interest (when possible) can reduce the overall range of error for that area and potentially for the entire image.

6.2. Implications for measuring lateral channel movement in GIS

Most approaches for measuring lateral channel movement with aerial imagery fall into one of two categories. Leopold (1973) introduced the concept (since used by many authors: e.g., Gurnell et al., 1994; O'Connor et al., 2003) of measuring the change in distance of the intersection of the channel centerline (or margin) with a series of floodplain or cross-valley transects. This method generates a set of change-distance measurements, the number of which depends on stream length and transect spacing. A second approach treats the floodplain and channel as rasters or polygons that can be mapped on aerial imagery to determine migration rates over time (e.g., Graf, 1984; Urban and Rhoads, 2004). In this approach, channel locations from sequential images are overlaid to calculate changes in channel area (m^2) per unit channel length (m), and therefore a distance of channel movement ($m^2/m = m$) for each river-length unit. Both approaches rely on image overlay, making them sensitive to geospatial error on component layers.

Alongside these two approaches of channel change detection, researchers have adopted several approaches to treat geospatial error in the measurement of channel change. Two approaches are common: (i) treating error as negligible with respect to the magnitude of geomorphic change, and (ii) applying buffers within which any apparent "change" is attributed to error and therefore disregarded. Until recently, many authors have adopted the first of these approaches without evaluating the effects of error on change measurements; however, the growing emphasis on remote sensing and GIS techniques in fluvial geomorphology has begun to shed light on issues of scale and error in geomorphic analyses (e.g., Gilvear and Bryant, 2003; Marcus et al., 2004), prompting some researchers to recognize the value of error-sensitive change detection methodologies. For example, Urban and Rhoads (2004) buffered channel centerlines during measurement of lateral channel movement by applying a value of twice the RMSE of the georectified photo; however, because our results indicate that RMSE can be a poor metric of georectification accuracy, we suggest that when possible buffer size be based on an analysis of independent test-points distributed across an area of interest.

To illustrate this concept, we calculated cumulative error probabilities (using a cumulative frequency function) for georectifiction errors of the 31 test points in Experiment 1 (Fig. 7; see description of data in *Section 5.1.*). These data can be used to specify channel centerline buffers according to the "risk" of error deemed acceptable by the user. In this case, we believe that aerial photos similar to the test photo can be georectified to an accuracy of approximately ± 5 m of the base layer coordinates with approximately 30 GCPs and an approximate 10% chance of encountering greater error within the area of interest; however, the relation between the optimal number and location of GCPs will vary among photos of different scale and regions of different topography, so the results from our analysis should not be used to prescribe a minimum number of GCPs in other studies. Rather, Fig. 7 should be viewed as one approach to defining error probabilities and change detection thresholds. In general, the magnitude of errors we documented in this study is consistent with that of other channel change studies that employed aerial photos (e.g., Lewin and Hughes, 1976; Gurnell et al., 1994; Winterbottom and Gilvear, 2000; Urban and Rhoads, 2004;) and digitally georeferenced satellite imagery (Zhou and Li, 2000), suggesting the existence of error thresholds across remote sensing platforms.

Buffer size can strongly affect change detection capability. Figure 8 demonstrates the effects of buffer size on the measurement of lateral channel movement on a 2-km test reach of the Umatilla River. Pre- and post-flood aerial photos dated 1964 and 1971 were georectified with 10, 20, 30 GCPs. Wetted channel centerlines were then digitized from each of these photos. Buffers corresponding to the 90th percentile value of test-point error for 10, 20, and 30 GCPs (5-, 7.8-, and 10.8-m buffers, respectively; see Fig. 7) were applied to each side of the corresponding centerlines and a series of polygons were generated by extracting from the GIS areas between the two centerline buffers. These polygons, representing areas of lateral channel movement, were then cut into smaller polygons along 50-m cross-valley transects. Finally, the area of these transect polygons was plotted versus distance downstream.

Figure 8 demonstrates the inverse relationship between buffer size and the magnitude of measurable lateral movement. Where lateral channel movement is greatest (e.g, transects 11-14), percent differences in measured lateral movement across buffer sizes are small. In comparison, percent differences in measured channel change across buffer sizes are large where channel movement is more subtle (e.g., transects 16-20). In areas of limited channel movement, estimated rates of channel change may be more sensitive to buffer size than to actual channel movement.

While these results suggest that buffers based on RSME values can lead to erroneous channel-change measurements, the use of RMSE for buffer delineation has another other problematic tendency: RSME-based buffers tend to be used to determine whether change has taken place despite the possibilities of true channel change within the RMSE buffer and no channel change outside it. Alternatively, we suggest that change detection be viewed in the context of the probability that measured change is real and that error probability be based on analyses of independent test points (Fig. 7). Termed the "empirical probability approach," this approach avoids the assumption that all channel movements within the buffer size are not real and that all movements outside the buffer are real. Researchers using the empirical probability approach can specify the probability of measuring actual change at their discretion and proceed with channel measurements knowing the likelihood that georectification error is affecting their measurements. This approach may be particularly useful in areas where channels are relatively confined (e.g., transects 16-21) and measured changes are often less than the RSME. Also, this approach is consistent with the probability-based approaches for reporting change advocated by Graf (1984, 2001) and implemented in GIS by Graf (2000) and Winterbottom and Gilvear (2000).

Despite its shortfalls as an error indicator, RMSE is still quite useful in reconstructing channel change with aerial photos. In particular, because RSME is readily calculated for each individual photo as the image is georectified, it provides a basis for evaluating interphoto variability in georectification accuracy and for varying the buffer size from image to image if necessary. In the case of the Umatilla River, we believe the error probability functions we developed for the Pendleton photo (Fig. 7) can be applied across many stream segments in that basin because the RMSE on other photos is similar, the topography from photo to photo is reasonably constant, and georectification methods have followed a consistent protocol; however, in basins (or portions of basins) with variable topography or inconsistent photo resolution and quality, development of probability functions for multiple photos would likely be necessary. In these cases, RMSE is a useful tool to screen photos that may require more detailed error analyses. We recognize the time costs associated with developing multiple probability functions and corresponding buffers must be weighed against the benefits of their application. In many fluvial hazard and river restoration studies, we believe that this cost-benefit would be justified by the improvements in information on channel movement rates and processes allowed by the empirical probability approach.

7. Conclusions

Results of this study show that the RMSE and the central tendency of locational error for 31 test-points were relatively insensitive to GCP number when eight or more GCPs were used. The 90th percentile cumulative error values of test-points, however, consistently decreased (i.e., improved) as more GCPs were used (Fig. 4), indicating that the upper range of georectifcation error can be significantly reduced by using more GCPs. We attribute the reduction in test-point error to a higher spatial density of GCPs within the area of interest and a better fit to local topography. Using more GCPs improves georectification accuracy only when additional points are positioned to better incorporate the topography of the area of interest.

A second-order polynomial transformation generated the best fit (Fig. 6), providing sufficient flexibility to correct for the range of topographic variation typical of the terrace-floodplain environment of this study. A first-order polynomial transformation generated a similar median error, but had higher outliers from poor transformation in areas of higher elevation near the river. First-order transformations may be appropriate for channel change studies if GCPs could be limited to the floodplain, but this may be impractical with historic photos of rural or forested settings. A third-order polynomial transformation generated poor results because of image warping at the outer GCP locations. The need to avoid edge effects by including GCPs far from the river suggests that third or higher order polynomial transformations are probably inappropriate for most river change studies.

The use of hard or soft GCP points did not dramatically affect median rectification errors, although the hard points generated fewer high-error values (Fig. 5). The similarity of results across GCP types indicates they can be intermixed without introducing spurious amounts of error.

Results clearly demonstrate that while RMSE may be an acceptable proxy of average error, it is generally a poor indicator of overall georectifcation accuracy across a photo. Therefore, using RMSE for error estimates and determination of buffer size may lead to over- or under-estimating the amount of true change, depending on the correspondence of the RMSE and the upper range of true error on the photo in an area of interest. We recommend that lateral movement measurements be based on empirical probability functions (e.g., Fig. 7), which are generated from a set of test-point errors independent of the GCPs. According to this study of a 1:20,000 image transformed with 30 GCPs and a second-order polynomial, a buffer distance of 5 m on each side of the channel centerline would remove ~ 90% of georectification error that may otherwise affect measurements of lateral channel movement. A 5-m value is equivalent to 1.25 times the RMSE for the 30 GCPs. Buffers of similar magnitude are likely to be necessary for error-sensitive photo-based studies of lateral channel movement. Researchers using aerial photos to measure channel change are encouraged to conduct similar error analyses in order to assess the magnitude of georectification error relative to the magnitude of channel migration. Accordingly, error probability should be explicitly stated so that photo-based studies of channel change may be better understood in the context geospatial error.

8. Bridge Section I

Chapter II addressed the effects of geospatial error in the measurement of lateral channel movement from vector data digitized from georectified aerial photographs and concluded that a 5-m buffer applied to each channel centerline would effectively mitigate the effects of such error. Chapter III applies the error-sensitive lateral movement measurement method of Chapter II to: (1) estimate the magnitude of lateral channel movement during and between two sequential flood periods on the Umatilla River, and (2) investigate the styles, frequency, and controls of lateral movement processes, and (3) explore linkages between channel processes and channel-landform changes.

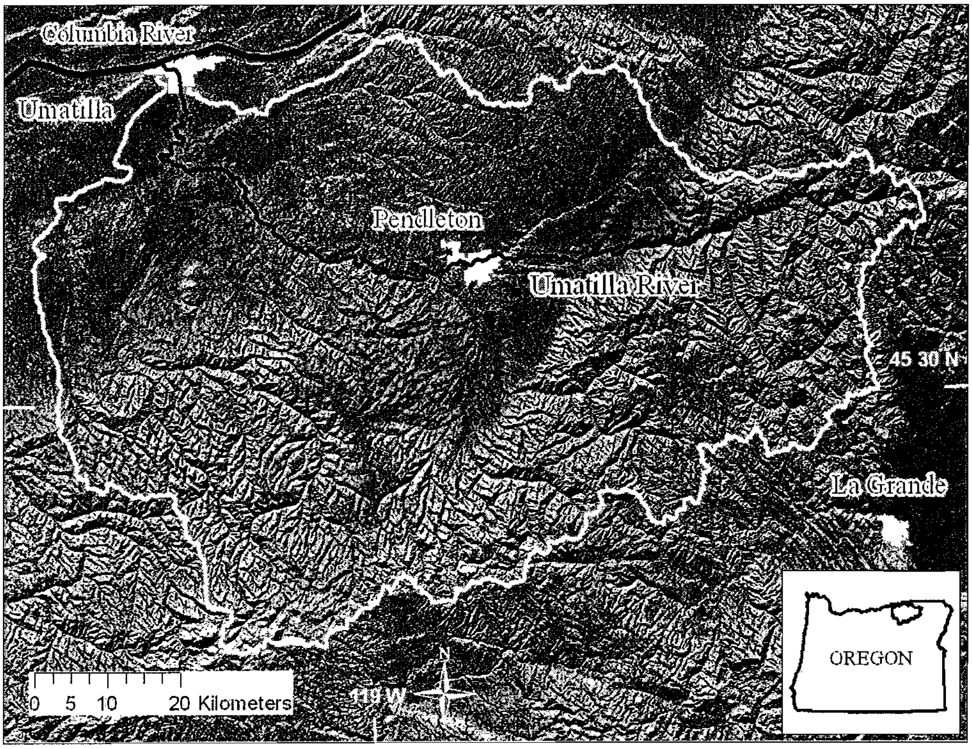


Figure 1. Location map of the Umatilla River watershed

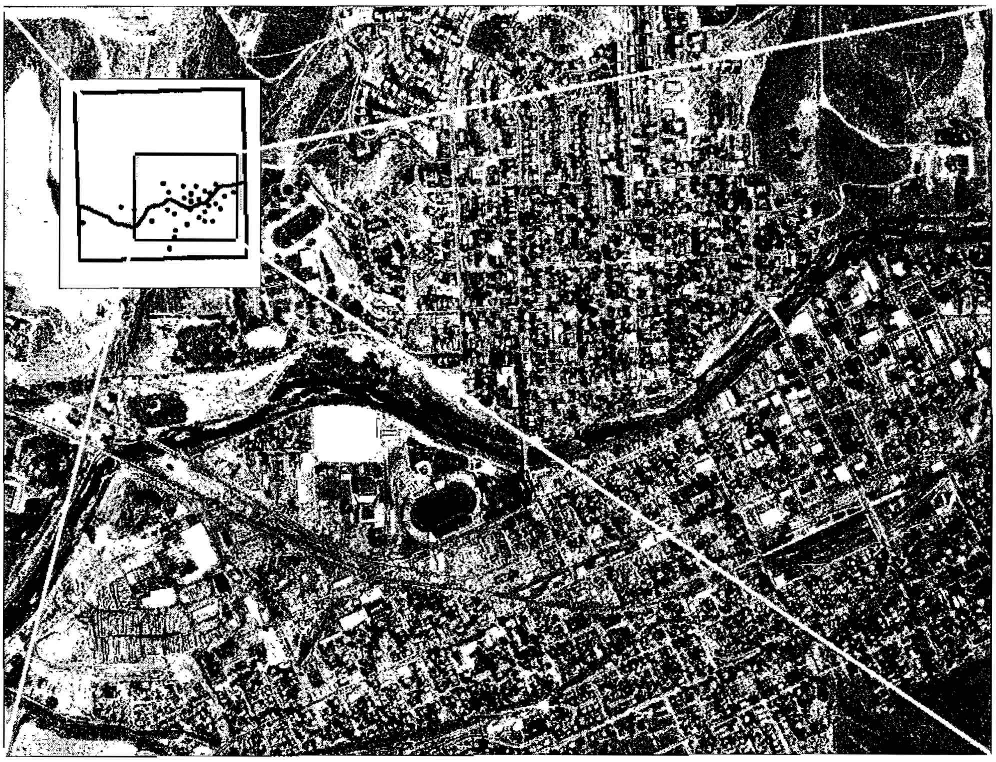


Figure 2. A portion of the aerial photo used for analysis. Photo was shot in 1964 by the Agricultural Stabilization and Conservation Service (ASCS) at a scale of 1:20,000. Location of the photo portion relative to entire photo shown by outline at upper left. The Umatilla River flows from right to left in this and subsequent images

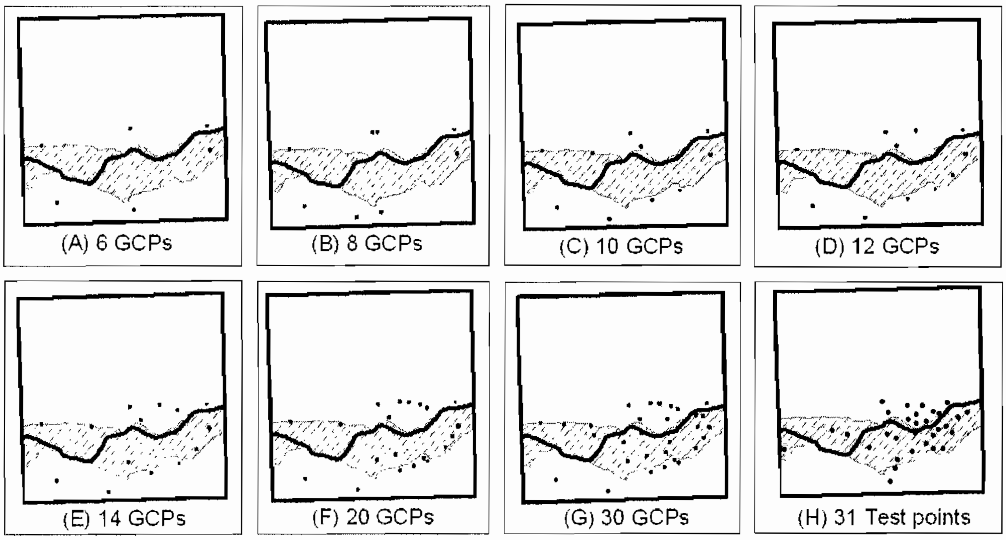


Figure 3. Spatial distribution of GCPs (A-G) and 31 independent test points (H) with respect to the Umatilla River channel (line) and floodplain (hatched). Boxes show extent of georectified aerial photo

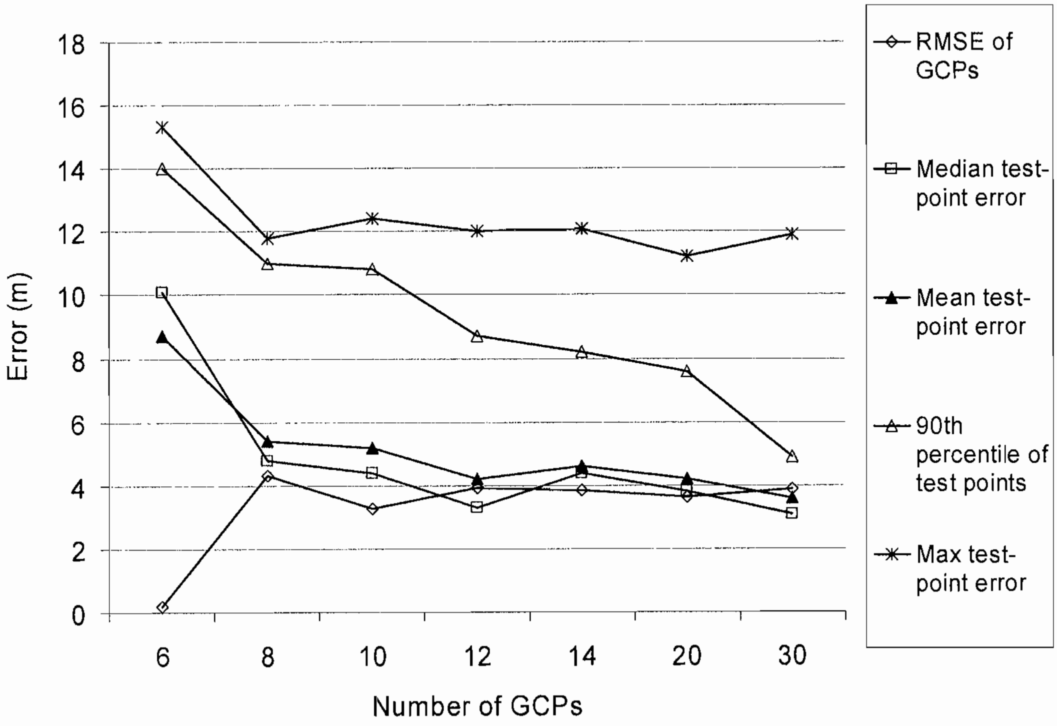


Figure 4. Number of GCPs versus error using different metrics of test-point error

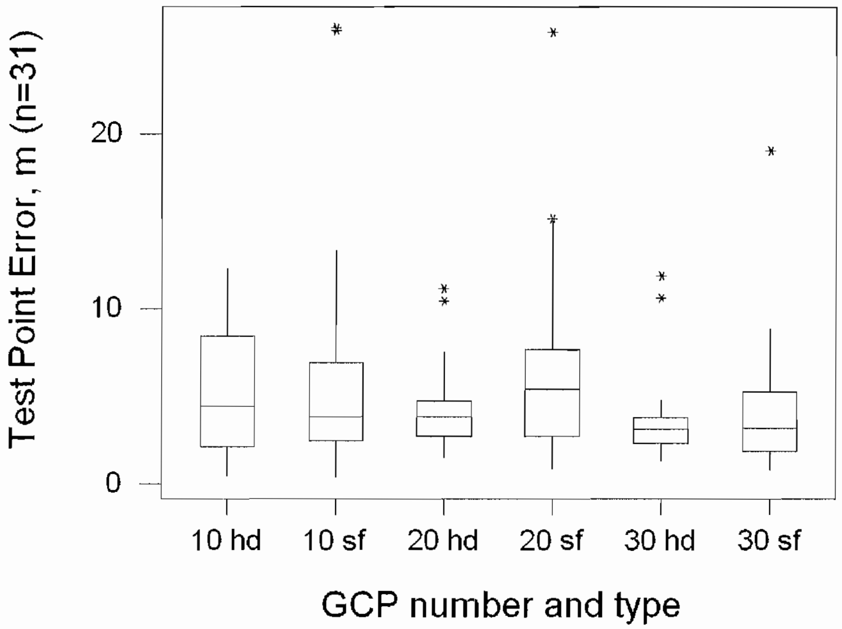


Figure 5. Boxplot shows GCP type versus distribution of test-point error, stratified by 10, 20, and 30 GCPs. GCP types include hard (hd) and soft (sf) points. Central tendency is the median, and boxes represent inner quartile ranges (25th – 75th percentile) of test points. Vertical lines indicate 1.5 times the inner quartile range or the median plus the extreme value, depending on which value is less. Asterisks indicate individual extreme values

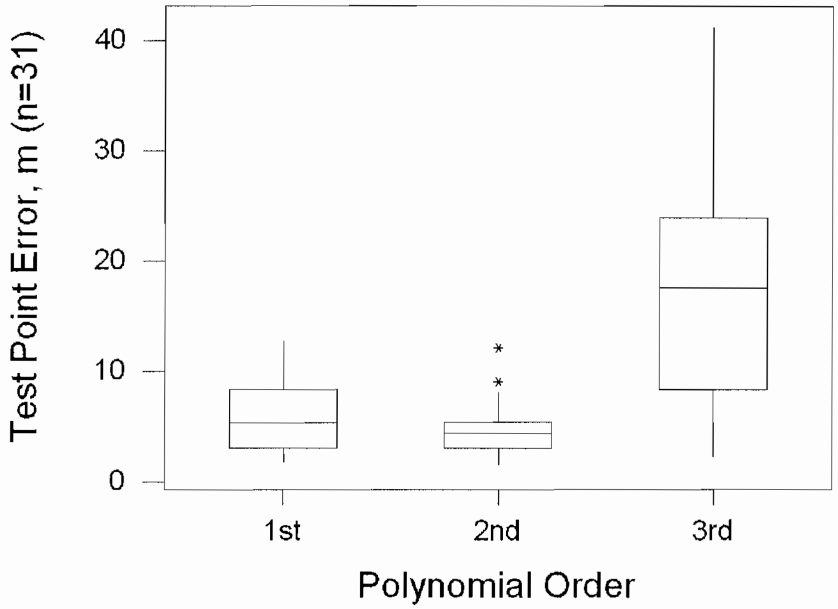


Figure 6. Boxplot shows polynomial order versus error distribution for the 31 test points. Interpretation of boxplot bars and lines is as in Figure 5

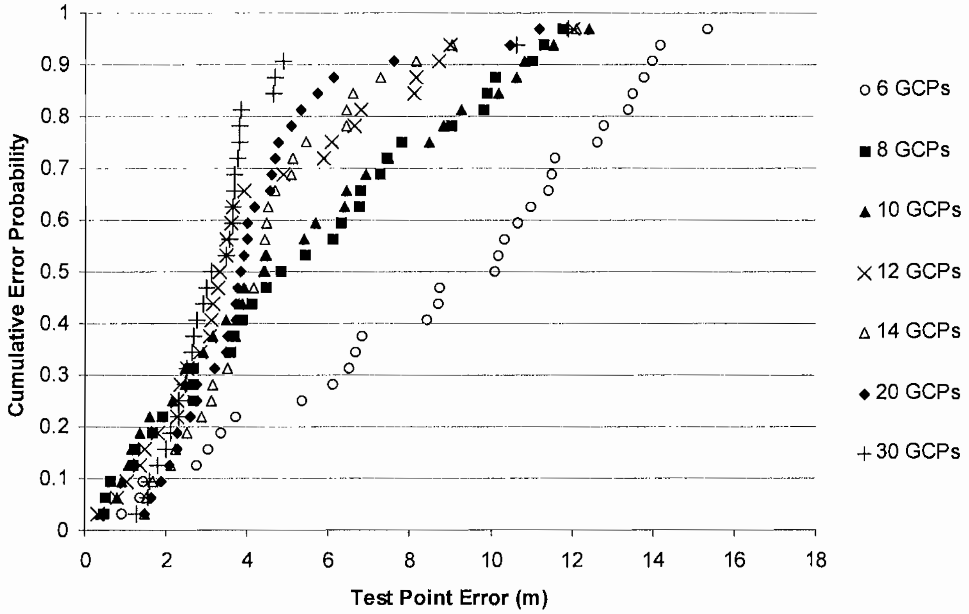


Figure 7. Test point error versus cumulative error probability for trials with 6 to 30 GCPs. Cumulative frequency percentile refers to the probability that georectification error (in meters) of a given value or smaller will occur

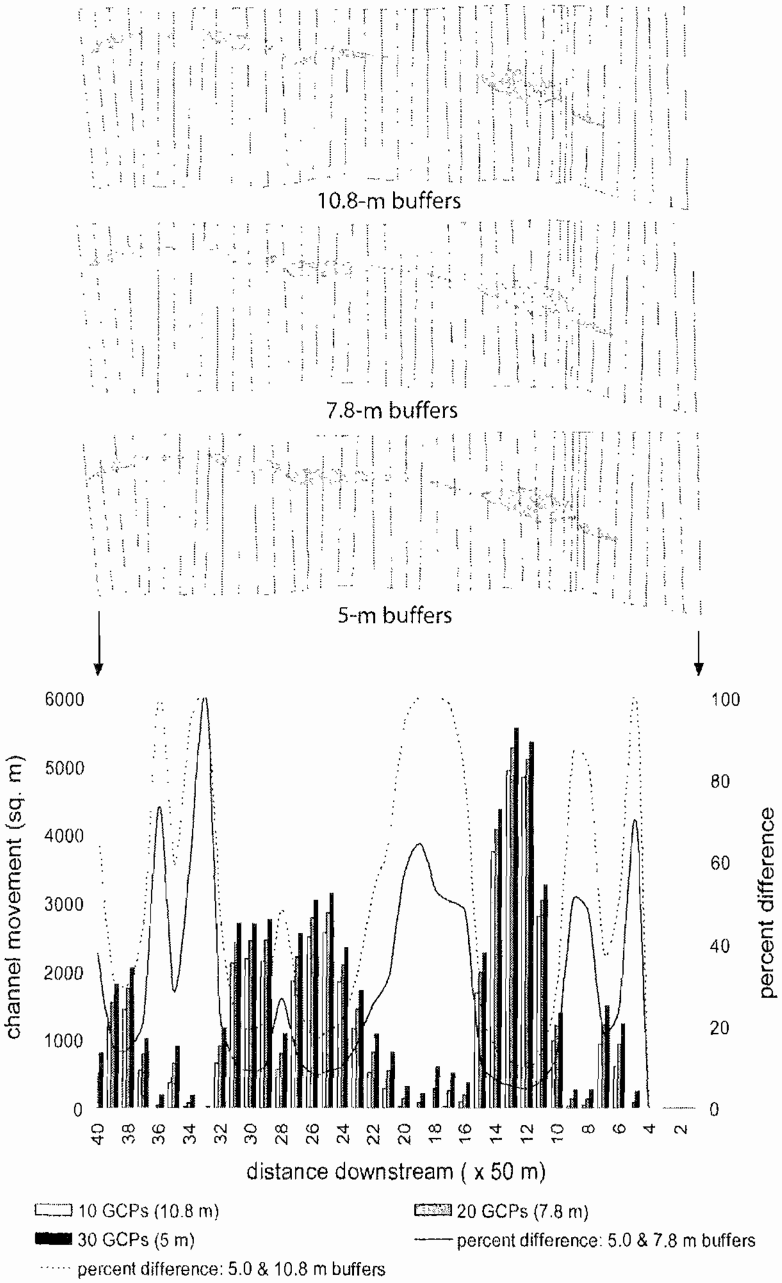


Figure 8. (Above) Cross-valley transects and lateral channel movement polygons for three channel centerline buffers (5-, 7.8-, and 10.8-m) along a 2-km test reach of the Umatilla River. Transects were generated approximately every 50 m along the valley floor centerline. (Below) Bar graph of lateral channel movement versus distance downstream for the three buffer scenarios. Superimposed are line graphs showing percent difference in channel movement between the 5- and 7.8-m buffers and 5- and 10.8-m buffers. Figures are spatially aligned

Table 1. Experiments for evaluating locational error on georectified aerial photos

Experiment	Factor addressed	Treatment	Control	Results
1	Number of GCPs	Georectified same image with 6, 8, 10, 12, 14, 20, and 30 GCPs; measured positional error of 31 independent test points on image and DOQ	Used second-order transformation function; used hard GCPs only	Figure 4
2	GCP type	Georectified same image with 10, 20, and 30 soft and hard GCPs; measured positional error of 31 independent test points on image and DOQ	Used second-order transformation function on same number of GCPs	Figure 5
3	Polynomial order	Georectified image with 14 GCPs using first-, second-, and third-order polynomial transformation functions; measured positional error between 31 indepenedent test points	Used identical GCPs for each transformation	Figure 6

CHAPTER III

PLANFORM CHANNEL CHANGE OF THE UPPER UMATILLA RIVER DURING AND BETWEEN FLOOD PERIODS

1. Introduction

Floods are notorious geomorphic agents, but they greatly vary in their ability to alter channel-floodplain systems. Floods are more effective in generating large channel adjustments in arid or semi-arid climates (Wolman and Gerson, 1978; Baker 1977) and in small, steep basins with flashy hydrographs, high bedload, low bank cohesion, and deep, narrow valley cross-sections (Kochel 1988). These characteristics promote a combination of relatively high sensitivity and high unit stream power, which can drive high-magnitude channel adjustments during floods. Channel widening, increased lateral movement, and loss of sinuosity are common planform channel adjustments during floods (Bridge, 1993; Knighton, 1998; Wohl, 2000); however, the occurrence and magnitude of these effects can vary within rivers during floods, and several different processes are often at play. Building on the work of Nanson and Beach (1977) and O'Connor et al. (2003), Beechie et al., 2006 recognized migration, avulsion, meander cutoffs, and "channel switching" as the dominant processes responsible for lateral movement, bank erosion, and sediment deposition in mountain river systems of the Pacific Northwestern U.S. Whereas the importance of these processes in creating heterogeneity in channel landforms has been increasingly recognized by river ecologists

(Ward et al., 2001, 2002), questions related to controls on the occurrence, frequency, and magnitude of these processes, as well as their effects on channel landforms, remain largely unresolved. These questions represent an ongoing challenge for geomorphologists working in multi-channel systems, where lateral movement and its impacts on channel landforms are notoriously complex.

The basic thesis explored in this paper is that floods play a significant role in the evolution of laterally active, multi-channel, gravel-bed rivers. This role is two-fold: (1) bed mobilization and deposition sustained during floods promotes large-scale lateral thalweg migration and bar accretion, which provide areas of fresh sediment that are necessary for the reproduction of native riparian trees such as cottonwoods and willows, and therefore the in-channel formation of island and floodplain landforms (Knighton, 1998), and (2) flood-driven avulsions and cutoffs cause the occupation, abandonment, and reoccupation of secondary channels, which operate to excise vegetated islands from the floodplain and help to maintain the multi-channel pattern (Nanson and Knighton, 1996). A better understanding of the relative occurrence, variability, and controls on lateral movement processes in wandering and anabranching mountain river systems, the influence of floods on these processes, and the interactions of these processes with channel landforms is currently needed for improved river management and restoration.

The Umatilla River is a semi-arid, gravel-bed channel system with laterally active multi-channel pattern. Examination of pre- and post-flood aerial photos of the Umatilla River revealed large lateral movements, channel widening, widespread scour of channel and floodplain surfaces, removal of channel vegetation, and complex bar construction in response to floods in 1964-5 and 1975. Aerial photos between these events showed channel narrowing and revegetation of areas disturbed by the first flood. This study draws upon streamflow records and historical aerial photos to compare and contrast reach-scale channel changes of the Umatilla River during periods with and without major floods. In so doing this study aims to identify flood-driven geomorphic processes and landform changes, characterize the variability and controls of these processes and landform changes, explore interactions between channel processes and landform changes that define the channel pattern, describe how flood processes and impacts differ from those of the post-flood recovery period, and conceptualize the role of floods in the overall evolution of the channel-floodplain system.

2. Study Area

The Umatilla River originates in the Blue Mountains of northeastern Oregon and flows west to the Columbia River (Figure 1). This study focuses on a segment of the upper Umatilla River between the confluences of Meacham and Wildhorse Creeks. This segment flows through a bedrock canyon that drains approximately 1,650 km^2 at its downstream end near the City of Pendleton. The geology of the watershed is dominated by the Columbia River Basalts, which originated from Miocene-age lava flows and form the uplands and canyons of the Umatilla River watershed. Quaternary alluvium forms the valley floor, averages 4 meters in thickness (Gonthier and Harris, 1977) and varies in width from approximately 500 to 2000 meters. The channel bed is composed of basalt gravel ($D50 \sim 6$ cm, $D84 \sim 15$ cm) that fines downstream. The river has a mixed multi-channel pattern typical of the wandering pattern described by Church

(1983) for the Bella Coola River in British Columbia. This pattern is similar to the Type 5 (gravel-dominated, laterally active) anabranching pattern described by Nanson and Knighton (1996) and the island-braided pattern described by Beechie et al. (2006). Some reaches primarily flow in a single meandering channel and others flow in braided or anabranching channels that are separated by bars or vegetated islands and share full (connected at the upstream and downstream ends) or partial connection (connected at the upstream or downstream end) to the main channel at low flow. Chutes and abandoned channels typically operate as secondary channels during high stages. Floodplains and islands have cottonwood-willow forests on their upper surfaces, and shrubby or herbaceous vegetation on their lower surfaces, including some bars. Land use includes forestry and dryland farming on the uplands, and ranching, irrigated farming, and residential development on the terraces and floodplains.

Most floods in northeastern Oregon occur from November through April, with large floods occurring as rain-on-snow events in mountain areas (Harris and Hubbard, 1983). Floods in December 1964 and January 1965 were among the largest recorded peak flows at the time of their occurrence, producing widespread geomorphic changes to channel-floodplain systems and damaging human infrastructure (Waananen et al., 1971) (Tables 1a-b). Developing a better understanding of flood disturbance, its influence on the evolution of mountain river systems, and its role in shaping riverine habitats of the Interior Pacific Northwest is a major research priority in regional river management and restoration (NRC, 1996; Beschta, 1997). The 1964-65 and 1975 floods on the Umatilla River, coupled with the availability of aerial photos and streamflow records during and between flood periods, provide an excellent opportunity to examine the nature and variability of flood-driven geomorphic processes and landform changes in a mixed multi-channel river system.

3. Flood Processes and Landform Changes

Floods can magnify in-channel sediment transport (Helley and LaMarche, 1973; Church, 1988; Kochel, 1988; Eaton and Lapointe, 2001), aggradation (Erskine and Melville, 1983; Erskine, 1993; Bull, 1988), degradation (Leopold et al., 1964; Bull, 1988), and lateral movement (Scott and Gravely, 1968; Hickin and Nanson, 1984; Miller et al., 1999). Floods also generate overbank flows that erode, transport, and deposit sediment and wood on the floodplain (Miller, 1990; Gomez et al., 1997; Magilligan et al., 1998; Meyer, 2001). Increased lateral movement, channel widening, and loss of sinuosity are common channel adjustments during floods (Knighton, 1998; Wohl, 2000; Schumm, 2005). These processes can cause substantial changes in the positions, dimensions, and patterns of river channels.

Lateral movement during floods can occur gradually as in migration or suddenly as in cutoffs and avulsions (Bridge, 1993; Knighton, 1998; Wohl, 2000). Lateral migration and cutoffs are primarily associated with channel meanders, which can migrate through a variety of mechanisms, including downstream translation, lateral extension, rotation, or a combination of these processes (Hooke, 1997). Lateral migration in meandering channels occurs in conjunction with bank erosion on the outer bends and bar accretion on the inner bends of meanders, and is often more rapid during floods. When rates of bank erosion and bar accretion are in phase, the channel may migrate, but its dimensions and pattern remain largely unchanged; however during floods, sediment transport and deposition rates, which drive bar accretion, may outpace bank erosion rates, thereby expanding the zone of erosion and deposition (both within and outside of the channel banks) and increasing the probability of cutoffs or braiding. Classic examples of channel widening in association with flood-driven bar accretion include the Cimarron River, Kansas (Schumm and Lichty, 1963), the Gila River, Arizona (Burkham,1972), and the Eel River, California (Sloan et al., 2001). Each of these rivers widened up to several times their pre-flood widths in response to high-magnitude 20th century floods and remained wider than their pre-flood dimensions for several decades.

Cutoffs, by definition, shorten and straighten river meanders. Neck cutoffs occur at the base of meanders and are common in highly sinuous channels, whereas chute cutoffs occur across the core of the meander, nearer to the apex (Hooke, 1998). The occurrence of cutoffs has been interpreted in various ways. Cutoffs were originally thought to be transient features that reflect channel instability, but more recently they have been linked to internally controlled, self-organized behavior (Hooke, 2007). In the latter view, cutoffs are thought to represent systematic negative feedback that operates to curtail unstable channel configurations. Floods are necessary to initiate incision of the cutoff channel, although cutoffs may occur in the absence of floods once the cutoff channel is sufficiently deep to allow passage of flow during high-flow pulses.

Avulsion is primarily associated with braided, wandering, or anabranching channels. It occurs as an abrupt movement of the channel from one position to another.

Avulsions differ from cutoffs in that they involve periodic movements around bars or islands that are large relative to the size of the channel, and do not necessarily involve obvious straightening of the channel or individual meanders. Like channel braiding, avulsion is thought to be driven by channel aggradation, which increases flow resistance, raises the elevation of the water surface, and lowers channel slope (Ashemore, 1991; Bridge, 1993; Leddy et al., 1993). Beyond a threshold, the channel moves abruptly into a position of lower elevation and higher slope, thereby gaining stream power and competence for sediment transport (Mackey and Bridge, 1995). Reoccupation and lateral incision of formerly abandoned channels is therefore common during avulsion, and these processes drive complex interactions with bars, islands, and floodplains (Dykaar and Wigington, 2000; O'Connor et al., 2003). Avulsion is a fundamental process of laterally active braided or anabranching rivers, which are inherently depositional and form wide floodplains (Nanson and Knighton, 1996). Floods often increase the likelihood of avulsion because they can deposit large volumes of sediment, which drives the aggradation that triggers avulsion. In the absence of floods, channels that divide islands from floodplains can fill with sediment and become vegetated, causing lapse of the island back to the floodplain and a shift to a single channel pattern (Burkham,1972). This process often occurs in conjunction with channel narrowing, floodplain accretion, and the growth of vegetation on bars and other flood-disturbed surfaces within the active channel (Williams, 1978; Friedman et al., 1996; Friedman and Lee, 2001). Anabranching patterns are maintained when the rate of island generation is equal to or greater than the rate of island loss (Taylor, 1999; Burge and Lapointe, 2005). The degree to which floods influence these rates is unknown.

While floods may increase lateral movement leading to channel widening, cutoffs, and avulsions, flood effects are variable over space and time, and channel change during floods of similar magnitude and frequency often differs within and across rivers of similar climate, geology, and history (Newson, 1980; Patton, 1988; Magilligan, 1992; Costa and O'Connor, 1995; Wohl et al., 2001; Fuller, 2007). Floods are generally more effective in generating large channel adjustments in arid or semi-arid climates (Langbein and Schumm, 1958; Wolman and Gerson, 1960; Baker 1977) and in small basins with relatively high energy slopes, flashy hydrographs, high ratios of bedload to suspended load, low bank cohesion, and deep, narrow valleys (Kochel 1988). In a comparison of flood responses across three gravel-bed mountain rivers in New Zealand, Fuller (2007) reported relatively high rates of bank erosion in the Kitea River, which was confined between terraces, in relation to two other rivers that had wider floodplains. High-magnitude bank erosion in the Kitea River occurred in conjunction with a 600% increase in bar area, whereas bar areas increased only 65% and 167% in the rivers with wider floodplains (Fuller, 2007). The author explained these differences in terms of concentration of stream power in the confined setting versus dissipation of stream power in wide floodplains, and he related high magnitudes of channel change to high levels of sensitivity (Brundsen and Thornes, 1979) and close proximity to thresholds (Miller, 1990; Magilligan, 1992; Werrity, 1997) in confined valley settings. Similar differences in channel response to floods in relation to valley morphology have been reported in other studies (Newson, 1980; Patton, 1988). Other factors such as flood duration (Huckleberry, 1994) and sequence (Wolman and Gerson, 1978; Gupta and Fox, 1974; Kochel, 1980; Cinderelli and Wohl, 1997) have also been invoked to explain high-magnitude channel changes, or lack thereof, during floods. These factors often interact during floods in unpredictable ways (Brewer and Lewin, 1998), resulting in deterministic complexity. Research addressing the controls of channel processes and their influences on channel landform changes continues to be important in the development of channel evolution theory and its application to river management and restoration. This research is especially needed in multi-channel river systems that have moderate-to-high, but poorly understood, channel-floodplain dynamism Beechie et al. (2006).

4. Research Design and Methods

This study uses streamflow records and historical aerial photos to compare and contrast reach-scale channel changes of the Umatilla River during periods with and without floods. This study addresses the following questions:

(1) What processes and landform changes characterize floods?

(2) How do these processes vary over space and time, and what are their controls?

(3) How do flood processes and impacts differ from those of the post-flood recovery period?

(4) How do channel processes and landforms interact to define the channel pattern and how do floods affect these interactions?

(5) How do floods affect the overall evolution of the channel-floodplain system?

The following hypotheses are explored in relation to the research questions:

- Large channel movements, channel widening, and loss of sinuosity occurred during the flood periods, whereas channel narrowing, small lateral movements, and increased sinuosity occurred in the interflood period.
- Because of their associations with sinuosity loss, migratory straightening, cutoffs, and avulsions were more frequent during flood periods. Because of the their association with static sinuosity or sinuosity gain, migratory translation and extension of meanders were more frequent during the interflood period
- Increases in bars and scoured areas, and a decrease in vegetated areas, occurred during flood periods, whereas a decrease in bars and scoured areas and an increase in vegetated area occurred during the interflood period
- Lateral movement, channel widening, and scour and bar changes are interrelated such that all three variables were greater in wide floodplain settings where the channel is less confined.

These hypotheses were explored by digitizing a series of river-channel maps from georectified aerial photographs (Table 2). The active channel was defined as the area of flowing channels plus adjacent areas of recent fluvial erosion or deposition of sediment plus the area of enclosed vegetated surfaces. Streamflow records were used to define two flood periods (FP1, FP2) and one interflood period (IFP) (Figure 2). Recurrence intervals of the floods of FP1 and FP2 ranged from 17 to 37 years. The 1965 flood had a larger recurrence interval at the downstream gage at Pendleton (35 years at Pendleton, 19 years at Gibbon), whereas the 1975 flood had a larger recurrence interval at the upstream gage at Gibbon (17 years at Pendleton, 37 years at Gibbon) (Tables 1a-b). FP1 includes two flood events, whereas FP2 includes one event (Figure 3). The IFP also includes a flood event with a recurrence interval of approximately 4-6 years. This event is not considered a major flood and can be differentiated from the major floods of FP1 and FP2. Aerial photos were scanned at a resolution of 800 dots per inch and georectified to digital orthophoto quadrangles (DOQs; USGS, 1994) in a GIS using a second-order polynomial transformation. Pixel size was approximately one square meter. Root-mean-square-error (RMSE) for georectification was three meters or less. Empirical testing of georectification accuracy demonstrated a spatial accuracy of approximately five meters or less for 90% of independent test points (Hughes et al., 2006).

A four-unit classification system of geomorphic surfaces within the active channel (Figure 4) was developed and applied to the 37-km segment of the Umatilla River between the Meacham and Wildhorse Creek confluences (Figure 5). This segment was divided into nine reaches of approximately 3-4 km in length. Reaches were delineated at tributary confluences, points of rapid change in floodplain width, or points of channelization (Figures 5 and 6). This active-channel classification system included: (1) low flow channels, (2) bars, (3) scoured areas, with and without flowing channels, and (4) vegetated areas. Low-flow channels included the primary channel and secondary channels that had a wetted width of at least half the width of the primary channel at the point of confluence. Channels that were less than half the width of the primary channel were classified as high-flow channels and were included in the digitizing of bars, scoured areas, or vegetated surfaces. Bar polygons were defined as barren areas within the channel having a typical barform, such as point, diagonal, or mid-channel (Church and Jones, 1982). Both simple and compound bars were digitized as single polygons. Scoured areas were defined as barren areas that were channel-like or amorphous in shape, and lacked a conventional bar form and position. These surfaces were interpreted as erosional landforms. Vegetated surfaces were defined as land areas that were completely surrounded by (low-flow or high-flow) channels, and that had at least 50% cover by a combination of grassy, shrubby or woody vegetation. Surfaces were digitized at a scale of approximately 1:1,000 and had a minimum area of 25 square meters.

Lateral movement, changes in the reach-average width and sinuosity, and changes in scoured areas, bars, and vegetated areas were measured in the nine reaches. The floodplain boundary was mapped based on floodplain soils (Johnson and Mankinson, 1988) and topography. Lateral channel movement was measured by digitizing channel axis centerlines from each of the photo years. Where multiple channels existed, the primary channel was identified (based on width) and the centerline of that channel was digitized. Centerlines were buffered to account for geospatial error, then overlayed, and the area of the polygon created between the outer channel buffers was extracted. Buffer magnitude was five meters on each side of the centerline, which accounted for geospatial error on over 90% of the points tested for georectification accuracy (Hughes et al., 2006). Lateral movement measured by this method represents the maximum probable displacement of two channel centerlines, thus the method can overestimate true lateral movement, but it provides a reasonable proxy for purposes of this analysis. Changes in reach-average channel width were measured by calculating the total area of the active channel for each reach (inclusive of all channel units), dividing this area by the length of the floodplain axis for the reach, and then subtracting the subsequent from the previous reach-average width for each of the aerial photo years.

Channel and floodplain centerlines were digitized by visual interpolation of the longitudinal axis midway between the margins of the primary low-flow channel and the floodplain. Lateral channel movements were classified as migrations, cutoffs, or avulsions. Migration was subdivided into lateral extension (movement with increasing in sinuosity and meander amplitude), downstream translation (channel movement with little or no change in sinuosity, meander frequency and amplitude), and migratory straightening (channel movement with a decrease in sinuosity, loss of meander frequency and amplitude) (Figures 7a-e). Although several clear instances of cutoffs were identified, many others involved only partial preservation of the vegetated area between channel positions and were therefore not consistently distinguishable from migratory straightening. These two processes were, therefore, grouped together for channel-change analysis. Avulsions were distinguished from cutoffs by their larger scale (usually involving more than a single meander) and a substantial preservation of the landform between the channel positions.

The 1971 aerial photos were collected at river flows of 282-775 ft^3/s. The remaining photos were collected at lower flows of 52-74 ft^3/s (Table 2). To minimize error associated with comparing changes of geomorphic surfaces at different flow levels, a correction factor was calculated and applied to the area of bars in 1971. This correction factor was calculated as the difference in area digitized as wet channel in 1971 and the mean area of wet channels in 1964, 1974, and 1977 by the following equation:

$$Ac = TWA_{1971} - MWA_{1964,\,1974,\,1977}$$

where:

Ac = Area corrected

TWA_{1971} = Total wet area in 1971

$MWA_{1964,\,1974,\,1977}$ = Mean of wet area in 1964, 1974, and 1977

Reasoning that the Ac would have been digitized as bar if the flow in 1971 had been comparable to the other photo years, it was then added to the 1971 bar area to determine the corrected total bar area:

$$TBA_{1971} = DBA_{1971} + Ac$$

where:

TBA_{1971} = Total Bar Area

DBA_{1971} = Digitized Bar Area

Ac = Area corrected

Table 3 shows the corrected and uncorrected areas. The 1971 flow was less than half the bankfull flow (~1550 ft3/s at 1.5-yr peak flow recurrence). Correcting only the bars is supported by the assumption that at such an intermediate flow level bars would be inundated, but scoured vegetated areas would be exposed. Comparison of the proportions of each of the channel units (wet channels, bars, scoured and vegetated areas) in 1971 to that of the average of the remaining photo years indicated that bars were indeed sensitive to the difference in flow levels (+/- 8.8% difference in area across years), whereas scoured and vegetated areas were less sensitive to this difference (+/- 1.3% and 3.4% difference in areas, respectively). The differences in these sensitivities are likely within the total error associated with digitizing and/or true differences in the geometry or landform assemblage of the channel.

5. Results

The trajectories and magnitudes of lateral movement, changes in (active) channel width and sinuosity, and changes in channel units across time periods were evaluated using a series of downstream plots of reach-averaged change values. Lateral movement processes were evaluated by calculating and plotting the number of occurrences within channel reaches. Channel maps of Reach 3 were used to illustrate commonly occurring processes.

5.1. Trajectories and Magnitudes of Interperiod Channel Changes

The trajectories and magnitudes of changes in reach-average channel width, lateral movement, and sinuosity are shown in Figures 8a-c. The reach-average channel width increased during both flood periods (FP1, FP2) and decreased during the interflood period (IFP) in eight of the nine study reaches. In six of these eight reaches, the width increased more during FP1 than FP2. Lateral channel movement was greater during both flood periods than during the IFP in seven of the nine reaches and was also greater in FP1 than in FP2. Sinuosity decreased in seven of nine reaches during FP1, then increased in eight of nine reaches during the IFP. During FP2 sinuosity changed was mixed; five reaches increased and four reaches decreased in sinuosity. The magnitude of sinuosity change during FP1 was high relative to the other two periods.

These results generally support the hypothesis that floods widen, straighten, and shorten the channel in association with increased lateral movement, although some reaches did not follow this pattern. In Reach 1 lateral movement was greater during the IFP than during either of the two flood periods. In Reach 7 lateral movement was exceptionally high during FP1, but lower during FP2 than during the IFP. Reach 7 also experienced continued narrowing during FP2, contrary to all other reaches. Sinuosity increased during FP1 in Reaches 2 and 6, decreased during the IFP in Reaches 6 and 7, and increased during FP2 in Reaches 2, 3, 4, 6, and 8. Overall Reaches 6 and 7 were most anomalous with respect to hypothesized channel changes. In these reaches floodplain width widens rapidly downstream and several levees locally inhibit bank erosion and constrain floodwaters.

Excluding Reach 8, which was channelized and artificially confined before the study period, the channel widened 1.3 to 2.9 times its pre-flood width during FP1, with an average factor of 1.6. At the time of FP2, the reaches remained 1.2 to 1.95 times their pre-FP1 width, with an average factor of 1.3. Therefore, the channel remained substantially adjusted to, and was still recovering from, the floods of FP1 at the time of FP2. The rate of post-flood channel narrowing during the IFP is approximately 10% of the pre-FP1 active width, or about 7 meters, per year. The widened channel in FP2 may have lowered channel resistance and unit stream power, thereby reducing lateral adjustment and sinuosity changes during FP2.

5.2. Lateral Movement Processes

Episodes of migratory straightening (with and without cutoffs) and avulsion occurred nearly twice as frequently as episodes of extension and translation during FP1 (Table 4). Migratory straightening occurred nearly twice as frequently as avulsions during FP1. Downstream translation of the channel was more common than lateral extension during FP1. During the IFP episodes of extension and translation occurred more than twice as frequently as the combined episodes of channel straightening, cutoffs, and avulsion. Lateral extension of the channel occurred nearly twice as frequently as downstream translation, while channel straightening and cutoffs occurred more frequently than avulsions, during the IFP. During FP2, episodes of channel straightening, cutoffs, and avulsion again occurred more frequently than episodes of extension and translation, although these process groups were more balanced during FP2 than FP1. Unlike FP1, lateral extension of the channel occurred more frequently than downstream translation, whereas, like FP1, channel straightening and cutoffs occurred more frequently than avulsions during FP2. These results support the hypothesis that episodes of migratory straightening, cutoffs and avulsions are more common than those of migratory extension and translation during flood periods than between them.

The relative frequency of these two process groups, (1) migratory straightening, cutoffs, and avulsions, and (2) migratory extension and translation, can affect changes in sinuosity (Figures 9a-c). During FP1, three of the four reaches with the largest decreases in sinuosity (3, 5, and 9) had more (combined) occurrences of migratory straightening, cutoffs, and avulsions than occurrences of migratory extension and translation. During the IFP, large increases in sinuosity occurred in reaches with at least as many occurrences of extension and/or translation as those of channel straightening, cutoffs, and/or avulsion. Slight decreases in sinuosity occurred in reaches with 2-4 occurrences of channel straightening, cutoffs, and/or avulsion mixed with 2-4 occurrences of extension and/or translation. Two reaches (5 and 6) experienced only extension and/or translation during the IFP, and both increased in sinuosity. During FP2 three reaches (2, 3, and 8) increased in sinuosity due to relatively numerous occurrences of extension and/or translation in comparison to those of channel straightening, cutoffs, and/or avulsion. Reach 9 had the largest loss of sinuosity during FP2 and among the most occurrences of channel straightening, cutoffs, and/or avulsion relative to extension and/or translation. These results illustrate that the frequency of lateral movement processes can substantially affect sinuosity, but other variables, such as the magnitude of the process, are may also be significant.

5.3. Changes in Channel Units

Substantial changes in channel units accompanied lateral movement and changes in channel width and sinuosity during the study period (Figures 10a-c). In general, the magnitude of changes in channel units was greatest during FP1, during which all nine reaches increased in scoured areas and eight of nine reaches increased in bars. Only four of nine reaches decreased in vegetation. During the IFP eight of nine reaches decreased in scoured areas, while six of nine reaches decreased in bars and vegetated areas. During FP2 eight of nine reaches again increased in scoured areas, but only two of nine reaches had substantial increases in bars. Six of nine reaches increased in vegetated areas during the IFP.

Changes in channel units were spatially variable. Reaches 6 and 7 consistently had the large lateral movement of all the reaches. These reaches also had the largest increases in scoured area during FP2 and largest decreases in scoured area during the IFP. Reach 6 had the highest decrease in scoured area during FP2, but changes in all channel units were low in Reach 7 during the IFP. Reach 7 had the largest increases in channel width during FP1, but it had a relatively low amount of narrowing during the IFP and continued narrowing (rather than widening) during the IFP. Reach 5 had the second most amount of widening during FP1, the most amount of narrowing during the IFP, and the third most amount of widening during FP2, making it the most consistently responsive in terms of width changes across study periods.

Reaches 1, 4, and 8 had the lowest amounts of lateral movement and generally low widening during FP1. These reaches experienced greater increases in scoured areas than bars (Reach 8 lost bar area), likely due to lack of space for dissipation of stream power and sediment deposition. These reaches had the lowest average sinuosity across study periods (Figure 6), and two of the three reaches (Reaches 1 and 4) had the narrowest floodplains. Reach 8 had the widest floodplain, but it had been channelized and artificially confined by levees, therefore it behaves more like a reach with a narrow floodplain. Of the six remaining reaches (2-3, 5-7, and 9), five experienced greater increases in bars than scoured areas during FP1. Like Reaches 1, 4, and 8, Reach 6 experienced a low amount of widening in association with larger increases in scoured areas than bars, despite a relatively large amount of lateral movement. Clear associations among lateral movement, widening and narrowing, and changes in channel units were less evident during the IFP and FP2 than in FP1, suggesting that such associations may depend on factors such as flood history or thresholds that are exceeded only during extreme events.

Despite spatial variability, these results generally support the hypothesis that floods increase scoured areas and bars, but they fail to support the hypothesis that floods decrease vegetation within and along the margins of the active channel. In fact, more vegetation was lost from the channel during the IFP than during either of the two flood periods. Examination of channel maps for Reach 3, a typical reach with increases in vegetation during both flood periods and a decrease in vegetation during the IFP, reveals the mechanisms of this phenomenon and sheds light on channel-vegetation interactions (Figure 11). During FP1 episodes of channel straightening, cutoffs, and avulsions outnumbered episodes of migration at a ratio 6-to-1 (Table 4), resulting in the largest loss of sinuosity among all reaches in the study (Figure 9a). Channel widening and sinuosity loss occurred in conjunction with bar accretion (mainly inside the lateral movement zone; 1 to 1' and 2 to 2' in Figure 11), increases in scoured and vegetated areas (mainly outside the lateral movement zone; 3 to 3' in Figure 11). Lateral movement primarily occurred as straightening (2 to 2' and 4 to 4') and cutoff (5 to 5') of meanders, with avulsion (6 to 6') and downstream translation of channel meanders as secondary processes. Vegetation was captured by the channel through lateral scour of the floodplain (3 to 3').

During the IFP episodes of migratory translation and extension of the channel outnumbered episodes of channel straightening, cutoffs, and avulsions at a ratio of 5-to-2 in Reach 3 (Table 4). Processes occurring in conjunction with channel narrowing during the IFP included localized migration of channel meanders (1' to 1" and 7 to 7") and revegetation of areas scoured during FP1 (3' to 3", 8 to 8', and 9 to 9'). Among migration processes, lateral extension occurred more frequently than downstream translation (at a 3-to-2 ratio), thereby increasing the sinuosity of the reach. Vegetated areas within the active channel decreased as the laterally scoured area became revegetated during the IFP, causing the vegetation to be excluded from the active channel (3' to 3''). Vegetation then increased during FP2 as vegetation grew on marginal areas (7' to 7", 10 to 10', and 11 to 11"), undisturbed or minimally disturbed by the flood. Overall, the largest increases in vegetation occurred in conjunction with lateral scour, outside the zone of lateral channel movement. Smaller changes in channel vegetation, both positive and negative, occurred in association with localized channel migrations and bar accretion. These results underscore the importance of processes operating outside the lateral movement zone (i.e, areas of overbank flow) during floods in driving channel-vegetation interactions and planform dynamism of multi-channel, gravel-bed mountain rivers.

6. Discussion

6.1. Channel Disturbance and Recovery

Despite remarkable spatial variability, channel change of the upper Umatilla River is broadly congruent with studies that have reported channel widening, straightening, and high rates of lateral movement during flood events (Knighton, 1998; Wohl, 2000; Schumm, 2005). Results are similarly congruent with studies reporting channel narrowing after floods (Friedman refs) and a decay in rates of change following disturbance (Graf, 1977). Extrapolation of the average narrowing rate calculated during the IFP (approximately seven meters per year) suggest that in the absence of the 1975 flood the channel may have narrowed to its pre-FP1 width approximately by 1977, or 13 years after the floods of FP1; however, adjustment of the channel to the floods of FP1 at the time of FP2 apparently reduced the sensitivity of the channel to change (Wolman and Gerson ,1978; Brundsen and Thornes, 1979) and dampened changes during FP2 (see examples by Gupta and Fox, 1974; Kochel, 1980; Cinderelli and Wohl, 1997).

Factors that likely contributed to the limited geomorphic response during FP2 include: (1) the occurrence of multiple flood events with greater cumulative flood duration in FP1 in comparison to one event of shorter duration in FP2 (Figures 2 and 3), and (2) a relatively high peak flow during the IFP (Figure 2), which may have contributed to the maintenance of adjustments in FP1. Two large, closely spaced floods may be more effective in creating channel change not only because of their greater combined duration (see for example Huckleberry, 1994), but also because of interactions between sediment delivery to the channel during the initial event and sediment processing during the subsequent event (Newson, 1980; Kochel et al., 1987).

Newspaper accounts describing the first of the FP1 events in December 1964 emphasized the occurrence of landslides and the subsequent blockage and failure of local bridges and culverts as waves of sediment and wood surged down tributaries (East Oregonian, 1964). This material was then reworked during the larger January 1965 event and it likely contributed to exceptional widening and lateral movement as the channel processed the materials delivered to it during the December flood.

Results of this study generally support the theory that floods create long-lived channel changes in arid or semi-arid mountain regions (Langbein and Schumm, 1958; Hack and Goodlett, 1960; Wolman and Gerson, 1960; Baker 1977; Kochel 1988). In this case, the channel remained substantially wider than its pre-flood width approximately ten years after the 1964-5 flood events. Although ten years is short in comparison to recovery periods for rivers in some arid climates (for example, see Burkham, 1972), it is long in comparison to recovery in many humid climates, which may be as short as one or two years, even for large floods (Patton, 1988).

6.2. Lateral Scour and Channel-Vegetation Interactions

Despite a generally mixed response in channel vegetation across periods, changes in channel vegetation driven by avulsion or lateral scour during floods were generally consistent with studies of similar rivers wherein these processes control island and floodplain generation (Dykaar and Wigington, 2000) and maintenance of multi-channel channel patterns (Burge and Lapointe, 2005; Beechie et al., 2006). In most reaches (5 of 9 in FP1; 6 of 9 in FP2), floods increased the overall amount of vegetation in the channel. Despite loss of vegetation by scour along the channel margins and bars, pre-existing vegetation was captured into the active channel by avulsion or lateral scour of high-flow channels around vegetated areas of the floodplain, thereby increasing the overall amount of vegetation within the active channel. Conversely, most reaches (6 of 9) decreased in vegetation during the IFP. Despite revegetation of some bars, areas scoured during the capture of vegetated areas in FP1 became revegetated and lapsed back to the floodplain. Examination of channel-change maps in reach 3 showed that lateral scour was more effective than avulsion in changing channel vegetation during flood periods. Moreover, lateral scour may be a step toward a true avulsion, and thus is likely an important mechanism driving broader scale channel-floodplain interactions. Floods likely drive this migration by mobilizing sediment downstream from areas loosing interaction with vegetated islands and floodplains (wherein the channel is likely incising) to areas gaining interaction with islands and floodplains (wherein the channel is aggrading). Similar interactions with sediment transport have been invoked to explain temporal cycling of anabranching and braided channels (Ashemore, 1991; Bridge, 1993; Leddy et al., 1993; Burge and Lapointe, 2005).

6.3. Channel Process-Form Relations

During FP1, moderate-to-high amounts of lateral movement and channel widening resulted in increases in bars and scoured areas, and mixed changes in vegetated areas. Many studies have emphasized large geomorphic responses to floods in confined valley settings where stream power is concentrated in comparison to wider valleys in adjacent reaches or rivers (Newson, 1980; Patton, 1988; Fuller, 2007). In contrast to these studies, lateral movement, widening, and overall changes in channel landforms were most limited in reaches with the narrowest floodplains (Reaches 1 and 4) and generally higher in reaches with wider floodplains (Reaches 6, 7 and 9). Reach 8 had the widest floodplain, but it was channelized and leveed prior to the study and as a result it behaved like a reach with a narrow floodplain (or no floodplain). In reaches with the narrowest floodplains and lowest average sinuosity values (Reaches 1, 4, and 8), changes in channel units were relatively low and increases in scoured areas were generally greater than increases in bars (Reaches 1 and 4), or scoured areas increased while bars decreased (Reach 8). Thresholds of approximately 450-480 m average floodplain width and an average sinuosity of 1.05-1.13 (see Figure 6) appear to separate reaches that favor scour over bar accretion during FP1. Below these thresholds the channel favored scour, whereas above them the channel favored bar accretion, as it widened. Reach 6 was the only reach above these thresholds that did not follow this pattern. It had the second highest amount of lateral movement, but only a moderate amount of widening, which was similar to the magnitude of widening in the narrowest reaches. This result suggests that changes in channel width may be a more important driver of bar accretion than lateral movement. Numerous channel structures are known to have occupied this reach and may have limited the widening necessary for larger amounts of bar accretion. Thus, structural variables appear to exert control on the spatial pattern of flood-driven channel changes, but observed channel changes on the Umatilla River are generally opposite of theories that emphasize a positive relationship between the magnitude of landform changes during floods and the relative structural confinement of the channel. Overall differences among reaches in structural confinement shown in the study area may be less than those of other studies, thereby complicating direct comparison of results across studies.

Unlike FP1, no obvious relations existed between lateral movement or width changes and changes in channel units during the IFP or FP2. Such relations may require a level of external forcing that was absent during these periods. Latent adjustment of the channel to the floods of FP1 may have diminished resistance of the channel during these periods such that relations between processes and landform changes observed in FP1 broke down. Future work should attempt to resample variables at a finer spatial scale to explore potential linkages that may be absent at the (reach) scale addressed in this study. Future work should also involve a detailed survey of channel slope and cross-sections, which would allow for calculation of unit stream power, which can be used to test the explanations of variability in channel changes offered in this study and to develop exploratory models that may provide deeper insights into unexplained channel behaviors.

6.4. Management Implications

Managers attempting to balance naturalization of river corridors with the control and/or mitigation of flood impacts on human communities and infrastructure should recognize that fluvial processes and their relations with channel landforms are variable. Two types of variability have been highlighted in this study: (1) spatial variability, and (2) temporal variability. Channel changes were generally greater in wider floodplain settings (Reaches 7-9), so these areas may have more response to potential future projects aimed at restoring naturalistic geomorphic processes. Channel changes in

Reach 8, which was channelized previous to the study period, were among the lowest in magnitude across the study area. While the lack of geomorphic changes in this reach evidences the effectiveness of previous flood-control activities, such activities inhibit lateral movement and overbank flow, which have been shown in this study as crucial in the creation and maintenance of vegetation within the active channel. Should the need or opportunity arise to manage the Umatilla River in a way to promote more interaction of the channel with riparian vegetation, Reach 8 may be an appropriate area to target. In this case, some homes and businesses in this area would likely have to be set back from the channel or relocated out of the floodplain to allow for increased flooding and channel movement. Successfully mitigating the hazardous effects of future floods on the Umatilla River may require recognition that the river adjusts to extreme events and such adjustments have the ability to reduce the effects of future floods. Because major floods on the Umatilla River have occurred in clusters, river managers may benefit from accepting the geomorphic effects of major floods, when and where possible, instead of attempting expensive projects to alter the channel or return it to pre-flood conditions.

7. Conclusion

Planform channel change of the Umatilla River during two flood periods (FP1, 1964-1971; FP2, 1974-1977) and an interflood period (IFP, 1971-1974) was generally consistent with theories emphasizing increases in channel dimensions and rates of change in response to floods, but only partially consistent with theories of structural controls of channel systems. Large lateral movements, widening, and straightening of the channel, coupled with widespread increases in bars and scoured areas, characterized channel change during FP1. Conversely, smaller lateral movements, channel narrowing, increases in sinuosity, and decreases in bars and scoured areas characterized the IFP. Large lateral movements and widening of the channel, and widespread increases in scoured areas were again evident during FP2, but were generally lower in magnitude than in FP1, reflecting a dampened response associated with continued recovery from the floods of FP1. Changes in sinuosity during FP2 were mixed, with some reaches increasing and others decreasing in sinuosity. Spatial variability of sinuosity change was poorly explained by differences in geomorphic setting. Instead, the relative frequency of lateral movement processes that inherently promote channel straightening (cutoffs and avulsions) versus those that promote static sinuosity (downstream translation) or channel elongation (lateral extension) drove the largest changes in sinuosity, suggesting intrinsic controls on sinuosity.

Lateral movement and channel widening were most limited in reaches with narrow floodplains and low average sinuosity over the study period. This result is generally inconsistent with studies emphasizing high-magnitude channel changes in structurally confined settings. In the narrowest three reaches, increases in scoured areas were greater than increases in bars or vegetated areas during FP1. In the other reaches except Reach 6, increases in bars were greater than increases in scoured or vegetated areas, thereby suggesting a threshold of floodplain width and/or sinuosity above which bar accretion (i.e., sediment deposition) is favored over erosion as the dominant channel-change process. The effects of such a threshold in Reach 6 may have been counteracted by channel structures, which confine the channel and mimic the effects of natural confinement observed in reaches with narrower floodplains.

Whereas emerging theories concerning the evolution of laterally active multi-channel river systems have emphasized flood-driven avulsions as the primary mechanism of channel-floodplain interaction and maintenance of the channel pattern, this study has demonstrated the importance of lateral scour in the capture of vegetation into the active channel form the floodplain as a genetic process of island landforms. These results highlight the importance of understanding the nature, relative frequency, and space-time variability of specific processes in characterizing the planform dynamism of multi-channel, gravel-bed mountain rivers, and suggest that models of process-form relations that fail to explicitly account for the spatial or temporal variability of the processes and landforms would have limited applicability in management or restoration of the Umatilla River or other rivers with similar landforms and disturbance histories.

8. Bridge Section II

Chapter III applied the error-sensitive lateral movement measurement method of Chapter II to: (1) estimate the magnitude of lateral channel movement during and between two sequential flood periods on the Umatilla River, and (2) investigate the styles, frequency, and controls of lateral movement processes, and (3) explore linkages between channel processes and channel-landform changes. Chapter IV extends the Chapter III's investigation of flood-driven channel changes to include the impacts of floods on channel-landform complexity. Changes in channel complexity are interpreted in the context of the intermediate disturbance hypothesis and the magnitude of lateral channel movement and changes in the active channel width.

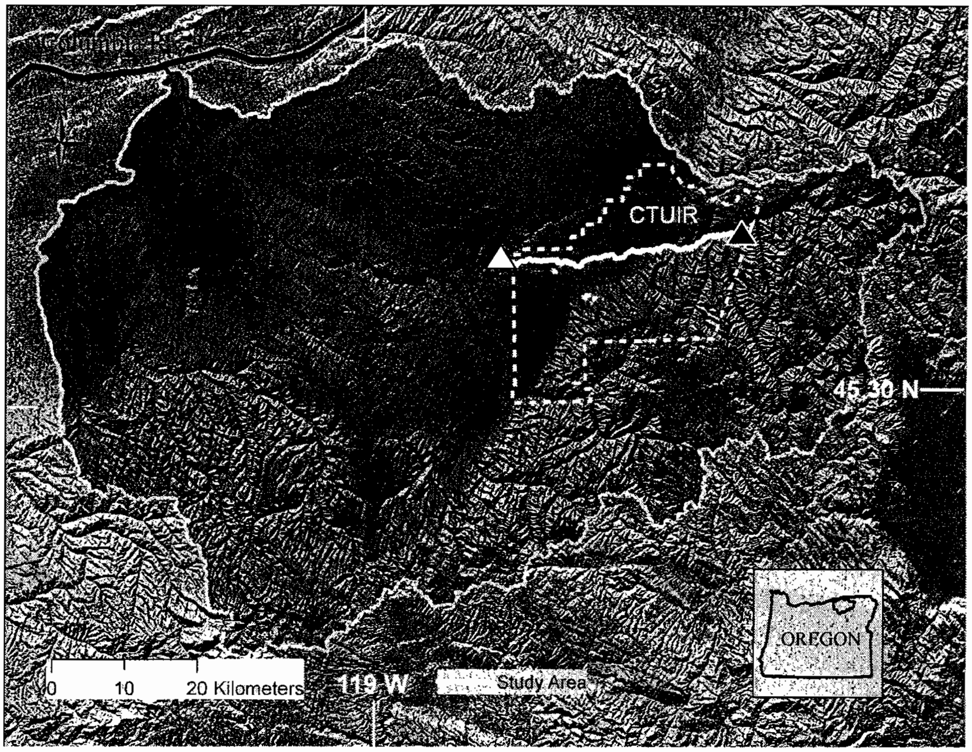


Figure 1. The Umatilla River watershed, with the upper Umatilla River and tribal reservation of the Confederated Tribes of the Umatilla Indian Reservation (CTUIR) highlighted in white. The white triangle indicates the Pendleton flow gauge and the black triangle indicates the Gibbon flow gauge.

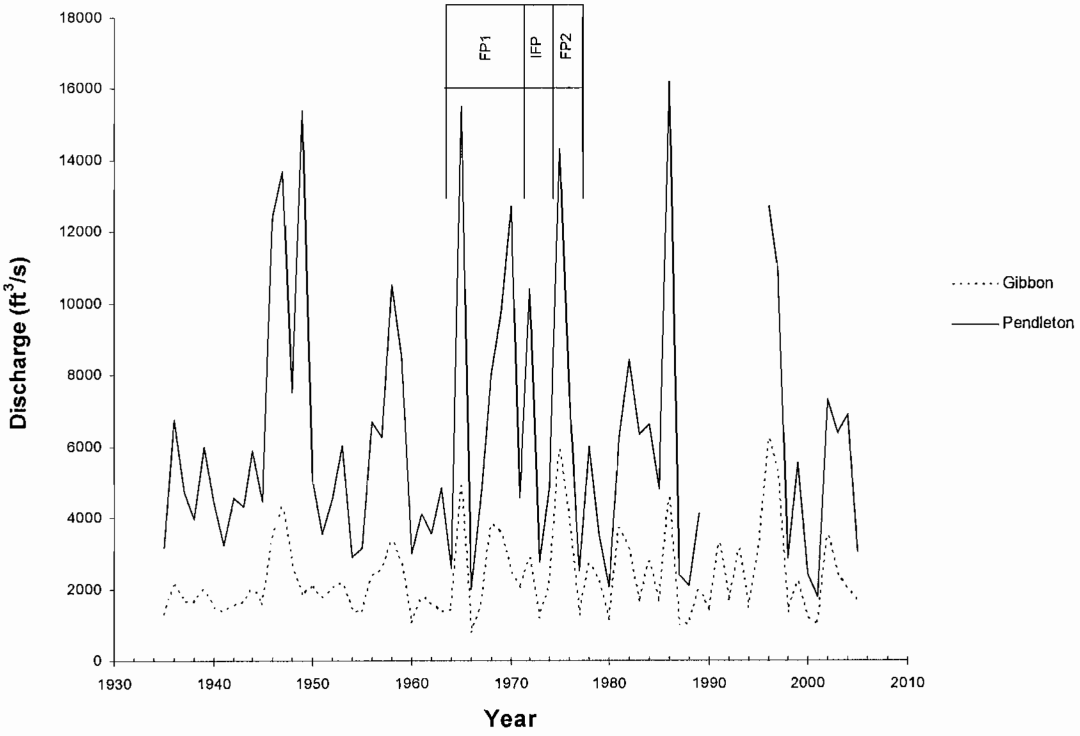


Figure 2. Peak flow hydrographs of the Umatilla River at Gibbon and Pendleton with Flood Period 1 (FP1), the Interfolld Period (IFP), and Flood Period 2 (FP2) shown in backets

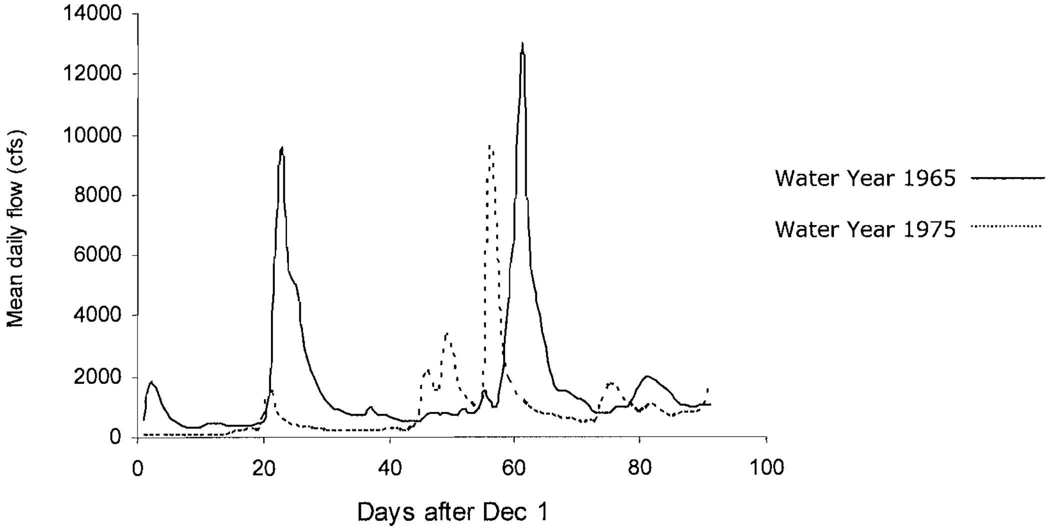


Figure 3. Daily flow hydrographs for peak flow events during FP1 (Water Year 1965) and FP2 (Water Year 1975)

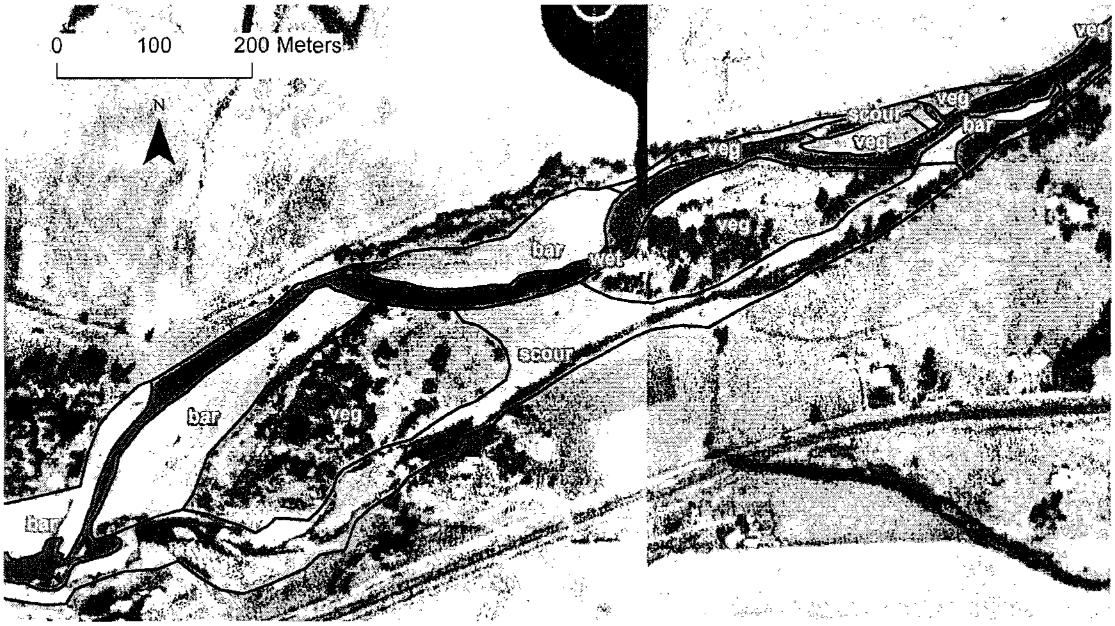


Figure 4. Active-channel classification of the Umatilla River, including: (1) wet channels (= wet), (2) bars (= bar), (3) scoured areas (= scour), and (4) vegetated areas (= veg)

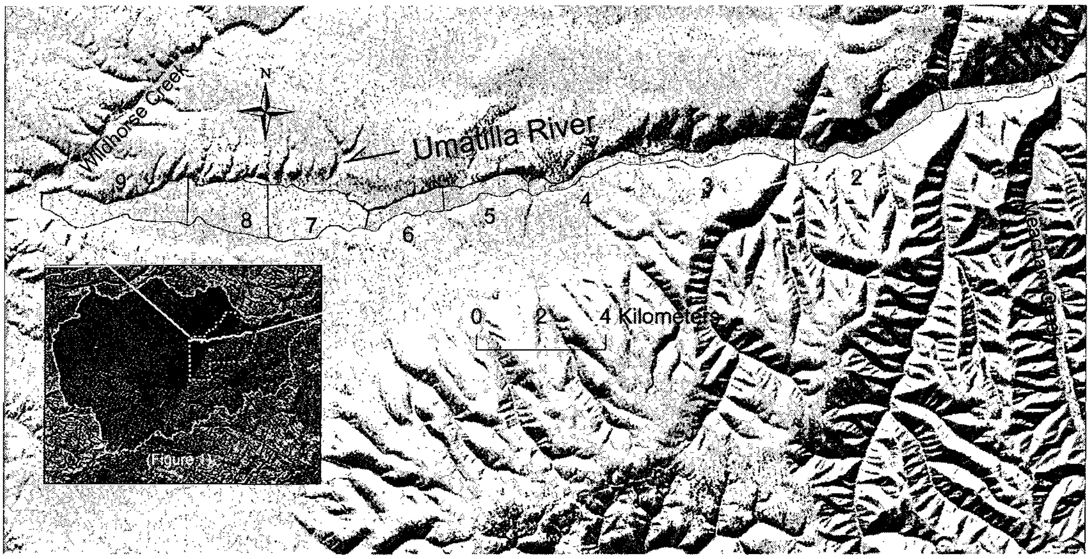


Figure 5. Reaches of the upper Umatilla River study area

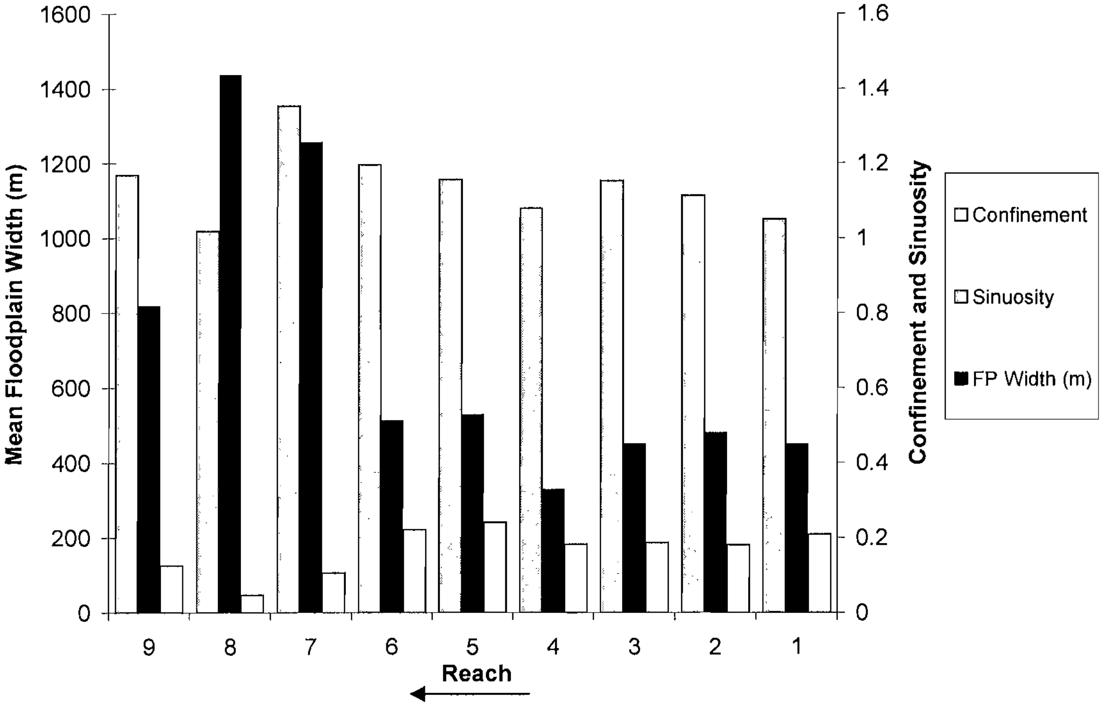
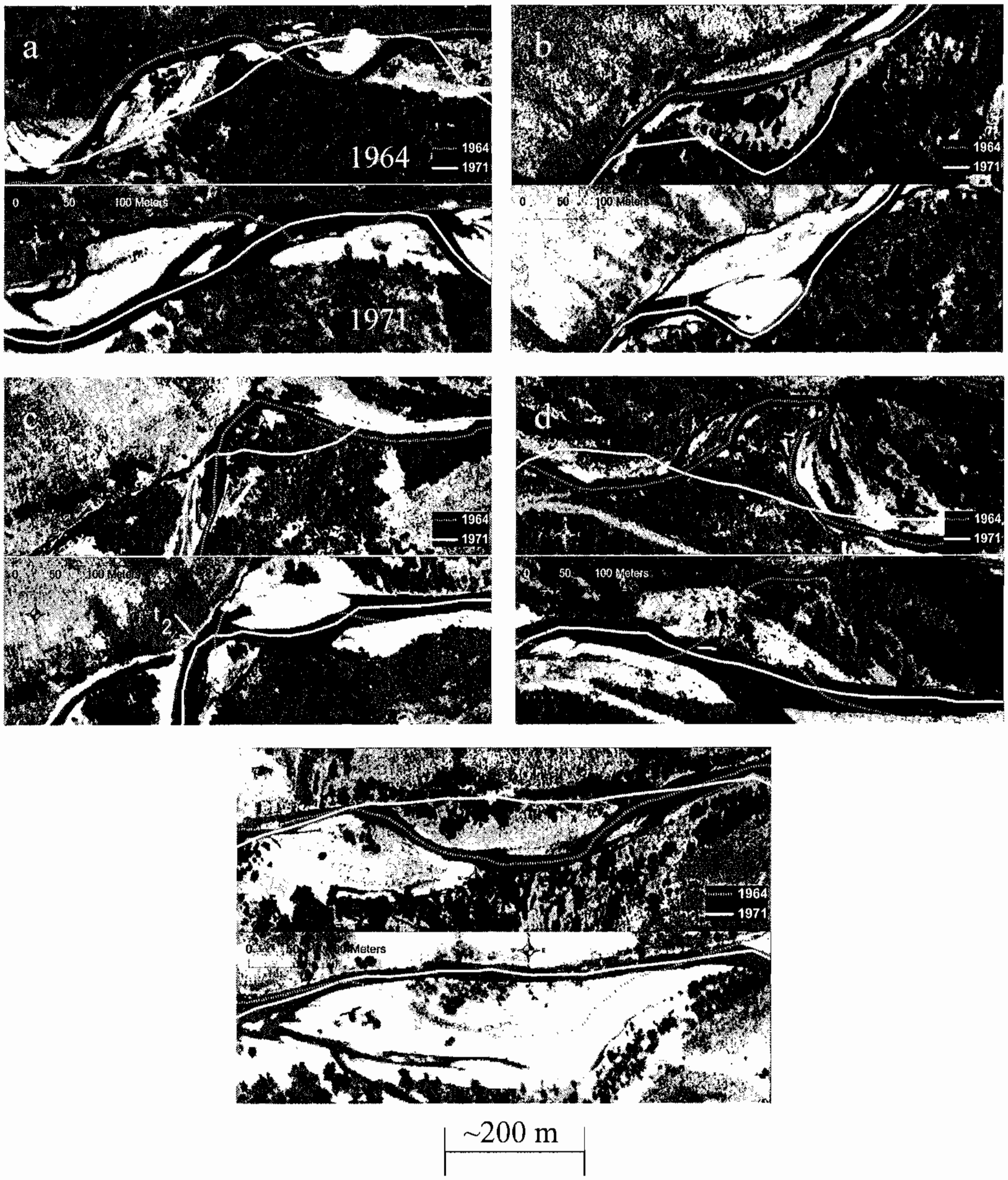
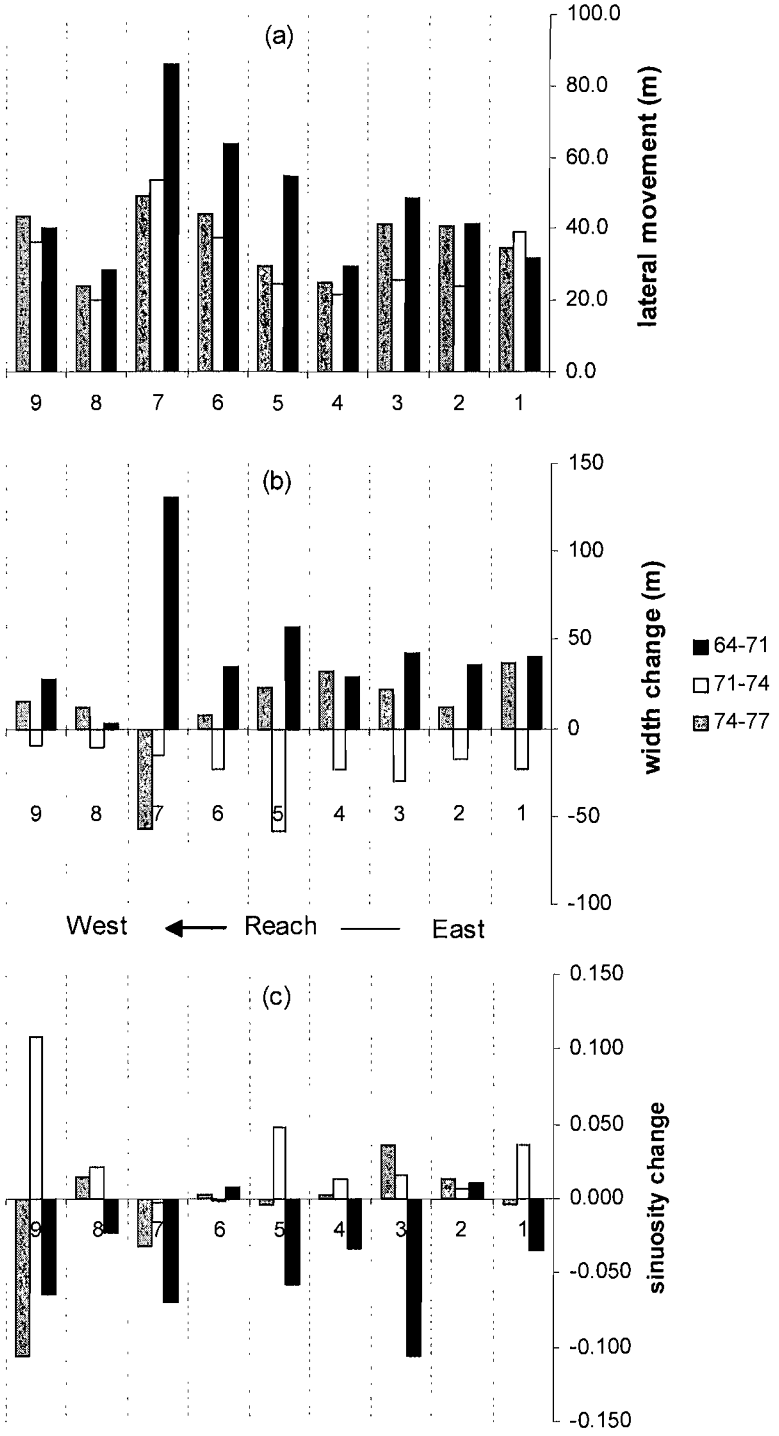


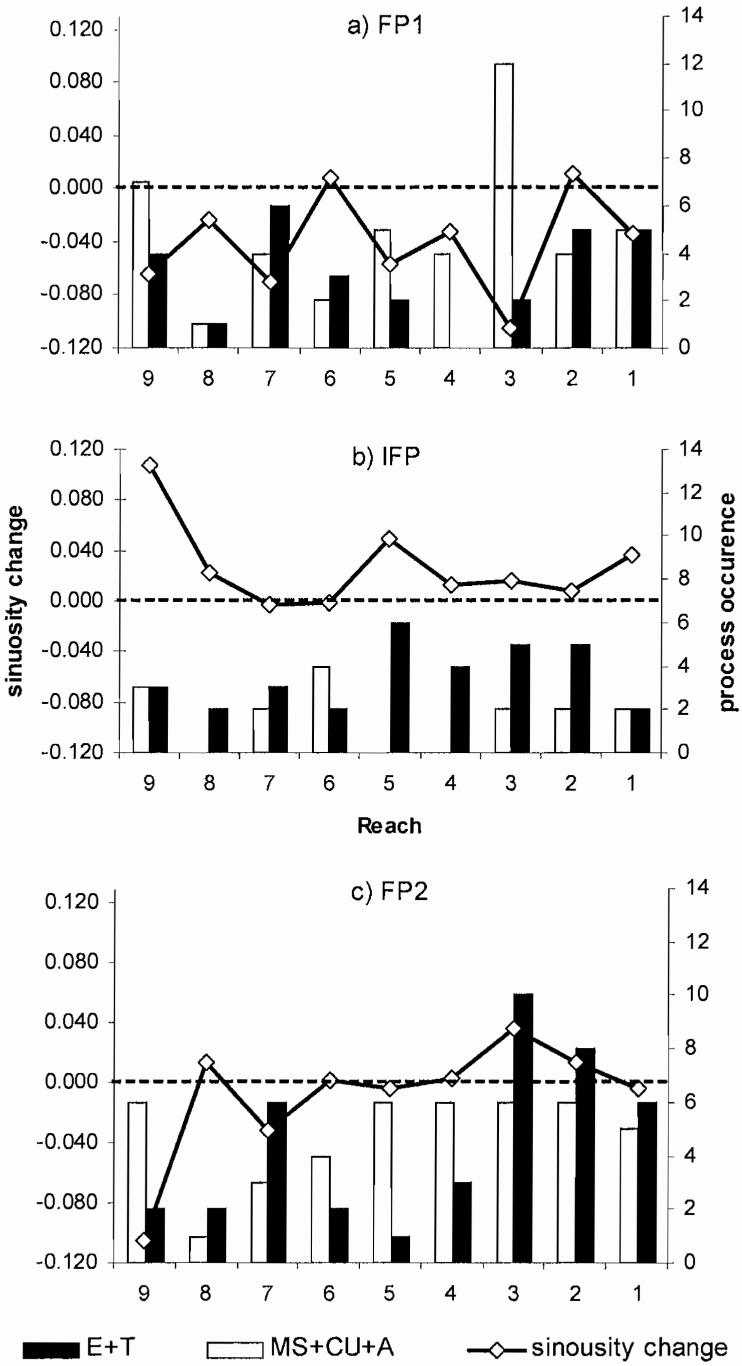
Figure 6. Floodplain width, channel confinement (mean active channel width / floodplain width), and mean sinuosity of the study reaches



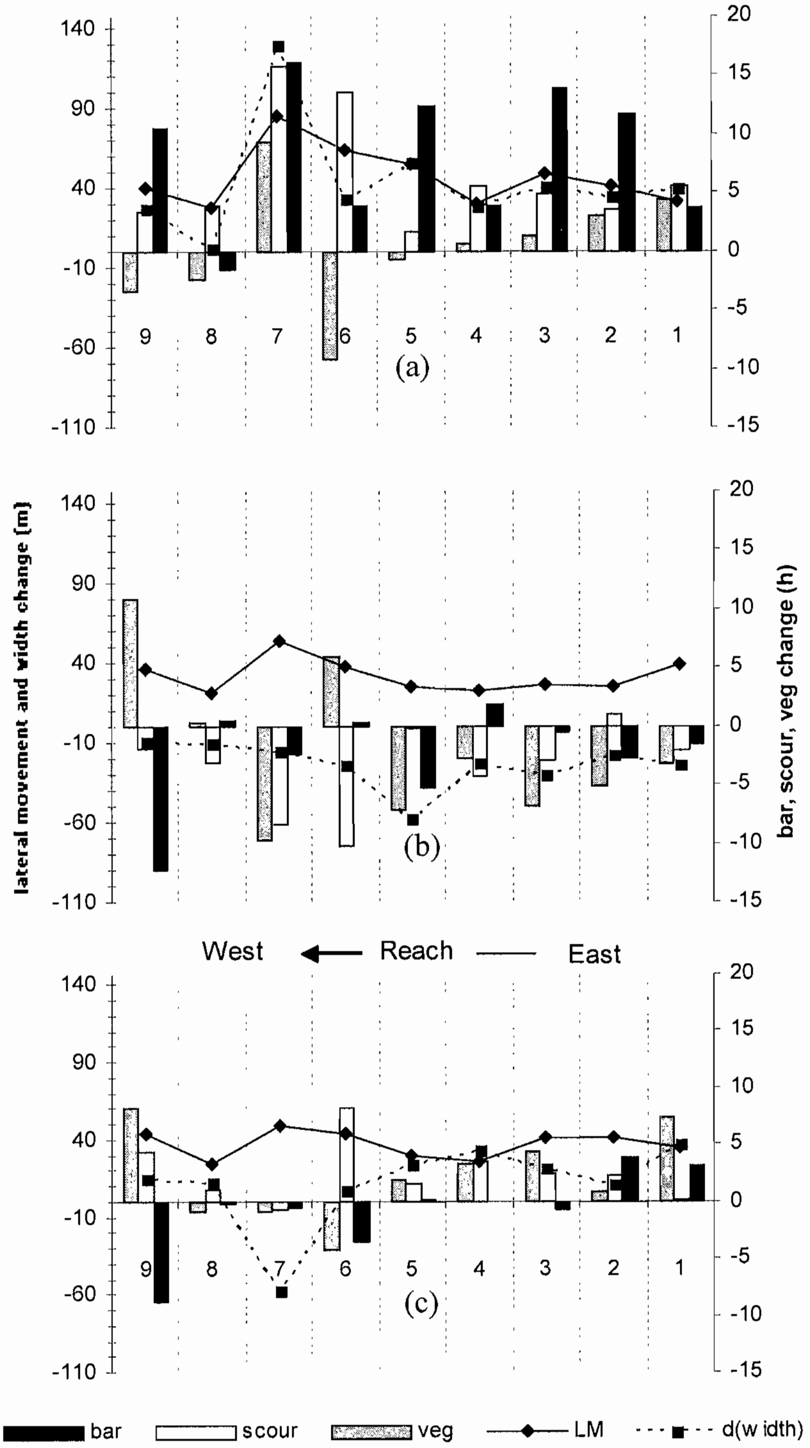
Figures 7a-e. Channel movement processes: (a) migratory straightening, (b) lateral extension, (c) downstream translation, (d) cutoff, (e) avulsion. Top images are from 1964; bottom images are from 1971.



Figures 8a-c. Channel-changes, 1964-1977: (a) lateral movement, (b) widening (+) and narrowing (-), and (c) sinuosity change



Figures 9a-c. Frequency of migratory extension and translation (E+T) versus migratory straightening, cutoffs, and avulsion (MS+CU+A) in relation to sinuosity changes: (a) FP1, 1964-1971, (b) IFP, 1971-1974, (c) FP2, 1974-1997



Figures 10a-c. Changes in channel units in relation to lateral channel movement, LM, and changes in active channel width, d(width): (a) FP1, 1964-1971, (b) IFP, 1971-1974, and (c) FP2, 1974-1977

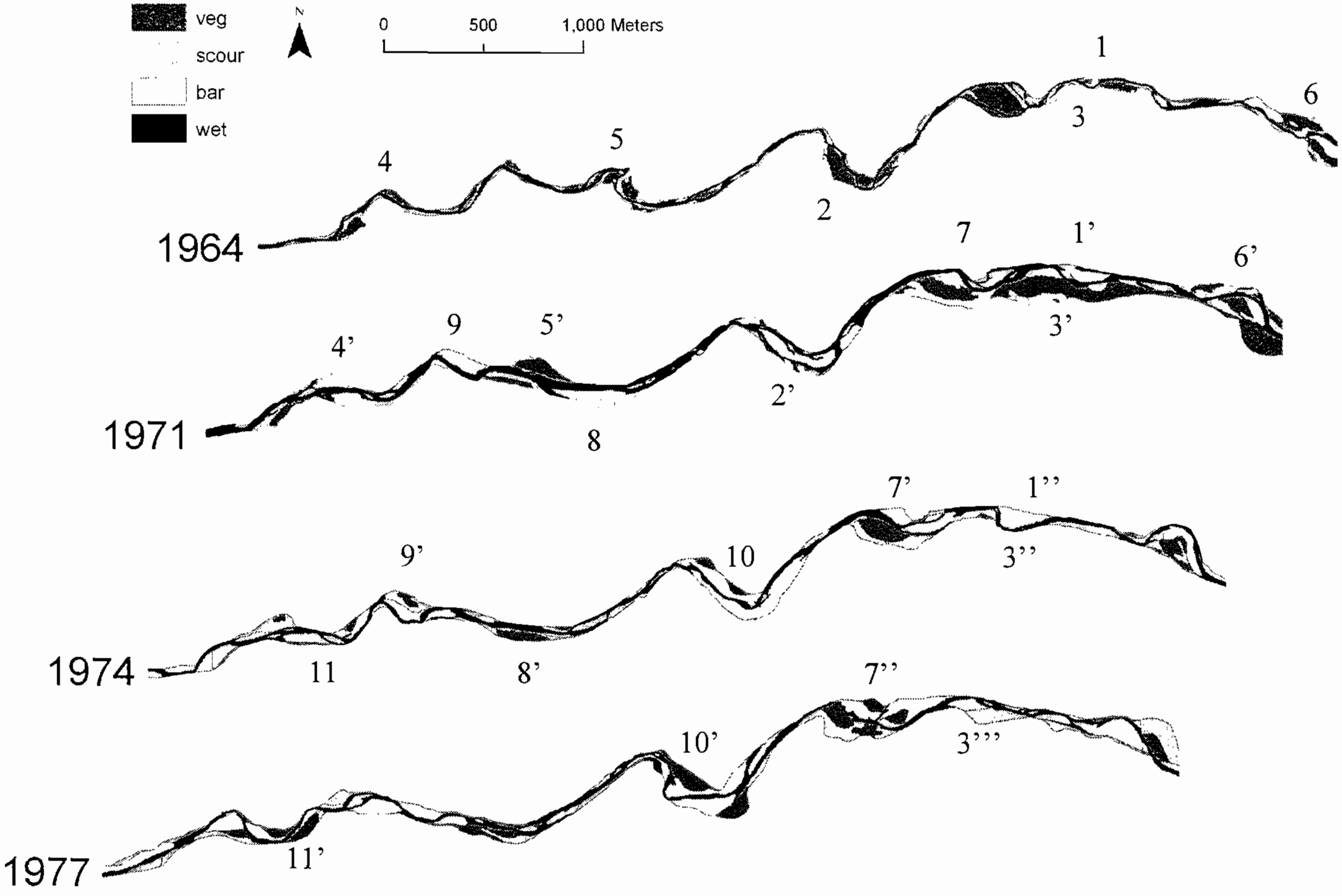


Figure 11. Channel change of the Umatilla River in Reach 3 and minor portions of adjacent reaches, 1964-1977. Numbers represent notes in text

Table 1a. Magnitude-frequency for peak flows of the Umatilla River at Gibbon, Oregon

Water Year	Discharge (ft^3/s)	Discharge (m^3/s)	Rank	Recurrence Interval	$Q/Q_{2.33}$
1996	6220	176	1	74.0	3.0
1975	5930	168	2	37.0	2.9
1997	5230	148	3	24.7	2.5
1965	4910	139	4	18.5	2.4
1986	4560	129	5	14.8	2.2
1947	4320	122	6	12.3	2.1
1976	3890	110	7	10.6	1.9
1968	3820	108	8	9.3	1.8
1981	3710	105	9	8.2	1.8
1969	3540	100	10	7.4	1.7

Table 1b. Magnitude-frequency for peak flows of the Umatilla River at Pendelton, Oregon

Water Year	Discharge (ft^3/s)	Discharge (m^3/s)	Rank	Recurrence Interval	$Q/Q_{2.33}$
1986	16200	459	1	69.0	2.7
1965	15500	439	2	34.5	2.6
1949	15400	436	3	23.0	2.6
1975	14300	405	4	17.3	2.4
1947	13700	388	5	13.8	2.3
1970	12700	360	6	11.5	2.1
1995	12700	360	7	9.9	2.1
1946	12400	351	8	8.6	2.1
1996	10900	309	9	7.7	1.8
1958	10500	297	10	6.9	1.8

Table 2. Aerial photogrpahs and associated metedata for the study area

Photo year	Photo date(s)	Scale	Gibbon discharge (cfs)	Pendleton discharge (cfs)	Source
1964	7/17/1964 8/6/1964	1:20,000	74 60	85 54	U.S.D.A., A.S.C.S.
1971	5/11/1971 5/22/1971	1:20,000	455 282	775 524	U.S.D.A., A.S.C.S.
1974	7/24/1974	1:15,840	70	83	U.S. Bureau of Indian Affairs
1977	August, 1977 (unspecified date)	1:24,000	45-114 (mean = 52)	24-126 (mean = 27)	Umatilla County, Oregon

Table 3. Mean, total, and corrected wet areas of the Umatilla River, 1964-1977

Reach	Mean Wet Area (1964, 1974, 1977) (h)	Total Wet Area (1971) (h)	Area corrected (h)
1	8.1	12.4	4.3
2	12.7	18.1	5.5
3	12.6	18.7	6.1
4	9.7	13.9	4.2
5	7.0	10.6	3.6
6	7.0	10.6	3.7
7	8.4	14.2	5.8
8	8.7	9.8	1.1
9	14.9	26.4	11.5

Table 4. Number of occurences of different lateral movement processes of the Umatilla River

Processes of lateral channel movement	**Number of occurences**		
	64-71	**71-74**	**74-77**
Migratroy translation (T)	16	12	12
Migratory extension (E)	12	20	28
Episodes of migration without straightening (T+E)	**28**	**32**	**40**
Channel straightening, with and without cutoffs (CS + CU)	29	9	26
Avulsion (A)	15	6	17
Epsiodes of channel straightening, cutoffs, avulsions (CS+CU+A)	**44**	**15**	**43**
(E+T] / (CS+CU+A)	**0.64**	**2.13**	**0.93**

CHAPTER IV

EFFECTS OF FLOODS ON THE PLANFORM COMPLEXITY OF THE UPPER UMATILLA RIVER

1. Introduction

River channel patterns reflect complex interactions between processes and forms in channel-floodplain systems. In multi-channel gravel-bed rivers these interactions can result in variable arrangements of channels, bars and islands. In many mountain regions channel patterns of gravel-bed rivers have been simplified by dams, channelization, wetland drainage and filling, levee and revetment building, and deforestation (Wohl, 2006). These activities have destroyed or diminished habitat for many aquatic and riparian species (National Research Council, 1992). In their promotion of an ecological perspective for aquatic and riparian restoration practices, Kaufman et al. (1997) cite an unprecedented need for the preservation and restoration of biological diversity, including restoration of the fluvial processes and landforms that underpin important linkages between native organisms and their environment. Based on a synthesis of case studies from several mountain regions Wohl (2006) stated that [ecological] management of mountain streams necessitates particular attention to, among other factors, process domains, physical and ecological roles of disturbance, and stream resilience. Incorporation of these concepts into river management remains hampered by the lack of scientific experiments that would elucidate their practical significance.

Ecological disturbance and biodiversity have been linked through the Intermediate Disturbance Hypothesis (IDH), which states that biodiversity is greatest when and where disturbance is neither too large and frequent, nor too small and infrequent (Connell, 1978; Resh et al, 1988; Petraitis et al., 1989). Biodiversity, commonly defined as species richness, is therefore maximized under conditions of intermediate disturbance. While still debated in ecology (Resh et al, 1988; Petraitis et al., 1989), the IDH has played a central role in ecological theory for thirty years. In the IDH, high diversity is achieved because two major groups of species -- colonizing species that establish following disturbance, and the more competitive species that would come to dominate without disturbance – coexist and are maintained by intermediate levels of disturbance. The goal of this study is to apply the intermediate disturbance hypothesis to fluvial geomorphology. While the specific ecological processes that support the IDH are not directly transferrable to fluvial geomorphological systems, there are many concepts shared by the IDH in ecology and fluvial geomorphology.

A concept in fluvial geomorphology that is somewhat parallel to biodiversity is physical complexity, defined by Graf (2006) as the number of geomorphic surfaces per unit length of channel. Riverine geomorphic surfaces are created by disturbance and post-disturbance recovery, similar to the ways in which processes determining biodiversity are influenced by disturbance. In the case of rivers, the main disturbance process is floods, but various forms of disturbance may be important in ecosystems. Multi-channel gravel-bed rivers typically go through disturbance-driven cycles of creation and abandonment of side channels (Burge and Lapointe, 2005). As in the IDH in ecology, the magnitude and frequency of disturbance events is a key concept used in fluvial geomorphology to explain development of and changes in landforms. The greatest amount of geomorphic work is accomplished by events of intermediate magnitude and frequency (Wolman and Miller, 1960). Effective discharge is the term given to that discharge that, on average over a period of years, transports the most sediment. This concept has been extended to argue that effective discharge is the dominant discharge – the discharge that controls channel form (Knighton 1998; Goodwin, 2004; Simon et al., 2004).

Concepts of disturbance and diversity in ecology and fluvial geomorphology are also directly linked, in that disturbance of the riverine geomorphic system has direct effects on aquatic and riparian ecology. Flood disturbance can physically displace some species from river channels because they cannot tolerate the forces generated during floods (Pearsons et al., 1992). Floods can also create habitat changes that provide competitive advantages to certain species among those remaining in rivers after a flood (Petraitis et al, 1989). Channel scour, removal of vegetation, and channel straightening are common flood impacts that are capable of producing significant habitat changes in mountain rivers (Swanson et al, 1998). These responses tend to reduce the hydraulic roughness and physical complexity of river channels, at least in some localities along channel corridors. Physical complexity of rivers is closely related to aquatic habitat diversity. Loss of physical complexity reduces available niches, thereby limiting the coexistence of species with different habitat requirements (Meffe, 1984) and presumably reducing biodiversity. Loss of physical complexity also reduces the resilience of the aquatic ecosystem to future disturbance (Sedell et al., 1990). The cycles of creation and abandonment of geomorphological surfaces caused by flood disturbance also have positive ecological effects -- they promote relatively high ecotone/area ratios and hydrological connectivity, and they create biotic patches in the channel-floodplain environment (Brown, 1997; Amoros and Bornette, 2002; Ward et al., 2002).

The fundamental thesis of this paper is that fluvial landform systems are like biological communities in that their diversity (physical complexity) is dependent on the magnitude and frequency of disturbance. If so, then the intermediate disturbance hypothesis will apply to fluvial landforms and can be used to predict the response of channel systems to flood disturbance. If floods are too large and/or frequent, or to small and/or infrequent, then according the IDH, multi-channel rivers would lose some physical complexity. Only a few studies to date have explored the link between magnitude and frequency of disturbance and physical complexity of channel systems, but their results are supportive of the applicability of the IDH to physical complexity in fluvial systems. Graf (2006) found that the reduction in flooding downstream of large dams reduced physical complexity 14-56% across 36 rivers in seven regions of the U.S. Sheldon and Thoms (2006) found a similar loss of physical channel complexity in response to flow regulation on the Barwon-Darling River in Australia and cited the loss as a potential contributing factor to low retention of organic matter within the river system.

Physical complexity of fluvial systems as used here is distinct from geomorphic complexity in the broader sense – what might be termed system complexity. In recent years geomorphologists have become increasingly interested in system complexity (Malanson, 1999; Phillips, 1999b, 2006; Schumm, 2005; Sheldon and Thoms, 2006; Thoms, 2006; Murray and Fonstad, 2007). Werner (1999) stated that complexity in natural landform patterns is a manifestation of [complex] nonlinear interacting processes that operate in open systems to both modify and respond to the environment in which they operate, implying that physical complexity results from complex interactions between processes and landforms. While the sources and manifestations of complexity in geomorphic systems continue to be modeled and debated (Murray and Fonstad, 2007), empirical studies of complexity are scarce. Because physical complexity (defined as number of surfaces per length of river channel) is an observable property, it is a logical starting point in the quest to develop a better understanding of behavioral complexity in geomorphic systems.

In a test of the IDH applied to a fluvial system, this study evaluates of the effects of the 1964-5 and 1975 floods (Table 1) on planform complexity of the upper Umatilla River of northeastern Oregon. In this study channel complexity is defined as the spatial density of distinguishable channel surfaces (see Graf, 2006), expressed as the number of surfaces within the active channel per length of floodplain. Channel landforms were classified and mapped from a series of pre-, post-, and inter-flood aerial photographs (Table 2). The following questions are addressed:

- How much does channel complexity vary over space and time?

- How and to what degree do moderate-to-large floods affect channel complexity?
- What factors affect the spatial variability of channel complexity?
- Can the intermediate disturbance hypothesis be adapted to explain changes in channel complexity in response to floods?

2. Study Area

The Umatilla River is a gravel-bed river that originates in the Blue Mountains of northeastern Oregon and flows west to the Columbia River (see Figure 1 in Chapter III). This study focuses on a segment of the upper Umatilla River between the confluences of Meacham and Wildhorse Creeks. This segment flows through a bedrock canyon that drains approximately 1,650 km^2 at its downstream end near the City of Pendleton. The geology of the watershed is dominated by the Columbia River Basalts, which originated from Miocene-age lava flows and form the uplands and canyons of the Umatilla River watershed. Quaternary alluvium forms the valley floor, averages 12 feet in thickness (Gonthier and Harris, 1977) and varies in width from approximately 500 to 2000 meters. The channel bed is composed of basalt gravel ($D_{50} \sim 6$ cm, $D_{84} \sim 15$ cm) that fines downstream.

The river has a mixed multi-channel pattern consistent with the wandering pattern described by Church (1983), the Type 5 (gravel-dominated, laterally active) anabranching pattern described by Nanson and Knighton (1996), or the island-braided pattern described by Beechie et al. (2006). In this pattern some reaches primarily flow in a single meandering channel and others flow in braided or anabranching channels that are separated by bars or vegetated islands. These channels may share full (connected at both upstream and downstream ends) or partial connection (connected at one end only) to the main channel at low flow. Floodplains and islands have cottonwood-willow forests on their upper surfaces, and shrubby or herbaceous vegetation on their lower surfaces,. Land use is dominated by forestry and dryland farming on the uplands, and ranching and irrigated farming on the valley floor.

Beaver trapping, mining, forestry, and agriculture have resulted in a mix of impacts on rivers throughout the Interior Pacific Northwest (Beschta, 1997). These impacts include river simplification, loss of large pools, disconnection from floodplains, loss of wood, and channel instability (McIntosh et al., 2000). These impacts have fundamentally altered the ecological setting for fish communities, resulting in changes in the composition, governing factors, and resilience of fish communities (Pearsons et al., 1992). Transportation has had a particularly significant impact in the upper Umatilla River valley. The Oregon Trail was cut through the valley in the mid-1800's. Journal entries of early wayfarers describe multiple channels and an abundance of beaver in the Umatilla River (Nagle, 1998). In the late 1800s the Union Pacific railway was routed down the valley. The embankment supporting the railway dissected the floodplain in the study area, isolating the channel from major portions of its floodplain, narrowing the river corridor, and reducing connections to oxbow channels and other floodplain habitats. The loss of connection to these waters has diminished the complexity of the Umatilla river-floodplain landscape, simplified hyporheic exchange flow, increased summer water temperature, and reduced habitat availability (Boyd, 2003). In the Umatilla River and similar rivers cool-water patches exist in alcoves and side channels, which receive hyporheic exchange flow from bars, islands, and floodplains, as well as groundwater discharge from hillslopes and subsurface bedrock fractures. (Arrigoni et al., 2002; Fernald et al., 2006). These patches are likely enhanced by the processes that promote alcoves and side channels, and therefore channel complexity. Because restoration of native aquatic biota such as salmon, lamprey, and mussels depends on the hydraulic and thermal diversity that accompanies channel complexity, maintaining and promoting the genetic processes of channel-landform complexity is a priority in ecological management of the Umatilla River.

Most floods in northeastern Oregon occur from November through April, with large floods resulting from rain-on-snow events in mountain areas (Harris and Hubbard, 1983). Floods in December 1964 and January 1965 were among the largest recorded at the time of their occurrence (see Tables 1a-b in Chapter III), producing widespread geomorphic changes to channel-floodplain systems and damaging human infrastructure (Waananen et al., 1971). Developing a better understanding of flood disturbance, its influence on the evolution of mountain river systems, and its role in shaping riverine habitats of the Interior Pacific Northwest is a major research priority in regional river management and restoration (NRC, 1996; Beschta, 1997). The 1964-65 and 1975 floods on the Umatilla River, coupled with the availability of aerial photos and streamflow records during and between flood periods, provide an excellent opportunity to examine the nature and variability of channel complexity with respect to floods and their associated geomorphic processes in a mixed multi-channel river system.

3. Methods

Streamflow records were used in conjunction with aerial photos collected in 1964, 1971, 1974, and 1977 (see Table 2 in Chapter III) to define two flood periods and one interflood period (see Figure 2 in Chapter III). The periods 1964-1971 and 1974-1977 are Flood Periods 1 and 2 (FP1, FP2), respectively, while 1971-1974 is an interflood period (IFP). Recurrence intervals of the floods of FP1 and FP2 ranged from 17 to 37 years. The 1965 flood had a larger recurrence interval at the downstream gage at Pendleton (35 years at Pendleton, 19 years at Gibbon), whereas the 1975 flood had a larger recurrence interval at the upstream gage at Gibbon (17 years at Pendleton, 37 years at Gibbon) (see Tables 1a-b in Chapter III). FP1 includes two flood events, whereas FP2 includes only one (see Figure 3 in Chapter III). The IFP also includes a flood event with a recurrence interval of approximately 4-6 years. Since this event is not a major flood, it was considered to be part of normal hydrological variation within the IFP. Aerial photos were scanned at a resolution of 800 dots per inch and georectified to digital orthophoto quadrangles (DOQs; USGS, 1994) in a GIS using a second-order polynomial transformation. Pixel size was approximately one square meter. Root-mean-square-error (RMSE) for georectification was three meters or less. Empirical testing of georectification accuracy demonstrated a spatial accuracy of approximately five meters or less for 90% of independent test points (Hughes et al., 2006). The 1971 aerial photos were collected when the river was flowing at 524-775 ft^3/s, whereas the river flowed at 54-88 ft^3/s at the time of the other photo sets (see Table 2 in Chapter III). Because river stage affects inundation of channel surfaces, it affects remotely sensed measurements of channel complexity, as herein defined. To examine this effect we digitized the dry surfaces according to our channel classification from photos of two reaches of the Umatilla River a few weeks apart and at slightly different streamflow rates (Table 1). These reaches represent areas wherein one subset of photos taken on one day overlaps with photos taken within the same set on a different day with a different flow rate. Results show that at relatively low stage, an increase in channel discharge slightly decreased the measured channel complexity, whereas at a relatively high stage (but less than half the bankfull flow) an increase in discharge increased channel complexity as bars and islands are dissected. These results suggest that within the streamflow range assessed in this study, complexity measurements are not dependent on discharge. Thus, complexity values, both within and across photo sets, are assumed to be operationally comparable.

A four-unit classification system of geomorphic surfaces within the active channel (see Figure 4 in Chapter III) was developed and applied to the 37-km segment the Umatilla River between the Meacham and Wildhorse Creek confluences (see Figure 1 in Chapter III). The geomorphic surfaces are: (1) low flow channels, (2) bars, (3) scoured areas, with and without well developed high-flow channels, and (4) vegetated areas. ESRI ArcGIS software was used to digitize polygons following the channel classification. Low-flow channels included the primary channel and secondary channels that were at least half as wide as the primary channel at the point of confluence. Narrow channels (less than half as wide as the primary channel) were classified as high-flow channels and were included in the polygons of bars, scoured areas, or vegetated surfaces. Bar polygons were defined as barren areas having a typical barform, such as point, diagonal, or mid-channel (Church and Jones, 1982). Both simple and compound bars were digitized as single polygons. Scoured areas were defined as barren areas that were channel-like or amorphous in shape, and lacked a conventional barform. These surfaces were interpreted as erosional landforms. Vegetated surfaces were defined as land areas that were completely surrounded by (low-flow or high-flow) channels, and that had no less than a 50% cover by a combination of grassy, shrubby or woody vegetation. The active channel included all low-flow channels, bars, scoured areas, and vegetated surfaces (as herein defined). Individual files were digitized for each of the four units for each photo year at a scale of approximately 1:1,000.

Lateral channel movement was measured by digitizing channel centerlines from each of the photo years, buffering these centerlines (to account for geospatial error), overlaying buffered centerlines for sequential channel positions, and extracting the area of the polygon created between the outer channel buffers. Buffer magnitude was five meters on each side of the centerline, which accounted for geospatial error on over 90% of the points tested for georectification accuracy (Hughes et al., 2006). Lateral movement measured by this method represents the maximum probable displacement of two channel centerlines, thus the method can overestimate true lateral movement, but it provides a reasonable proxy for purposes of this analysis. The floodplain boundary was mapped based on floodplain soils (Johnson and Mankinson, 1988) and topography.

Channel change was analyzed by dividing the floodplain into 200-m cells along the floodplain axis, overlaying the cells on the polygons representing and then extracting the areas of lateral movement and the active channel for each cell. Changes in channel width were calculated by dividing the area of the active channel within each cell and then dividing it by 200 m. Channel complexity was measured by calculating the number of individual geomorphic surfaces (polygons) within each 200-meter cell (following Graf, 2006). Changes in channel width and complexity changes were quantified by calculating the 1-km moving average value for each photo year and then subtracting the earlier from later value for each of the study periods (FP1, the IFP, and FP2). The 200-meter cell was chosen because it is a large enough distance to incorporate changes in large channel units (such as bars and islands), while the one-kilometer moving average was used because it reflects a scale on which interactions among channel units occur, thereby affecting complexity.

4. Results

Channel complexity was highly variable over space (Figure 1) and time (Figure 2), ranging from approximately 1.6 to 10.4 surfaces per 200-m of floodplain over the study period (Table 2). The mean, median, maximum, and minimum channel complexity values decreased during flood periods FP1 and FP2, and increased during the IFP. Areas of large complexity loss during flood periods generally correspond to channels with narrow floodplains, which were laterally confined by bedrock valley walls, terraces, or both. Between flood periods complexity rebounded in these areas. Thus, floodplain width appears to be a factor controlling changes in complexity over time.

Lateral channel movement was higher during FP1 and FP2 than during the IFP (Figure 3). During FP1, low values of lateral movement generally corresponded with complexity loss, whereas high rates of lateral movement corresponded with complexity gain. Conversely, during the IFP low rates of lateral movement corresponded with complexity gain, whereas high rates of lateral movement corresponded with complexity loss. During FP2, as in FP1, low rates of lateral movement corresponded with complexity losses; however, unlike FP1, no relation between high lateral movement and complexity was apparent during FP2. Relations between complexity change and lateral movement were more generally more evident for values of high lateral movement.

The channel generally widened during FP1, narrowed during the IFP, and widened again during FP2 (Figure 4). The relationship between complexity change and channel-width change was similar to that of complexity change and lateral movement during FP1; complexity increased in association with large values of widening. Relations between complexity and width changes during the IFP and FP2 were varied. During the IFP large narrowing values were as likely to correspond to increased complexity as to decreased complexity. In contrast to FP1, large widening values were more frequently associated with complexity loss during FP2.

5. Discussion

Channel complexity generally decreased during flood periods and increased during the interflood period, but with spatial variability. Loss of complexity during flood periods was high in reaches with narrow floodplains, which were laterally confined by bedrock valley walls, terraces, or both. These features promote constriction of flood discharges, thereby increasing shear stress and stream power (Fuller, 2007) and magnifying channel disturbance. These effects likely promote simplification of channel landforms by increasing sediment transport and incision, which decreases lateral connection to bars and floodplains. Complexity increased, or complexity loss was less, during flood periods in wider floodplains, where stream power is lower, sediment is more likely to be deposited, and large bars are built. In these areas, channels gain complexity as aggradation drives channels to split around bars and islands. These interpretations are generally consistent with the results of Benda (1994), which differentiates between areas that process sediment in vertical cut-and-fill cycles from those that respond mainly by lateral channel movement.

Temporal oscillation of complexity mirrors spatial oscillation of complexity, and both are consistent with conceptualized changes in habitat (complexity) described by Revees et al. (1996). In the Reeves et al. model, complexity is positively linked to sediment supply, which oscillates in response to the movement of sediment pulses through the channel system. As a pulse moves through a reach, channel complexity first increases in conjunction with high sediment supply and aggradation, but then decreases in conjunction with low sediment supply and degradation (Miller and Benda, 2000). To the author's knowledge, the present study is the first to empirically measure oscillation of channel complexity over space and time. While these measurements support the conceptual model of Reeves et al. (1996), variation in the frequency and amplitude of the observed oscillation, which are believed to reflect localized sediment import and export cycles, remains largely unexplained. Future studies should include detailed surveys of the river's profile in order to evaluate whether fluctuations in channel complexity can be explained by the presence and evolution of sediment waves along the channel corridor. If this explanation is valid, then differences in the magnitude of complexity changes observed in narrow versus wide reaches should be evidenced in morphological differences in the expression of sediment waves across these domains. Future work should also attempt to differentiate the impacts of different lateral movemement processes on complexity. This may help to determine which processes, or groups of processes, are most important in the generation of channel complexity.

The physical complexity of the Umatilla River, a quantifiable and ecologically significant property, responded to flood disturbance in a way that is predicted by the IDH. This result provides evidence that conceptualized changes in aquatic biodiversity are likely moderated by changes in the physical complexity of the channel environment. Thus, the IDH provides a conceptual bridge that links the abiotic and biotic components of riverine ecosystems, as well as a logical basis for making predictions about changes in aquatic biodiversity in response to externally forced environmental changes. Complexity loss over the entire study period (1964-1977) provides further evidence that the effects of superimposed disturbances may be particularly significant. Overall loss of complexity during 1964-1971 was most obvious in the lower reaches of the study area near river kilometers 82-95 (Figure 5), where the floodplain is wide and complexity rebound during the IFP was limited. This portion of the channel has been channelized and leveed. Some of this work was done in the study period, therefore loss of complexity in this area may have been amplified by human disturbance. River managers who wish to promote channel complexity as a means to naturalize or restore the Umatilla River should target this area. Strategies that would enhance the river's ability to make large lateral movements during floods may help to increase the complexity, and perhaps the hydraulic diversity, of the channel system.

6. Conclusion

Channel complexity generally decreased during flood periods and increased during the interflood period. Loss of complexity during flood periods occurred in conjunction with channel widening and large lateral channel movements. Complexity loss during floods was greatest in areas with narrow floodplains, where confinement of the channel by bedrock, terraces, or levees promotes excessive stream power, erosion, and incision. Complexity loss was less, or complexity increased, in wider floodplains, where sediment is likely deposited during floods promoted and large lateral movements that substantially changed the channel landforms. Loss of channel complexity during individual and combined flood periods, and rebound in complexity between flood periods, supports application of the intermediate disturbance hypothesis to channel-landform systems. Channelization in the lower part of the study area appears to have partially limited recovery of complexity during the interflood period, thereby amplifying complexity loss. Oscillation of channel complexity over space and time was consistent with previously conceptualized changes in habitat complexity, which have been linked to cycles of degradation and aggradation driven by the passage of sediment pulses in large channel systems. Although many aspects of this oscillation remain unexplained, including variation in its frequency and amplitude, floods clearly play a role in driving channel complexity; however, this role apparently depends on factors such the geomorphic setting, human impacts, and sediment supply. Developing a better understanding of these factors will be a necessary element of managing and restoring simplified river landscapes.

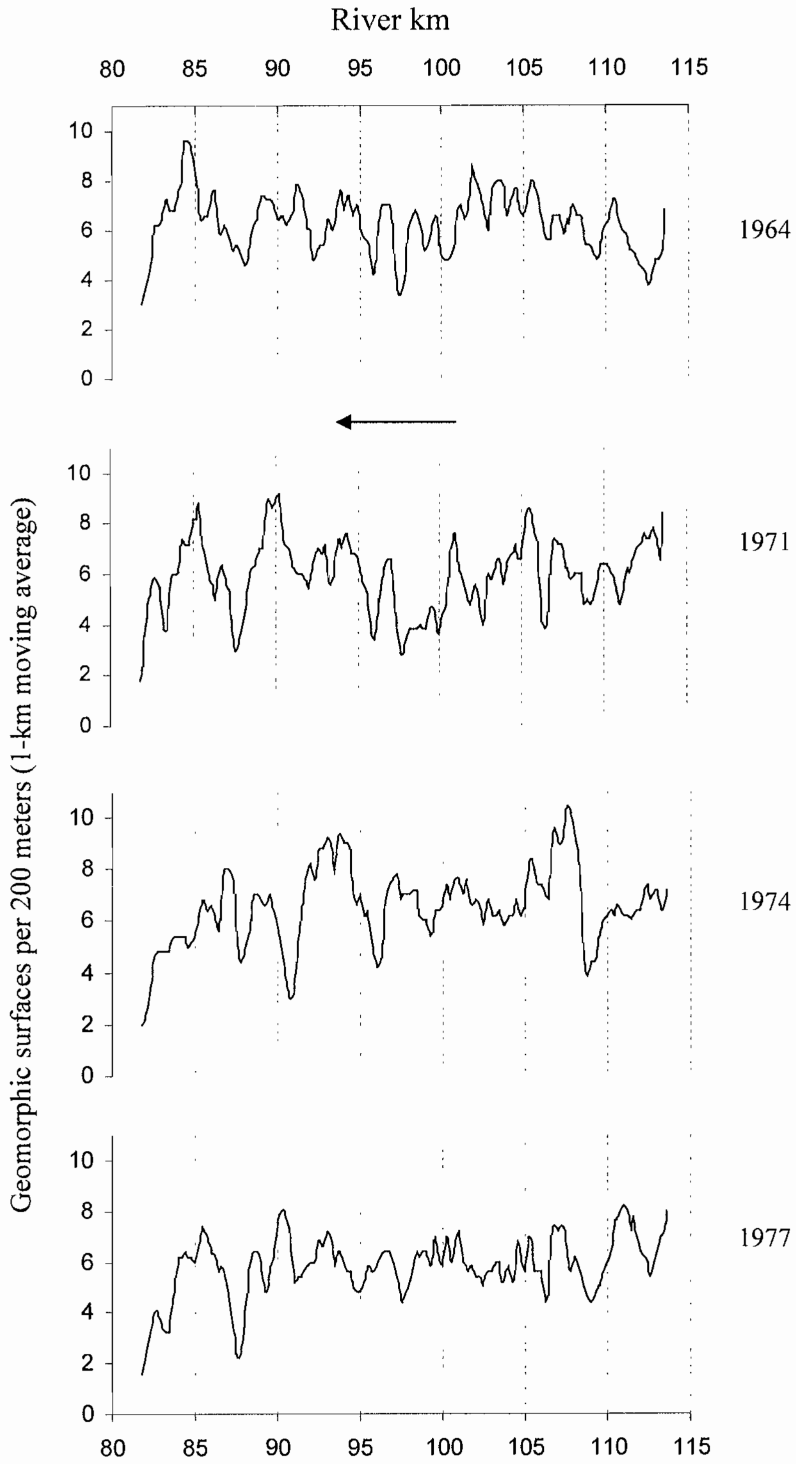


Figure 1. Downstream changes in channel complexity: 1964, 1971, 1974, 1977

River km

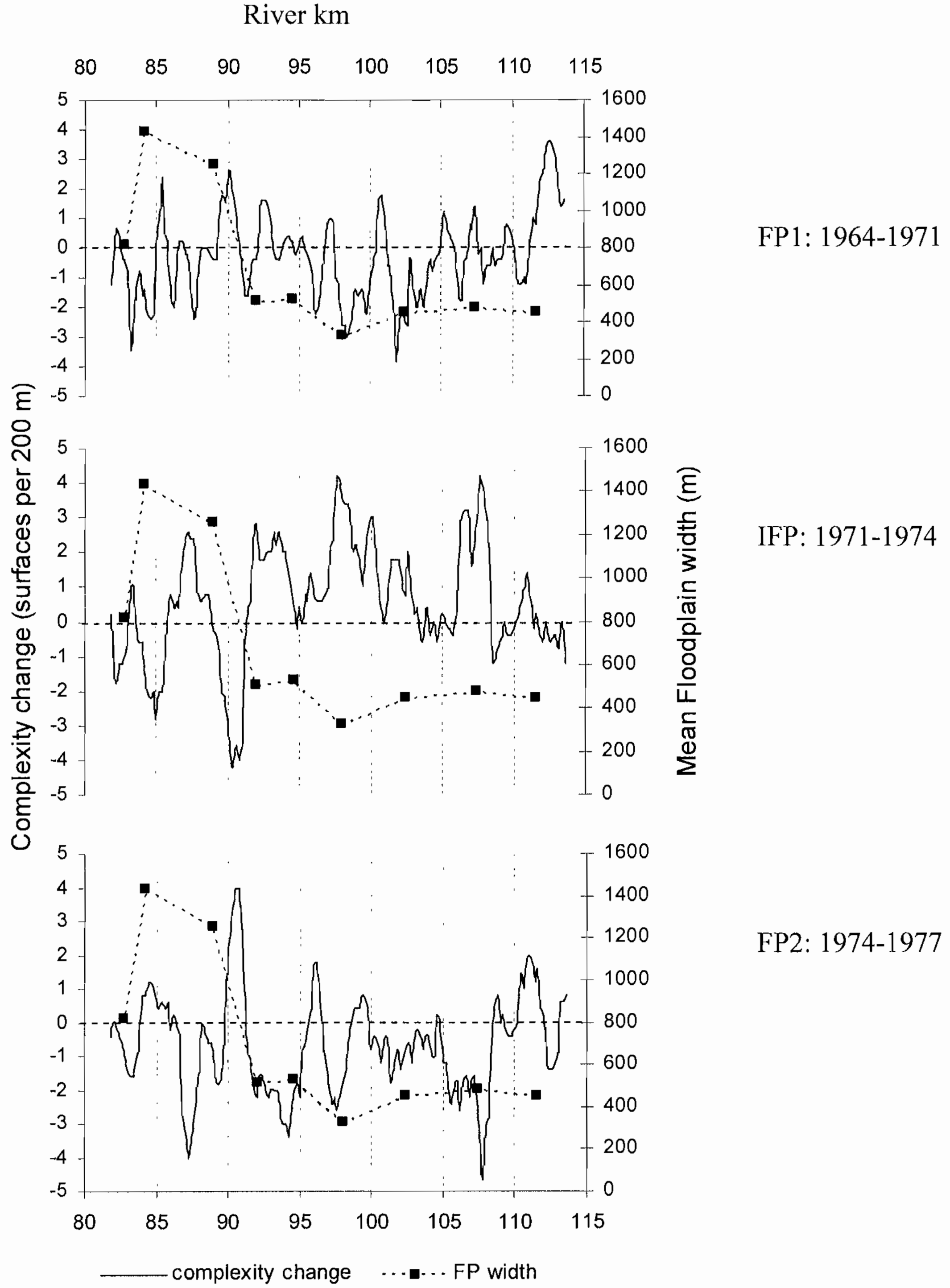


Figure 2. Changes in channel complexity (1-km moving average of geomorphic surfaces per 200 m) and floodplain width: 1964-1971, 1971-1974, 1974-1977

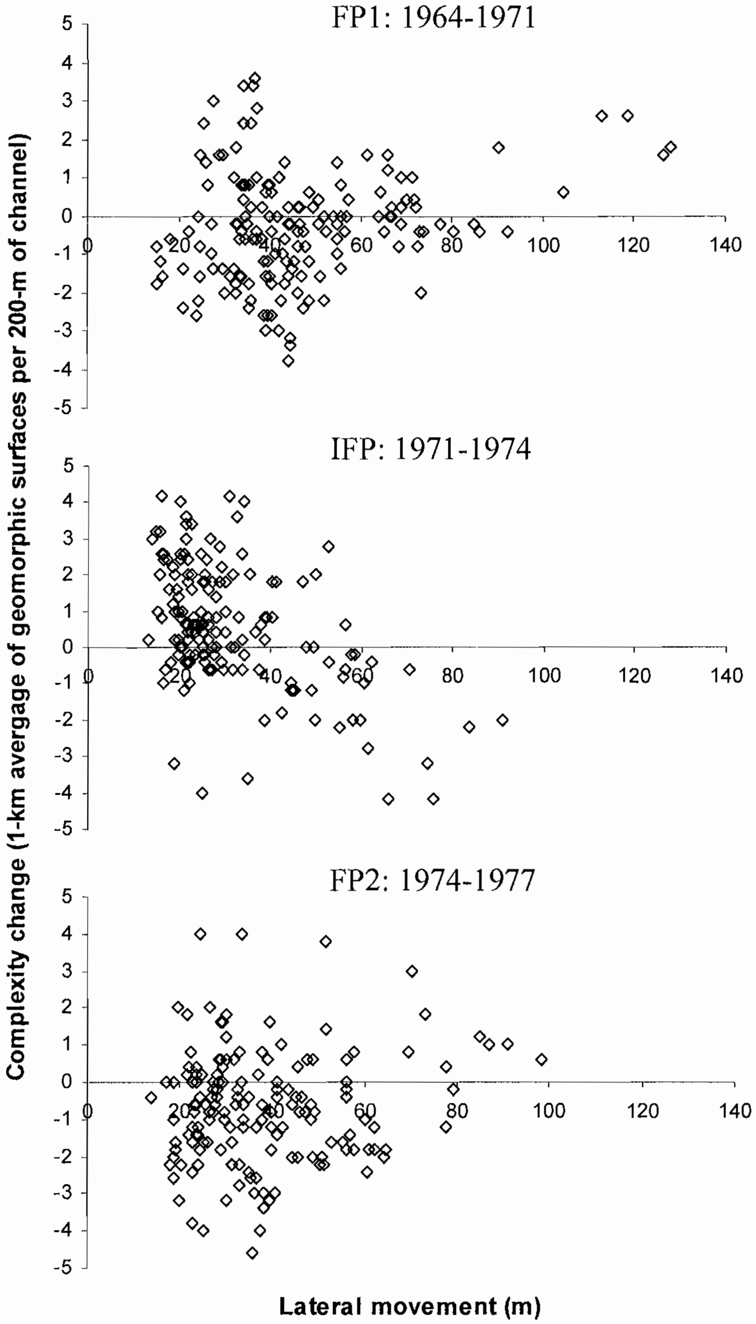


Figure 3. Complexity change versus lateral movement: 1964-1971, 1971-1974, 1974-1977

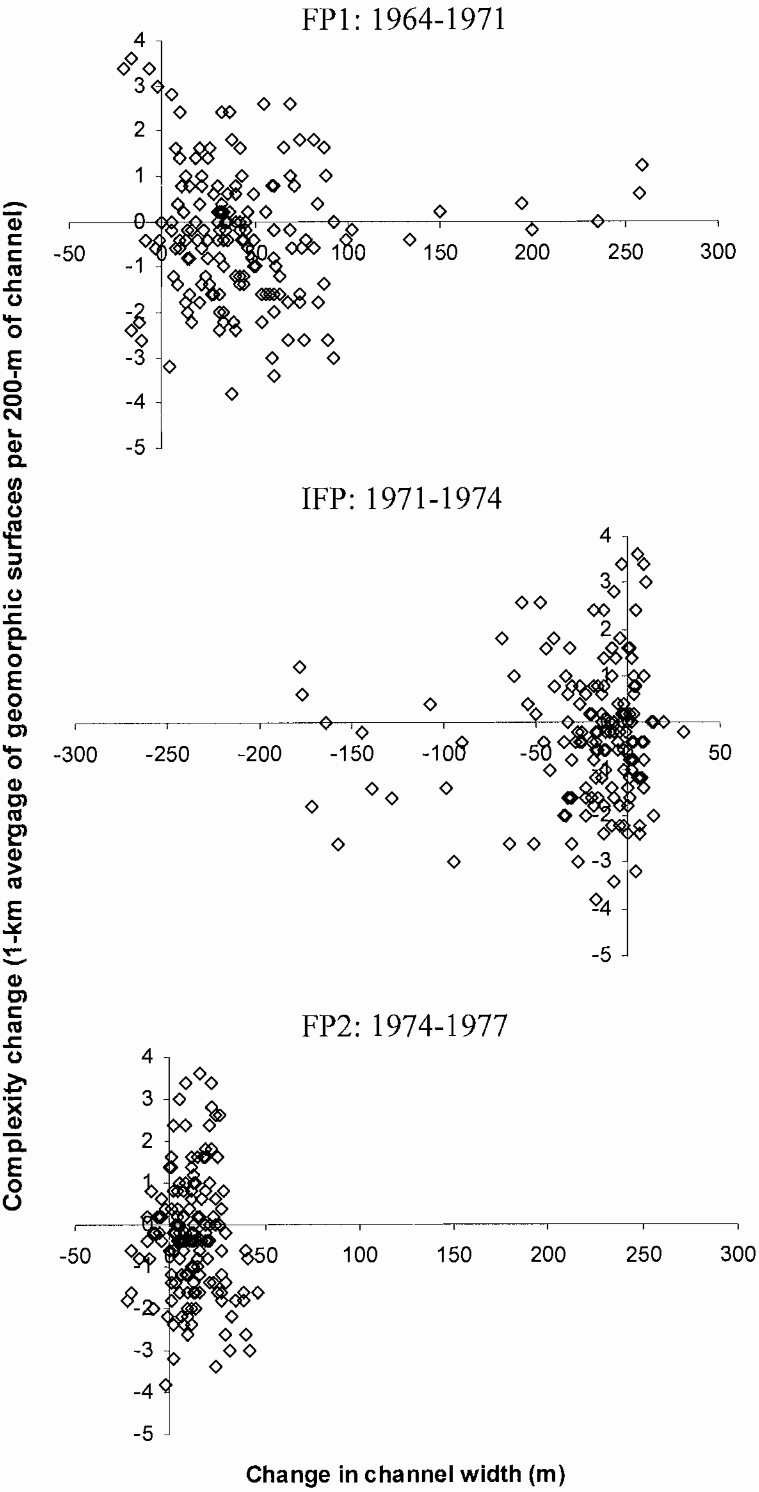


Figure 4. Complexity change versus change in channel width: 1964-1971, 1971-1974, 1974-1977

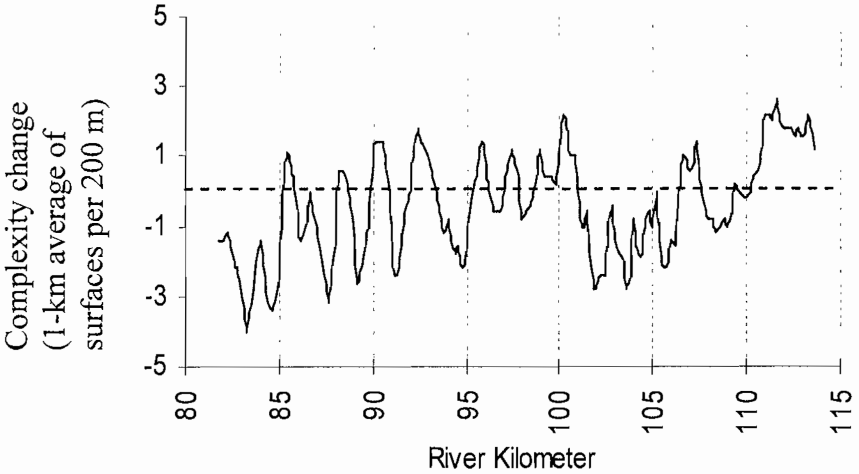


Figure 5. Changes in channel complexity 1964-1971

Table 1. Number and spatial density of geomorphic surfaces above the flow margin for aerial photos in 1964 and 1971

Photo year	Photo date	Streamflow (cfs)	Length of channel (m)	Number of Surfaces Above Flow Margin	Surfaces / 200 m
1964	8/6/1964	54	4144	31	1.5
	7/17/1964	85	--	29	1.4
1971	5/22/1971	524	2781	26	2.4
	5/11/1971	775	--	33	1.9

Table 2. Indices of channel complexity and its changes, 1964-1977

Indices of channel complexity (1-km moving average of # of surfaces / 200-m floodplain axis), n = 160

	Mean	Median	Max	Min	Standard Deviation
1964	6.3	6.4	9.6	3.0	1.2
1971	6.0	6.0	9.2	1.8	1.4
1974	6.5	6.6	10.4	2.0	1.5
1977	5.8	6.0	8.2	1.6	1.2

Changes in indices of channel complexity (1-km moving average of # of surfaces / 200-m floodplain axis), n = 160

	Mean	Median	Max	Min	
FP1 (1964-1971)	-0.3	-0.4	-0.4	-1.2	--
IFP (1971-1974)	0.6	0.6	1.2	0.2	--
FP2 (1974-1977)	-0.7	-0.6	-2.2	-0.4	--
All Periods (1964-1977)	-0.4	-0.4	4.0	-5.0	--

CHAPTER V

CONCLUSION

In this dissertation I have presented: (1) the development and application of an error-sensitive aerial photo-based planform channel-change detection and measurement methodology, (2) an examination of the occurrence, variability, and landform impacts of channel widening, straightening, and lateral movement during two mid-to-late 20th century flood periods, and (3) an investigation of the effects of these floods on channel complexity, a proxy of habitat quality and indicator of ecological health in multi-channel rivers. A summary and synthesis of each of these components are as follows.

Sources of error in aerial-photo based measurements of historical channel change included georectification error, which affects the spatial accuracy of digitized channel maps, and comparison error, which stems from the effects of variable river stage shown on photos within and across photo sets. The effects of georectification error in measurement of lateral channel movement were treated with an empirically derived 5-meter buffer of channel centerlines. This buffer accounted for the spatial error of 90% of the test points. Lateral movement was then reported as the area of displacement between the outer buffers of sequential channel positions, which represented the maximum probable displacement of the channel and a liberal proxy of true channel movement. Error driven by comparison of river geomorphology at different flow levels error was treated in by excluding minor channels that were relatively are sensitive to sub-bankfull fluctuations in flow and by attributing the difference of inundated areas during high versus low flows to the area of channel bars. Empirical evaluation of the effects of inundation on channel complexity suggested that differences in the flow levels included in this study did not systematically affect channel complexity measurements; therefore, no corrections were applied.

Planform channel change of the Umatilla River during two flood periods (FP1, 1964-1971; FP2, 1974-1977) and an interflood period (IFP, 1971-1974) was generally consistent with theories emphasizing increases in channel dimensions and rates of change in response to floods, but only partially consistent with theories of structural controls of channel systems. Large lateral movements, widening, and straightening of the channel, coupled with widespread increases in bars and scoured areas, characterized channel change during FP1. Conversely, smaller lateral movements, channel narrowing, increases in sinuosity, and decreases in bars and scoured areas characterized the IFP. Large lateral movements and widening of the channel, and widespread increases in scoured areas were again evident during FP2, but were generally lower in magnitude than in FP1, reflecting a dampened response associated with continued recovery from the floods of FP1. Changes in sinuosity during FP2 were mixed, with some reaches increasing and others decreasing in sinuosity. Spatial variability of sinuosity change was poorly explained by differences in geomorphic setting. Instead, the relative frequency of lateral movement processes that inherently promote channel straightening (cutoffs and avulsions) versus those that promote static sinuosity (downstream translation) or channel elongation (lateral extension) drove the largest changes in sinuosity, suggesting intrinsic controls on sinuosity.

Lateral movement and channel widening were most limited in reaches with narrow floodplains and low average sinuosity over the study period. This result is generally inconsistent with studies emphasizing high-magnitude channel changes in structurally confined settings. In the narrowest three reaches, increases in scoured areas were greater than increases in bars or vegetated areas during FP1. In the other reaches except Reach 6, increases in bars were greater than increases in scoured or vegetated areas, thereby suggesting a threshold of floodplain width and/or sinuosity above which bar accretion (i.e., sediment deposition) is favored over erosion as the dominant channel-change process. The effects of such a threshold in Reach 6 may have been counteracted by channel structures, which confine the channel and mimic the effects of natural confinement observed in reaches with narrower floodplains.

Channel complexity generally decreased during flood periods and increased during the interflood period. Loss of complexity during flood periods occurred in conjunction with channel widening and large lateral channel movements. Complexity loss during floods was greatest in areas with narrow floodplains, where confinement of the channel by bedrock, terraces, or levees promotes excessive stream power, erosion, and incision. Complexity loss was less, or complexity increased, in wider floodplains, where sediment is likely deposited during floods promoted and large lateral movements that substantially changed the channel landforms. Loss of channel complexity during individual and combined flood periods, and rebound in complexity between flood periods, supports application of the intermediate disturbance hypothesis to channel-landform systems. Channelization in the lower part of the study area appears to have partially limited recovery of complexity during the interflood period, thereby amplifying complexity loss. Oscillation of channel complexity over space and time was consistent with previously conceptualized changes in habitat complexity, which have been linked to cycles of degradation and aggradation driven by the passage of sediment pulses in large channel systems. Although many aspects of this oscillation remain unexplained, including variation in its frequency and amplitude, floods clearly play a role in driving channel complexity; however, this role apparently depends on interrelated factors such geomorphic setting, human impacts, and sediment supply.

Whereas emerging theories concerning the evolution of laterally active multi-channel river systems have emphasized flood-driven avulsions as the primary mechanism of channel-floodplain interaction and maintenance of the channel pattern, this study has demonstrated the importance of lateral scour in the capture of vegetation into the active channel. While this process may lead to avulsion, it appears to affect channel-vegetation interactions by itself and is therefore an important process affecting the assemblage, complexity, and functionality of channel landforms. Other results of this dissertation are broadly congruent with theories (and their corollaries) emphasizing adjustment of channel dimensions, increased rates of change, and reduced complexity in response to flood disturbance, but only partially consistent with theories emphasizing large geomorphic changes in structurally confined settings. These results support the idea that biocomplexity and geocomplexity are intertwined in riverine ecosystems, and highlight the importance of understanding the nature, relative frequency, and space-time variability of specific processes in characterizing the planform dynamism of multi-channel, gravel-bed mountain rivers. Results further illustrate that models of process-form relations that fail to explicitly account for the spatial or temporal variability of the processes and landforms would have limited applicability in management or restoration of the Umatilla River or other rivers with similar landforms and disturbance histories.

Managers attempting to balance naturalization of river corridors with the control and/or mitigation of flood impacts on human communities and infrastructure should recognize that fluvial processes and their relations with channel landforms are variable. Two types of variability have been highlighted in this study: (1) spatial variability, and (2) temporal variability. Channel changes were generally greater in wider floodplain settings (Reaches 7-9), so these areas may have more response to potential future projects aimed at restoring naturalistic geomorphic processes. Channel changes in Reach 8, which was channelized previous to the study period, were among the lowest in magnitude across the study area. While the lack of geomorphic changes in this reach evidences the effectiveness of previous flood-control activities, such activities inhibit lateral movement and overbank flow, which have been shown in this study as crucial in the creation and maintenance of vegetation within the active channel.

Should the need or opportunity arise to manage the Umatilla River in a way to promote channel complexity, or greater interaction of the channel with riparian vegetation, Reach 8 may be an appropriate area to target. Strategies that would enhance the river's ability to make large lateral movements during floods may help to increase the complexity, and perhaps the hydraulic diversity, of the channel system. In this case, however, some homes and businesses in this area would likely have to be set back from the channel or relocated out of the floodplain to allow for increased flooding and channel movement. Successfully mitigating the hazardous effects of future floods on the Umatilla River may require recognition that the river adjusts to extreme events and such adjustments have the ability to reduce the effects of future floods. Because major floods on the Umatilla River have occurred in clusters, river managers may benefit from accepting the geomorphic effects of major floods, when and where possible, instead of attempting expensive projects to alter the channel or return it to pre-flood conditions.

Future work should attempt to resample variables of channel change at a finer spatial scale to explore potential linkages that may be absent at the (reach) scale addressed in this study. Future work should also involve a detailed survey of channel slope and cross-sections, which would allow for calculation of unit stream power. Using stream power, future researchers could test the explanations of variability in channel changes offered in this study and develop exploratory models that may provide deeper insights into unexplained channel behaviors. A detailed channel profile could also support evaluation of whether fluctuations in channel complexity can be explained by the presence and evolution of sediment waves along the channel corridor. If this explanation is valid, then differences in the magnitude of complexity changes observed in narrow versus wide reaches should be evidenced in morphological differences in the expression of sediment waves across these domains. Lastly, future work should also attempt to differentiate the impacts of different lateral movement processes on channel complexity. This may help to determine which processes, or groups of processes, are most important in the generation of physical complexity in fluvial systems.

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