ABSTRACT

LAND USE AFFECTS ON MODERN BANKFULL HYDRAULIC GEOMETRY IN SOUTHWEST OHIO AND ITS IMPLICATIONS FOR STREAM RESTORATION

by Elizabeth J. Ellison

Channel morphology is affected by land use change nationwide. In Southwest Ohio, streams are influenced by agricultural and urban landscapes. The purpose of this study was to determine how agricultural and urban landscapes alter the modern bankfull hydraulic geometry within five watersheds: Upper Four Mile Creek, Indian Creek, Harkers Run, Marshalls Branch and Bull Run. A combination of field and LiDAR data were used to determine the bankfull channel geometry. Recurrence intervals of bankfull hydrology were determined from Log-Pearson Type III distribution of peak annual discharges for two streams. Analysis shows that four out of the five streams have bankfull channels larger than expected based on hydrologic and regional indicators. However, Upper Four Mile Creek does not appear to have an enlarged channel, most likely a result of base level rise from downstream dam construction. Accurate identification of bankfull hydraulic geometry is essential for effective stream restoration and management projects.
LAND USE AFFECTS ON MODERN BANKFULL HYDRAULIC GEOMETRY IN SOUTHWEST OHIO AND ITS IMPLICATIONS FOR STREAM RESTORATION

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INTRODUCTION

Land use change since Euro-American settlement in the Eastern U.S. has transformed channel morphology and hydrologic regime in many watersheds. The impacts of land use change on stream systems began to be realized in the early 20th century (Costa, 1975; Birch and Wharton, 1983; Knox, 2001). During the 1960s, the United States Geological Survey conducted extensive research to understand the specific impacts that land use change has on streams (Wolman, 1967; Chin, 2006). Among the findings was that a change in land use alters the sediment yield and hydraulic regime in streams (Leopold and Maddock, 1953; Wolman, 1967; Dunne and Leopold, 1978). The change in land use induces a common sequence of events that occur within alluvial streams. These events include aggradation and degradation of the stream bed as they adjust to fluctuations in discharge, local channel slope, and sediment supply (Leopold and Maddock, 1953; Dunne and Leopold, 1978).

Stream restoration has emerged as a means to improve aquatic systems by returning streams to their pre-disturbed state (Shields et al., 2003; Wohl, 2005; Wohl et al., 2005). The pre-disturbed state of streams can be seen as a reference condition to guide stream restoration projects. Stream restoration seeks to restore streams either based on (1) the aesthetic appeal or (2) function, and (3) sometimes both (Wohl, 2005; Wohl et al., 2005). Projects that are concerned with restoring stream function are typically on a larger scale, focusing on processes that sustain aquatic and riparian habitat. On the other hand, aesthetic-restoration typically occurs on a local-reach scale focusing on the visual perception of the river (Kondolf et al., 2002; Wohl, 2005). Some approaches to stream restoration consist of riparian set-back ordinances (see Ritter et al., 2007), “natural” channel-design (see Rosgen, 1994; Rosgen, 1997; Shields et al., 2003), and two-stage ditches (see Powell et al., 2007; Biske et al., 2007). All of these require quantitative estimates of desired channel size.

Reconstructing streams to a pre-disturbed state is difficult because we know that the landscape will never return to its condition before the initial human-disturbance. Therefore, we rely on accurate determination of the modern bankfull channel geometry to approach stream restoration projects (Doll et al., 2002; Sweet and Geratz, 2003; Sherwood and Huitger, 2005). Bankfull refers to the elevation in the channel where the flow begins to spill onto the active floodplain (Leopold et al., 1964; Leopold and Dunne, 1978). Flows at this stage typically carry large amounts of sediment over time. Therefore, it is at bankfull stage that the flow is able to sustain the channel form (Leopold and Maddock, 1953; Wolman and Miller, 1960). However, land use disturbance alters the channel behavior thereby changing the bankfull channel geometry.

Creation of empirical bankfull hydraulic geometry relationships, also known as regional curves is commonly used to estimate the bankfull measurements for stream restoration projects (Dunne and Leopold, 1978; Doll et al., 2002; Sweet and Geratz, 2003). Bankfull hydraulic geometry relationships are created for different physiographic regions because of influences of different topography, underlying geology, and vegetation (Doll et al., 2002; Sweet and Geratz, 2003). However, for highly disturbed watersheds these bankfull hydraulic geometry relationships may not be accurate to determine bankfull measurements. Inaccurate determination of bankfull channel geometry can result in ineffective stream restoration projects.
To create effective stream restoration we need an improved understanding of modern stream channel geometry and the factors that influence it, including topography, vegetation, climate and land use disturbances. Current approaches to stream restoration use minimal scientific understanding of streams to approach stream management (Shield et al., 2003; Wohl, 2005; Wohl et al., 2005). The lack of effective communication between scientists and stream managers is one of several limitations to the stream restoration process (Wohl et al., 2005). To improve the science of stream restoration, further studies must be conducted and monitored long-term to understand the complexities of entire watersheds (Wohl et al., 2005). Continued studies on local-watersheds will provide stream restoration managers with the scientific context to proceed with effective stream restoration.

This study seeks to improve our understanding of the controls on stream channel characteristics on local watershed scales. Its purpose is to determine how agricultural and urban land use have affected modern bankfull hydraulic geometry within Southwest Ohio. Five streams were used, including Upper Four Mile Creek, Indian Creek, Harkers Run, Marshalls Branch and Bull Run. The modern bankfull channel geometry was identified from field surveys and LiDAR-extracted cross-sections. Bankfull hydrology was determined from Log-Pearson Type III distribution for two gauged streams, Upper Four Mile Creek and Marshalls Branch. The modern bankfull channel geometry was compared between agricultural and urban watersheds to identify the land use effects on bankfull channel geometry and hydrology. The bankfull hydraulic geometry for the five watersheds is also compared to regional bankfull predictions for the state of Ohio to see if channel form and flow is consistent with state measurements (Sherwood and Huitger, 2005).

BACKGROUND

Hydraulic Geometry

Hydraulic geometry is the quantitative relationship between channel form (channel depth, width, meander wave length) and hydraulic variables (mean velocity, mean channel slope) for a given flux in discharge and sediment load (Leopold and Maddock, 1953; Dunne and Leopold, 1978). Simple power functions conceptualize hydraulic geometry relationships:

\[ w = aQ^b \]
\[ d = cQ^f \]
\[ v = kQ^m \]
\[ L = pQ^j \]

where \( w \) is the channel width, \( d \) is the mean depth, \( v \) is the mean velocity, \( L \) is the suspended-sediment load (in units of mass per time), \( Q \) is the discharge and \( a, b, c, f, k, m, p, \) and \( j \) are all numerical constants (Leopold and Maddock, 1953). Hydraulic geometry relationships are sensitive to changes in hydrology, sediment load and land use of a watershed (Doll et al., 2002).

Determining the hydraulic geometry of a stream is relatively easy for a stream that is in a state of equilibrium or quasi-equilibrium (Ritter et al., 2007). The equilibrium or quasi-equilibrium channel is characterized by a balance of inputs and outputs with a distinguishable channel form and pattern, and returns relatively quickly after disturbance (Leopold and Maddock, 1953; Renwick, 1992). Some streams, however, are in a state of disequilibrium. These streams are characterized by a disconnection between channel form and process making it
more difficult to determine hydraulic geometry (Leopold and Maddock, 1953; Dunne and Leopold, 1978; Renwick, 1992).

**Bankfull Characteristics**

Bankfull refers to the elevation in the channel at which the flow fills the channel to the level of the active floodplain (Leopold et al., 1964; Leopold and Dunne, 1978). Bankfull events typically are the most effective at carrying sediment through a range of flow magnitudes (Simon et al., 2004; Crowder and Knapp, 2005). Therefore, bankfull is defined and measured by channel morphology, but is also linked to hydrology and geomorphic work. In an equilibrium channel, bankfull flow is typically observed with a recurrence interval of 1-3 years, and flows of this magnitude are expected to transport more sediment over time compared to smaller or larger flows. Thus, we would expect that the morphological bankfull discharge, the 1.5-year flow and the flow that transports the most sediment to be approximately the same (Simon et al., 2004; Crowder and Knapp, 2005). For a channel in disequilibrium, we might expect significant differences among these three bankfull measurements.

![Figure 1](image.png)

**Figure 1** Schematic graphic illustrating bankfull channel features and floodplain surfaces. Active-channel stage is not addressed within the context of this study. (Diagram taken from Sherwood and Huitger, 2005)

The morphologic bankfull is defined by the development of an active-floodplain. The active floodplain is the flat-depositional surface immediately adjacent to the stream formed during the present climatic-conditions (Figure 1; Dunne and Leopold, 1978; Sherwood and Huitger, 2005). Abandoned floodplains that are no-longer hydrologically connected to the stream are referred to as terraces (Dunne and Leopold, 1978). Other physical attributes that distinguish bankfull channel features are changes in vegetation, fine-deposition (i.e. sand) on-top of banks, and sharp breaks along the channel banks (Harrelson et al., 1994; USDA Forest Service, 2003).

In a disequilibrium channel, bankfull morphologic features are less distinguishable. Channels in a state of disequilibrium have typically have incised into the basal channel gravels and underlying deposits (Ritter et al., 2007). Within the incised channel, incipient meander migration begins to reconstruct bankfull morphologic features. The redefined features are sometimes referred to as benches or incipient floodplains (Landwehr and Rhoads, 2005; Ritter et al., 2007; Jayakaran and Ward, 2007). The development of these features suggests that the stream is attempting to reestablish a state of equilibrium and thereby redefining the bankfull morphologic features (Landwehr and Rhoads, 2005).
Flow frequency is also a useful indicator of the bankfull channel (U.S. Water Resources, 1982; Simon et al., 2004; Crowder and Knapp, 2005; Sherwood and Huitger, 2005). Studies in the humid-continental U.S. indicate that bankfull discharge in alluvial streams occurs at a recurrence interval between 1-5 years, and is more commonly observed between 1.5-2 years (Simon et al., 2004; Crowder and Knapp, 2005; Ritter et al., 2007). For an equilibrium channel, this flow will also produce the greatest amount of geomorphic work.

Some argue that a single recurrence interval for bankfull discharge is not universally recognizable (Crowder and Knapp, 2005; Powell et al., 2006). The argument is that local channel slope influences the recurrence interval of the bankfull discharge and the higher-gradient channel tends to inundate its floodplain less frequently (Sherwood and Huitger, 2005; Dunne and Leopold, 1978). Other factors that influence the recurrence interval include drainage area, land use, channel geometry and hydrologic regime (Dunne and Leopold, 1978; Crowder and Knapp, 2005; Sherwood and Huitger, 2005).

Lastly, bankfull is linked to geomorphic work produced within the channel. The definition of geomorphic work varied through the years (Wolman and Miller, 1960; Dunne and Leopold, 1978; Wolman and Gerson, 1978). In this context, geomorphic work is defined as the greatest amount of suspended sediment that can be transported by the stream to sustain the channel shape. The flow that transports the greatest amount of sediment over time is the effective discharge (Crowder and Knapp, 2005; Simon et al., 2004). For a stream in equilibrium, the recurrence interval of the effective discharge is commonly between 1-2 years (Simon et al., 2004; Crowder and Knapp; 2005; Powell et al., 2006). This recurrence interval is similar to the recurrence interval of the bankfull discharge. Equilibrium streams usually exhibit similar effective and bankfull discharges (Wolman and Miller, 1960; Shields et al., 2003; Crowder and Knapp, 2005; Powell et al., 2006; Ritter et al., 2007). The Wolman-Miller model emphasizes this concept in that the most geomorphic work does not occur at either low-flow or at extreme high-flow events (e.g., floods) (Wolman and Miller, 1960; Powell et al., 2006; Ritter et al., 2007).

![Figure 2 Schematic of Wolman’s geomorphic work theory (from Powell et al., 2006).](image-url)
For a stream in disequilibrium, the greatest amount of geomorphic work may not be associated with the effective discharge (Simon et al., 2004; Crowder and Knapp, 2005; Powell et al., 2006). Stream channel flow in disequilibrium streams is typically disconnected from the physiographic floodplain. In such streams the effective discharge, although carrying the greatest amount of sediment, may not produce the greatest amount of geomorphic work. This can be seen in data from the Maumee River at Waterville, Ohio (Figure 2; Powell et al., 2006). The effective discharge may have the greatest suspended sediment transport at a lower discharge rate whereas the greatest amount of geomorphic work occurs at a higher discharge rate transporting less suspended sediment (Powell et al., 2006).

**Land Use Effects on Channel Equilibrium**

Land use change has large affect on stream channels (Wolman, 1967; Trimble, 1977; Knox, 2001). Typically, streams in disturbed watersheds are in a state of disequilibrium (Simon, 1989; Kondolf et al., 2002; Poff et al., 2006). This is usually a result of land use change that modifies the channel form and process (Wolman, 1967; Knox, 2001; Kondolf et al., 2002). The channel response to land use change is related to fluxes in the hydrologic regime and sediment yield (Kondolf et al., 2002; Poff et al., 2006). However, channel response is also dependent on soil, lithology, vegetation and regional climate (Wolman, 1967). Streams in disequilibrium may not be well-connected to their physiographic floodplains, or if the channel is aggrading may be inundating their floodplains more frequently. In these situations it can be difficult to determine the modern bankfull channel (Sherwood and Huitger, 2005). This is common in the Northeastern United States because of the major changes in land use since European settlement (Birch and Wharton, 1983; USDA Forest Service, 2005; Montgomery, 2008).

In the Midwestern US, deforestation and agricultural development in the 1800s accelerated runoff and soil erosion due to cultivation, soil compaction and depletion of surface cover (Wolman, 1967; Trimble, 1977; Trimble and Lund, 1982; Knox, 2001). In agricultural river systems, the increase in runoff-induced sediment overload led to channel widening and downstream stream bed aggradation of alluvium (Costa, 1975; Kondolf et al., 2001; Knox, 2001). Wolman developed a historical model illustrating the affects of land use on the sediment yield in streams (Figure 3; Wolman and Miller, 1960). As agricultural practices expanded, sediment yield increased stream beds aggraded. Hydrologically, stream bed aggradation increases flow variability whereby there is a decrease in minimum flow and an increase in the magnitude of flood events (Wolman, 1967; Poff et al., 2006).
Figure 3 Schematic sequence of land use, sediment yield, and channel response in the United States since 1800 (from Wolman, 1967).

In the early 1900s, soil erosion was recognized as a major problem (Costa, 1975; Trimble, 1977; Knox, 2001; Trimble, 2003). Economic and technological changes in agriculture resulted in a significant decline in cropland area, and soil conservation practices were implemented (Costa, 1975; Knox, 2001; Trimble, 2003). Some of the soil conservation practices implemented included strip-cropping, contour plowing, improved fertilization and controlled grazing (Trimble, 1982; Knox, 2001). As intended, erosion of agricultural soil decreased concurrently decreasing sediment yield within river systems. Better conservation practices also led to a decrease in flood magnitude and erosion (Wolman, 1967; Trimble, 1977; Knox, 2001) resulting in stream channel incision into the deposited alluvium (Wolman, 1967; Kondolf et al., 2002; Urban and Rhoads, 2003).

Urbanization induces a rapid alteration of stream channel form and processes compared to the relatively slow response in agricultural watersheds. Stream response in an urbanized watershed begins with a temporary peak in sediment load from the exposure of bare surfaces during construction. This is followed by a decline in sediment yield due to an increase in impervious surfaces. The increase in impervious surfaces induces an increase in peak flows and bankfull stage, a decline in duration of near-bankfull flows and an increase in flow variability (Poff et al., 2006; Schoonover et al., 2007). The decrease in sediment yield also leads to erosion and enlargement of the stream channel (Chin, 2006; Schoonover et al., 2007). Erosion rates following urban construction may increase by up to 40,000 times pre-disturbance rates and the channel generally enlarges 2-3 times its original size (Chin, 2006). Chin (2006) adopted Wolman’s historical model specifically for stream channel response to urbanization (Figure 4).
As urbanization expands, net erosion and channel enlargement of streams tend to continue. Some argue that urbanized channels have little chance of re-establishing a state of quasi-equilibrium and will remain in a state of non-equilibrium (Doll et al., 2002; Phillips, 2007). A channel in non-equilibrium is characterized by its inability to return to a pre-disturbed state. The inability to return to the pre-disturbed state stems from the high level of disturbance within the watershed. The high level of disturbance induces a large disconnect between channel form and flow (Renwick, 1992; Phillips, 2007).

A model of stream channel evolution after initial disturbance has been developed to summarize the common morphologic adjustments after channelization (Simon and Hupp, 1986; Simon, 1989). Simon’s stream channel evolution model may also represent morphologic adjustments after other major channel modifications associated with land-use change or direct channel modification such as channelization. Simon’s model of stream channel evolution is categorized into six phases after initial disturbance. The initial disturbance in Simon’s studies was channelization within an urban landscape. The six phases are: (1) premodified, (2) constructed, (3) degradation, (4) threshold, (5) aggradation and (6) restabilization (Figure 5).

The phases of Simon’s stream channel evolution can also describe the state of stability or channel equilibrium. After initial disturbance, streams are characterized by rapid incision and subsequent undercutting of the basal surfaces. As basal erosion continues, banks continue to steepen and mass-wasting occurs. Eventually, aggradation of the stream bed begins depositing fine sands on bank surfaces. The upper banks of the channel are still not stable and continue to

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**Figure 4** Schematic sequence of channel condition and morphological change to urbanization (from Chin, 2006).
have low-angle slides. Vegetation begins to become established on the banks during the earlier stages of aggradation and continues to stabilize upslope away from the channel over time. During these initial stages after disturbance streams are in a state of disequilibrium whereby the stream is attempting to reconnect the channel form and processes. Streams eventually reach a state of quasi-equilibrium in which the channel becomes restabilized. Restabilization is evident when bank heights are reduced within the inset channel because of stream bed aggradation from the reworking of fluvial materials. Vegetation is also stabilized along the channel banks and mass-wasting of the upper banks no longer occurs (Simon, 1989; Doll et al., 2002). The duration required for a stream to reach a state of quasi-equilibrium is variable and difficult to predict. Streams that are highly disturbed may take more than 1000 years to reach a state of quasi-equilibrium, if at all (Simon, 1989).

![Diagram of channel evolution after disturbance](image)

**Figure 5** Schematic of channel evolution after disturbance (from Simon, 1989).

**Regional Characterization of Bankfull Dimensions**

Bankfull hydraulic geometry relationships relate the bankfull channel dimensions (width, depth and area) to various drainage areas (Leopold and Maddock, 1953; Dunne and Leopold, 1978). Bankfull hydraulic geometry relationships are created for similar physiographic regions
and are sometimes referred to as regional curves (Dunne and Leopold, 1978; Sherwood and Huitger, 2005). Bankfull hydraulic geometry relationships are specific to their physiographic regions because they are sensitive to changes in hydrology, sediment yield, land use practices and underlying geology of each watershed (Dunne and Leopold, 1978; Doll et al., 2002). Bankfull hydraulic relationships assist in determining characteristics for alluvial channels (Doll et al., 2002; Sweet and Geratz, 2003; Sherwood and Huitger, 2005). Comparison of bankfull hydraulic relationships between urban and agricultural watersheds also has the capability of illustrating the impacts of land use on bankfull characteristics (Doll et al., 2002).

Several states have created regional curves for predicting bankfull characteristics (see Sherwood and Huitger, 2005; Messinger, 2009; Rachol and Boley-Morse, 2009). In Ohio, several studies have described typical bankfull characteristics (see Dunne and Leopold, 1978; Webber and Roberts, 1981; Roth, 1985; Sherwood and Huitger, 2005). To expand the understanding of modern bankfull characteristics in Ohio another study was conducted in 2005 (Sherwood and Huitger, 2005). This study used a series of 50 rural, un-regulated streams of which 40 had a gauging-station near the study reach of the stream (Figure 7). Large variations in bankfull characteristics forced the creation of two regional curves for the state of Ohio. The resulting regional curves have simple-regression equations which related bankfull characteristics to drainage area and multiple-regression equations relating other physical attributes of the stream (e.g. local channel slope, elevation and bed material) to the bankfull characteristics (Figure 6).

**Figure 6** Simple-regression equations for the bankfull regional curves created for the state of Ohio (Sherwood and Huitger, 2005).
Figure 7 Map of Ohio Regional Curve locations for the state of Ohio (Sherwood and Huitger, 2005).
Using LiDAR data in Fluvial Geomorphic Studies

Light detection and ranging (LiDAR) is a relatively new remote-sensing technique with growing use in geomorphic studies (see White, 2003; Jones et al., 2008; Notebaert et al., 2008; Feurer et al., 2008; Bater and Coops, 2009). The low cost of using Airborne LiDAR data, rapid access to large data sets, and the high precision of the data are appealing to a variety of fields of study (Charlton et al., 2003). In fluvial geomorphic studies, LiDAR can be used both qualitatively and quantitatively. Qualitatively, LiDAR can be used to determine location of paleochannels, terraces, levees and fan deposits. LiDAR can also be used quantitatively to determine channel migration and quantify other current fluvial processes such as bank erosion (Notebaert et al., 2008).

Airborne LiDAR is obtained by flying over the landscape with a laser scanner that emits near-infrared wavelengths to measure the distance between the earth’s surface and its point of origin (Figure 8) (Bater and Coops, 2009). The near-infrared wavelength is incapable of penetrating water surfaces as water absorbs the light and nothing is returned to the point of origin. Recent advances in LiDAR use two pulses of different wavelengths, a near-infrared and a narrow-green beam. This narrow-green beam is able to penetrate the water surface and should return from the surface below the water. The variability between the narrow-green beam and the last recorded near-infrared points will indicate the water depth at that location (Feurer et al., 2008). The combination of the two beams creates a more accurate representation of the landscape.

Figure 8 Schematic diagram of the collection of data using airborne-LiDAR (from Campbell, 2007).

LiDAR can be post-processed to create a bare earth digital elevation model (DEM) that allows for quick and efficient information on the terrain (Figure 8). The vertical precision of LiDAR is typically within 15 cm (Charlton et al., 2003). The resulting DEMs created from LiDAR are most efficient in landscapes with high topographic relief where there is clear
definition of elevational changes (e.g. rolling hills, mountains). Locations in low-topographic relief such as floodplains, river deltas and wetlands are not as efficient. The accuracy of Airborne LiDAR is typically poor in these locations because the surface water is influenced by variations in the hydrologic scheme such as tides, bi-directional flow and variations in river discharge (Jones et al., 2008; Bater and Coops, 2009).

For Ohio, LiDAR data were collected and processed between March and May of 2007 in collaboration with The Ohio Statewide Imagery Program (OSIP). The Ohio LiDAR-based digital elevation model (DEM) has a 1-foot vertical accuracy with 2- and 5- foot contours. The Ohio LiDAR data did not use the 2-beam system and therefore river systems are not accurately represented within the data set unless flow depth is very low. Along river channels and perennial streams the elevation closest to the water line on each side of the banks is interpolated across the water surface. Ohio’s LiDAR is made widely available as ESRI ArcINFO GRID raster and ASCII grid formats through their online database of imagery (http://gis3.oit.ohio.gov/geodata/).

PURPOSE OF STUDY

The purpose of this study was to understand how land use affects modern bankfull channel geometry in Southwest Ohio. Understanding modern bankfull channel geometry is important for the implementation of effective stream management and restoration projects. In this paper I will address a series of sub-questions:

- What are the modern land use practices in the study watersheds?
- Can LiDAR be used to determine bankfull channel geometry?
- What is the modern bankfull channel geometry in the study watersheds?
- How do bankfull characteristics differ between agricultural and urbanized watersheds?
- Are bankfull characteristics in the study watersheds consistent with predicted bankfull characteristics for Ohio?

To answer these questions I (1) examined and quantified the modern land use in Southwest Ohio; (2) determined and measured bankfull channel geometry (width, depth and cross-sectional area) using a series of field cross-sections; (3) I used the field cross-sections to compare and evaluate the validity of using LiDAR-extracted cross-sections to determine bankfull channel geometry; (4) I then used hydrologic modeling to estimate expected bankfull channel characteristics; and lastly (5) I compared the measured and predicted bankfull channel geometry based on hydrologic modeling and regional generalization of bankfull in agricultural and urbanized watersheds.

My specific hypotheses are as follows:

- From a bare earth DEM from the Ohio LiDAR data I will be able to extract accurate cross-sections of the majority of streams within this study.
- Streams will be incised, resulting in channel bankfull geometry that diverges from the norms. This divergence will be indicated by:
  - Presence of recent terraces and/or incipient floodplains;
  - bankfull channels that are enlarged compared to the 1.5-year bankfull flow, or
  - bankfull channels that are larger than predicted in regional bankfull relations developed for Ohio (Sherwood and Huitger, 2005), or both.
- Urban watersheds will show greater incision than rural ones.

**STUDY AREA**

My study focuses on five streams (Figure 9). All are located within Preble and Butler counties in Southwest Ohio and one watershed extends into Union and Franklin Counties in Indiana. These five streams were selected because of their dominant land use types and varying watershed sizes. Upper Four Mile Creek and Indian Creek represent larger watersheds whereas Marshalls Branch, Harkers Run and Bull Run represent smaller drainage areas. All of the watersheds are dominated by agricultural land use except Bull Run, which is highly developed. The variation in watershed size and land use types allows for a broader understanding of land use affects on modern bankfull channel geometry.

![Study area map](image)

**Figure 9** Study reaches of streams in Southwest Ohio and their respective drainage areas.
The larger watersheds are Upper Four Mile Creek and Indian Creek with a drainage area of 38.5 mi\(^2\) and 45.58 mi\(^2\) respectively. Smaller watersheds are Marshalls Branch (5.08 mi\(^2\)), Harkers Run (7.6 mi\(^2\)) and Bull Run (1.8 mi\(^2\)). Upper Four Mile Creek and Indian Creek are dominated by agricultural land use. Development of Hueston Woods State Park and the Miami University Natural Areas has contributed to reforestation of a small portion of Marshalls Branch and Harkers Run watersheds, respectively, but they remain predominately agricultural. Bull Run is heavily urbanized by the city of Oxford. Oxford has a population of about 22,000, with several neighborhoods within Bull Run’s watershed.

Southwest Ohio is underlain by limestone, dolomite and limey shale bedrock. This bedrock of the Ordovician system (446-450 million years old) is some of the oldest exposed bedrock in Ohio. This region was originally cut by large streams with steep valley sides and later many of these streams were buried by glacial outwash during the Pleistocene Epoch glacial advances. Remnants of river valleys before the glacial advances are apparent by large terraces. Some of these terraces sit over 75 feet above the modern day channel. During the Pleistocene, over three-quarters of Ohio was covered by a sheet of ice. There were several glacial advances over the state, but the most recent advance was the Wisconsonian glaciations (between 14,000-24,000 years ago). Glacial deposits of Wisconsinian age are in the form of ground moraines.

**Bull Run**

The Bull Run watershed is characterized by a high level of urbanization from housing development. The City of Oxford, Ohio continues to grow within the watershed. Several neighborhoods and private property back up right to the edge of the banks of the channel. Bull Run’s channel is heavily incised with steep banks that are failing in many areas. Land owners are concerned that their land will fall into the stream channel, and at least one home has sustained structural damage. In some reaches, land owners attempted channelization and placed rip rap on channel banks to prevent further erosion. Within the channel, the stream is characterized by a cobble stream bed with intermittent deep pools (Figure 10a).

**Harkers Run**

The Harkers Run watershed is characterized by a moderate level of agricultural land use. In the southern portion of the watershed near the confluence with Lower Four Mile Creek, an increase in forest landscape has resulted from the establishment of the Miami University Natural Areas. The Natural Areas were set aside beginning in 1992 in an effort to increase the green space surrounding Miami University. The Harkers Run channel is characterized by incision and heavy vegetation along the banks. Vegetation consists of tall grasses and small trees. The channel bed is a combination of gravel and cobble with intermittent deep pools with coarse sand (Figure 10b).

**Indian Creek**

The study reach of Indian Creek’s watershed extends into Indiana from Ohio. The landscape has a high percentage of agricultural land use with a very small percentage of other land uses. The agriculture is dominated by corn and soybeans. Cattle-grazing occurs along much of the channel in my study reaches. Tall grasses crowd several reaches of the channel banks. The channel bed is dominated by gravel within straight reaches of the channel and a sandier stream bed within cut banks and intermittent deep pools (Figure 10c).
**Marshalls Branch**

Marshalls Branch watershed is mainly agricultural, with the exception of the portion of Marshalls Branch within Hueston Woods State Park near Acton Lake, which is mainly forested. Marshalls Branch channel bed is characterized by small boulders and larger cobbles. Vegetation, especially grasses encroach the banks of the stream (Figure 10d).

**Upper Four Mile Creek**

Upper Four Mile Creek’s watershed is highly agricultural. Upper Four Mile Creek is upstream of Acton Lake, in Hueston Woods State Park. Development of new active floodplains is apparent. Vegetation along the banks includes trees and tall grasses. Riparian vegetation along the terraces of Upper Four Mile Creek assists in stabilizing the banks (Figure 10e).

![Figure 10 Images from each of the five study watersheds; a) Bull Run, looking upstream near confluence with Collins Run; b) Harkers Run, Looking upstream north of the Miami University Natural Areas; c) Indian Creek, looking upstream near the southern extent of the study reach; d) Marshalls Branch, looking upstream within Hueston Woods State Park; e) Upper Four Mile Creek, looking upstream at confluence with East Fork Four Mile Creek before heading into Hueston Woods State Park.](image)
METHODS

To understand the historical land use effects on modern bankfull channel geometry I needed to understand the land use history, channel geometry, and hydrologic patterns of each of the five watersheds. Drainage areas were delineated for each study reach of the streams using StreamStats for Ohio created by the United States Geologic Survey (USGS) (Koltun et al., 2006). Each of the StreamStats-generated watersheds was compared to the contour lines of digital raster graphics (DRGs) of USGS topographic maps (1:24000 scale) to test the accuracy of the delineated watershed. I created geodatabases of each watershed to organize all GIS data including study reach locations, cross-section locations, drainage area, and digitized channels from 2007 aerial photography of the region.

Site Selection

The five streams in this study were chosen because they are a representative sample of streams in the area. Study reaches within each stream were determined by the availability of landowner permission and then by the ability to identify bankfull indicators within the field. The appropriate landowners were contacted to obtain permission to walk on their property; most streams are located within Miami University property or Hueston Woods State Park and permission was unnecessary. Private land owners were contacted for Indian Creek and Bull Run. Bull Run is part of an on-going study by Miami University identifying the stability of the stream channel.

Gauging stations are located on four of the five streams in this study. A sufficient period-of-record from gauging stations provides further assistance in determining bankfull characteristics. Upper Four Mile Creek and Marshalls Branch have 15 years of record, while Harkers Run and Bull Run have a record of less than two years. There are no rating curves for Harkers Run and Bull Run, so only stage data are available. There is no gauging station within this reach of Indian Creek (Table 1).

<table>
<thead>
<tr>
<th></th>
<th>Longitude</th>
<th>Latitude</th>
<th>DA (sq. mi)</th>
<th>Year(s)</th>
<th>Period of Use*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bull Run</td>
<td>84°44'52.257&quot;W</td>
<td>39°29'47.774&quot;N</td>
<td>1.8</td>
<td>2</td>
<td>2008 -</td>
</tr>
<tr>
<td>Harkers Run</td>
<td>84°43'1.102&quot;W</td>
<td>39°30'29.953&quot;N</td>
<td>7.6</td>
<td>2</td>
<td>2008 -</td>
</tr>
<tr>
<td>Indian Creek</td>
<td>84°48'6.216&quot;W</td>
<td>39°28'40.074&quot;N</td>
<td>45.71</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Marshalls Branch</td>
<td>84°45'18.048&quot;W</td>
<td>39°35'18.019&quot;N</td>
<td>5.08</td>
<td>15</td>
<td>1994 -</td>
</tr>
<tr>
<td>Upper Four Mile Creek</td>
<td>84°46'13.283&quot;W</td>
<td>39°35'35.916&quot;N</td>
<td>38.55</td>
<td>15</td>
<td>1994 -</td>
</tr>
</tbody>
</table>

Table 2 Geographical location and information for each study reach of five streams. *All gauging stations run by Miami University
Land Use Analysis

The National Land Cover Dataset (NLCD) was used to determine the percent land use in each watershed. The 2001 land use data are sufficient for identifying the modern land use practices since there is little known land use change since 2001 within each of the study watersheds. The NLCD 2001 raster was reclassified in ArcGIS to four different categories of interest: (1) open water, (2) urban (including all developed spaces and barren land), (3) agricultural or (4) forest (Table 2). Percent land cover was calculated for each watershed. Each watershed was then classified by the dominant land-use practice unless the watershed was greater than 10% urban. The urban threshold was set at this level because as little as 10% developed landscape is attributed to stream degradation and has a greater influence on bankfull channel dimensions (Doll et al., 2002).

<table>
<thead>
<tr>
<th>#</th>
<th>NLCD Classification</th>
<th>Reclass ID</th>
<th>#</th>
<th>NLCD Classification</th>
<th>Reclass ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Open Water</td>
<td>1</td>
<td>43</td>
<td>Mixed Forest</td>
<td>4</td>
</tr>
<tr>
<td>21</td>
<td>Developed, Open Space</td>
<td>2</td>
<td>52</td>
<td>Shrub/Scrub</td>
<td>3</td>
</tr>
<tr>
<td>22</td>
<td>Developed, Low Intensity</td>
<td>2</td>
<td>71</td>
<td>Grassland/Herbaceous</td>
<td>3</td>
</tr>
<tr>
<td>23</td>
<td>Developed, Medium Intensity</td>
<td>2</td>
<td>81</td>
<td>Pasture/Hay</td>
<td>3</td>
</tr>
<tr>
<td>24</td>
<td>Developed, High Intensity</td>
<td>2</td>
<td>82</td>
<td>Cultivated Crops</td>
<td>3</td>
</tr>
<tr>
<td>31</td>
<td>Barren Land (Rock/Sand/Clay)</td>
<td>2</td>
<td>90</td>
<td>Woody Wetlands</td>
<td>1</td>
</tr>
<tr>
<td>41</td>
<td>Deciduous Forest</td>
<td>4</td>
<td>95</td>
<td>Emergent Wetlands</td>
<td>1</td>
</tr>
<tr>
<td>42</td>
<td>Evergreen Forest</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Reclassification scheme used with NLCD 2001. Reclassification of the NLCD fields are 1= Open Water, 2= Urban, 3= Agriculture, and 4= Forest.

Determining Bankfull Channel Geometry

Field cross-sectional surveys were conducted to determine channel geometry of each stream using guidelines from the United States Department of Agriculture (USDA) (Harrelson et al., 1994; USDA Forest Service, 2005). Study reaches in each stream were identified where an active floodplain was present that facilitated clear identification of the bankfull channel (Figure 11). Morphologic features surveyed include: bankfull, active-floodplain, thalweg. Notes were taken on the occurrence of incipient floodplains and other distinct channel features and the particle-size of the channel bed. GPS points of each cross-section were collected. Planform surveys were developed using GIS to determine sinuosity and slope for each stream. The same methods were used in field measurements as outlined by Sherwood and Huitger (2005) in an attempt to keep results consistent with bankfull identification for the state of Ohio.
Figure 11 Field surveys used tape across the channel width, and survey equipment to measure the bankfull channel features. Notes were taken across the cross-section identifying bankfull features, and vegetation patterns. When possible, the tape was placed at the most recent abandoned floodplain to estimate channel incision.

Determining bankfull dimensions in the field may be difficult for streams that are in disequilibrium. Disequilibrium channels are typically hydrologically disconnected from their active-floodplain with development of in-channel morphologic features (e.g. benches and incipient floodplains) (Ritter et al., 2007; Jayakarn and Ward, 2007). For disequilibrium channels and other reaches in which bankfull determination is difficult, indicators of bankfull stage include the following (Harrelson et al., 1994; Shields, 2003; USDA Forest Service, 2003; Sherwood and Huitger, 2005):

- deposits of fine material or debris on the active floodplain,
- change in vegetation,
- breaks along the channel banks,
- change in particle size of bank material,
- undercuts in banks,
- stain lines on banks or boulders,
- lower extent of lichens on boulders.

For a confident measure of the morphologic bankfull elevation, I identified these bankfull characteristics within several reaches of the streams. (Harrelson et al., 1994; USDA Forest Service, 2003).
Light detection and ranging (LiDAR) data were also used to obtain cross-sectional data for the streams. Bare-earth DEMs created from LiDAR for Ohio were used to extract cross-sections for each watershed. Using 3D Analyst in ArcMap, LiDAR cross-sections were extracted at the same location as the field cross-sections (identified by GPS points). LiDAR cross-section were then exported to Microsoft Excel to compare with the field cross-section surveys. Several other cross-sections were extracted along the stream to enhance the amount of cross-sectional data. Cross-section locations are shown in Figure 12 (a through e).

Figure 12 Cross-section locations of LiDAR and field cross-sections for each of the five study areas; a) Bull Run, b) Upper Four Mile Creek, c) Indian Creek, d) Marshalls Branch, e) Harkers Run.
Determining Bankfull Channel Flow

For the two gauged streams with a longer period-of-record (Upper Four Mile Creek and Marshalls Branch) I was able to determine the 1.5-year recurrence interval typically associated with bankfull discharge in the state of Ohio. The 1.5-year flow was identified by creating a flood-frequency curve. A flood-frequency curve plots the recurrence interval or exceedence probability against annual flood peaks (Dunne and Leopold, 1978; Powell et al., 2006). I used Log-Pearson Type III distribution (Dunne and Leopold, 1978; Sweet and Geratz, 2003; Powell et al., 2006) to stay consistent with government agencies. Government agencies generally have accepted the technique to accurately estimate flood-frequency at USGS gauging-stations (U.S. Water Resources, 1982, Sweet and Geratz, 2003; Powell et al., 2006). The Log-Pearson Type III distribution is more accurate for flood frequencies within the middle range of historical data versus the relatively small magnitude of bankfull discharge (Sweet and Geratz, 2003).

I used the Hydrologic Engineering Center River Analysis System (Hec-RAS), to simulate the discharge at my measured bankfull elevation and thus compare the 1.5-year flow to the discharge at my measured bankfull channel dimensions. Hec-RAS allows for one-dimensional hydraulic calculations of river systems. In this study, we used steady-flow analysis within Hec-RAS to determine stage of a given flow within each stream. The input data that allowed me to run the analysis consisted of the bare earth DEM (created from LiDAR data), location of banks (field identified bankfull elevation), Manning’s channel roughness coefficient, and manual input of various flows. The Manning’s roughness coefficient was determined for entire watersheds based on dominant land use type. The defaults given by Hec-RAS for Manning’s roughness coefficient for urban (0.055), agriculture (0.06) and forest (0.15) landscapes were used for the entire watershed and a roughness coefficient of 0.035 was used for within the stream channels. For this analysis we simulated the observed 1.5-year flow, field-determined bankfull flow, and the predicted bankfull flow from the Ohio bankfull regional curve (Sherwood and Huitger, 2005).

For the remaining three streams, an indirect estimate of bankfull discharge was calculated using Manning’s equation:

\[ Q = A \cdot \frac{1.486}{n} \cdot \frac{R^{2/3}}{S^{1/2}} \]

where Q is the bankfull discharge, A is cross-sectional area, R is the hydraulic radius, S is the channel slope, and n is the roughness coefficient. The cross-sectional area, hydraulic radius and slope were calculated using the field measurements. The roughness coefficients were based on estimates for the main alluvial channel with different in-channel characteristics (Dunne and Leopold, 1978) and were the same as the defaults for Hec-RAS modeling (0.035). Manning’s equation was also calculated for Upper Four Mile Creek and Marshalls Branch to estimate what the bankfull flow would be given the field-measured bankfull channel geometry. The Manning’s equation result for these two streams is compared to the 1.5-year recurrence interval from the flood-frequency analysis. Percent difference between the observed 1.5-year flow and the indirect-estimated bankfull flow, from Manning’s equation was calculated.
Comparison of Measured and Predicted Bankfull Characteristics

The hydraulic geometry relationships for the measured bankfull characteristics in Southwest Ohio were compared to the predicted bankfull characteristics for the state of Ohio. Bankfull channel geometry (width, depth and area) from cross-sectional surveys were plotted against predicted bankfull channel geometry for Ohio. Bankfull discharge, calculated from Manning’s Equation and the Log-Pearson Type III analysis were plotted against the predicted bankfull discharge. Hec-RAS was also used to simulate the cross section of the Sherwood & Huitger (DATE) predicted flow. I was then able to compare (1) calculated bankfull flow, (2) 1.5-year flow and (3) predicted flow for the two gauged streams of Upper Four Mile Creek and Marshalls Branch. Comparing the three bankfull measurements allowed me to distinguish if (1) the measured bankfull channel is enlarged compared to the 1.5-year flow and (2) if the measured bankfull channel is enlarged compared to the regional prediction.

Enlargement ratios were calculated between measured and predicted bankfull characteristics to determine variation between the two bankfull calculations. The enlargement ratio between measured and predicted bankfull characteristics is adopted from Doll et al. (2002) where the enlargement between bankfull characteristics in urban and agricultural watersheds is calculated. The enlargement ratio is calculated by

$$E_r = \frac{X_{bf}}{X_{rbf}}$$

where $E_r$ is the enlargement ratio, $X_{bf}$ is the bankfull cross-sectional dimensions (width, depth, area, or discharge) for my field-measured streams, and $X_{rbf}$ is the bankfull cross-sectional dimensions of the regional model predictions of the rural, un-regulated streams (adopted from Doll et al., 2002).

RESULTS AND DISCUSSION

Land Use Analysis

Reclassification of the NLCD 2001 indicates land use within each of the five study watersheds. Bull Run is the most heavily urbanized watershed with 19.44% urban land use. However, there is a small percentage of forest land use. The forest is mainly as riparian vegetation on private property. The remaining four watersheds have over 70% agricultural land use with forest coverage second in importance (Table 3). Harkers Run includes the Miami University Natural Areas in the southern portion of the watershed near the confluence with Lower Four Mile Creek; this area is mainly forest. Similarly, Marshalls Branch has Hueston Woods State Park located within the western part of its watershed. For the agriculturally dominated watersheds, the forest cover is still predominately riparian vegetation with little to no other patches of forest cover away from the stream.
Table 4 Percent land cover for each watershed and the respective land use dominance classification. Bull Run is over 10% urban land use and therefore is classified as urban. The 10% threshold was determined because a minimum of 10% urban land use affects stream degradation (Doll et al., 2002).
Figure 13 Land use maps for each watershed; a) Bull Run, b) Harkers Run, c) Indian Creek d) Upper Four Mile Creek and e) Marshalls Branch. The land use is categorized by open water (blue), urban (red), agriculture (yellow) and forest (green).
Using LiDAR in fluvial geomorphic studies

I compared six field cross-sections from each stream to LiDAR-extracted cross-sections to evaluate the usefulness of the bare earth DEM for fluvial geomorphic studies. The locations of the field cross-sections were obtained using GPS so that I could extract the cross-section location using LiDAR. The GPS points were also used at the two end-points of the field surveys to determine the approximate elevations of the field cross-sections. The elevation throughout the rest of the cross-sections were determined using the field measurements. Figure 14-16 shows a sample of the LiDAR cross-section validation to the field measurements. Figures 14 and 15 indicate only small variability between field and LiDAR data. These cross-sections are located along riffles within the stream. Figure 16 indicates a different result from the accurate comparisons between field- and LiDAR-extracted cross-sections. Cross-section 3 in Indian Creek is located in a meander bend where there is heavy incision along the left bank (looking downstream). Based on these observations I am confident that LiDAR cross-sections can be used in the context of this study but a set of rules must be developed to eliminate errors in using the bare earth DEM.

Figure 14 LiDAR and field survey cross-section comparison for XS 1 in Harkers Run. This cross-section is looking upstream north of Miami University Natural Areas on private property.
Figure 15 LiDAR and field survey cross-section comparison for XS 1 in Indian Creek. This cross-section is looking upstream. There is relatively large island development as seen in the cross-section which is only noticed to the left of the image.

Figure 16 LiDAR and field survey cross-section comparison for XS 3 in Indian Creek. This cross-section is looking downstream with heavy incision on the left bank. The heavy incision leads to deep pools of water where Ohio LiDAR cannot determine the elevation of the channel bed. Cross-sections such as this one should be avoided with extracting LiDAR.
Using LiDAR data for stream cross sections can be problematic because water absorbs the wavelengths and therefore depth below the water surface is not known. In some areas, LiDAR can be used for cross-sectional purposes but rules are developed to eliminate any possible errors. To extract LiDAR data for cross-sectional purposes the following sets of rules were used for this study:

- Streams used in this analysis had little to no flow when airborne LiDAR was collected. Streams that work well are either (1) ephemeral or (2) they are heavily influenced by the landscape with little flow throughout the year except for large rainfall events. Gauging station information is beneficial where available to know exactly how much water is within the stream. Further investigation of the regional precipitation patterns at the time LiDAR data were collected was used to fill gaps for non-gauged streams.
- Cross-section length should be wide enough to obtain a full cross-section including some terraces for better comprehension of the streams morphologic features. A length four times wider than the width of the stream will typically work for smaller watersheds.
- Cross-sections should be extracted in straight reaches (i.e. riffles) where water is typically shallow. Straight reaches along streams typically tend to exhibit well defined geomorphic features. Staying clear of point bar development and deep pools will help eliminate areas where LiDAR was absorbed by water (as seen in Figure 16).
- Avoid extraction near roads or bridges. Simply overlaying aerial photography over the LiDAR data will allow for analysis of the landscape. We are concerned with the shape of the channel and the stream bed elevation, and roads and bridges may cause inconsistencies within the post-processing of the LiDAR data. It is better to find other locations suitable for LiDAR-extraction. Aerial photography was taken during the collection of the LiDAR data in 2007 and is available through OSIP.
- Be aware of rip-rap within a stream that will skew bankfull channel dimensions in the LiDAR. Overlaying aerial photography or field observations will assist with finding and avoiding these locations.

To determine bankfull channel characteristics from airborne-LiDAR data, I used a second set of criteria to accurately determine these features:

- First, field reconnaissance should be conducted to look for bankfull indicators including deposits of fine material or debris on the active floodplain, change in vegetation, breaks along the channel banks, change in particle size of bank material, undercuts in banks, stain lines on banks or boulders, and lower extent of lichens on boulders (Shields, 2003; Sherwood and Huiter, 2005; USDA Forest Service, 2003; Harrelson et al., 2004). Identifying these features will assist with understanding the channel shape and subsequently be able to easily interpret the LiDAR extracted cross-sections.
- Once all LiDAR cross-sections are extracted, they should all be overlain to look for consistent levels of adjacent flat surfaces. In-channel features can temporarily develop but do not indicate the modern floodplain, therefore finding a consistent flat surface for all cross-sections will indicate an accurate representation of the active floodplain. This should be done first before looking at individual cross-sections. One cross-section is insufficient to define bankfull for an entire stream.
• When interpreting individual cross-sections, look for the defined adjacent flat-surface or the formation of natural levees that may be visible in the extracted cross-section. Natural levee formation is an excellent indicator of bankfull elevation (Figure 17a).

• For heavily disturbed streams adjacent flat-surfaces may not be apparent. Look for sharp changes in slope on the channel banks (Figure 17b). Sharp changes in slope may be an indicator of a drastic change in the flow at the elevation within the stream.

• Be aware of change in watershed size on the stream of interest that may quickly alter bankfull measurements. Continuous reference to aerial photography will assist in eliminating these errors.

• After bankfull dimensions have been determined, there may occasionally be an anomaly that needs to be removed from the dataset which do not correlate with other bankfull measurements. There should be at least 8 cross-sections with similar results to confidently state the bankfull channel dimensions.

A summary of these criteria is presented in Table 4.

Figure 17 Example of bankfull channel formations within cross-sections. These cross-sections are extracted from the Ohio LiDAR data; a) indicators of natural levee formation within Bull Run, b) indication of a sharp change in bank slope within Bull Run.
Table 5 Summary of criteria for using the bare earth DEM created from Ohio’s airborne LiDAR data in fluvial cross-sections.

<table>
<thead>
<tr>
<th>Extracting LiDAR cross-sections</th>
<th>Defining bankfull dimensions with LiDAR cross-sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Heavily incised stream</td>
<td>• Field reconnaissance to observe consistent bankfull indicators</td>
</tr>
<tr>
<td>• Little to no flow</td>
<td>• Should NEVER determine bankfull of a stream from one cross-section</td>
</tr>
<tr>
<td>• Extracted at straight reach</td>
<td>• Overlay extracted cross-sections</td>
</tr>
<tr>
<td>• Extract two times the stream width</td>
<td>• Look for natural levee formation</td>
</tr>
<tr>
<td>• Avoid point bar development and deep pools</td>
<td>• Look for sharp changes in slope angle on the banks</td>
</tr>
<tr>
<td>• Avoid locations near roads/bridges</td>
<td>• Look for adjacent flat-surfaces (active-floodplain)</td>
</tr>
<tr>
<td>• Be aware of rip-rap within the stream channel</td>
<td></td>
</tr>
<tr>
<td>• Use aerial-photography to analyze the landscape</td>
<td></td>
</tr>
</tbody>
</table>

Characteristics of the Bankfull Channel Geometry

Field observations of bankfull channel geometry in four out of the five study watersheds indicate substantial incision. Incision is apparent in the study watersheds by the presence of historic terraces and the development of incipient floodplains within the inset channel. Historic terraces are floodplains that have been abandoned since human settlement. There also are terraces that sit well above the modern day channel, but were abandoned long before human settlement—perhaps in the Pleistocene or early Holocene. These terraces are not of concern in this study because they do not indicate historic incision.

Terrace locations for a cross-section in each stream are presented in Figures 18 (a through e). Older terraces, most likely of Pleistocene/early Holocene, age are located within all of the watersheds. Historic terraces are evident in all of the study watersheds except for Upper Four Mile Creek. For example, within Bull Run there is development of historic terrace that sits about fifteen feet above the channel bed. Evidence from aerial photography demonstrates that this terrace is the 1935 floodplain. Similar change in historic terraces is apparent in Indian Creek, Marshalls Branch, Harkers Run and Bull Run.
Development of incipient floodplains within the inset channel is apparent in four of the five study streams. Indian Creek, Bull Run, Marshalls Branch and Harkers Run exhibit development of incipient floodplains as seen in Figure 19 (a through d). However, Marshall’s Branch does not have consistent levels of incipient floodplain development. Bankfull channel geometry in Marshalls Branch is more consistent with the cross-section in Figure 19e. Therefore, determining Marshalls Branch morphologic bankfull features used several cross-sections to identify consistent levels of floodplain development. On the other hand, Upper Four Mile Creek tends to have a well-defined floodplain with little development of incipient floodplains within the inset channel (Figure 19f).
Figure 19 Examples of inset channel morphologic features. Incipient floodplain development is apparent in a) Indian Creek, b) Harkers Run, c) Bull Run and e) Marshalls Branch. Most cross-sections in Marshalls Branch do not exhibit development of incipient floodplains and are more characteristics of the cross-section in f. Upper Four Mile Creek (d) does not indicate significant development of inset channel features such as incipient floodplains. Red line on each graph indicates the elevation of the measured modern bankfull channel.

Another indication of heavy incision is the exposure of glacial till through several reaches of the study watersheds. Field inspection of stream channel banks reveals historic deposits on the top of the banks with different magnitudes of glacial till exposure. For example, the
agricultural watershed of Indian Creek has incised through about 4.9 feet of historic deposits and now exposes 4.3 feet of glacial till within most reaches (Figure 20). Exposure of glacial till is apparent in all the study streams except Upper Four Mile Creek.

**Figure 20** Deep incision within cross-section 3 at Indian Creek. a) Image of XS3 looking upstream. Till is visible about 1.5 feet above the water surface (till marked by the green line in plot b). The profile of the cross-section (b; looking downstream) shows the location of the water surface (blue line) and how deep the stream has incised into the glacial till. Total incision into the glacial till is about 3.6 feet.

*Measurements of Bankfull Channel Geometry*

Careful analysis of several reaches of the streams assisted in making accurate measurements of the modern geometry. The resulting average bankfull measurements for each stream are summarized in Table 5. Indian Creek has a much larger bankfull channel characteristics (width, depth and cross-sectional area) most likely a result of having a larger drainage area than the other streams. Bull Run has bankfull channel dimensions similar to those of Marshalls Branch. However, Marshalls Branch watershed is over two-times the magnitude of Bull Run’s watershed. Width-to-depth ratios were also calculated from the average bankfull channel geometry (Table 5).

<table>
<thead>
<tr>
<th></th>
<th>$w_{bf}$</th>
<th>$d_{bf}$</th>
<th>$a_{bf}$</th>
<th>Sinuosity</th>
<th>LCSL</th>
<th>W/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bull Run</td>
<td>49.15</td>
<td>2.97</td>
<td>145.81</td>
<td>1.34</td>
<td>0.0004</td>
<td>17.97</td>
</tr>
<tr>
<td>Harkers Run</td>
<td>85.09</td>
<td>3.27</td>
<td>278.09</td>
<td>1.17</td>
<td>0.0050</td>
<td>26.80</td>
</tr>
<tr>
<td>Indian Creek</td>
<td>114.30</td>
<td>4.81</td>
<td>549.78</td>
<td>1.23</td>
<td>0.0055</td>
<td>24.99</td>
</tr>
<tr>
<td>Marshalls Branch</td>
<td>63.10</td>
<td>2.53</td>
<td>159.92</td>
<td>1.60</td>
<td>0.0094</td>
<td>27.83</td>
</tr>
<tr>
<td>Upper Four Mile Creek</td>
<td>96.55</td>
<td>3.72</td>
<td>359.41</td>
<td>0.94</td>
<td>0.0054</td>
<td>26.89</td>
</tr>
</tbody>
</table>

**Table 6** Summary of the average bankfull channel characteristics for the five watersheds. Sinuosity, local channel slope (LCSL) and width-to-depth ratios (W/D) were also calculated.
The bankfull channel geometries from each stream were used to calculate width-to-depth ratios. Comparing the width-to-depth ratios for each stream, the agricultural streams exhibit a greater width-to-depth ratio (Figure 21). All of the agriculturally-dominated streams have similar ratios. Bull Run, however, has a much smaller ratio characteristic of urban streams. Urban streams exhibit greater incision compared to agriculturally-dominated streams because of the increase in impervious surfaces (Trimble, 1977; Knox, 2001; Chin, 2006). An increase in impervious surfaces induces an elevated rate at which water reaches the stream increasing peak flows and stream power. This increase in stream power allows for further incision into the stream bed (Leopold and Maddock, 1953; Wolman, 1967; Trimble, 1977; Dunne and Leopold, 1978; Knox, 2001).

Figure 21 Width-to-depth ratios for the five study watersheds.

Bankfull Channel Hydrology

Bankfull channel hydrology was determined for Upper Four Mile Creek and Marshalls Branch using at least a fifteen period-of-record of daily discharges. The flood frequency analyses for Upper Four Mile Creek and Marshalls Branch are shown in Figures 22 and 23. The 1.5 year recurrence interval for Marshalls Branch and Upper Four Mile Creek was determined from the logarithmic regression equations created for each stream. Resulting regression equations, their R-square value and calculated 1.5-year flow are listed in Table 6.
Figure 22 Flood Frequency Analysis for Upper Four Mile Creek.
Figure 23 Flood Frequency Analysis of Marshalls Branch.

<table>
<thead>
<tr>
<th>Equation</th>
<th>$R^2$</th>
<th>1.5-yr flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marshalls Branch</td>
<td>$Q = 18.191 \ln(RI) + 163.79$</td>
<td>0.9912</td>
</tr>
<tr>
<td>Upper Four Mile Creek</td>
<td>$Q = 383.66 \ln(RI) + 2110.5$</td>
<td>0.9912</td>
</tr>
</tbody>
</table>

Table 6 Logarithmic regression equations from flood frequency analysis and their respective $R^2$ square values. The 1.5-year flow was determined from the regression equations.

Indirect estimates of discharge using the Manning’s equation for the remaining three streams are listed in Table 7, along with data for Upper Four Mile Creek and Marshalls Branch. Discharge was calculated for Upper Four Mile Creek and Marshalls Branch to determine what the flow would be given the measured bankfull channel geometry. For Marshall’s Branch the indirect estimate is eight times greater than the measured 1.5-year flow. The difference between the indirect estimate of discharge and the measured discharge is an indication that the bankfull
channel is enlarged relative to the 1.5-year flow. On the other hand, Upper Four Mile Creek’s estimated and measured bankfull flow is more similar, with only 11% difference.

<table>
<thead>
<tr>
<th></th>
<th>DA</th>
<th>n</th>
<th>Manning’s Discharge (cfs)</th>
<th>Gage Discharge (cfs)</th>
<th>Percent Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bull Run</td>
<td>1.8</td>
<td>0.035</td>
<td>249.49</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Harkers Run</td>
<td>7.6</td>
<td>0.040</td>
<td>556.55</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Indian Creek</td>
<td>45.71</td>
<td>0.040</td>
<td>2395.48</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Marshalls Branch</td>
<td>5.08</td>
<td>0.035</td>
<td>171.2</td>
<td>1365.8</td>
<td>697.9</td>
</tr>
<tr>
<td>Upper Four Mile Creek</td>
<td>38.55</td>
<td>0.040</td>
<td>2266.1</td>
<td>2532.9</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Table 6 Results from Manning’s Equation for the five streams and the percent error for the two gauged streams of Marshalls Branch and Upper Four Mile Creek.

Hec-RAS simulations of the indirect estimate of bankfull discharge (from Manning’s Equation) and 1.5-year recurrence interval for Upper Four Mile Creek are seen in Figures 24-27. The simulation of 1.5-year flow for Marshalls Branch further demonstrates the large difference between the indirect estimate of bankfull discharge and measured 1.5-year flow. The elevation in the inset channel for the 1.5-year observed flow has no morphologic characteristics typical of the bankfull channel (i.e. active-floodplain development). However, Upper Four Mile Creek has almost identical indirect estimates of the bankfull discharge and the measured 1.5-year flow. There is clear definition of a floodplain where the 1.5-year flow occurs.

Figure 24 Simulated cross-section of Marshalls Branch. Cross-section is looking downstream at the gauging station which is on the left bank. The floodplain indicated in the field is well above the elevation of the 1.5-year flow.
Figure 25 Simulated cross-section of Marshalls Branch looking downstream. This cross-section is further upstream of the gauging station in Marshalls Branch. The physiographic floodplain indicated within the field is well above the 1.5-year flow.

Figure 26 Simulation of Upper Four Mile Creek’s flow. This cross-section is looking downstream at the upper most cross-section of the study reach of Upper Four Mile Creek. The field bankfull (indirect estimate flow) and the 1.5-year flow occur at a similar level.
Bankfull discharge is expected to have a recurrence interval of every 1.5-2 years. Assuming this recurrence interval as the bankfull discharge, I would expect to see development of bankfull features correlated with the 1.5-year flow. The flood-frequency analysis reveals that for Upper Four Mile Creek the 1.5-year recurrence interval is consistent with the indirect estimate of bankfull discharge. On the other hand, the indirect estimate of the bankfull discharge for Marshalls Branch is 2-times than the magnitude of the 1.5-year flow. Therefore, the observed flow in Marshalls Branch is inundating the physiographic floodplain less often. The results for Marshalls Branch are consistent of my hypothesis regarding a large difference between morphologic and hydrologic bankfull dimensions.

**Bankfull Hydraulic Geometry Relationships**

The bankfull hydraulic geometry relationships for the determined bankfull channel geometry (width, depth and cross-sectional area) and flow are plotted in Figures 37-31. A total of 77 field and LiDAR-extracted cross sections was used to create a power function regression of the bankfull characteristics versus their watershed. Table 8 lists the resulting regression equations and their R-squared values. The average bankfull hydraulic geometry (width, depth, cross-sectional area, and discharge) for the five streams in this study have a relatively strong correlation with their respective drainage areas (bankfull width and cross sectional area have a $R^2 > 0.5$). The smallest R-square for bankfull measurements is the depth with a $R^2$ of 0.27.
Figure 28 Bankfull hydraulic geometry relationship for bankfull cross-sectional area for the five study watersheds.

Figure 29 Bankfull hydraulic geometry relationship for the average bankfull depth for the five study watersheds.
Figure 30 Bankfull hydraulic geometry relationship for bankfull width for the five study watersheds.

Figure 31 Bankfull hydraulic geometry relationship for bankfull discharge for the five study watersheds.
Bankfull hydraulic geometry relationships are also plotted by the watersheds land use dominance as seen in Figures 32-35. Power function regression equations and their R-square values are listed in Table 9. From these bankfull hydraulic geometry relationships I can see that bankfull dimensions for the urban streams, particularly the bankfull depth and discharge, are much greater than what we would expect for an agricultural stream of the same drainage area in Southwest Ohio. Furthermore, for the agricultural streams, Marshalls Branch tends to have larger bankfull characteristics than the other three agricultural streams.

**Table 7** Power function regressions of the given bankfull characteristics versus their watershed and their respective R-square values.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Regression Equation</th>
<th>R-square</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_{bf}$</td>
<td>$45.069 \times DA^{0.2308}$</td>
<td>0.5357</td>
</tr>
<tr>
<td>$d_{bf}$</td>
<td>$2.3103 \times DA^{0.1523}$</td>
<td>0.2769</td>
</tr>
<tr>
<td>$a_{bf}$</td>
<td>$104.12 \times DA^{0.383}$</td>
<td>0.5341</td>
</tr>
<tr>
<td>$q_{bf}$</td>
<td>$59.941 \times DA^{0.8204}$</td>
<td>0.6157</td>
</tr>
</tbody>
</table>

Bankfull hydraulic geometry relationships are also plotted by the watersheds land use dominance as seen in Figures 32-35. Power function regression equations and their R-square values are listed in Table 9. From these bankfull hydraulic geometry relationships I can see that bankfull dimensions for the urban streams, particularly the bankfull depth and discharge, are much greater than what we would expect for an agricultural stream of the same drainage area in Southwest Ohio. Furthermore, for the agricultural streams, Marshalls Branch tends to have larger bankfull characteristics than the other three agricultural streams.

**Figure 32** Bankfull hydraulic geometry relationship for cross-sectional area for urban and agricultural streams.
**Figure 33** Bankfull hydraulic geometry relationship for width for urban and agricultural streams.

**Figure 34** Bankfull hydraulic geometry relationship for average depth for urban and agricultural streams.
Figure 35 Bankfull hydraulic geometry relationship for discharge for urban and agricultural streams.

<table>
<thead>
<tr>
<th></th>
<th>Equation</th>
<th>$R^2$</th>
<th></th>
<th>Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban $W_{bf}$</td>
<td>$43.836*DA^{0.1894}$</td>
<td>0.0265</td>
<td>Urban $A_{bf}$</td>
<td>$118.78*DA^{0.2869}$</td>
<td>0.0177</td>
</tr>
<tr>
<td>Agricultural $W_{bf}$</td>
<td>$48.352*DA^{0.2083}$</td>
<td>0.3727</td>
<td>Agricultural $A_{bf}$</td>
<td>$89.398*DA^{0.432}$</td>
<td>0.4968</td>
</tr>
<tr>
<td>Urban $D_{bf}$</td>
<td>$2.7097*DA^{0.0976}$</td>
<td>0.0048</td>
<td>Urban $Q_{bf}$</td>
<td>$209.55*DA^{0.134}$</td>
<td>0.0012</td>
</tr>
<tr>
<td>Agricultural $D_{bf}$</td>
<td>$1.8489*DA^{0.2237}$</td>
<td>0.3734</td>
<td>Agricultural $Q_{bf}$</td>
<td>$37.686*DA^{1.0605}$</td>
<td>0.8258</td>
</tr>
</tbody>
</table>

Table 8 Power function regressions of the given bankfull characteristics versus their watershed and their respective R-square values for urban and agricultural streams.

Land Use Effects on Bankfull Hydraulic Geometry

Stream channel response is highly complex and varies based on individual watershed practices. Variety in channel responses is largely a result of the land use type and magnitude of disturbance (Wolman, 1967; Trimble, 1977; Knox, 2001; Chin, 2006). My research shows that land use has an effect on bankfull channel geometry. Bull Run is characteristic of other urban watersheds that are deeply incised (Wolman, 1967; Chin, 2006). For the most part, the agricultural watersheds within this study are similar to those in similar studies elsewhere (Costa, 1975; Trimble, 1977; Knox, 2001) in that the streams in this study are wider than natural streams and are incised into the floodplain. These channels are attempting to reestablish a state of quasi-equilibrium. However, Upper Four Mile Creek differs, in that it has a well-developed active
floodplain, and at the gauging station there is no indication of aggradation. This difference in Upper Four Mile Creek relative to other agricultural streams is most likely a result of the impoundment downstream.

Bull Run’s watershed has been heavily disturbed by both urban and agricultural practices since the settlement of Oxford about 200 years ago. Although there is development of incipient floodplains, the upper slopes of the banks within Bull Run are continuing to fail. Private land owners along the upper terrace of Bull Run continue to complain as their land falls into the channel. Field excursions into Bull Run indicate frequent bank failure and several trees have fallen into the channel (Figure 36). The development of incipient floodplains within the channel coupled with upper bank failures is consistent with the aggradation stage of Simon’s stream channel evolution (Simon, 1989). Simon’s stream channel evolution model indicates that the next stage of development for a stream is to become restabilized or rather reach a state of quasi-equilibrium; the small incipient floodplains in the Bull Run channel may be evidence of this.

![Figure 36](image)

**Figure 36** Two segments along the upper banks in Bull Run indicating heavy incision and bank failure. Several trees have fallen into the channel and continue to erode away private property.

The incipient floodplains within Bull Run may be temporary if disturbance within the watershed continues. To see if there has been an increase in the severity of disturbed landscapes within Bull Run I digitized the land use using 2009 aerial photography and compared to the NLCD 2001 classification scheme. For Butler County, 2009 aerial photography was recently released. There may be some discrepancies between the NLCD 2001 classification procedures and my digitization of the 2009 aerial photographs. Some of these discrepancies include (1) the user criteria for a particular landscape to be considered urban (e.g. amount of impervious surfaces, sewers and water pipes, any sort of developed landscape), and (2) differences in raster versus polygon creation within ArcGIS. Nonetheless, the imagery indicates that several neighborhoods and large parks have expanded on the west side of Oxford increasing the amount of impervious surfaces. Between 2001 and 2009 the percentage of urban land use jumped from 19.44% to 56.11% (Figure 37). The remaining undisturbed landscape is only 15% of the total watershed. The increase in the urbanization induces further disruption to the stream channel, and it may be many years before the channels restabilize.
Figure 37 Land use maps of Bull Run from 2001 and 2009. The 2001 is from the NLCD which is in a raster format. The 2009 land use map was digitized from 2009 aerial photography for Butler County, OH. A discrepancy with the aerial photography is that the image was taken during leaf-on season and it is more difficult to read some of the landscape. Most of the vegetation is riparian which made for a more clear representation of the land use within Bull Run’s watershed.

The agricultural stream of Indian Creek, Harkers Run and Marshalls Branch also exhibit similar characteristics of other agricultural streams (Costa, 1975; Trimble, 1977; Knox, 2001). These three agricultural streams have inconsistent levels of floodplain development, or development of incipient floodplains. The inconsistent levels are a result of deep incision from changes in flow regime from the changes in the landscape. As with the urban channel, this is apparent by historic terraces, development of incipient floodplains and exposure of glacial till. However, these channels are not as heavily incised as Bull Run. Bull Run has bankfull channel dimensions larger than Marshalls Branch, which has a drainage area over two times larger than Bull Run.

Within this study, I have seen that there are other factors besides land use that may play a major role in the development of modern bankfull channel geometry. This is especially apparent in Upper Four Mile Creek and Marshalls Branch, which have almost identical land use practices between agricultural and forested landscapes. However, in Marshalls Branch there is a much larger difference between the elevation of the indirect estimates of the bankfull discharge and the 1.5-year flow. This difference may be due to (1) the smaller drainage area compared to Upper Four Mile Creek or (2) backwater effects of Acton Lake on Upper Four Mile Creek and Marshalls Branch. Other factors that may contribute to the difference between the indirect estimates of bankfull discharge and 1.5-year flow include local-channel slope, riparian vegetation, quantity of instream debris and the underlying stratigraphy that affects water storage.
Acton Lake has raised the base level of both Marshall’s Branch and Upper Four Mile Creek. Base levels were obtained from gauging stations on Upper Four Mile Creek (869 feet) and Marshalls Branch (883 feet), as well as the base level at the dam of Acton Lake (863.4 feet, 866 ft at flood stage) (Figure 38). There is a small difference between base level at Upper Four Mile Creek and Acton Lake. This base level may act as a threshold for incision for Upper Four Mile Creek and may be a reason why we see consistent levels of active-floodplain connected to the bankfull flow. On the other hand, Marshalls Branch base level sits twenty feet above Acton Lake. The base level threshold set by Acton Lake may be inducing the magnitude of incision within Marshalls Branch causing a large disconnect between channel form and flow.

Figure 38 Map of Acton Lake in relation to Upper Four Mile Creek and Marshalls Branch. Base-level of each of the gauging stations for the two streams are labeled, as well as the base level at the dam of Acton Lake.
Comparison to Ohio Bankfull Hydraulic Geometry Relationships

Bankfull hydraulic geometry relationships of measured and predicted bankfull channel characteristics (width, depth, area and discharge) are shown in Figure 39-42. For all bankfull characteristics there is a greater difference between the measured and predicted for smaller drainage areas (e.g. Bull Run, Harkers Run and Marshalls Branch). As drainage area increases, there is a trend of greater correlation between bankfull characteristics. This is particularly apparent for bankfull depth. Bull Run’s channel is markedly larger than predicted. Bull Run is the only stream that would not been used in the creation of the regional bankfull hydraulic geometry relationship. If we remove Bull Run from our stream sample, the difference between observed and predicted decreases for smaller drainage areas but still is substantial.

![Bankfull XS Area](image)

**Figure 39** Bankfull hydraulic geometry relationship comparison between the five study watersheds and the predicted bankfull cross-sectional area for Ohio.
**Figure 40** Bankfull hydraulic geometry relationship comparison between the five study watersheds and the predicted bankfull width for Ohio.

**Figure 41** Bankfull hydraulic geometry relationship comparison between the five study watersheds and the predicted average bankfull depth for Ohio.
Figure 42 Bankfull hydraulic geometry relationship comparison between the five study watersheds and the predicted bankfull discharge for Ohio. Indirect estimates are used for the ungauged streams while the observed 1.5-year flow is used for the two gauged stations.

Hec-RAS simulations of the 1.5-year flow, indirect estimates of bankfull flow and the predicted bankfull flow are shown in Figures 43-44. For Marshalls Branch, the observed 1.5-year flow is consistent with the predicted bankfull flow. The indirect estimates for Marshalls Branch overestimate the bankfull flow compared to observed and simulated flows. Conversely, Upper Four Mile Creek has an observed 1.5-year flow similar to the indirect estimate of bankfull flow, and at the 1.5-year flow there is a well-developed active-floodplain.
**Figure 43** Simulation of the Upper Four Mile Creek indirect estimate bankfull flow, 1.5-year observed flow and the predicted flow for Ohio streams.

**Figure 44** Simulation of the Marshalls Branch indirect estimate bankfull flow, 1.5-year observed flow and the predicted flow for Ohio streams.
Enlargement ratios between measured and predicted bankfull channel features are listed in Table 10. For the most part, enlargement ratios indicate much larger bankfull channel features for the study area compared to what is predicted for the state of Ohio. Bull Run exhibits much larger enlargement ratios for bankfull channel features. Bull Run is the only stream that is not characteristic of streams that were used to create the regional bankfull hydraulic geometry relationships for Ohio (e.g. rural, un-regulated streams) (Sherwood and Huitger, 2005). However, the large enlargement ratios for Bull Run are another indicator of the deep incision that is occurring within the urban stream. We would expect much smaller bankfull characteristics for an rural-unregulated stream of the same drainage area. Overall, it is apparent from the enlargement ratios that streams in this study are larger than what we would expect for rural-unregulated streams within Ohio.

<table>
<thead>
<tr>
<th></th>
<th>$w_{bf}$</th>
<th>$d_{bf}$</th>
<th>$a_{bf}$</th>
<th>$q_{bf}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR</td>
<td>2.37</td>
<td>1.75</td>
<td>4.36</td>
<td>1.98</td>
</tr>
<tr>
<td>HR</td>
<td>2.35</td>
<td>1.28</td>
<td>3.05</td>
<td>1.69</td>
</tr>
<tr>
<td>IC</td>
<td>1.64</td>
<td>1.16</td>
<td>1.89</td>
<td>2.30</td>
</tr>
<tr>
<td>MB</td>
<td>2.01</td>
<td>1.11</td>
<td>2.35</td>
<td>0.65</td>
</tr>
<tr>
<td>FMC</td>
<td>1.46</td>
<td>0.93</td>
<td>1.38</td>
<td>2.01</td>
</tr>
</tbody>
</table>

Table 9: Enlargement ratios between the measured and Ohio-predicted bankfull channel characteristics for the five study watersheds.

**Implications for Stream Restoration**

Streams in this study are examples of why stream restoration is needed because land use changes have affected the natural processes that occur within these stream systems. Alterations to the natural landscape tend to accelerate runoff and soil erosion forcing streams into a state of disequilibrium. This is apparent in Indian Creek, Marshalls Branch, Harkers Run and Bull Run. Channel widening and bank failure continue to occur within these streams. Figure 36 shows some of the banks within Bull Run. Exposure of piping and large tree falls has occurred within several reaches of the stream. Within Indian Creek, channel widening threatens farmers’ crops. Placement of rip-rap along channel reaches through the study reach and further downstream has increased throughout the last year (Figure 45). However, these management practices are not effective at managing the entirety of the stream and may be only a local-temporary fix.

Some stream restoration projects use regional bankfull hydraulic geometry relationships to estimate bankfull characteristics. Accurately measuring the bankfull stage is commonly used to determine the approach to stream restoration and the creation of regional bankfull hydraulic geometry relationships are used to mitigate field excursions to estimate and understand the modern channel. However, regional bankfull hydraulic geometry relationships may not be specific to every local watershed. This is apparent within this study.
The regional bankfull hydraulic geometry relationship for Ohio does not accurately predict the modern bankfull channel geometry for the five study watersheds. All streams in this study, especially Bull Run, have larger bankfull characteristics than the predicted measurements of the state of Ohio. Therefore, if the predictive model was used for restoration projects on any of the five streams in this study there would be an underestimation of the bankfull dimensions appropriate to this region. This underestimation of bankfull characteristics would lead to the creation of ‘restored-channel’ that is too small for the actual modern channel. Powell et al (2006) report that this is common for streams in Ohio and elsewhere throughout the Midwest region of the U.S.

**Figure 45** Rip-rap placement upstream of cross-section 1 on Indian Creek. Rip-rap placement throughout the study reach in Indian Creek has increased over the last year.

**SUMMARY AND CONCLUSIONS**

Five watersheds of various land uses and drainage areas were used in this study to determine how land use may have affected modern bankfull channel geometry. In Southwest Ohio, the landscape is at least 70% disturbed, predominately by present or historical agricultural land use practices. Previous research indicates that high disturbance by anthropogenic factors causes a shock to fluvial systems inducing rapid morphologic and hydrologic changes. To quantify land use effects on bankfull channel geometry in Southwest Ohio I have addressed a series of sub-questions: (1) can LiDAR cross-sections be used to supplement field data and determine bankfull channel geometry, (2) what is the bankfull channel geometry and flow in the five watersheds in this study, (3) what is the difference of bankfull dimensions between
agricultural and urban watersheds, (4) and lastly how do these bankfull measurements compare to predicted bankfull measurements for the state of Ohio.

From the Ohio LiDAR analysis, I determined that cross-sections could be extracted for fluvial studies. However, this can only be done with a careful set of rules. The second hypothesis was confirmed for four out of the five streams. Deep incision in four streams affirms the enlargement of the channel relative to the 1.5-year flow. However, Upper Four Mile Creek is an agricultural watershed that remains hydrologically connected to its floodplain with no indication of channel incision. Lastly, the urban stream of Bull Run had some of the greatest incision for its drainage area compared to the other agricultural streams in this study.

Use of LiDAR in fluvial geomorphic studies

LiDAR is becoming an increasingly popular tool to obtain quick and efficient access to a surplus of data concerning stream channels and related features. However, LiDAR is typically not as effective in the low-topographic relief common in floodplains, river deltas and stream channels. Using LiDAR in such low-relief regions is more effective with the two-beam LiDAR collection process but the Ohio data available to me did not use this process. However, in the five watersheds in this study the Ohio LiDAR was sufficient to obtain useful cross-sectional information. Using LiDAR in this study was more effective because the flow in the channels is relatively small which allows for an accurate representation of the stream bed (Jones et al, 2008; Bater, 2009). In all cases careful consideration of the effects of water in channels should be used with LiDAR data.

LiDAR data has elevation information to supplement cross-sectional surveys. However, the quick access to LiDAR data does not eliminate the need for field verification and observations of bankfull channel dimensions for stream management projects. There may be adverse affects of using LiDAR data in fluvial geomorphic-mapping and careful consideration and analysis needs to be conducted when using these data. In either case, a careful set of rules should be created to accurately identify ideal locations for LiDAR cross-sections. For the Ohio LiDAR dataset, we suggest using the set of rules given in this paper to guide identifying good cross-sections and determining the bankfull characteristics.

Bankfull Hydraulic Geometry and the Land Use Affects

In terms of the bankfull hydraulic geometry, my hypothesis was confirmed in that majority of the streams in this study exhibit evidence of incision with a difference between morphologic and hydrologic bankfull dimensions. This difference is apparent in four out of the streams. Evidence of incision is apparent by the presence of historic terraces, incipient floodplains and exposure of glacial till. However, Upper Four Mile Creek shows an absence of incision and a close correspondence between the morphologic bankfull and the hydrologic bankfull of the 1.5-year flow.

This research supports previous studies showing that land use affects stream channel characteristics (Leopold and Maddock, 1953; Dunne and Leopold, 1978; Wolman, 1967; Knox, 2001; Chin, 2006). Land use disturbance is the major factor influencing the bankfull channel geometry within this study. Furthermore, I’ve seen that in this study land use disturbances can alter the state of equilibrium within the channel (Leopold and Maddock, 1953; Dunne and Leopold, 1978; Renwick, 1992; Phillips, 2007).
Stream channel response is complex and varies based on individual watershed practices. In this study, the four agriculturally-dominated streams are widening with variation in the width-depth ratios for each stream. The agricultural streams are continuing to experience incision within the channel and developing benches and incipient floodplains within the inset channel.

Tools for Stream Restoration

Techniques used in this study are valuable tools for accurately determining modern bankfull channel geometries. Bankfull hydraulic geometry relationships provide an estimation of what bankfull channel geometry should be given a certain drainage area. However, the use of bankfull hydraulic geometry relationships need to be region specific since the use of the relationships are commonly used in stream restoration and management projects. For the streams in this study, if the predictive model was used for restoration projects there would be a gross underestimation of the bankfull characteristics. Multiple techniques should be used to accurately determine the bankfull hydraulic geometry for streams at a local-watershed scale.
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