EFFECTS OF URBANIZATION ON CHANNEL MORPHOLOGY OF THREE STREAMS IN THE CENTRAL REDBED PLAINS OF OKLAHOMA

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Dedicated to my parents

(Mr. Gurdip S. Kang and Mrs. Pushpinder K. Kang)

and Advisors

(Dr. Richard A. Marston and Dr. Daniel E. Storm)

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It is my great pleasure to express my gratitude to those who played a significant role in helping me to complete this dissertation. This dissertation is dedicated to my two advisors and parents who have contributed the most to my academic career.

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Ranbir Singh Kang

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CHAPTER 1

INTRODUCTION

Urbanization is one of the most complex phenomena of the 20th Century (Allen et al., 2002). This involves rural to urban transformation and the growth of urban population; at twice the rate of total population growth (UNPF, 2004). These urban growth patterns have transformed fluvial landscapes in different parts of the world (Chin, 2006; Urban et al., 2006). By directly and indirectly modifying components of the landscape, urbanization can alter flow and sediment discharge into streams. The primary measure of urbanization in a watershed is the area under impervious cover (May et al., 2002). Impervious cover refers to any surface that prevents the infiltration of water into soil (Arnold and Gibbons, 1996) and can be divided into two components: non-transportation components (i.e. roof tops), and the transport network composed of roads, driveways, and parking lots (Schueler, 1994).

Urbanization can affect river systems in unexpected ways (Booth and Jackson, 1994). The increase in impervious cover, deforestation, soil compaction, and decreased roughness of stream banks that urbanization often entails are the most obvious manifestations of urban development (May et al., 2002). These surfaces decrease the infiltration capacity of land, and lead to higher runoff by adding more water to streams than areas not affected by urbanization. Because water runs faster over impervious surfaces (concrete, asphalt, roof tops, roads, and streets), construction decreases the lag time of surface runoff (from decreased infiltration) and increases flood peaks that affect channel morphology in different ways, such as alterations in channel cross-sections, types of bed materials, types of channel units, and riparian vegetation (Avolio, 2003; Booth, 1990; Booth, 1991; Brierley and Fryirs, 2005; Jeje and Ikeazota, 2002; Johnson, 2001; May et al., 2002; Morisawa and Laflure, 1979; Nanson, 1981; Othitis et al., 2004). Therefore, a strong association commonly exists between the degree of urbanization, as measured by imperviousness in a drainage basin, and the morphology of its receiving stream (Benfield et al., 1999). Charbonneau and Resh (1992) noticed the influence of urbanization on channel morphology that involved channel down-cutting, stream bank erosion, and destruction of the natural pool-riffle sequence.

The degree of association between urbanization and channel morphology depends on the type of impervious surface (Avolio, 2003; May et al., 2002; Schueler, 1994). The transportation component (road networks) is a particularly pervasive type of urban development impacting stream morphology. The area covered by roads generally exceeds the area under other impervious surfaces by a great margin (Schueler, 1994). Roads increase runoff and sediment yields by delivering large amounts of storm water into stream channels during heavy rains (Chin and Gregory, 2001; Forman and Alexander, 1998). The decreased lag time for flood events due to increased imperviousness is the major source of impact associated with roads. Major sources of sediment associated with roads include road surfaces, cutbanks, hillslopes, bridge/culvert sites, and ditches. As a result, the rate and extent of erosion increases with increased stream discharge rates.

Additionally, new road crossings may cause bank erosion and affect the presence or absence of pools, large woody debris (LWD), and the type of substrate materials that deteriorate geomorphic conditions of streams (Avolio, 2003). Construction of bridges can alter streams for considerable distances both upstream and downstream of bridges (Forman and Alexander, 1998). This impact, however, varies locally with the degree of imperviousness (urbanization) and is determined by the watershed and adjacent riparian conditions. Due to the growth of urbanization there is a need to study the impact of such land-transformation processes (Grimm et al., 2000). This research examines the spatial variations in such impacts on three streams with different levels of impervious cover.

Based upon the degree of imperviousness, this project considered three stages of urbanization in a watershed: rural, ex-urban, and urban. By convention, the rural stage is a pre-urbanization period with up to 3% of its area under impervious cover; the ex-urban stage is the transition period from rural to urban with 3--10% of its area under impervious cover (Neller, 1988); the urban stage is characterized by > 10% of the watershed area under impervious cover (May et al., 2002).

1.1 Problem Statement

Geomorphic response of stream channels to different degrees of urbanization is not sufficiently understood (Graf, 1976). The lack of geomorphic understanding is more evident in the Central Redbed Plains geomorphic province. Fifty-eight English language studies have reported the impacts of urbanization on channel morphology, but to date no study has been completed in the South-Central region of the United States (Arnold and Gibbons, 1996; Booth, 1990; Booth, 1991; Booth and Jackson, 1997; Chin, 2006; Chin and Gregory, 2001; Hammer, 1972; Morisawa and Laflure, 1979; Trimble, 1997). This project directly targeted that research gap. The use of ergodic reasoning (substitution of space-for-time) in the three similar streams contributed to the understanding of geomorphic response of a single stream to the changing degrees of urbanization in the south-central part of United States.

The purpose of this research was to evaluate the geomorphic impact of urbanization on channel morphology of three streams in the Central Redbed Plains geomorphic province of Oklahoma. The three watersheds are experiencing transformation from rural to urban land cover. The rural watershed, Skeleton Creek, is predominantly agricultural, and the urban watershed, Deep Fork Creek, is dominated by urban land cover. The ex-urban watershed, Stillwater Creek, is experiencing urbanization in the downstream section. It was anticipated that the effects of urbanization were primary factors changing channel morphology of ex-urban and urban streams as compared to a rural stream (Paul and Meyer, 2001). The following research questions and hypotheses were used to address the goals of this research.

1.2 Research Questions and Hypotheses

Six research questions were addressed by testing eight hypotheses for each research question. The research questions were based on two standard approaches commonly used in fluvial geomorphology to study the impacts of urbanization on channel morphology (Chin, 2006). The first approach (Approach 1), is dividing each river into upstream and downstream sections and comparing the two sections (Gregory and Park, 1976). This approach was used to address the first three research questions (Questions 1, 2, and 3) and test respective hypotheses (Hypotheses 1.1-1.8, 2.1-2.8, and 3.1-3.8). The second approach (Approach 2) involves comparison of similar streams with different degrees of urbanization, such as rural, ex-urban, and urban (Morisawa and Laflure, 1979). This approach was used to address the next three research questions (Questions 4, 5 and 6) and test respective hypotheses (Hypotheses 4.1-4.8, 5.1-5.8, and 6.1-6.8).

Question 1: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) of Stillwater Creek downstream of Boomer Creek as compared to upstream? Can this change be explained by urbanization in the downstream section of Stillwater Creek watershed?

It was anticipated that Stillwater Creek is influenced by urbanization in the downstream section of Boomer Creek, and thus the influence of urbanization on Stillwater Creek will affect channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size downstream of Boomer Creek.

Hypothesis 1.1: Channel width is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.2: Width depth ratio is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.3: Gradient is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.4: Bankfull area is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.5: Friction factor is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.6: Threshold grain size is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.7: Sinuosity is significantly less downstream of Boomer Creek compared to upstream as measured at a 0.05 level of significance.

Hypothesis 1.8: Mean depth is significantly less downstream of Boomer Creek compared to upstream as measured at a 0.05 level of significance.

In order to corroborate the same approach, the other two streams, Skeleton and Deep Fork Creeks, were also divided into upstream and downstream sections with the help of major tributaries. This was followed by framing the same research questions (Questions 2 and 3) and hypotheses as follows:

Question 2: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) of Skeleton Creek downstream of Bitter Creek as compared to upstream? Can this change be explained by land cover type in the downstream section of the Skeleton Creek watershed?

Hypothesis 2.1: Channel width is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.2: Width depth ratio is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.3: Bankfull area is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.4: Gradient is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.5: Friction factor is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.6: Threshold grain size is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.7: Sinuosity is significantly less downstream of Bitter Creek compared to upstream as measured at a 0.05 level of significance.

Hypothesis 2.8: Mean depth is significantly less downstream of Bitter Creek compared to upstream as measured at a 0.05 level of significance.

Question 3: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) of Deep Fork Creek downstream of its major tributary Deep Fork Creek as compared to upstream? Can this change be explained by land cover type in the downstream section of the Deep Fork Creek watershed?

Hypothesis 3.1: Channel width is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.2: Width depth ratio is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.3: Bankfull area is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.4: Gradient is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.5: Friction factor is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.6: Threshold grain size is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.7: Sinuosity is significantly less downstream of Deep Fork Creek compared to upstream as measured at a 0.05 level of significance.

Hypothesis 3.8: Mean depth is significantly less downstream of Deep Fork Creek compared to upstream as measured at a 0.05 level of significance.

The next three questions compared the three streams with each other (Approach 2) to address possible changes in channel morphology due to the changing degree of urbanization from Skeleton to Stillwater to Deep Fork Creek.

Question 4: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) from Skeleton Creek (rural) to Stillwater Creek (ex-urban)? Can this change be explained by increasing urbanization from a rural to an ex-urban watershed?

It is believed that urbanization is a trait that represents conversion of watersheds from rural to ex-urban. The conversion of a rural to an ex-urban watershed was expected to affect channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size.

Hypothesis 4.1: Channel width is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.2: Width depth ratio is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.3: Bankfull area is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.4: Gradient is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.5: Friction factor is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.6: Threshold grain size is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.7: Sinuosity is less in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.8: Mean depth is less in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Question 5: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) from Stillwater Creek (ex-urban) to Deep Fork Creek (urban)? Can this change be explained by increasing urbanization from an ex-urban to an urban watershed?

The process of urbanization is expected to transform an ex-urban watershed into an urban watershed. This urban transformation would lead to further change in channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size.

Hypothesis 5.1: Channel width is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.2: Width depth ratio is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.3: Bankfull area is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.4: Gradient is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.5: Friction factor is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.6: Threshold grain size is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.7: Sinuosity is less in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.8: Mean depth is less in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Question 6: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) from Skeleton Creek (rural) to Deep Fork Creek (urban)? Can this change be explained by increasing urbanization from a rural to an urban watershed?

The process of urbanization is expected to transform a rural watershed into an urban watershed. This urban transformation would lead to further change in channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size.

Hypothesis 6.1: Channel width is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.2: Width depth ratio is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.3: Bankfull area is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.4: Gradient is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.5: Friction factor is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.6: Threshold grain size is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.7: Sinuosity is less in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.8: Mean depth is less in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

1.3 Significance

During the last century, human activities such as urbanization have dramatically transformed river environments (Grimm et al., 2000; Karr, 1999). Due to the growing impact of urban areas on the surface processes, there is a strong need to study these environments (Grimm et al., 2000; Hammer, 1971). Wolman (1967) completed one of the earliest studies on how urbanization alters stream channel morphology (Fig. 1.1). According to this study, channel morphology experiences radical changes during the construction stage. Since then, only 58 English language studies have looked at morphological changes in river landscapes due to urbanization in different parts of the world (Chin, 2006). Out of these, most of the studies (27) were conducted in the United States, followed by the U.K., Nigeria, Malaysia, Canada, Zimbabwe, France, and Israel (Fig. 1.2, Table 1.1).

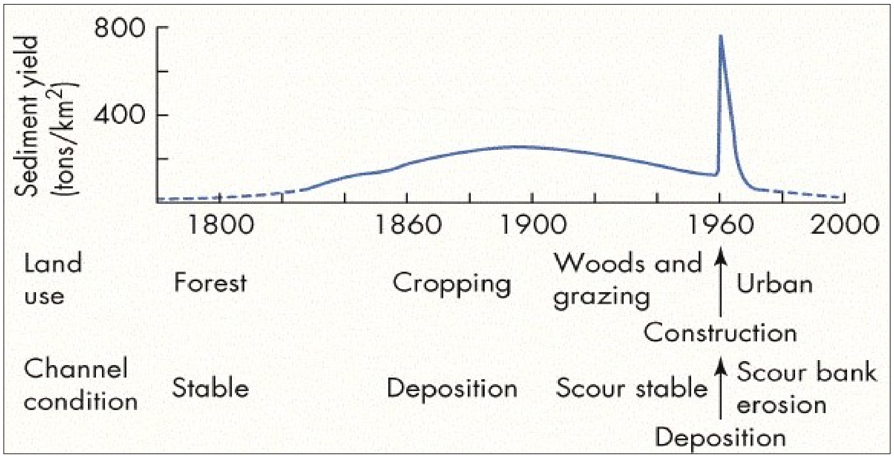

Figure 1.1: Effects of land use on sediment yield and channel conditions (Wolman, 1967)

Each of those studies emphasize the role of local conditions in controlling the scale of channel enlargement due to urbanization (Booth and Henshaw, 2001; Hession et al., 2002; Hollis, 1976; Leopold, 1972; Montgomery, 1997; Nanson, 1981). At the same time, the significance of time in evaluating channel response to urbanization is very critical (Chin, 2006). The magnitude and direction of channel response/adjustment will vary according to the degree of urbanization (Figs. 1.3 and 1.4). Therefore, it is important to specify where on the sediment yield curve a stream channel is being studied. This will help to understand possible future adjustments in stream channels.

Each stream selected for this study represents one of three distinct time periods on the sediment curve (Figs. 1.3 and 1.4), i.e. aggradation due to cropping and construction, respectively followed by erosion due to urbanized landscapes such as rooftops, parking lots and road networks. Most studies have been conducted in the eastern and western United States. Therefore, less is known regarding channel enlargement due to urbanization in the Central Redbed geomorphic province.

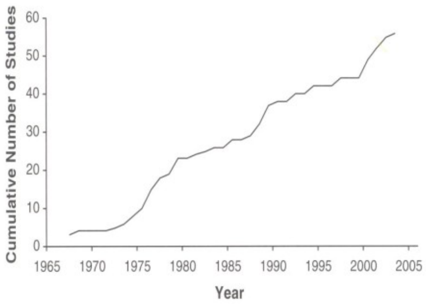

Figure 1.2: Cumulative number of studies reporting urban-induced morphological change from 1956 to 2005 (Chin, 2006)

Table 1.1: Number of post-56 English language publications reporting urban-induced morphological change by decade and study location (Chin, 2006)

Region	1960s	1970s	1980s	1990s	2000s
U.S.	4	9	3	2	9
U.K.		8	3	2	
Australia		3	3		
Malaysia		1	1		
Nigeria			2	2	1
Zimbabwe			1		
France			1		
Canada				1	1
Israel					1
Total	4	21	14	7	12

This project is the first comprehensive study to characterize stream channel adjustment in response to urbanization in the Central Redbed geomorphic province. Therefore, the findings of this project may provide useful insight into the geomorphic behavior of streams in this geomorphic province. Likewise, the results of this study may provide critical knowledge needed to develop tools for stabilizing streams affected by urbanization in this part of the USA. These findings may also be used to test the effectiveness of existing measures in stabilizing streams affected by urbanization in this geomorphic province.

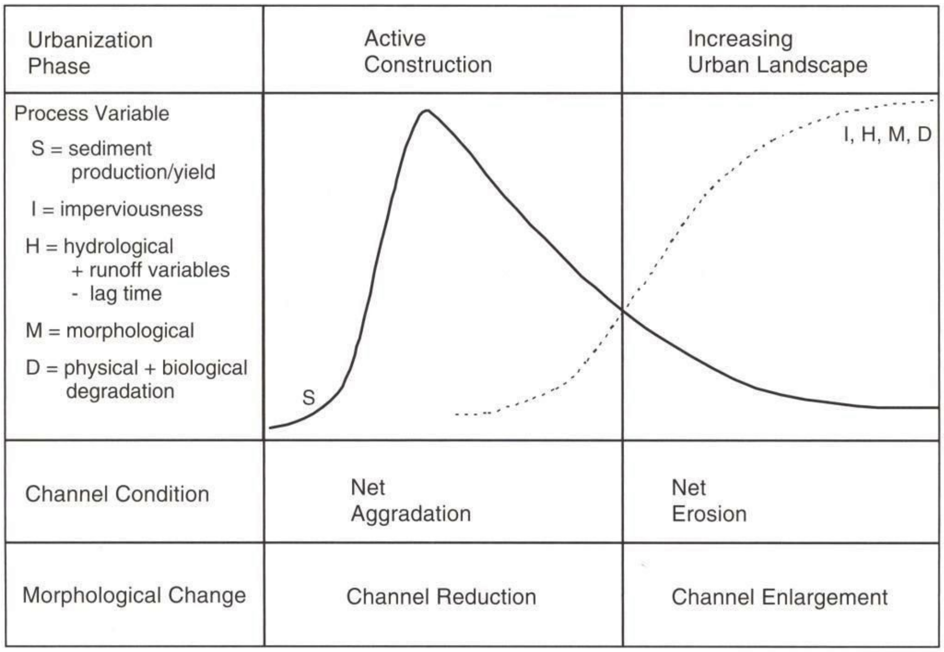

Figure 1.3: Modified version of Wolman's model showing channel conditions and adjustments in response to changing degrees of urbanization (Chin, 2006)

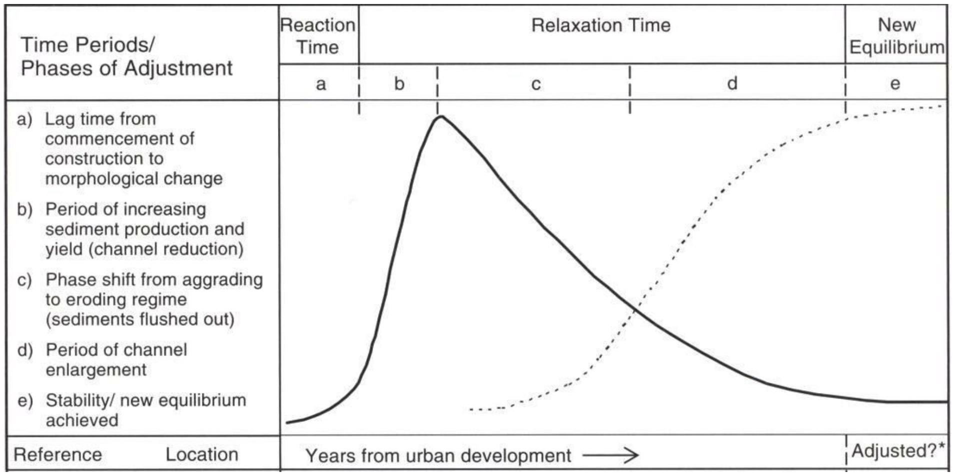

Figure 1.4: Time periods of channel adjustments in response to different degrees of urbanization (Chin, 2006)

CHAPTER 2

PRESENT STATE OF KNOWLEDGE

2.1 Impacts of urbanization on stream channel morphology

Impervious surfaces dramatically impact river systems (Arthington, 1985; Charbonneau and Resh, 1992; Karr, 1999) and impair the beneficial uses of over 50,000 kilometers of streams and rivers in the United States (Bowles et al., 2006). The most common types of impervious surfaces include rooftops, parking lots, roads, streets, bridges, drive ways, and side walks (Arnold and Gibbons, 1996; Bavard and Petts, 1996; Booth, 1990; Booth and Henshaw, 2001; Charbonneau and Resh, 1992; Fusillo et al., 1977; Konard, 2002; Leopold, 1968; May et al., 2002; Schueler, 1994). Compared to pre-development conditions, these surfaces increase storm runoff volume, the frequency of floods, and peak discharges (Booth, 1991).

Streams adjust to increased runoff regimes by altering their morphology through the undercutting of banks and the deposition of sediment downstream. Debris from storm scour blocks stream flow, straightens stream channels, and causes stream channel enlargement. Therefore, the increased runoff and sediment supply from watersheds with increasing impervious surfaces affect channel morphology by altering channel cross-sections (Hammer, 1972). All of these alterations, however, vary at different locations and lead to complex stream channel characteristics (Morisawa and Laflure, 1979).

The most important factor in explaining spatio-temporal variability in alterations in channel cross-sections is the length of time an impervious area has been in existence. Because downstream channel enlargement is time dependent, impervious areas that have been in existence for 4-15 years have the maximum impact on channel enlargements; however, these impacts decrease considerably after 30 years because of a tendency for recovery (Hammer, 1972).

Another factor is variable channel enlargements caused by the similar urban growth in different streams. Hollis (1976) found a similar increase in imperviousness leading to dissimilar increase in cross-sections of two streams in southeastern England. The main reason for such variation is a difference in local conditions (bedrock geology, soil structure, entrenchment ratio, and riparian vegetation). Finally, drainage basin area is another factor that can affect the impact of urbanization on stream channels. Even small changes in imperviousness can have significant downstream consequences in small drainage basins. However, due to dilution effects, urbanization in large basins might lead to less significant downstream consequences. As a result, rural to urban land cover change can lead to larger cross sections in urban streams as compared to rural streams (Hession et al., 2002; Pizzuto et al., 2000; Trimble, 1997).

Urbanization can also reduce channel cross-sectional area (Booth and Henshaw, 2001; Leopold, 1972; Nanson, 1981). For example, Nanson (1981) observed downstream reduction in channel cross-sectional area in an urbanizing river on the Illawara escarpment in New South Wales, Australia, and attributed the phenomenon to resistant sediments, vegetation, and a sudden decline in channel slope and associated stream power. Similarly, Leopold (1972) observed a slow reduction in channel cross-sectional area in Washington, D.C. during the first decade of urbanization. During a later period of urbanization, channel area increased because of increased sediment deposition caused by annual flooding. Over a twenty year period (1953-1972), however, the channel area showed a 20% decrease as opposed to an increase advocated by Hammer (1972). Booth and Henshaw (2001) also observed a decrease in channel cross-sectional area in urban channels in western Washington because of geologic conditions that limited erosion. In urban streams, sinuosity is lower (8% lower), pools are less deep (31% shallower), channel gradients are steeper, and the substrate is more easily erodable (Hession et al., 2002).

In the case of impervious surfaces, road networks have significant influences on channel morphology (Forman and Alexander, 1998). In the United States, road density is 1.2 km/km^2. High road density also affects subsurface flow. The influence of roads on channel morphology is due to water runoff and sediment yield. During storm events, roads provide rapid runoff and increase the stream discharge causing erosion. Such impacts of roads tend to influence larger sections of streams and more heavily in the downstream direction.

2.2 Impacts of riparian vegetation on stream channel morphology

Riparian vegetation and land cover play equally important roles in shaping channel morphology (Hession et al., 2002). Riparian vegetation performs various functions for streams, such as reducing sediment and nutrient loads, attenuating peak flow, and initiating fluvial adjustments (Simon et al., 2004). Therefore, it is important to understand the impact of riparian vegetation on channel morphology. The presence of riparian vegetation enhances stream bank stability and increases flow resistance by disrupting flow paths. The absence or removal of riparian vegetation, however, leads to higher rates of runoff, erosion, and the alteration of channel morphology (Simon et al., 2004).

Urbanization can also lead to a reduction in riparian corridors. As urban areas increase, improper construction and maintenance of roads can degrade the process, structure, and function of riparian corridors. This degradation leads to alterations in channel morphology, changes in the amount of organic debris in streams, hill slope drainage alterations, and base flow changes.

Avolio (2003) suggests that increasing road density has an impact on channel morphology and argues that maintaining a thick riparian corridor can help mitigate the impacts of road crossings on channel morphology. Riparian vegetation and channel cross-sections directly affect each other (Hession et al., 2002), and riparian vegetation interacts with stream flow during urban-induced high flow periods influencing channel morphology (Leavitt, 1998).

Hession et al. (2002) and Montgomery (1997) recognize the existence of a debate between two schools of thought on whether streams with grass-bordered banks are wider than streams with forested banks or vice versa. The main reason for such disagreement is site specific variation in local conditions such as vegetation, soils, flow regime, stream size, slopes, geologic settings, disturbance history, and watershed characteristics. Therefore, local conditions must be considered in any such analyses.

Many interpretations have been made concerning the impact of grass cover versus tree or large woody debris (LWD) on stream banks (Trimble, 2004). For example, long grass interspersed with small woody plants provide the best protection against bank erosion; however, in humid areas, tree cover increases the rate of erosion (Trimble, 2004). Trimble argues the importance of riparian vegetation for managing sediment budgets; his argument de-emphasizes the role of tree roots in controlling erosion and stabilizing streams. Other studies have argued that tree covered channels have wider cross-sections and are difficult to erode compared to grass covered banks (Allmendinger et al., 2005; Davis-Colley, 1997; Hession et al., 2002; Trimble, 1997). It is possible that the shade over flood plains due to large tree canopy can impede the growth of grass, which would lead to more erosion and channel widening, as well as increased sediment discharge. However, in general, forested channels are characterized by lower rates of floodplain formation and cutbank erosion compared to nonforested banks.

2.3 Stream channel adjustments in response to urbanization

Streams have a geomorphic tendency to recover from temporary disturbances caused by urbanization (Booth, 1991). In the case of watersheds experiencing different degrees of urbanization, channel morphological recovery occurs at variable rates. In urban watersheds, the increased magnitudes and frequencies of peak flows may inhibit geomorphic recovery, so urban streams may not have enough time to return to their pre-urban morphology. Many studies have concentrated on small watersheds (< 100 km^2). The present study focused on three watersheds that are somewhat larger than earlier studies. Also, these watersheds are experiencing conversion from agriculture (rural) to ex-urban and urban environment as a result of construction activities. These transformations lead to changes in sediment yield and channel morphology (Odermerho, 1984; Wolman, 1967). Agricultural activities yield substantial sediment supply into river channels (Quinn, 2000; Quinn and Hick, 1990). However, during construction, the land is cleared of vegetation leading to soil compaction that accelerates sediment contribution into streams (Fusillo et al., 1977).

The impacts of sediment yield from agriculture on stream channels appear after 30% coverage of the watershed area under agriculture (Quinn, 2000; Quinn and Hick, 1990). Whereas in case of imperviousness, stream channels start experiencing changes in morphology after 10% imperviousness in the watershed (Paul and Meyer, 2001; Stepenuck et al., 2002). Fusillo et al. (1977) found that construction sites contribute approximately 50 times more sediment yield than other land covers. Therefore, urban land cover leads to higher sediment yield in relatively smaller drainage areas experiencing transformation from rural to urban land cover (Fig. 1.1). Klein (1979) addresses construction as an environmental insult and agrees with Wolman (1964) and Fox (1974) that construction sites generate significantly higher sediment yield than sites with other types of land cover.

One possible explanation for such high sediment yield in case of urban watersheds is the decreased lag time leading to increased flood frequencies (Avolio, 2003; Booth, 1990; Booth, 1991; Brierley and Fryirs, 2005; Jeje and Ikeazota, 2002; Johnson, 2001; May et al., 2002; Morisawa and Laflure, 1979; Nanson, 1981; Othitis et al., 2004). In general, lag time decreases by one-half to one-fifth, while peak discharge increases from two to four times due to urbanization (Gregory, 1976). The classic model by Wolman (1967) is one of the first works on stream channel response to urbanization (Fig. 1.1). Wolman considers four stages of land cover change: forest (the pre-farming era), followed by cropping, construction, and post construction stages. Each stage of land cover affects sediment production and river channels. Sediment yield increases as the model progresses from forest to cropping to the construction stage. However, areas exposed during the construction stage produce sediment loads of 10 x 10^5 tons/square mile which are far more than sediment loads produced during the cropping stage (300 to 800 t/sq mi). All of these successive stages affect the stream channel morphology.

For almost forty years, scholars have used Wolman's (1967) model to understand channel response to urbanization in different parts of the world (Fig. 1.1). Chin (2006) synthesized the results of the studies and modified Wolman's model (Figs. 1.2 and 1.3) to describe how stream channels adjust to any changes in sediment yields and runoff by undergoing channel enlargements (Morisawa and Laflure, 1979). The watersheds in this study represent three critical stages in this model of channel adjustment due to urbanization. The rural watershed, Skeleton Creek, is an example of pre-urban stage. The ex-urban watershed, Stillwater Creek is experiencing a reaction stage due to active construction. The reaction stage refers to the lag time from initiation of construction activities to the morphological change in a stream channel (Chin, 2006). And the urban watershed, Deep Fork Creek, is the representation of relaxation time followed by new equilibrium. The relaxation stage includes channel reduction due to increase in sediment yields, sediment movement due to erosion of aggraded stream, and channel enlargement (Chin, 2006).

Previous studies have shown that stream channel responses are dramatic during the conversion from rural to ex-urban (Graf, 1976). During this stage of transformation, net aggradation leads to possible channel reduction followed by net erosion and channel enlargement once construction is complete. The construction stage is responsible for a radical increase in sediment production and serves as the reaction time period. The reaction time period is relatively short and followed by relaxation time that is characterized by an urban landscape with increased runoff and decreased lag time (time period between peak rainfall and peak discharge). As a result, stream channels adjust to the altered flow regime because the channel is large enough to accommodate the increased urban runoff (Fig. 1.4: Stage e). Therefore, the stream has achieved a new equilibrium with no further significant channel enlargement (Chin, 2006; Morisawa and Laflure, 1979).

CHAPTER-3

STUDY AREAS

The Skeleton Creek, Stillwater Creek, and Deep Fork Creek watersheds are located in the Central Redbed geomorphic province of Oklahoma (Fig. 3.1). These watersheds are characterized by a sub-humid climate (Cfa) with a slight decline in moisture westward. The average annual climate is similar in the three watersheds (Table 3.1) and they share the similar bedrock geology of the central Redbed plains. Red Permian shales and sandstones are dominant bedrock types in this region, forming gently rolling hills and broad flat plains. The bedrock formations of the Pennsylvanian and Permian periods contain red iron oxides (Johnson, 1996).

All the watersheds are similar in most respects, except for land cover, which is why they were selected for this study. Almost a century ago, all three watersheds were predominantly rural with substantial area under cropping systems (Fitzpatrick et al., 1939; USDA, 1969). Since then a significant rural to urban transformation has occurred in these watersheds. Increases in population from 1910-2000 serve as the primary reason for such land cover change (Figs 3.2 and 3.3). However, the rate of change in population has been variable among the three watersheds (Fig. 3.4). Therefore, the three watersheds (Figs. 3.5—3.7), are experiencing different degrees of urbanization (rural, ex-urban/urbanizing, and urban, respectively).

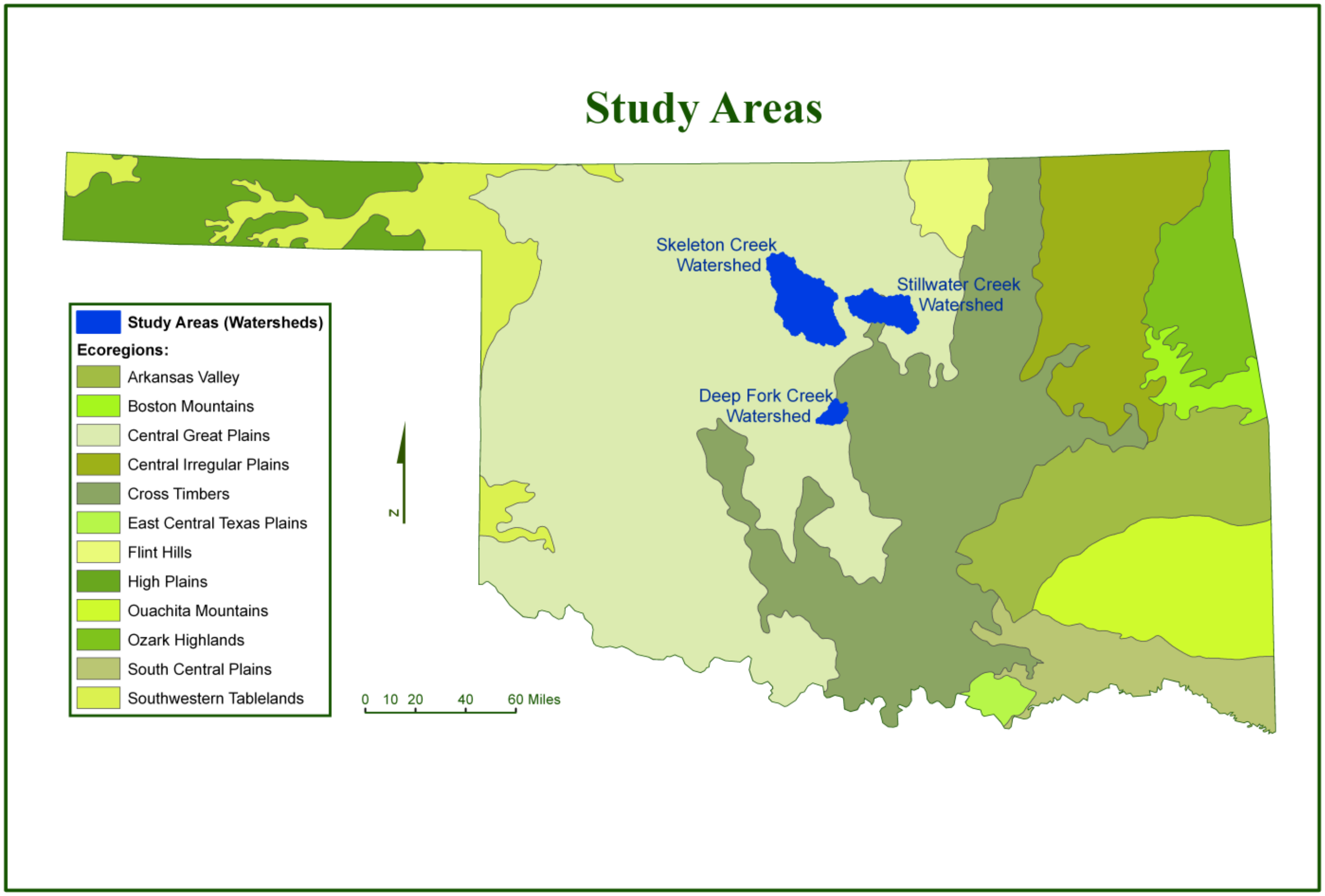

Figure 3.1: Three Study Areas in Central Oklahoma sharing the Central Great Plain Geomorphic Province (produced from data provided by the US Geological Survey and the US Environmental Protection Agency)

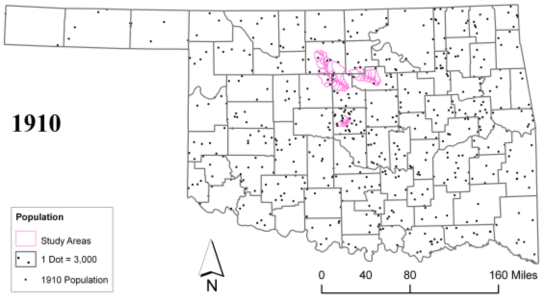

Figure 3.2: Oklahoma State Population (1910)

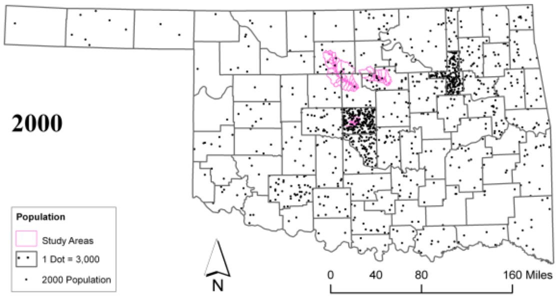

Figure 3.3: Oklahoma State Population (2000)

Population change in Oklahoma from 1910 to 2000
(produced from data from US Census Bureau)

Table 3.1: Average annual climate conditions in the three watersheds in Central Oklahoma
Source: Oklahoma Climatological Survey (http://climate.ocs.ou.edu)

County	Average Annual Temperature (^{O}C)	Average Maximum Temperature (^{O}C)	Average Minimum Temperature (^{O}C)	Average Annual Precipitation (centimeters)
Payne	15.6	22.2	8.89	94.7
Noble	15.6	22.2	8.89	94.7
Logan	15.6	22.2	8.89	94.7
Garfield	15.6	22.2	8.89	94.7
Oklahoma	15.6	22.2	8.89	94.7
Kingfisher	15.6	22.2	8.89	94.7

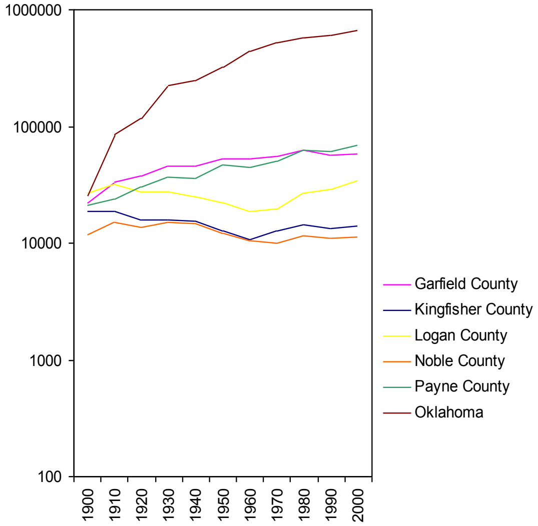

Figure 3.4: Population change in study areas (1910 to 2000)
(produced from data provided by the US Census Bureau)

Table 3.2: 2001 Land cover in the three watersheds in Central Oklahoma
Source: National Land Cover Data, 2001 (www.epa.gov/mrlc/nlcd.html)

	% of Total watershed area		
Type of land cover	**Skeleton Creek Watershed**	**Stillwater Creek Watershed**	**Deep Fork Creek watershed**
Open Water	0.3	3.1	0.5
Pervious Though Developed (Urban Pervious)	5.5	6.4	18.7
Developed High Intensity (Impervious)	3.0	3.9	45.6
Barren	0.0	0.0	0.0
Deciduous Forest	3.8	22.2	17.7
Grasslands/Herbaceous	34.5	55.5	13.8
Pasture/Hay	0.4	2.6	1.9
Cultivated	52.6	6.3	1.9
Total	100	100	100

3.1 Skeleton Creek Watershed

The Skeleton Creek watershed (Figs. 3.5 and 3.8; Table 3.2) is the largest of all three watersheds with an area of $1.09*10^3$ km^2 in Garfield, Kingfisher, and Logan Counties in Oklahoma. It is a rural watershed with approximately 3% of its area under impervious cover (MRLC Consortium, 2001). The city of Enid, where Skeleton Creek originates, constitutes the major impervious cover in the northern part of the watershed. Because of its rural nature, the Skeleton Creek watershed is dominated by agricultural and pasture land separated by riparian vegetation bordering the stream (Figs. 3.5 and 3.8). Dry mollisols, along with bluestem grama prairies, are the main soil types in the watershed. This region transitions from humid prairies grasslands to sub-humid plains with bluestem and tall bluestem as the main native vegetation.

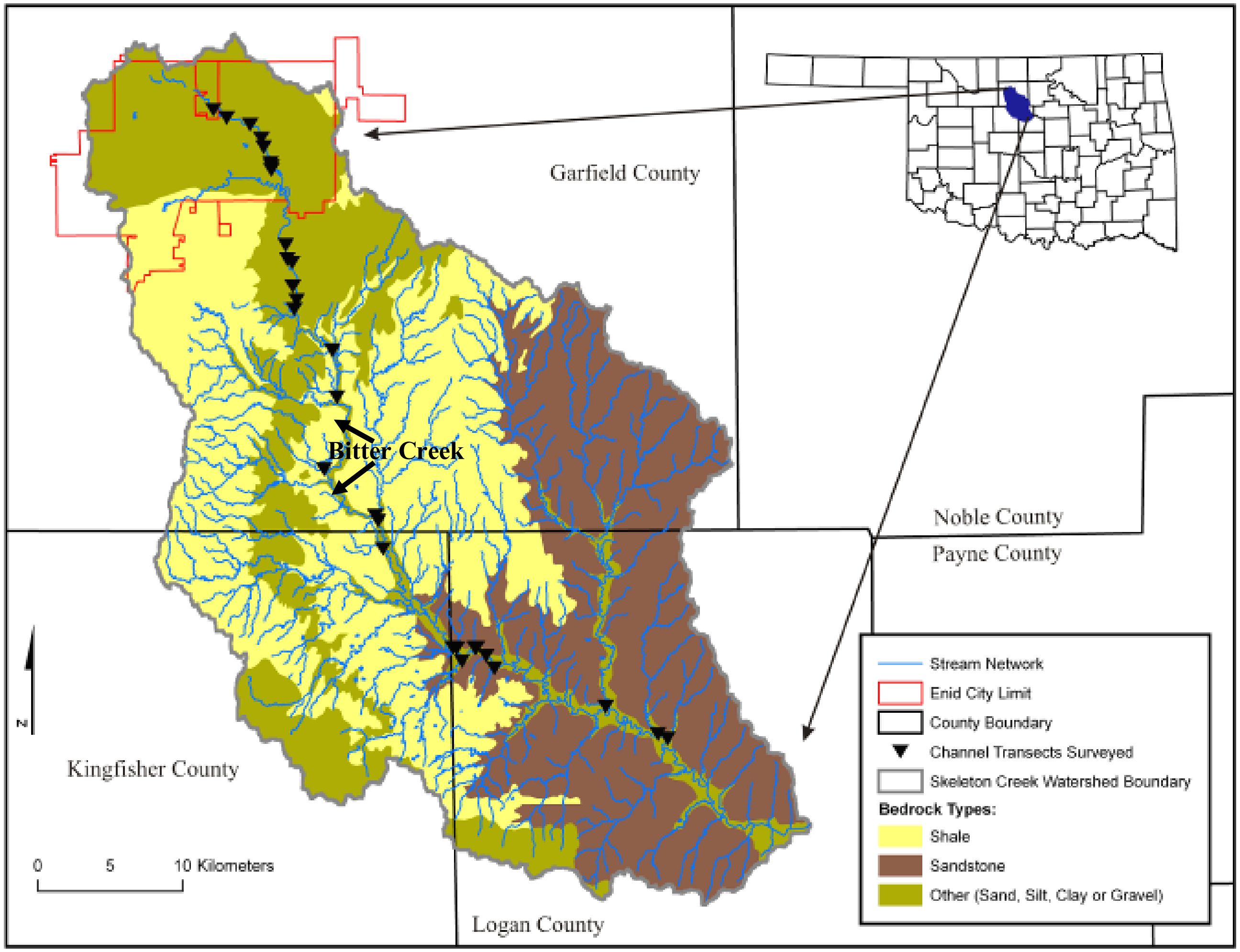

Figure 3.5: The Skeleton Creek Watershed in Central Oklahoma

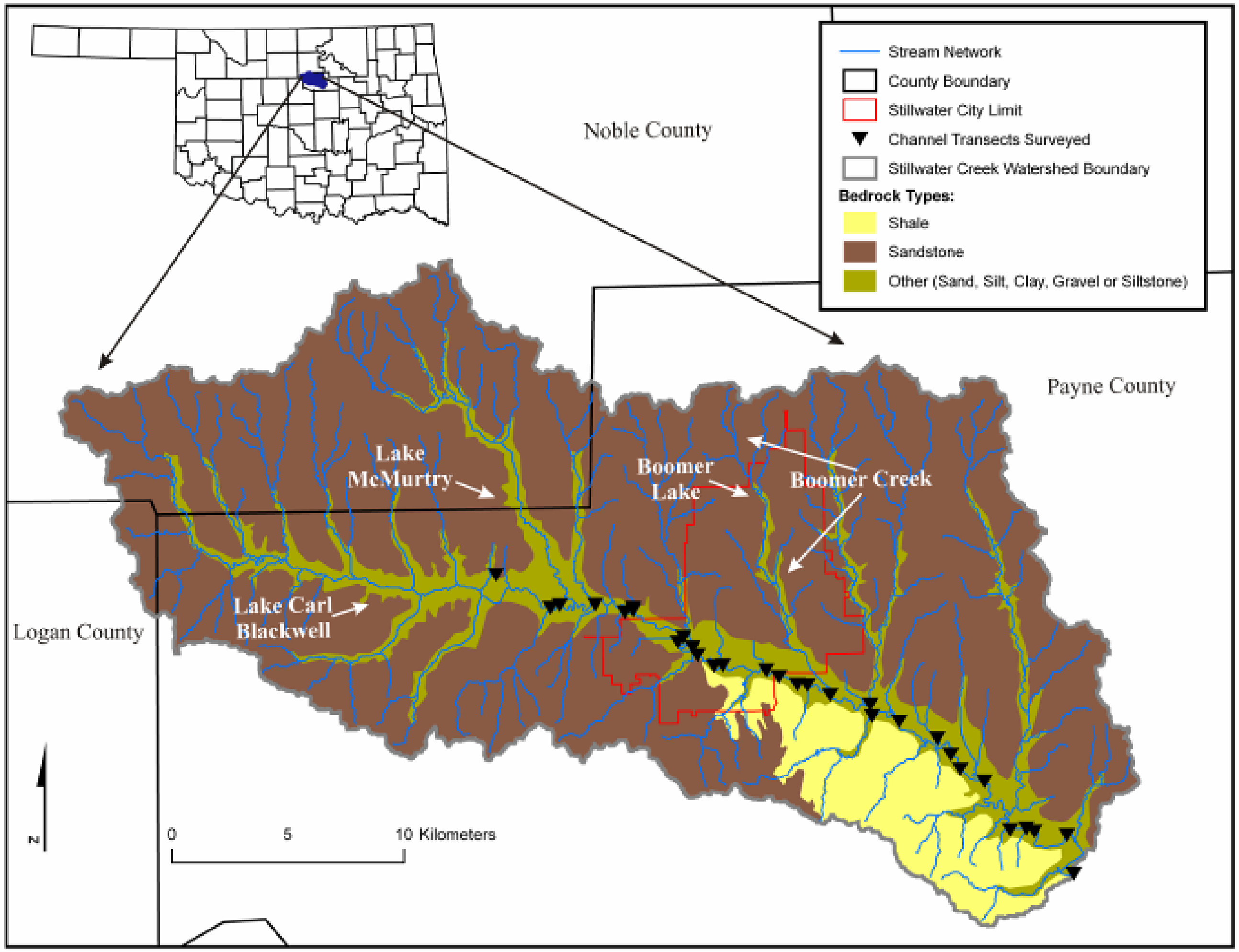

Figure 3.6: The Stillwater Creek Watershed in Central Oklahoma

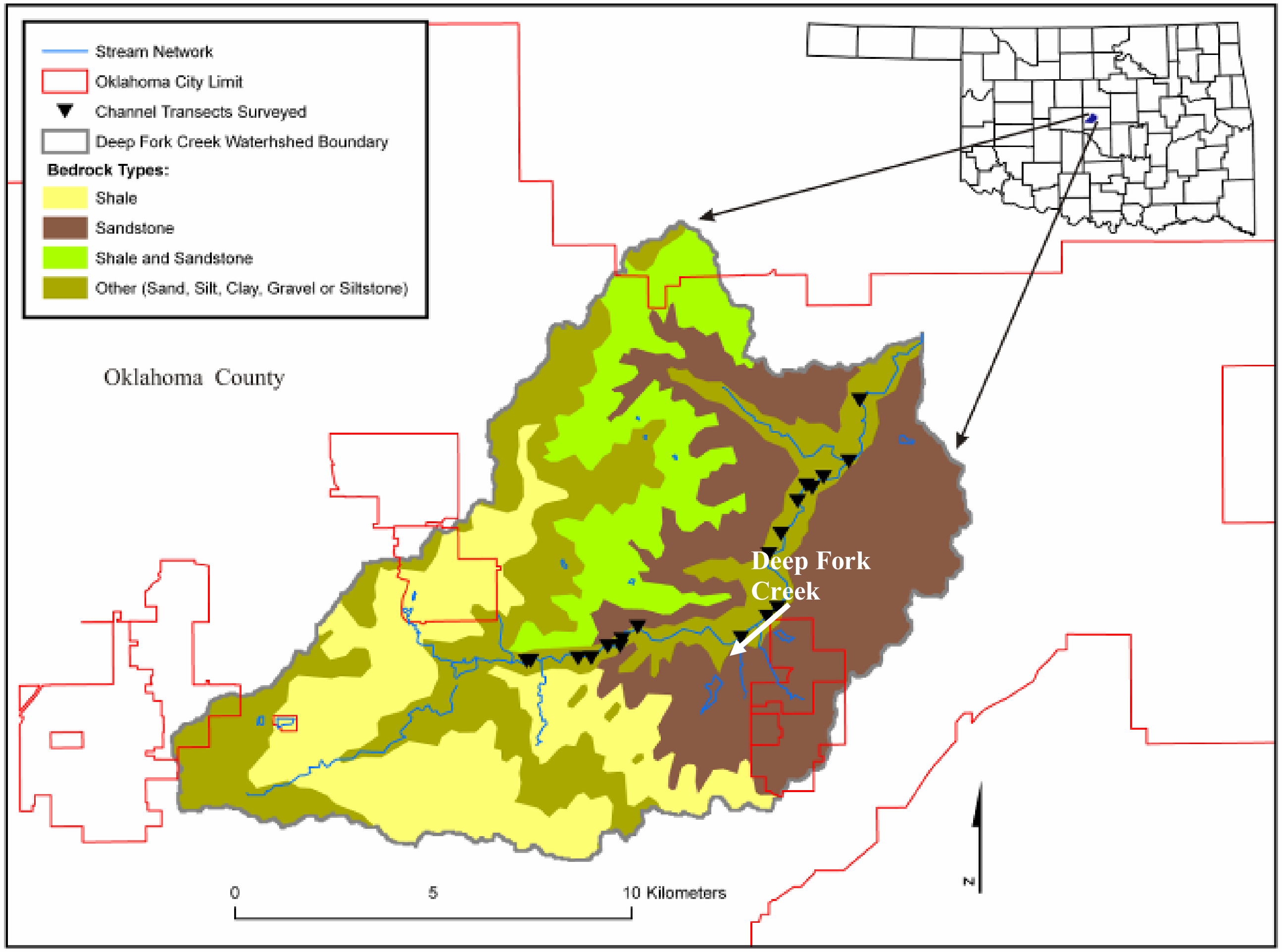

Figure 3.7: The Deep Fork Creek Watershed in Central Oklahoma

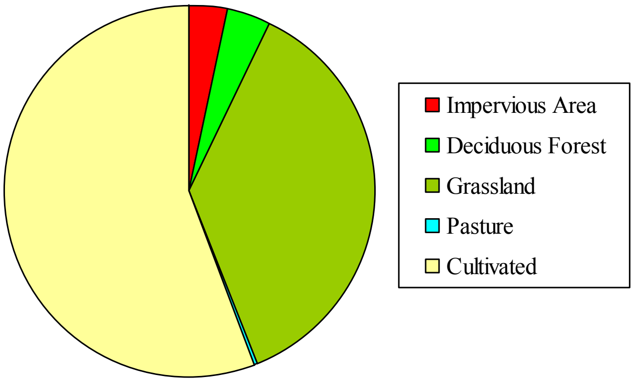

Figure 3.8: Land cover in Skeleton Creek Watershed (MRLC Consortium, 2001)

The majority of the Skeleton Creek Watershed is in Garfield County, which includes the City of Enid. Before settlement began in 1850, herds of buffalo, deer, elk and antelope roamed the area (Fitzpatrick et al., 1939). For almost one hundred years, this watershed experienced only minor changes in land cover, making it an ideal example of a rural watershed.

3.2 Stillwater Creek Watershed

The Stillwater Creek Watershed (Figs. 3.7 and 3.10, Table 3.2) is located in Payne, Noble and Logan Counties and has a drainage area of 733 km^2. Approximately 4% of its area is under impervious cover (MRLC Consortium, 2001). This watershed is an example of an ex-urban watershed that supports agricultural land (pasture, forest, grassland, and crops) and an expanding urban area of Stillwater, Oklahoma (Figs. 3.6 and 3.9). It is characterized by dry mollisols along with bluestem grama prairies. Stillwater Creek, which flows through Payne County, is an ungauged tributary of the Cimarron River.

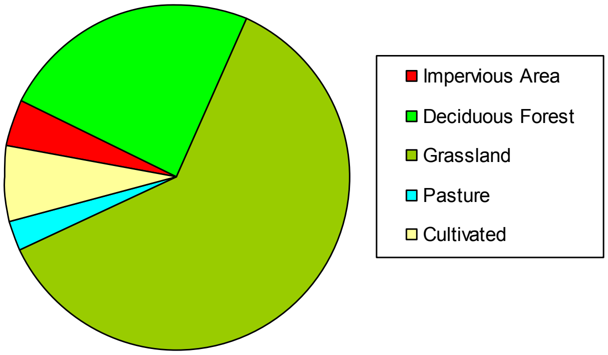

Figure 3.9: Land cover in Stillwater Creek Watershed (MRLC Consortium, 2001)

Three reservoirs--Lake Carl Blackwell, Lake McMurtry and Boomer Lake--are located in the Stillwater Creek watershed, two of which are located above the urban area of Stillwater (Fig. 3.6). Lake Carl Blackwell is the largest reservoir with an area of 14.2 km^2 and shoreline of 93.3 km. Built in 1932 and opened in 1938, this lake is located 11.3 km west of the city of Stillwater and is owned by Oklahoma State University (Cunningham, 1979). The primary purpose of this lake is recreation, but it also serves as a secondary source of water for Oklahoma State University. Lake McMurtry, with an area of 5.26 km^2 and shoreline of 43.5 km, is located 14.5 km north of the City of Stillwater. It was built for recreation, fishing, and flood control. It also provides water to the City of Perry for drinking and recreational purposes. Boomer Lake is the smallest of the three reservoirs with an area of 1 km^2 and shoreline of 14.5 km. The lake was named after Boomer Creek, which brings the urban runoff from the City of Stillwater into Stillwater Creek. It is located within the city limits of Stillwater and was built for recreation, fishing, and as a supply of water to cool a natural gas powered plant that generates electricity.

In 1889, the city of Stillwater, Oklahoma was established in a fertile valley at the confluence of two streams (Fig. 3.10) now known as Boomer and Stillwater Creeks

(Bivert, 1988b). What impressed the settlers the most was the fact that these two streams (Fig. 3.10) never ran dry and were surrounded by fertile land (Bivert, 1988a; Cunningham, 1979). The population of Stillwater changed from 300 in 1890 to 5962 in 1920 and 41,320 (estimated) in 2003 respectively (U S Census Bureau, 2007). In order to accommodate the growing population, imperviousness also increased in the same fashion from only 150 completed buildings in 1890. The primary reason for such growth is the presence of the then unknown stream now known as Stillwater Creek.

Figure 3.10: Historical photograph of Boomer Creek (1884). This photograph shows the perennial nature of Boomer Creek which really attracted the early settlers (Cunningham, 1979). Notice the tree cover along stream banks.

The presence of Oklahoma State University in Stillwater increases the imperviousness of this watershed (Figs: 3.11 and 3.12). Ongoing urban expansion makes this stream an ideal example of an ex-urban stream. At the same time, the confluence of Boomer Creek (bringing urban runoff from the city of Stillwater), into the lower section of Stillwater Creek, makes it a good location for comparing (see methods section for detail) upstream and downstream channel morphology (Chin, 2006).

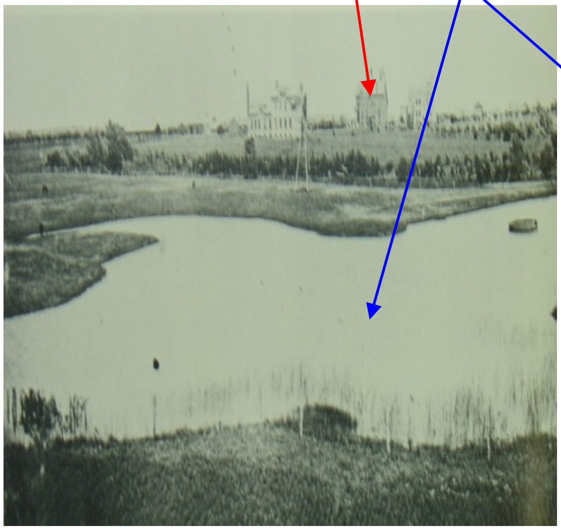

Figure 3.11 (Newsom, 1989)
Theta Pond and Old Central on Oklahoma State University Campus (1894)

Figure 3.12 (GoogleEarth, 2005)
Theta Pond and Old Central on Oklahoma State University Campus (2005)

Notice the growth of imperviousness between Theta Pond and Old Central building in the two photos

3.3 Deep Fork Creek Watershed

Deep Fork Creek (Figs. 3.7 and 3.13, Table 3.2) near the town of Arcadia, Oklahoma, is characterized as an urban watershed covering an area of 175 km^2 with more than 45% (according the city office of Oklahoma City) of its area under impervious cover, the majority of which lies in Oklahoma City (Figs. 3.7 and 3.13).

As the smallest of the three watersheds, Deep Fork Creek flows through central, northern, and northeastern parts of Oklahoma County. The dominant soil types in this watershed are dry mollisols along with bluestem grama prairies. The potential natural vegetation includes cross-timbers, a mosaic of bluestem prairie (blue stem, and Indian grass), and oak/hickory forest. The riparian vegetation along Deep Fork Creek is bordered by industrial buildings, governmental facilities, homes, and other urban structures. As a result, it is not unusual to see the presence of rip-rap along stream banks in a few reaches (Fig. 3.14).

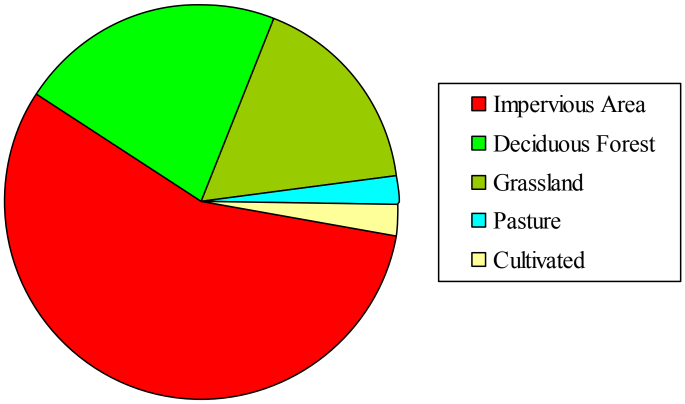

Figure 3.13: Land cover in Deep Fork Creek Watershed (MRLC Consortium, 2001)

Homesteaders from the northern states settled in Oklahoma County after the area was opened to settlement in 1889. Farming (winter wheat and livestock) was the primary occupation of those who settled here until the first half of the 20th century. This included raising beef cattle as the most important farming enterprise (USDA, 1969). According to the Soil Survey (USDA, 1969), the sale of livestock and livestock products accounted for approximately 65 percent of the total farm income, whereas, the sale of crops accounted for approximately 35 percent. The growth of the metropolitan area of Oklahoma City and its status as the state capital led to radical population growth and urban transformation in the watershed during the second half of the twentieth century (Figs. 3.2, 3.3, and 3.4). Deep Fork Creek has experienced the most urban population growth, as well as land cover change among the three watersheds.

Figure 3.14: The urban stream, Deep Fork Creek with occasional presence of rip-rap and trash

CHAPTER 4

METHODS OF INVESTIGATION

As a means of understanding urban-induced changes in the channel morphology of a stream, the collection of fluvial data for the predevelopment period is necessary. However, the predevelopment periods for Deep Fork Creek (urban watershed) and Stillwater Creek (ex-urban watershed) date back to the second half of the nineteenth century (1880s). Therefore, this research was based on "ergodic reasoning," which means space-for-time substitution (also referred to as the location for evolution substitution) (Chin and Gregory, 2001; Schumm, 1991), to understand the geomorphic effects of rural-to-urban land cover conversion. The space-for-time substitution method has been commonly used in various studies (Chin, 2006) in different parts of the world to understand stream channel adjustments in response to urbanization.

In this project, the space-for-time substitution was used to understand impacts of urbanization (imperviousness) on the morphology of all three streams over a long period of time under similar physical conditions (lithology and climate). The size of the three watersheds is different, but in the same order of magnitude with minor variations in the precipitation regime as expected from different watersheds. The three watersheds lie in the same geomorphic province with similar lithology, climate conditions (Table 3.1), and soil types. As a result, they are ideal for using ergodic reasoning. According to ergodic reasoning, different degrees of urbanization will affect these watersheds (with homogenous physical conditions) in a similar fashion, but with varying scales of impact (Hammer, 1971). Therefore, past and present geologic uniformity of the study areas, knowledge of the nature of relationships between landscape elements, and applicability of the same landform conditions to past and present timescales are the main assumptions involved in this method (Paine, 1985).

According to this method, the rural watershed, Skeleton Creek, provided predevelopment geomorphic information about a stream. Stillwater Creek provided information on the geomorphic conditions of a stream during transition from rural to urban. Similarly, Deep Fork Creek provided information on post-urban geomorphic conditions of a stream. Therefore, the three streams represent three stages of urbanization through time.

4.1 Data collection

4.1.1 Field survey of channel morphology

Geomorphic survey of channel morphology was one of the most time consuming tasks in this project. The three streams were surveyed with the help of different research and field teams. Channel cross-sections and riparian vegetation were measured at 30 sites (reaches) along each of the three streams for a total of 90 sites (reaches). The channel cross-section measurements included the measurements of channel width, mean depth, and maximum depth, at bankfull stage. This also included identification of channel bed materials (by visual observations), percent canopy cover, and presence or absence of woody debris jams. The bankfull stage was determined (Figs. 4.1 and 4.2) by the break in the stream bank slope, perennial vegetation limit, rock discoloration, root exposure, and the deposits of sand or silt at the active scour marks (Knighton, 1998; Rosgen, 1996).

Figure: 4.1 Figure: 4.2
Determination of Bankfull Stage in Skeleton Creek

The step-by-step description of methods used to complete geomorphic surveys follows:

List of equipment: TopCon (laser level), tripod, tapes, rebar, flags, hammer, a ruler, a rope, stadia rod, life jackets, air-photos, US Geological Survey (USGS) Topographic Maps, pencils, notebook, GPS (Trimble Geo 3 and XT).

Step One (Planning for field work): The three streams were divided into reaches using USGS topographic maps (1:24,000). A reach was defined as a channel segment between any two adjacent tributaries (with changing channel form, valley form, vegetation type, and land cover) (Harrelson et al., 1994; Moore et al., 2002). Therefore, changing sinuosity and channel gradient were also used to divide the three streams into reaches.

Step Two (Selection of sites for measuring channel cross-section): Beginning of each creek was selected as the spot for channel cross-section measurements.

Step Three (Select the location for channel cross-section): Channel cross-sections were selected by pushing a rebar pole into the ground on one side of the stream.

Step Four (Stretching a tape across the stream): A tape was stretched from the rebar on one side of the stream to the other side stream to make it as tight as possible.

Step Five (Set up the tripod and TopCon): The tripod was setup preferably on or near a rebar and the TopCon was mounted on the top of tripod and leveled for proper functioning.

Step Six (Record the location in GPS unit): GPS was used to record the point location of the tripod.

Step Seven (Establish a reference datum): A reference datum was established for the location of the tripod. All of the elevations measured across the channel cross-section were relative to the datum.

Step Eight (Surveying of channel cross-section): Channel cross-sections were surveyed by measuring elevation from a stadia rod at regular intervals across the stream (Figs. 4.3 and 4.4). Elevation measurements were also recorded in case of any significant break in the slope across the channel.

Figures 4.3
Survey of channel cross-section in
Stillwater Creek

Figures 4.4
Survey of channel cross-section in
Skeleton Creek

Step Nine (Determine the flood prone width): Flood prone width was determined (ESFa) at twice the maximum bankfull depth (Fig. 4.5).

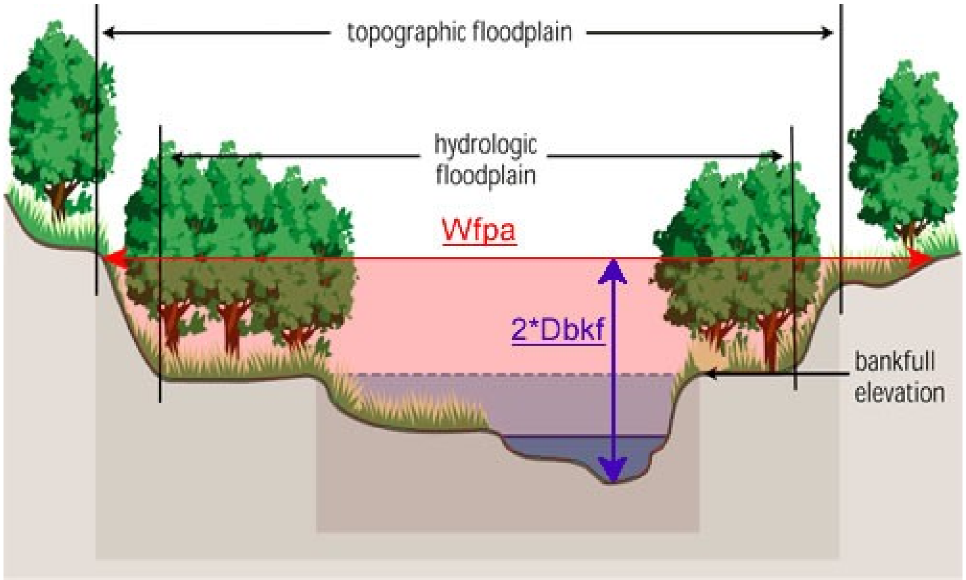

Figure 4.5: Method used to determine flood-prone width (ESFa)

Step Ten (Determine the entrenchment ratio): Entrenchment ratio is an index value that is used to describe the degree of vertical containment of a river channel. It was calculated

(Fig. 4.6) as the ratio of the width of the flood prone area (at an elevation twice the maximum bankfull depth) to the bankfull width (Rosgen, 1996).

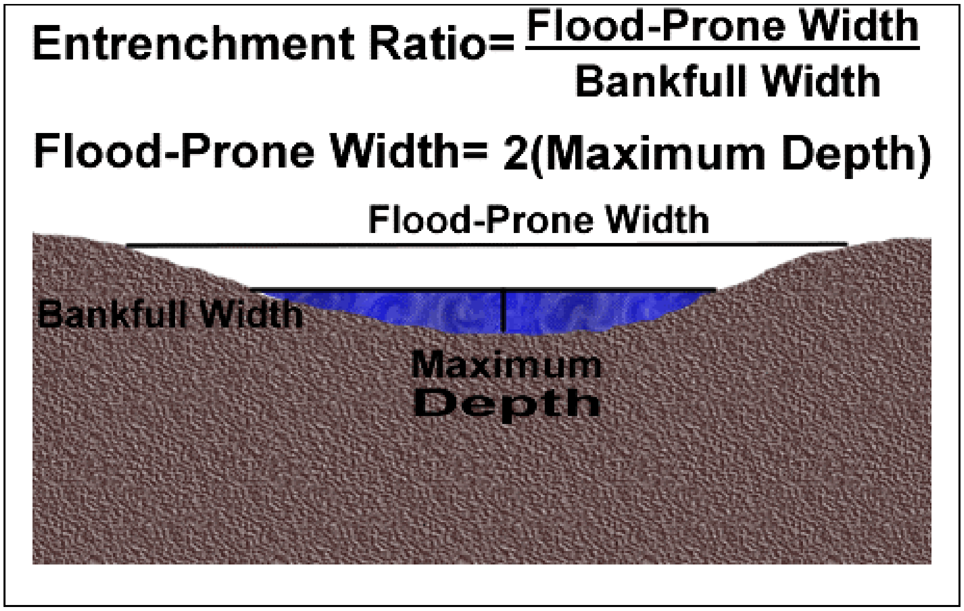

Figure 4.6: Method used to determine Entrenchment Ratio (ESFb)

Step Eleven (Determine the channel type according to Rosgen Classification): Channel type was determined according to the Rosgen Classification of Natural Rivers (Rosgen, 1996). Since none of the three streams was radically disturbed, the Rosgen system was appropriate for these three stream channels. Also, this classification (Fig. 4.7) was used very carefully to make sure that streams were not forced to fit into this classification system. Although concerns are emerging about the end uses of this classification (Gillilan, 1996), this classification provided a common language for describing these streams.

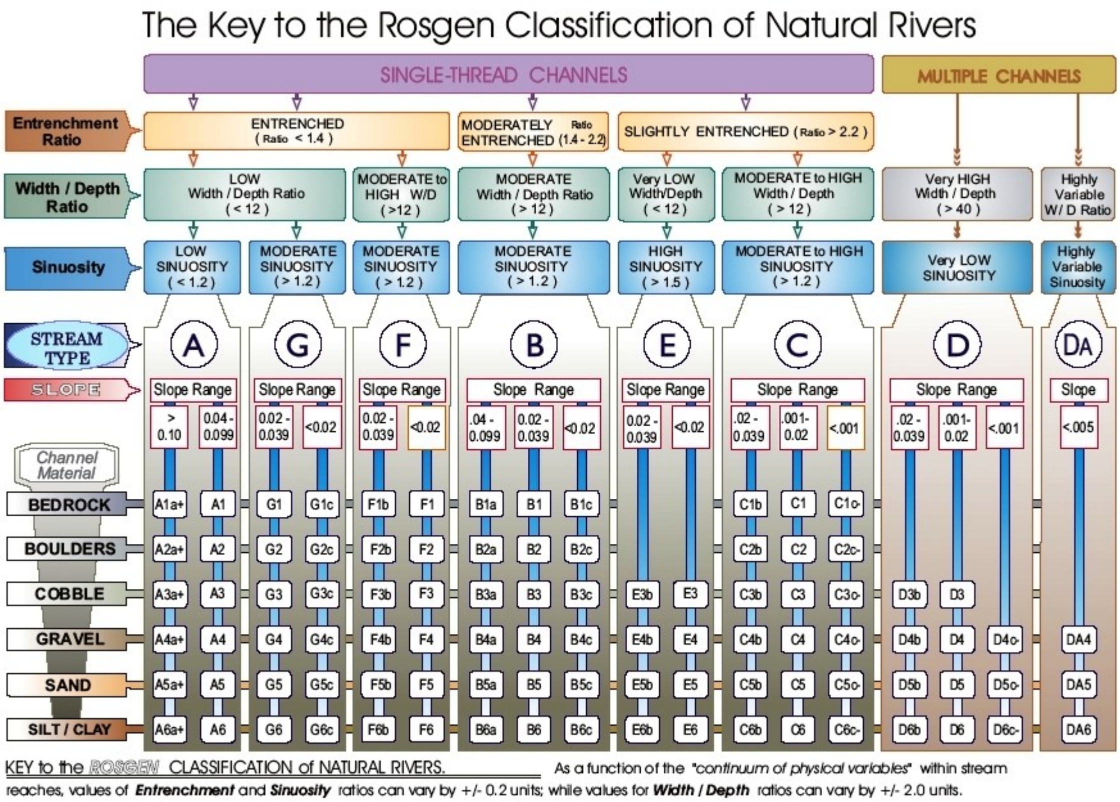

Figure 4.7: Method used to determine channel type according to Rosgen Classification (Rosgen, 1996)

Step Twelve (Determine the valley width): This was accomplished by stretching a tape from the one side of the stream valley to the other. This task was often very difficult and time consuming and involved frequent exposure to poison ivy.

Step Thirteen (Visual observations): Dominant bed materials, bed rocks, land cover types, canopy cover over stream, and presence or absence of woody debris jams were observed visually.

Step Fourteen (Identification of channel unit types): The identification of the types of channel units were based on the following four categories (Harrelson et al., 1994; Moore et al., 2002) as applied along each transect in the three streams:

(i) pool (slow and deep)

(ii) glide (slow and shallow)

(iii) riffle (fast and shallow)

(iv) run (fast and deep)

4.1.2 Fluvial data processing

Channel morphology data, collected through fourteen steps as mentioned above, were entered into a specially designed MS Excel© Reference Reach Tool©, an Excel© programmed macro (Mecklenburg and Ward, 2004). This macro was used to calculate the following hydraulic variables:

(i) Maximum bankfull depth: the maximum depth of flow at bankfull stage.

(ii) Mean bankfull depth: average depth measure at the bankfull discharge.

(iii) Wetted perimeter: perimeter of the channel cross-section formed by bed and banks.

(iv) Width of flood prone area: flooded width at a stage twice the maximum depth in a riffle or straight section.

(v) Bankfull area: area of the stream channel cross-section at bankfull stage.

(vi) Threshold grain size: particle size predicted to be at the threshold of motion at the calculated shear stress. It is derived from the Shields curve that is a plot of particle size against the shear stress required to initiate movement.

(vii) Friction Factor: Friction Factor varies from about two for rough streambeds to 16 for smooth streambeds.

Friction Factor = velocity / shear velocity = $V / (32.2 \times d * S)^{0.5}$

Where, V = velocity (ft/s)

32.2 = gravitational acceleration (ft/s2)

d = depth (ft)

s = slope (ft/ft)

Other stream variables were calculated from USGS 1:24,000 DEMs (Digital Elevation Models) using AVSWAT (ArcView Soil and Water Assessment Tool 2000) (Luzio et al., 2002). These variables included actual stream lengths, straight-line stream lengths, sinuosity, and gradient. The above method was used at 90 sites (30 sites along each stream) along three streams to conduct geomorphic surveys (Figs. 3.5, 3.6, and 3.7).

4.1.3 Field survey of riparian vegetation

An inventory of riparian vegetation was prepared that consisted of a belt transect (Figs. 4.8 and 4.9) extending along the riparian zone perpendicular to the stream channel on one side of the stream (Moore et al., 2002). Vegetation transects starting near the upstream half of the reach (same as geomorphic survey of channel cross-sections) extended 5 m perpendicular to the main axis of the stream (on either the left or right side), and 30 m in the longitudinal dimension. This 30-m-long transect was divided into three zones of 10 m each to record the percent canopy closure, grass and shrubs, tree groups (based on size and species), and number of trees. Similar to geomorphic surveys, riparian surveys were also conducted at 90 sites (30 sites along each stream) along three streams to collect data on riparian vegetation (Figs. 3.5, 3.6, and 3.7). These data from field surveys were used to calculate basal areas for trees in all three zones of riparian transect. Similar to geomorphic surveys, this method was used at the 90 sites (30 sites along each stream) along three streams to conduct riparian surveys.

The use of a small airplane was another tool that was used to capture a perspective of the three watersheds. This technique provided oblique photographs and videos. Although not useful for quantitative analyses, the photographs (Figs. 4.10, 4.11, and 4.12) and videos of the three watersheds were used to understand the general land cover in the three watersheds.

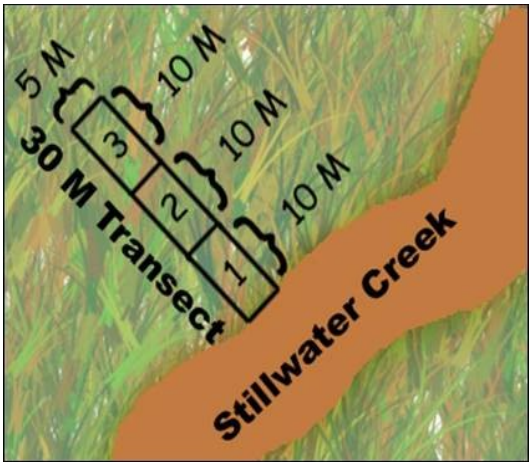

Figure 4.8: An example of the transect extending across the riparian zone perpendicular to the stream channel (Lehmert and Marston, 2005)

Figure 4.9: A transect extending across the riparian zone perpendicular to the Skeleton Creek

Figure 4.10: Aerial view of slightly entrenched meanders and land cover adjacent to Skeleton Creek

Figure 4.11: Aerial view of a reservoir and land cover in the Stillwater Creek watershed

Figure 4.12: Aerial view of urban land cover adjacent to Deep Fork Creek

4.1.4 Use of GIS in delineating the three watersheds

Boundaries of all three watersheds and the sub-watersheds were delineated using standard GIS methods. This involved the use of digital elevation models (DEMs) with a 30x30-m resolution for the different counties that covered the three watersheds. DEMs and the stream networks were downloaded from the USGS web page. The two data sets (DEMs and stream networks) were used in the ArcView Soil and Water Assessment Tool (AVSWAT$^{©}$) to delineate the boundaries of the three watersheds, and boundaries of sub-basins within the three watersheds. AVSWAT$^{©}$ is an ArcView extension and a graphical user interface for the Soil and Water Assessment Tool (SWAT$^{©}$). SWAT$^{©}$ is a physically based and computationally efficient watershed-scale hydrologic model used to predict the impact of management practices on water, sediment, agricultural chemical yields, and more (Luzio et al., 2002).

4.1.5 Data on degree of urbanization and other types of land cover

The National Land Cover Dataset (NLCD) for the year 2001 (MRLC Consortium, 2001) was used to map and measure the area under impervious cover in the three watersheds . It was important to study land cover other than imperviousness that might be affecting channel morphology of the three streams. Therefore, the same NLCD was used to calculate areas under other types of land cover such as cultivation, pasture, deciduous forest, and grassland in all of the sub-watersheds of the three study areas. These dataset were obtained for the year 2001 from USGS in grid format. The dataset were clipped according to the watershed boundaries of the three watersheds. This was followed by further clipping of land cover data for every watershed into sub-basins according to the surveyed reaches. All of these data were reprojected with the help of Arc Toolbox. Areas under different types of land cover were calculated for every subbasin in each of the three watersheds. The following categories (developed by USGS) were used to calculate data on land cover:

(i). Open Water
(ii). Pervious (though Developed)
(iii). Impervious Cover (High Intensity Developed)
(iv). Barren Land
(v). Deciduous Forest
(vi). Grassland
(vii). Pasture / Hay
(viii). Cultivation

Open Water refers to area covered by stream water as well as reservoirs. Pervious (though developed) refers to green pockets within urban boundaries such as soccer fields, play grounds, parks, and other recreational areas. The USGS calls this category “Low Intensity Developed Areas” referring to pervious areas within urban boundaries. Therefore, this category was not included in the impervious category.

For detailed analysis of impervious areas within city limits for the year 2001, shape files of impervious surfaces in the cities of Enid, Stillwater, and Oklahoma City were obtained from the following sources:

(i). Skeleton Creek watershed: City of Enid and Garfield County Assessor office in Enid, OK.
(ii). Stillwater Creek watershed: City of Stillwater office in Stillwater, OK.
(iii). Deep Fork Creek watershed: Oklahoma City office in Oklahoma City, OK.

The respective city offices prepared these GIS shapefiles for various purposes, such as property management, code enforcement, emergency management, and infrastructural maintenance. These shapefiles were prepared from different sources and provide comprehensive digital details of imperviousness within city limits. These GIS shapefiles were re-projected using Arc Toolbox 9.0 into UTM Zone 14. The shapefiles of roads and other impervious surfaces were clipped along watershed boundaries to remove areas lying outside of the three watersheds. Shapefiles for roads in the three watersheds were line features, so buffers were created to find areas using Arc Toolbox 9.0. Roads were divided into two categories for this purpose: (i) urban roads (i.e., roads within the city limits of Enid, Oklahoma City, and Stillwater) were given a 10-m buffer width, and (ii) rural roads (i.e., roads outside the city limits of Enid, Oklahoma City, and Stillwater) were given a 7.5-m buffer width. Areas of the road buffers were calculated using the "Open Tool" option in ArcMap 9.0. This completed the data collection for 90 sites (30 sites in each watershed) in the three watersheds.

4.2 Statistical analysis of downstream trends and hypotheses testing

This project involved two standard approaches (as discussed in Chapter 1) used in fluvial geomorphology to study the impacts of urbanization on stream channel morphology (Chin, 2006). The first approach (Approach 1) is dividing a river into upstream and downstream sections and comparing the two sections (Gregory and Park, 1976). This approach was used to address the first three research questions (Questions 1, 2, and 3) and test the respective hypotheses (Hypotheses 1.1-1.8, 2.1-2.8, and 3.1-3.8). The second approach (Approach 2) involves selecting two or more similar streams with different degrees of urbanization (rural, ex-urban, and urban) and comparing them with each other (Morisawa and Laflure, 1979). This approach was used to address the next three research questions (Questions 4, 5 and 6) and test respective hypotheses (Hypotheses 4.1-4.8, 5.1-5.8, and 6.1-6.8).

Data on channel morphology, riparian vegetation, and land cover (impervious cover, area under cultivation, area under pasture, area under deciduous forest, area under rangeland, and area under grassland) were collected for 90 reaches in the three watersheds (30 reaches in each watershed). In the case of the urban stream, Deep Fork Creek, 11 reaches had rip-rap along stream banks. Such controlled reaches may fail to respond to changing runoff and sediment supply. Therefore, only 19 uncontrolled reaches (out of 30 surveyed) from Deep Fork Creek were included in the statistical analysis.

4.2.1 Approach 1 (Comparison of upstream and downstream sections)

The first three questions (Questions 1, 2, and 3) were addressed and their respective hypotheses (Hypotheses 1.1-1.8, 2.1-2.8, and 3.1-3.8) were tested by comparing upstream and downstream sections. This approach involved two steps as discussed below:

Step 1 (Upstream and downstream comparison of channel morphology)

The hypotheses were tested by comparing the upstream sections with the downstream sections of each of the three streams (Gregory and Park, 1976). This involved the use of ANCOVA (Analysis of Covariance) to compare upstream and downstream trends according to individual channel morphology variables. The ANCOVA test used channel morphology variables as the response variables.

Changes in channel morphology may result from increasing runoff due to increasing drainage area downstream. Therefore, channel morphology variables may change as one moves downstream along a stream due to increasing drainage area contributing more water (Downs and Gregory, 2004). The literature revealed a lack of any statistical method to normalize such effects of increasing drainage area on channel morphology downstream. Therefore, channel morphology variables were normalized based on drainage area. The drainage area above each transect was used as the covariate in the ANCOVA test.

Since ANCOVA is a parametric test based upon an assumption of normality, each geomorphic variable was transformed at eight levels (original units, square root, cube root, logarithm, reciprocal root, reciprocal, cube, and square) as suggested by Helsel and Hirch (2002). Details of these transformations can be found in Table 4.1. Histograms, boxplots, and probability plots of individual variables at each level of transformation were used to select the best possible transformation for statistical analysis (ANCOVA) for each geomorphic variable. Tables 4.2, 4.3, and 4.4 show the finally selected transformation for each variable for all three streams (Skeleton Creek, Stillwater Creek, and Deep Fork Creek).

Table 4.1: Eight levels of transformations (Helsel and Hirch, 2002)

	Power	**Equation**	**Name of Transformation**
For – skew	3	X^{3}	Cube
	2	X^{2}	Square
	1	X	Original Units
For + skew	½	$X^{½}$	Square Root
	1/3	$X^{1/3}$	Cube Root
	0	Ln X	Logarithm
	-1/2	$-1 / X^{½}$	Reciprocal Root
	-1	$-1 / X$	Reciprocal

Table 4.2: Transformations selected for comparing upstream and downstream sections of Stillwater Creek

Stillwater Creek	
Variable Tested	**Transformation Used in ANCOVA**
Sinuosity	Reciprocal Root
Gradient	Square Root
Mean Depth	Reciprocal Root
Width	Natural Log
Width Depth Ratio	Reciprocal
Bankfull Area	Reciprocal
Drainage Area	Square Root
Threshold Grain Size	Natural Log
Friction Factor	Natural Log
Basal Area of Trees1	Natural Log

Table 4.3: Transformations selected for comparing upstream and downstream sections of Skeleton Creek

Skeleton Creek	
Variable	**Transformation Used in ANCOVA**
Sinuosity	Untransformed
Gradient	Natural Log
Mean Depth	Square Root
Width	Natural Log
Width Depth Ratio	Natural Log
Bankfull Area	Natural Log
Drainage Area	Square Root
Threshold Grain Size	Natural Log
Friction Factor	Reciprocal Root
Basal Area of Trees1	Reciprocal Root

Table 4.4: Transformations selected for comparing upstream and downstream sections of Deep Fork Creek

Deep Fork Creek	
Variable	**Transformation Used in ANCOVA**
Sinuosity	Untransformed
Gradient	Cube Root
Mean Depth	Cube
Width	Untransformed
Width Depth Ratio	Natural Log
Bankfull Area	Untransformed
Drainage Area	Square Root
Threshold Grain Size	Square Root
Friction Factor	Cube
Basal Area of Trees1	Natural Log

The p values reported from ANCOVA were used to accept or reject the hypotheses (Hypotheses 1.1-1.8, 2.1-2.8, and 3.1-3.8) at a 0.05 level of significance. This was followed by the next step (Step 2) involving the use of multiple linear regression to help explain the results of hypotheses testing.

Step 2 (Multiple linear regression to help explain the changes in channel morphology from upstream to downstream)

Multiple linear regression was used to explain the results of hypotheses testing and address whether any changes from upstream to downstream channel morphology could be explained by imperviousness (urbanization) or some other land cover types. This involved developing a multiple linear regression model for each variable that differed from upstream to downstream sections of the three streams. The values of channel morphology variables which changed significantly between upstream and downstream sections (according to ANCOVA results) were used as dependent variables, whereas land cover variables were used as independent variables to analyze the trends in channel morphology variables. A step-by-step description of developing regression models follows (Helsel and Hirch, 2002) :

Step One (Normalize channel morphology variables with drainage area):
Channel morphology variables were normalized according to the increasing drainage area downstream along the three streams. This was accomplished by dividing the values of channel morphology variables with a reach specific drainage area for every reach in the three streams.

Step Two (Choose the best units for Y (the dependent variable)):
(i). Run the regression equation with all variables included
(ii). Plot the residuals vs. fitted values, and check for non-constant variance
(iii). If yes (non-constant variance), transform Y and repeat

Step Three (Choose the best units for Xs (independent variables)):

(i). Use partial plots to look for curvature, i.e. we want a linear relationship.

(ii). If yes (curvature), transform X and repeat

(iii). Repeat for all Xs

Step Four (Check multicollinearity):

(i). Are any VIFs > 10? VIF or Variation Inflation Factor is used as a measure of multicollinearity. The value of VIF should be less than 10 for a good regression model

(ii). If yes (VIFs > 10), drop one or more with strong multicollinearity, or collect more data if possible

Step Five (Choose the best model):

(i). Use an overall criterion such as Mallows Cp, adjusted R-square, or PRESS (Prediction Sum of Squares)

(ii). Use Best Subsets Regression

Backward elimination method was used in developing regression models. This involved starting with all of the predictors (land cover variables) in the model and removing the least significant variable on the basis of VIF and Mallows Cp. Each subsequent step eliminated the least significant variable in the model until all remaining variables had VIF < 10, Mallows Cp ≤ Number of Predictors, and P values smaller than 0.05. The results of multiple regression models were summarized in tabular format.

These results were used to argue whether urbanization explained changes in channel morphology.

4.2.2 Approach 2 (Comparison of three streams with each other)

The next three research questions (Questions 4, 5, and 6) were addressed and their respective hypotheses were tested by comparing Skeleton Creek with Stillwater Creek (Question 4), Stillwater Creek with Deep Fork Creek (Question 5), and Skeleton Creek with Deep Fork Creek (Question 6). This approach involved two steps as discussed below:

Step 1 (comparison of streams with each other)

The hypotheses (4.1-4.8, 5.1-5.8, and 6.1-6.8) were tested by comparing Skeleton Creek with Stillwater Creek (Hypotheses 4.1-4.8), Stillwater Creek with Deep Fork Creek (Hypotheses 5.1-5.8), and Skeleton Creek with Deep Fork Creek (Hypotheses 6.1-6.8). This involved the use of the Mann-Whitney nonparametric statistical test to compare trends of channel morphology variables among these streams.

As discussed in the previous section, drainage area contributing to each transect along a stream likely influences channel morphology variables (Downs and Gregory, 2004). Therefore, channel morphology variables were normalized according to the drainage area above every transect. The Mann-Whitney nonparametric test is not based upon the assumption of normality. Therefore, channel morphology variables were not transformed for normality. The hypotheses (Hypotheses 4.1-4.8, 5.1-5.8, and 6.1-6.8) were tested at a 0.05 level of significance. The next step was to provide possible explanation for any differences among the streams, which follows.

Step 2 (Multiple linear regression to explain the changes in channel morphology among streams)

Multiple linear regression was used to explain the results of hypotheses testing and address if any changes among channel morphology of the three streams were due to imperviousness (urbanization) or some other land cover types. This involved developing a multiple linear regression model for each of the geomorphic variables that differed among any two streams. Channel morphology variables which differed between two streams (according to Mann-Whitney results) were used as dependent variables, whereas land cover variables were used as independent variables to explain trends in channel morphology. Multiple linear regression models were developed using similar procedures as discussed in the previous section on multiple linear regression (Approach 1, Step 2) to explain the changes in channel morphology from upstream to downstream sections. The results of multiple linear regression models were summarized in tabular format. These results were used to argue whether urbanization explained changes in channel morphology among the three streams. The following table (Table 4.5) shows a step-by-step description of this.

Table 4.5: Summary of various steps involved in this project

Project Planning Selection of three streams in same geomorphic province with similar geophysical characteristics but different degrees of urbanization Rural Stream (Skeleton Creek), Ex-Urban Stream (Stillwater Creek), Urban Stream (Deep Fork Creek) Division of streams into reaches Division of watersheds into subbasins according to reaches
Data collection and management (Field work and data collection from secondary sources) Field survey at the beginning of reach 30 reaches surveyed (channel morphology & riparian vegetation) Calculation of more hydraulic variable from field data on the stream Collection of land cover data for every subbasin from US Geological Survey using GIS Excel spreadsheet for the stream showing geomorphic, riparian and land cover data for every surveyed reach (sample of 30)

Table 4.5 (Continued): Summary of various steps involved in this project

Data Analysis **Approach 1** (Research Questions 1, 2, and 3 ; Hypotheses 1.1-1.8, 2.1-2.8, and 3.1-3.8) Step-1: Division of the stream (upstream & downstream Sections) with the help of major tributary ANCOVA: Compare upstream and downstream sections: hypotheses testing Step-2: Multiple Linear Regression to explain the results of hypotheses testing: Dependent Variables: Channel Morphology, Independent variables: Land cover and riparian vegetation Results and Discussion **Approach 2** (Research Questions 4, 5, 6; Hypotheses 4.1-4.8, 5.1-5.8, and 6.1-6.8) Step-1: Mann Whitney Test (Comparison of Rural stream with Ex-Urban Stream) (Comparison of Ex-Urban stream with Urban Stream) (Comparison of Rural stream with Urban Stream) Step-2: Multiple Linear Regression to explain the results of hypotheses testing: Dependent Variables: Channel Morphology, Independent variables: Land cover and riparian vegetation Results and Discussion
Summary and Conclusions

CHAPTER-5

RESULTS AND DISCUSSION

5.1 Results of field survey of channel morphology

Skeleton Creek, the rural stream, showed the expected morphological changes in downstream hydraulic geometry. Bankfull width and mean depth increased in the downstream direction, as did bankfull area and wetted perimeter. Values of these variables increased in the downstream direction with increasing drainage area. The ex-urban stream of Stillwater Creek also showed a similar increase in these variables in a downstream direction. Although three reservoirs (Lake Carl Blackwell, Lake McMurtry and Boomer Lake) exist in this watershed, two are upstream of the urban area of Stillwater. These reservoirs were built for recreation, flood control and urban use (see Chapter 3: Study Areas).

The urban stream of Deep Fork Creek, however, showed a slightly different trend in the variation of channel morphology. Mean bankfull depth, bankfull width, bankfull area, and threshold grain size did not show an increasing trend in the downstream direction in Deep Fork Creek. Supported by statistical analysis, these findings were similar to personal observations made during field surveys in the three watersheds. These trends were analyzed in the section on statistical analysis of downstream trends and hypotheses testing.

5.2 Types of channel units

The three streams showed similar types of channel units. The rural stream of Skeleton Creek showed the random presence of all four types of channel units: pool, glide, riffle, and run. With the increasing degree of urbanization, however, glides appeared slightly more often in the ex-urban (Stillwater Creek) than the urban stream (Deep Fork Creek). Visual observations revealed that bank materials (predominantly silt and clay) remained almost unchanged in all three streams. In the case of Deep Fork Creek, certain areas had bedrock as the bed material. Eleven sections (reaches) of Deep Fork Creek had engineering controls (rip rap) along stream banks. Such controls prevent the geomorphic response of stream channels to imperviousness. Therefore, only 19 sections were used in the final analysis (those without any engineering control) of Deep Fork Creek. Channel gradients were very low (< 0.001), and sinuosity was consistently low (< 2) in the three streams.

5.3 Riparian vegetation

The riparian corridor along the rural stream was bordered by agricultural fields that rarely adjoin the stream. Personal discussions with farmers in the rural watershed of Skeleton Creek revealed that the riparian buffer has been unchanged since the 1950s. Similar riparian buffers existed along ex-urban and urban streams that are commonly bordered by pastures and impervious areas (see Chapter 3: Study Areas). All three streams had a significant amount of barbed-wire fencing along the riparian corridors, which suggested that the riparian corridor was undisturbed. Riparian corridors included three types of vegetation: trees, shrubs, and grass. The dominant trees in the three watersheds were cottonwoods (*Populus sp.*), green ash (*Fraxinus pennsylvanica*), and American elm (*Ulmus americana*). Field surveys revealed substantially similar riparian corridors in all three watersheds (Figs. 5.1--5.3), which included measurements of 30 m x 10 m riparian plots perpendicular to stream reaches (Fig. 4.8). Riparian buffers rarely extended beyond 30 m of any stream. Differences in acreage of riparian vegetation were not dependent on location along the stream or the width, mean depth, channel area, or degree of urbanization for the streams. Therefore, many geomorphologic variables were ruled out as the reason for the width of the riparian corridor. Human factors, such as land-use changes from agriculture to residential, or from grazing to recreation and urban uses, are often key factors in the width and quality of the riparian zones that appeared almost intact in all three study regions (Lehmert and Marston, 2005).

Figure 5.1: Typical Riparian Corridor in the rural watershed Skeleton Creek

Figure 5.2: Typical Riparian Corridor in the ex-urban watershed Stillwater Creek

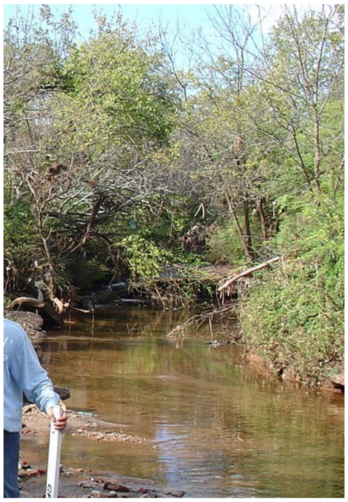

Figure 5.3: Typical Riparian Corridor in the urban watershed Deep Fork Creek

5.4 Degree of urbanization and other types of land cover in the three watersheds

Table 5.1 shows the summary of eight types of land cover in the three watersheds derived from the NLCD 2001 dataset. These categories included areas under: open water, pervious (though developed) cover, impervious cover (high intensity developed), barren land, deciduous forest, grassland, pasture / hay, and cultivation (Figs. 5.4, 5.5, and 5.6).

More than half of the rural watershed, Skeleton Creek, was under cultivation (52.3%) with grassland as the second major land cover type (34.5%). In case of the ex-urban watershed, Stillwater Creek, grassland covered the maximum area (55.5%), followed by deciduous forest (22.2%). The urban watershed was dominated by impervious cover (45.6%), followed by a similar percentage of area under pervious developed (18.7%) and deciduous forest (17.7%). There was a substantially low percentage area under barren land in these watersheds.

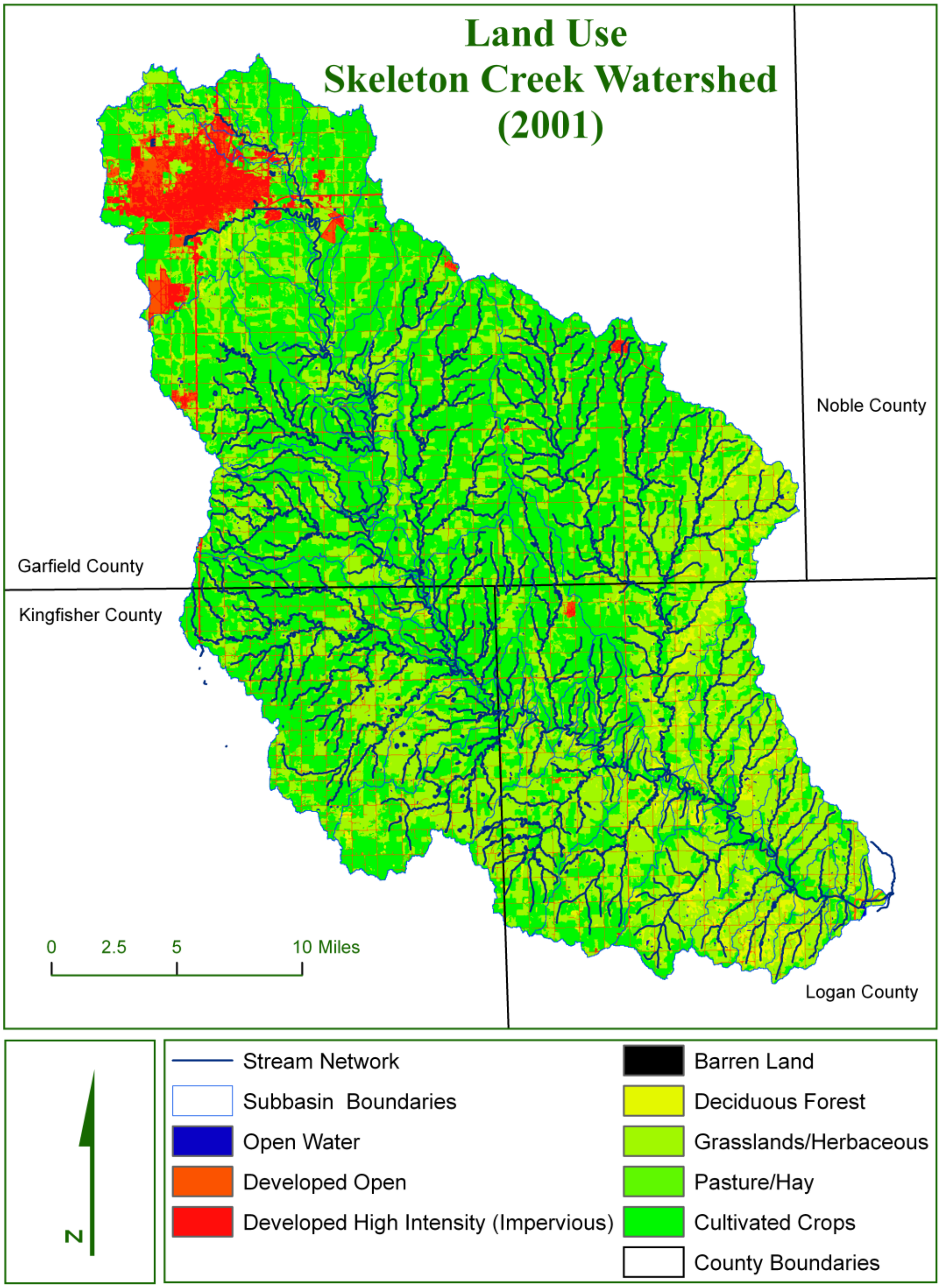

Figure 5.4: Land cover in Skeleton Creek Watershed
(produced from data provided by the US Geological Survey)

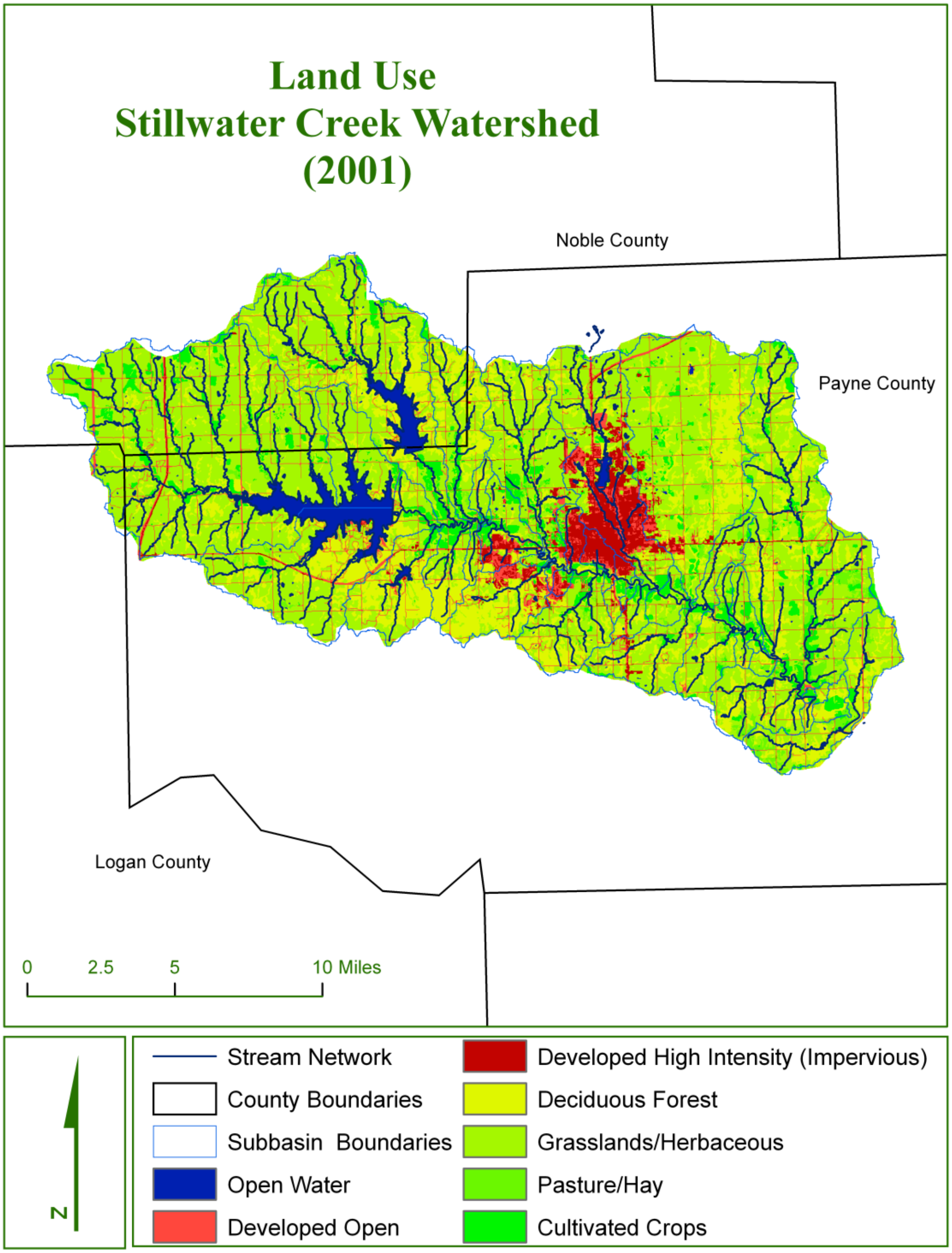

Figure 5.5: Land cover in Stillwater Creek Watershed
(produced from data provided by the US Geological Survey)

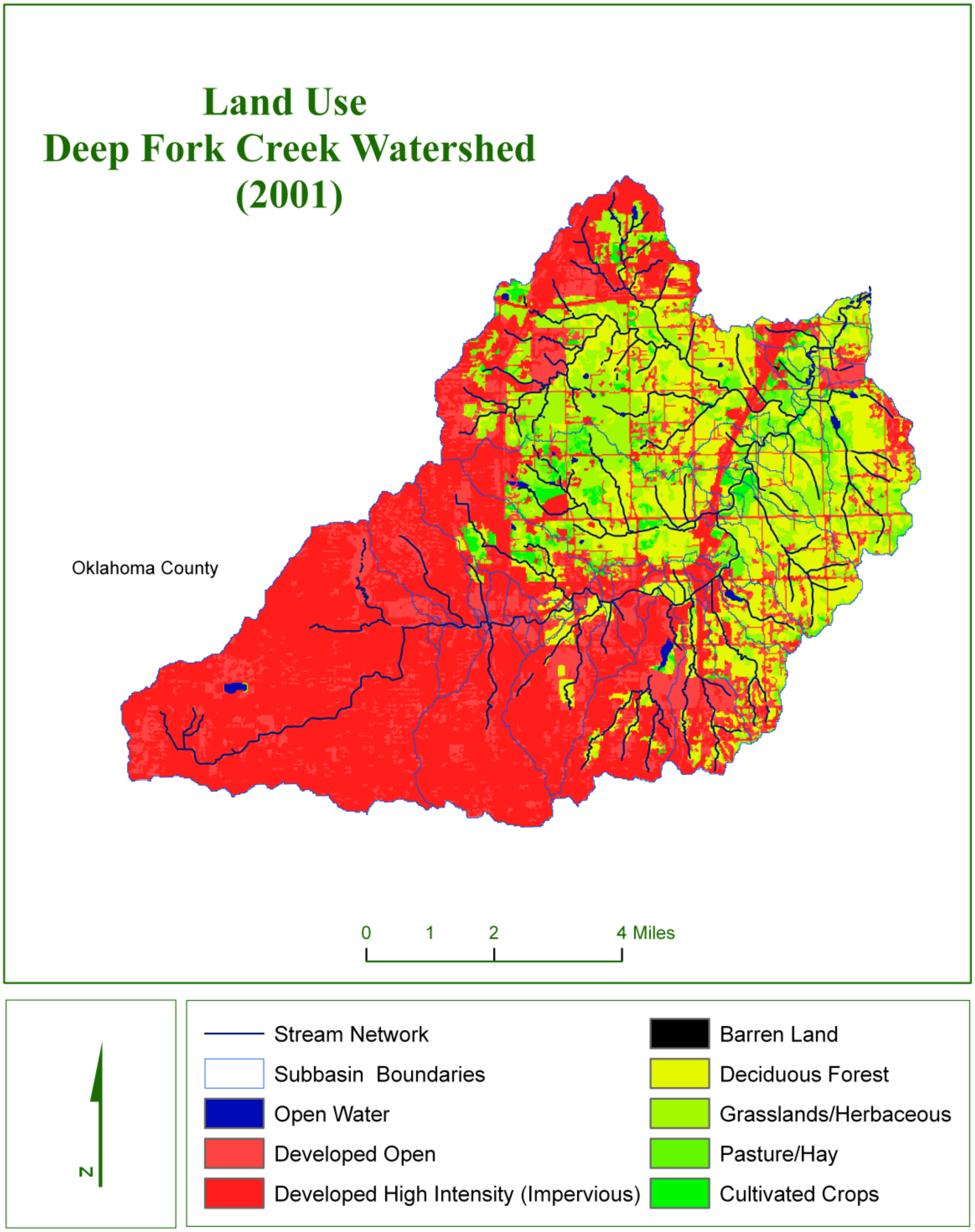

Figure 5.6 Land cover in Deep Fork Creek Watershed
(produced from data provided by the US Geological Survey)

Table 5.1: Land cover in the three watersheds derived from NLCD 2001 dataset

	Skeleton Creek	**Stillwater Creek**	**Deep Fork Creek**
Open Water (%)	0.3	3.1	0.5
Pervious Though Developed (%)	5.5	6.4	18.7
Impervious (%)	3.1	3.9	45.6
Barren Land (%)	0	0	0.01
Deciduous Forest (%)	3.8	22.2	17.7
Grassland/ Herbaceous (%)	34.5	55.5	13.8
Pasture / Hay (%)	0.2	2.6	1.9
Cultivated (%)	52.6	6.3	1.9

Table 5.2: Comparison of road area in the three watersheds in Central Oklahoma
Source: City of Enid, GIS Division; City of Stillwater, GIS Division;
and City of Oklahoma City, GIS Division

Characteristic	**Rural watershed** (Skeleton Creek)	**Ex-urban/converting watershed** (Stillwater Creek)	**Urban watershed** (Deep Fork Creek)
% Impervious Area (Urban Roads)	0.7	0.8	11.1
% Impervious Area (Rural Roads)	0.3	1.5	0.1

Shape files of impervious surfaces in the cities of Enid, Stillwater, and Oklahoma City revealed (Table 5.2) that roads (rural and urban) alone constituted the major impervious surface in the three watersheds (Forman and Alexander, 1998). Skeleton Creek, the rural watershed, contained the least area under impervious cover (3.0%) compared to Deep Fork Creek, the urban watershed (45.6%). The percentage of areas covered by roads in Skeleton, Stillwater, and Deep Fork Creeks were 1.0%, 2.3%, and 11.2%, respectively.

5.5 Statistical analysis of downstream trends and hypotheses testing

5.5.1 Approach 1 (Comparison of upstream and downstream sections)

Question 1: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) of Stillwater Creek downstream of Boomer Creek as compared to upstream? Can this change be explained by urbanization in the downstream section of Stillwater Creek?

Hypothesis 1.1: Channel width is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.2: Width depth ratio is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.3: Gradient is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.4: Bankfull area is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.5: Friction factor is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.6: Threshold grain size is significantly greater downstream of Boomer Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 1.7: Sinuosity is significantly less downstream of Boomer Creek compared to upstream as measured at a 0.05 level of significance.

Hypothesis 1.8: Mean depth is significantly less downstream of Boomer Creek compared to upstream as measured at a 0.05 level of significance.

The city of Stillwater is the major impervious zone in the ex-urban watershed of Stillwater Creek. The confluence of Boomer Creek, which brings urban runoff from the city of Stillwater, was used to divide Stillwater Creek into upstream and downstream sections (Fig. 3.6). Therefore, the upstream section of the Stillwater Creek watershed represented relatively rural land cover, whereas the downstream section represented relatively urban land cover (Figs. 3.6 and 5.5). The above hypotheses were framed with the expectation that Stillwater Creek was influenced by urbanization in the downstream section of Boomer Creek, and thus the influence of urbanization on Stillwater Creek would affect channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size downstream of Boomer Creek.

Table 5.3: Final transformations selected for ANCOVA analysis of Stillwater Creek

Stillwater Creek	
Variable Tested	**Transformation Used in ANCOVA**
Sinuosity	Reciprocal Root
Gradient	Square Root
Mean Depth	Reciprocal Root
Width	Natural Log
Width Depth Ratio	Reciprocal
Bankfull Area	Reciprocal
Drainage Area	Square Root
Threshold Grain Size	Natural Log
Friction Factor	Natural Log
Basal Area of Trees1	Natural Log

Table 5.4: ANCOVA results comparing
upstream and downstream sections of Stillwater Creek

Stillwater Creek		
Variable	**Change from upstream to downstream** (α = 0.05)	**P Value**
Width	No Change	0.29
Width Depth Ratio	Increase	0.03
Bankfull Area	No Change	0.07
Gradient	No Change	0.54
Friction Factor	Increase	0.02
Threshold Grain Size	No Change	0.1
Sinuosity	No Change	0.16
Mean Depth	Decrease	0.01

Step 1 (Upstream and downstream comparison of channel morphology of Stillwater Creek:

The p values reported from ANCOVA (Table 5.4) were greater than 0.05 for sinuosity, gradient, width, bankfull area, and threshold grain size. Therefore, these variables did not show statistically significant change in the downstream section of Stillwater Creek as compared to the upstream section. The three variables that exhibited any significant change between upstream and downstream sections of Stillwater Creek were mean depth, width depth ratio, and friction factor. Therefore, majority of hypotheses (1.1, 1.3, 1.4, 1.6, and 1.7) for Stillwater Creek were rejected. Only three hypotheses (1.2, 1.5, and 1.8) were accepted for three variables, which were width depth ratio, friction factor, and mean depth (Table 5.5). This also meant that all other channel morphology variables did not change between upstream and downstream sections of Stillwater Creek.

Table 5.5: Results of hypotheses testing for Stillwater Creek

Status of Hypotheses (Upstream and downstream comparison of Stillwater Creek)				
Hypothesis	Change in the variable from upstream to downstream	Variable Tested	Status of Hypothesis (at 0.05 level of significance)	
			Rejected	Accepted
1.1	No Change	Width	X	
1.2	Increase	Width Depth Ratio		X
1.3	No Change	Gradient	X	
1.4	No Change	Bankfull Area	X	
1.5	Increase	Friction Factor		X
1.6	No Change	Threshold Grain Size	X	
1.7	No Change	Sinuosity	X	
1.8	Decrease	Mean Depth		X

Then the following question arises: are these changes in the three variables due to urbanization or some other land cover type or other factor? This question was addressed in Step 2 of the statistical analysis with the help of multiple linear regression which follows.

Step 2 (Multiple linear regression to explain the changes in channel morphology from upstream to downstream of Stillwater Creek)

Mean depth, width depth ratio, and friction factor were the three variables that changed significantly between upstream and downstream sections. The mean depth of the channel decreased from upstream to downstream, whereas width depth ratio and friction factor increased from upstream to downstream of Stillwater Creek. Although Stillwater Creek has three reservoirs, the two major reservoirs (Lake Carl Blackwell and Lake McMurtry) are upstream of the urban area. The presence of reservoirs in the Stillwater Creek watershed may have been a confounding factor for differences in mean depth, width depth ratio, and friction factor of the three streams.

Multiple linear regression was used to analyze these trends and help answer the question: is this change in the three variables from upstream to downstream of Stillwater Creek due to imperviousness (urbanization) or some other land cover types? Therefore, multiple linear regression models were developed for each of the three variables according to the method (Helsel and Hirch, 2002) discussed in Chapter 4. The results of multiple linear regression models for mean depth, width depth ratio, and friction factor are summarized in Tables 5.6, 5.7, and 5.8.

In case of mean depth, R^2 was low which reflected unexplained variance (Table 5.6). However, R^2 improved in the case of width depth ratio and explained even more in the case of friction factor. The upstream to downstream change in these variables was not completely explained by urbanization alone. Presence of riparian trees and deciduous forest in this watershed were two other factors that may contribute to this trend (Tables 5.6, 5.7, and 5.8). The hypothesis for decreasing mean depth from upstream to downstream was based on the argument that the process of urbanization would increase sediment production and aggrade the channel leading to decrease in mean depth. This anticipated change in mean depth was the main reason for hypothesizing the increasing width depth ratio from the upstream to downstream section. The friction factor was anticipated to increase due to finer sediment production from construction activities, leading to smoother streambeds. The hypothesized trends for these three variables stand valid, however, not due to urbanization alone.

According to regression models, these trends were due to multiple factors such as urbanization along with riparian trees and deciduous forest in this watershed (Booth and Henshaw, 2001; Hession et al., 2002; Hollis, 1976; Leopold, 1972; Montgomery, 1997;

Nanson, 1981). Therefore, results of statistical analysis clearly indicated that the majority of channel morphology variables did not change in this stream. Only three variables (mean depth, width depth ratio, and friction factor) changed due to combined effects of local conditions (urbanization, riparian trees, deciduous forest and cohesive bed materials). As an ex-urban watershed with active construction stage, Stillwater Creek is characterized by substantial sediment production and runoff. However, imperviousness provided minimum explanation of channel morphology from upstream to downstream.

As one moves downstream of Boomer Creek (the tributary that delivers runoff and sediment), none of the downstream trends showed a statistically significant change that can be attributed to urbanization alone. The greater density of trees may have helped to stabilize the banks against increasing flows (Fig. 5.7) and provided woody debris for trapping and depositing sediments leading to decreasing mean depth. At the same time increasing friction factor from upstream to downstream indicated smoothening of the streambed which was explained by field observation of bed materials.

The channel bed and bank materials did not change over the entire length of Stillwater Creek. They consisted of 95-100% silt-clay. Such cohesive bed materials help to protect stream banks as well as increase friction factor (increasing smoothness of streambed) from upstream to downstream. Therefore, increasing friction factor downstream cannot be completely attributed to urbanization either. At the same time, there was no change in the bedrock from upstream to downstream. According to the Rosgen Classification, Stillwater Creek was classified as an E6b channel (Fig. 4.7), which is a very stable channel type (Rosgen, 1996) with slight entrenchment. Although the impervious surface area increased by 65% in 24 years (1979 to 2003) in the Stillwater

Creek watershed (Lehmert and Marston, 2005), no statistically significant impact of urban runoff and sediment can be discerned on the lower reaches of Stillwater Creek in the case of channel width, bankfull area, gradient, threshold grain size, and sinuosity.

Field observations in this watershed also revealed the entrenched nature of this stream along with occasional presence of woody debris jams. The presence of woody debris jams along with no significant change in the gradient are indications of stream equilibrium with low energy dissipation sufficient to transport sediments smaller than gravel (Marston, 1980). Therefore, the riparian vegetation, cohesive bed materials, and presence of woody debris jams provided possible answers to why Stillwater Creek is not exhibiting significant changes in morphology (downstream of Boomer Creek) as expected in a watershed that is transitioning from rural to urban. The potential effects of urbanization in this watershed are being countered by such local conditions. In other words, Stillwater Creek is behaving like a flume where urbanization induced sediment and runoff is flushed out without any radical changes in the channel morphology, and this contradicts Hession (2002), Pizzuto et al. (2000), Trimble (1997), and Fryirs and and Brierley (2000).

Figure 5.7: Thick riparian corridor dominated by trees on the banks of Boomer Creek (A Tributary of Stillwater Creek that delivers urban runoff and sediment) helps protect the stream bank from erosion

Table 5.6: Multiple linear regression model to explain decrease in mean depth from upstream to downstream sections of Stillwater Creek

Multiple Linear Regression
(Stillwater Creek)

Dependent Variable:	Transformation	
- Mean Depth	Cube Root	R^2 = 50.7 % R^2 Adjusted = 45.1 % S (meters) = 0.079 PRESS = 0.14
Independent Variables:		
- Pervious Area	Reciprocal Root	
- Impervious Area	Square	
- Deciduous Forest	Reciprocal	
- Grassland	Untransformed	
- Pasture	Square	
- Cultivated	Square	
- Total Trees	Cube Root	

The regression equation:
Stillwater Creek Mean Depth (meters) = 0.5 - 0.000125 Impervious Area (% of total area) + 1.78 Area Under Deciduous Forest (% of total area) - 0.08 Riparian Trees (number of trees)

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	0.49	0.04	10.0	0.00	
Impervious Area	-0.0001245	0.0000411	-3.03	0.005	1.5
Area Under Deciduous Forest	1.79	1.47	1.21	0.23	1.4
Riparian Trees	-0.08	0.01	- 4.62	0.00	1.2

S: Standard Deviation, PRESS: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

Table 5.7: Multiple linear regression model to explain increase in width depth ratio from upstream to downstream of Stillwater Creek

Multiple Linear Regression
(Stillwater Creek)

Dependent Variable:	Transformation	
• Width Depth Ratio	Reciprocal	R^2 = 61.3 % R^2 Adjusted = 58.5 % S (meters) = 50.9 PRESS = 8.1 * 10^3
Independent Variables:		
• Pervious Area	Square Root	
• Impervious Area	Square Root	
• Deciduous Forest	Untransformed	
• Grassland	Natural Log	
• Pasture	Natural Log	
• Cultivated	Cube Root	
• Total Trees	Square Root	

The regression equation:
Stillwater Creek Width Depth Ratio = 549 - 134 Area under Grassland/Herbaceous (% of total area) + 17.4 Riparian Trees (number of trees)

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	549	178	3.08	0.01	
Area under Grassland/Herbaceous	-134	30.5	- 4.40	0.005	1.2
Riparian Trees	17.5	6.77	2.58	0.02	1.2

S: Standard Deviation, PRESS: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

Table 5.8: Multiple linear regression model to explain increase in friction factor from upstream to downstream of Stillwater Creek

Multiple Linear Regression **(Stillwater Creek)**		
Dependent Variable:	Transformation	R^2 = 83.6 % R^2 Adjusted = 81.4% S (meters) = 0.16 PRESS = 0.74
- Friction Factor	Natural Log	
Independent Variables: - Pervious Area	Cube	
- Impervious Area	Cube	
- Deciduous Forest	Cube	
- Grassland	Natural Log	
- Pasture	Natural Log	
- Cultivated	Square Root	
- Number of Riparian Trees	Cube Root	

The regression equation:
Stillwater Creek Friction Factor = 0.23 - 0.000014 Impervious Area (% of total area) - 0.62 Area under Grassland/Herbaceous (% of total area) - 0.11 Riparian Trees (number of trees)

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	0.23	0.94	0.25	0.81	
Impervious Area	-0.0000144	0.00000607	-2.37	0.03	3.7
Area under Grassland/Herbaceous	-0.62	0.17	-3.56	0.002	3.9
Riparian Trees	-0.11	0.05	-2.45	0.02	1.1

S: Standard Deviation, Press: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

Question 2: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) of Skeleton Creek downstream of Bitter creek as compared to upstream? Can this change be explained by land cover type in the downstream of Skeleton Creek?

Hypothesis 2.1: Channel width is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.2: Width depth ratio is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.3: Bankfull area is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.4: Gradient is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.5: Friction factor is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.6: Threshold grain size is significantly greater downstream of Bitter Creek than upstream as measured at the 0.05 level of significance.

Hypothesis 2.7: Sinuosity is significantly less downstream of Bitter Creek compared to upstream as measured at a 0.05 level of significance.

Hypothesis 2.8: Mean depth is significantly less downstream of Bitter Creek compared to upstream as measured at a 0.05 level of significance.

Step 1 (Upstream and downstream comparison of channel morphology of Skeleton Creek)

Histograms, boxplots, and probability plots of individual variables at each level of transformation were used to select the best possible level of transformation for statistical analysis (ANCOVA) of each variable. Table 5.9 shows the finally selected transformation for each variable.

Table 5.9: Final transformations for ANCOVA analysis of Skeleton Creek

Skeleton Creek	
Variable	**Transformation Used in ANCOVA**
Sinuosity	Untransformed
Gradient	Natural Log
Mean Depth	Square Root
Width	Natural Log
Width Depth Ratio	Natural Log
Bankfull Area	Natural Log
Drainage Area	Square Root
Silt Clay	Square
Threshold Grain Size	Natural Log
Friction Factor	Reciprocal Root
Basal Area of Trees1	Reciprocal Root
Water	Natural Log

Table 5.10: ANCOVA results comparing
upstream and downstream sections of Skeleton Creek

Skeleton Creek		
Variable	**Change From upstream to downstream** ($\alpha = 0.05$)	**P Value**
Width	No Change	0.61
Width Depth Ratio	No Change	0.17
Bankfull Area	No Change	0.43
Gradient	No Change	0.72
Friction Factor	No Change	0.90
Threshold Grain Size	No Change	0.42
Sinuosity	No Change	0.49
Mean Depth	No Change	0.41

According to the ANCOVA test there was no change (Table 5.10) in any geomorphic variable from the upstream to downstream sections of Skeleton Creek. The p values reported from ANCOVA (Table 5.10) are greater than 0.05 for channel morphology variables. Therefore, all hypotheses (Hypotheses 2.1-2.8) were rejected at a 0.05 level of significance (Table 5.11). This means there is no significant change in channel morphology of Skeleton Creek from the upstream to downstream sections.

Field observations revealed this stream as a relatively natural system with entrenched meanders (Fig. 4.10). Since there is no change in the channel morphology of this stream from the upstream to downstream section, step 2 (multiple linear regression to explain changes in channel morphology with the help of land cover) was not carried out for this stream. According to the Rosgen Classification (Fig. 4.7), Skeleton Creek had both C and E types of stream channels (Rosgen, 1996). These are stable in nature with slight entrenchment in case of E types, and moderate entrenchment along with well developed flood plain with meanders and point bars in case of C type. Similar to Stillwater Creek, no significant change in the gradient of Skeleton Creek also suggested that an equilibrium had been reached within this stream.

Table 5.11: Results of hypotheses testing for Skeleton Creek

Status of Hypotheses (Upstream and downstream comparison of Skeleton Creek)				
Hypothesis	Change in the variable from upstream to downstream	Variable Tested	Status of Hypothesis (at 0.05 level of significance)	
			Rejected	Accepted
2.1	No Change	Width	X	
2.2	No Change	Width Depth Ratio	X	
2.3	No Change	Bankfull Area	X	
2.4	No Change	Gradient	X	
2.5	No Change	Friction Factor	X	
2.6	No Change	Threshold Grain Size	X	
2.7	No Change	Sinuosity	X	
2.8	No Change	Mean Depth	X	

Question 3: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) of Deep Fork Creek downstream of Deep Fork Creek (a tributary of Deep Fork Creek) as compared to upstream? Can this change be explained by land cover type in the downstream section of Deep Fork Creek?

Hypothesis 3.1: Channel width is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.2: Width depth ratio is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.3: Bankfull area is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.4: Gradient is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.5: Friction factor is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.6: Threshold grain size is significantly greater downstream of Deep Fork Creek than upstream as measured at a 0.05 level of significance.

Hypothesis 3.7: Sinuosity is significantly less downstream of Deep Fork Creek compared to upstream as measured at a 0.05 level of significance.

Hypothesis 3.8: Mean depth is significantly less downstream of Deep Fork Creek compared to upstream as measured at a 0.05 level of significance.

Step 1 (Upstream and Downstream comparison of channel morphology of Deep Fork Creek)

Table 5.12: Final transformations for ANCOVA analysis of Deep Fork Creek

Deep Fork Creek	
Variable	**Transformation Used in ANCOVA**
Sinuosity	Untransformed
Gradient	Cube Root
Mean Depth	Cube
Width	Untransformed
Width Depth Ratio	Natural Log
Bankfull Area	Untransformed
Drainage Area	Square Root
Silt Clay	Untransformed
Threshold Grain Size	Square Root
Friction Factor	Cube
Basal Area of Trees1	Natural Log
Water	Square Root

Table 5.13: ANCOVA results comparing upstream and downstream sections of Deep Fork Creek

Deep Fork Creek		
Variable	**Change From upstream to downstream** ($\alpha = 0.05$)	**P Value**
Width	Increase	0.01
Width Depth Ratio	No Change	0.7
Bankfull Area	No Change	0.16
Gradient	No Change	0.85
Friction Factor	No Change	0.7
Threshold Grain Size	No Change	0.8
Sinuosity	Decrease	0.04
Mean Depth	No Change	0.2

In the case of Deep Fork Creek, the p values reported from ANCOVA (Table 5.13) were greater than 0.05 for most variables (gradient, mean depth, bankfull area, width depth ratio, friction factor, and threshold grain size) revealing no significant change from upstream to downstream. Only two variables, sinuosity and width, changed significantly from upstream to downstream with p values less than 0.05. Therefore, majority of hypotheses (3.2, 3.3, 3.4, 3.5, 3.6, and 3.8) for Deep Fork Creek were rejected. Only two hypotheses (3.1 and 3.7) were accepted for two variables, which were width and sinuosity (Table 5.14).

Table 5.14: Results of hypotheses testing for Deep Fork Creek

Status of Hypotheses (Upstream and downstream comparison of Skeleton Creek)				
Hypothesis	Change in the variable from upstream to downstream	Variable Tested	Status of Hypothesis (at 0.05 level of significance)	
			Rejected	Accepted
3.1	Increase	Width		X
3.2	No Change	Width Depth Ratio	X	
3.3	No Change	Bankfull Area	X	
3.4	No Change	Gradient	X	
3.5	No Change	Friction Factor	X	
3.6	No Change	Threshold Grain Size	X	
3.7	Decrease	Sinuosity		X
3.8	No Change	Mean Depth	X	

Then the question arised: what is the possible cause of this change in sinuosity and width of Deep Fork Creek from upstream to downstream sections? This question was addressed in the next step with the help of multiple regression.

Step 2 (Multiple linear regression to explain the changes in channel morphology from upstream to downstream of Deep Fork Creek)

Width and sinuosity were the two variables that changed significantly between upstream and downstream sections of Deep Fork Creek. The sinuosity of the channel decreased from upstream to downstream whereas width increased from upstream to downstream of Deep Fork Creek. Multiple linear regression was used to analyze these trends and answer the question: are these changes in the two variables from upstream to downstream of Deep Fork Creek due to imperviousness (urbanization) or some other land cover types?

The results of multiple regression models for sinuosity and width are summarized in Tables 5.15 and 5.16. High R^2 values examined a large portion of the variation (88.2% and 95.3 % respectively). Urbanization did not explain downstream changes in these variables. The changes in these variables were explained by other types of land cover such as area under deciduous forest, pasture, and some cultivation.

Deep Fork Creek is a predominantly urban watershed with approximately 45% of area under high intensity urban land cover. Also, the urban land cover rarely changed along this stream in downstream direction, unlike Stillwater Creek which is urbanized in the downstream section only. At the same time, deciduous forest, pasture and cultivation appeared as other land cover types in the downstream section of the Deep Fork Creek watershed which were actually not present in the upstream section (Fig. 5.6). The possible runoff and sediment production from such land cover types along with naturally accepted behavior of any stream explained the decreasing sinuosity of Deep Fork Creek in the downstream direction. This also explained the change in width downstream. Such hydrologic changes lead to more erosion and increasing width in the downstream direction.

At the same time, this stream was also entrenched into shale. With no significant change in gradient (similar to Skeleton and Stillwater Creeks), Deep Fork Creek has achieved equilibrium in terms of its hydrologic and land cover regimes. Similar to Skeleton Creek, Deep Fork Creek was also classified with C and E types (Fig. 4.7) of stream channels (Rosgen, 1996). These are stable in nature with slight entrenchment in case of E types, and moderate entrenchment along with well developed flood plain with meanders and point bars in case of C type. At the same time, lack of woody debris jams is the explanation for increasing width with no significant change in the mean depth downstream. The bed materials and riparian corridor did not change downstream. Therefore, urbanization did not explain any changes in the downstream channel morphology of the urban watershed Deep Fork Creek.

Table 5.15: Multiple linear regression model to explain decrease in sinuosity from upstream to downstream of Deep Fork Creek

Multiple Linear Regression (Deep Fork Creek)		
Dependent Variable:	Transformation Used	R^2 = 88.2 % R^2 Adjusted = 87.5% S (meters) = 0.00269 PRESS = 0.000155
- Sinuosity	Untransformed	
Independent Variables: - Water	Cube Root	
- Pervious Area	Cube Root	
- Impervious Area	Square Root	
- Deciduous Forest	Natural Log	
- Grassland	Natural Log	
- Pasture	Cube Root	
- Cultivated	Natural Log	
- Total Trees	Cube Root	

The regression equation:
Deep Fork Creek Sinuosity = 0.02 - 0.00 Area under Deciduous Forest (% of total area)

Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	0.02	0.0006269	28	0.00
Area Deciduous Forest	-0.00261	0.000231	-11.3	0.00

S: Standard Deviation, Press: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

Table 5.16: Multiple linear regression model to explain increase in width from upstream to downstream of Deep Fork Creek

Multiple Linear Regression (Deep Fork Creek)		
Dependent Variable:	Transformation Used	R^2 = 95.3% R^2 Adjusted = 94.4 % S (meters) = 0.07 PRESS = 0.15
• Width	Untransformed	
Independent Variables:		
• Pervious Area	Cube Root	
• Impervious Area	Cube Root	
• Deciduous Forest	Reciprocal Root	
• Grassland	Reciprocal Root	
• Pasture	Reciprocal Root	
• Cultivated	Cube Root	
• Total Trees	Untransformed	

The regression equation:
Deep Fork Creek Width (meters) = 0.4 - 0.06 Area under Deciduous Forest (% of total area) - 0.14 Area under Pasture (% of total area) - 0.3 Area under Cultivation (% of total area)

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	0.4	0.06	6.72	0.00	
Area under Deciduous Forest	-0.06	0.01	-6.74	0.00	2.7
Area under Pasture	-0.14	0.02	-8.02	0.00	1.3
Area under Cultivation	-0.3	0.05	-6.06	0.00	2.5

S: Standard Deviation, Press: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

5.5.2 Approach 2 (Comparison of streams with each other)

Following upstream and downstream comparisons (as discussed earlier), the evaluation of a rural stream with an urban stream is another standard geomorphic method used to evaluate geomorphic effects of urbanization on channel morphology (Morisawa and Laflure, 1979). This method (Approach 2) was used to address the next three research questions (Questions 4, 5, and 6) and test their hypotheses respectively (Hypotheses 4.1-4.8, 5.1-5.8, and 6.1-6.8).

Question 4: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) from Skeleton Creek (rural) to Stillwater Creek (ex-urban)? Can this change be explained by increasing urbanization from a rural to an ex-urban stream?

Hypothesis 4.1: Channel width is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.2: Width depth ratio is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.3: Bankfull area is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.4: Gradient is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.5: Friction factor is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.6: Threshold grain size is greater in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.7: Sinuosity is less in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 4.8: Mean depth is less in Stillwater Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Skeleton Creek is predominantly a rural watershed with cultivation as the major land cover type, whereas Stillwater Creek is in the process of transition from rural to urban with substantial impervious growth in the downstream section. According to ergodic reasoning (Chin and Gregory, 2001; Schumm, 1991), Skeleton Creek would represent the pre-urban stage geomorphic characteristics of Stillwater Creek. Therefore, channel morphologies of the two streams were compared to find any significant changes that can be attributed to urbanization or any other type of land cover. Two steps were involved in this process. First, a statistical comparison of the two streams, and secondly, use of multiple linear regression to explain any such changes in channel morphology due to urbanization or any other land cover.

Step 1 (comparison of Skeleton and Stillwater Creeks with each other)

The hypotheses were tested by comparing Skeleton Creek with Stillwater Creek. This involved the use of the Mann-Whitney nonparametric statistical test to compare trends of channel morphology variables between Skeleton and Stillwater Creeks. As discussed in the previous section on Stillwater Creek, drainage area contributing to each transect along a stream directly influences channel morphology variables (Downs and Gregory, 2004). Therefore, channel morphology variables were normalized according to the drainage area above each transect.

According to this test (Table 5.17), most variables did not show significant change between Skeleton and Stillwater Creeks. The only variables that changed were sinuosity (decreased) and bankfull area (increased) from Skeleton to Stillwater Creek. Therefore, six hypotheses (Hypotheses 4.1, 4.2, 4.4, 4.5, 4.6, and 4.8) in case of channel width, width depth ratio, gradient, friction factor, threshold grain size, and mean depth between Skeleton and Stillwater Creeks were rejected at a 0.05 level of significance (Table 5.18).

Only two hypotheses were valid in case of sinuosity (decrease from Skeleton to Stillwater Creek), and bankfull area (increase from Skeleton to Stillwater Creek) at a 0.05 level of significance. This also meant that most geomorphic characteristics are similar within these two streams. The only difference existed in the case of two variables: sinuosity and bankfull area. This means Stillwater Creek is relatively less sinuous with more bankfull area than Skeleton Creek. The next step was to find the possible explanation for this difference between the two streams which follows.

Table 5.17: Mann-Whitney results comparing Skeleton Creek and Stillwater Creek

Variable	**Change From Skeleton Creek To Stillwater Creek** ($\alpha = 0.05$)
	Change
Width	No Change
Width Depth Ratio	No Change
Bankfull Area	Increase
Gradient	No Change
Friction Factor	No Change
Threshold Grain Size	No Change
Sinuosity	Decrease
Mean Depth	No Change

Table 5.18: Results of hypotheses testing for change from Skeleton Creek to Stillwater Creek

Status of Hypotheses (Change from Skeleton Creek to Stillwater Creek)				
Hypothesis	Change in the variable from Skeleton Creek to Stillwater Creek	Variable Tested	Status of Hypothesis (at 0.05 level of significance)	
			Rejected	Accepted
4.1	No Change	Width	X	
4.2	No Change	Width Depth Ratio	X	
4.3	Increase	Bankfull Area		X
4.4	No Change	Gradient	X	
4.5	No Change	Friction Factor	X	
4.6	No Change	Threshold Grain Size	X	
4.7	Decrease	Sinuosity		X
4.8	No Change	Mean Depth	X	

Step 2 (Multiple linear regression to explain the changes in channel morphology from Skeleton to Stillwater Creek)

The results of multiple linear regression models for sinuosity and bankfull area are summarized in Tables 5.19 and 5.20. High R^2 value for a decrease in sinuosity between Skeleton and Stillwater Creeks provided significant explanation (95.5%) (Tables 5.19 and 5.20). Urbanization as hypothesized explained this change but not completely. Two other land cover types, pervious area and area under deciduous forest, also contributed to this change in sinuosity between the two streams. Therefore, the hypothesis suggesting decreasing sinuosity from Skeleton Creek to Stillwater Creek can be accepted; however, the anticipation that urbanization is the primary reason for this change was partially validated. In the case of Stillwater Creek, the downstream impervious growth contributed more runoff into the river. At the same time, pervious areas, i.e. green parks, lawns, and playgrounds within the urban boundaries of Stillwater also contributed runoff. There combined runoff contributions, along with runoff and sediment production from forest areas, make this stream less sinuous than Skeleton Creek. This along with the occasional presence of woody debris jams in Stillwater Creek also helped explain the increasing bankfull area from Skeleton to Stillwater Creek. However, in the case of bankfull area, the regression model provided minimal explanation. Due to relatively low values of R^2 (54.9 %), there was a large unexplained natural variation which is not clarified by statistical analysis. Nonetheless, urbanization did not completely explain this change.

Table 5.19: Multiple linear regression model to explain decrease in sinuosity from Skeleton to Stillwater Creek

Multiple Linear Regression
(Skeleton and Stillwater Creeks)

Dependent Variable:	Transformation Used	R^2 = 95.5% R^2 Adjusted = 95.3 % S (meters) = 1.56 PRESS = 156
• Sinuosity	Reciprocal Root	
Independent Variables:		
• Pervious Area	Square Root	
• Impervious Area	Natural log	
• Deciduous Forest	Square	
• Grassland	Reciprocal	
• Pasture	Reciprocal	
• Cultivated	Reciprocal Root	
• Total Trees	Natural Log	

The regression equation:
Sinuosity = 0.18 - 4.25 Pervious (% of total area) + 1.66 Impervious (% of total area) - 0.00 Deciduous Forest (% of total area)

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	0.18	0.57	0.32	0.75	
Pervious Area	-4.25	0.18	-24.3	0.00	2.8
Impervious Area	1.67	0.25	6.66	0.00	2.6
Area Under Deciduous Forest	-0.0000945	0.00003011	-3.14	0.003	1.2

S: Standard Deviation, Press: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

Table 5.20: Multiple linear regression model to explain increase in bankfull area from Skeleton Creek to Stillwater Creek

Multiple Linear Regression
(Skeleton & Stillwater Creeks)

Dependent Variable:	Transformation Used	R^2 = 54.9% R^2 Adjusted = 53.3% S (meters) = 1.18 PRESS = 84
• Bankfull Area	Natural log	
Independent Variables: • Pervious Area	Square	
• Impervious Area	Cube	
• Deciduous Forest	Reciprocal	
• Grassland	Reciprocal Root	
• Pasture	Reciprocal Root	
• Cultivated	Square	
• Total Trees	Square	

The regression equation:
Bankfull Area (square meters) = - 0.49 - 0.00 Impervious Area (% of total area) + 5.15 Area Under Grassland /Herbaceous (% of total area)

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	-0.48	0.31	-1.59	0.12	
Impervious Area	-0.0000328	0.00000399	-8.21	0.00	1.1
Area Under Grassland/Herbaceous	5.15	1.74	2.95	0.01	1.1

S: Standard Deviation, Press: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

Question 5: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) from Stillwater Creek (ex-urban) to Deep Fork Creek (urban)? Can this change be explained by increasing urbanization from an ex-urban to an urban stream?

Hypothesis 5.1: Channel width is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.2: Width depth ratio is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.3: Bankfull area is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.4: Gradient is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.5: Friction factor is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.6: Threshold grain size is greater in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.7: Sinuosity is less in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

Hypothesis 5.8: Mean depth is less in Deep Fork Creek compared to Stillwater Creek as measured at a 0.05 level of significance.

The process of urban growth transforms an ex-urban watershed into an urban watershed. This urban transformation would lead to changes in channel morphology. Therefore, Stillwater Creek and Deep Fork Creek were compared to evaluate such changes.

Step 1 (comparison of Stillwater Creek and Deep Fork Creek)

The results of the Mann-Whitney non-parametric test revealed that there is no change in sinuosity, gradient, mean depth, friction factor, and threshold grain size between Stillwater and Deep Fork Creeks (Table 5.21). Only three variables changed from Stillwater to Deep Fork Creek: width, bankfull area, and width depth ratio. These variables increased from Stillwater Creek to Deep Fork Creek. This means that Deep Fork Creek is relatively wider and with more capacity (bankfull area) and higher width depth ratio. Therefore, only three hypotheses (5.1, 5.2, and 5.3) were accepted in the cases of increasing width, bankfull area, and width depth ratio from Stillwater to Deep Fork Creek (Table 5.22). Five hypotheses (5.4, 5.5, 5.6, 5.7, and 5.8) were rejected in case of other variables (gradient, friction factor, threshold grain size, sinuosity, and mean depth). The next step involved multiple linear regression to explain possible causes for increase in width, width depth ratio, and bankfull area from Stillwater Creek to Deep Fork Creek.

Table 5.21: Mann-Whitney results comparing Stillwater Creek and Deep Fork Creek

Comparison of Stillwater Creek and Deep Fork Creek	
Variable	**Change From Stillwater Creek To Deep Fork Creek** ($\alpha = 0.05$)
	Change
Width	Increase
Width Depth Ratio	Increase
Bankfull Area	Increase
Gradient	No Change
Friction Factor	No Change
Threshold Grain Size	No Change
Sinuosity	No Change
Mean Depth	No Change

Table 5.22: Results of hypotheses testing for change from Stillwater Creek to Deep Fork Creek

Status of Hypotheses (Change from Stillwater Creek to Deep Fork Creek)				
Hypothesis	Change in the variable from Stillwater Creek to Deep Fork Creek	Variable Tested	Status of Hypothesis (at 0.05 level of significance)	
			Rejected	Accepted
5.1	Increase	Width		X
5.2	Increase	Width Depth Ratio		X
5.3	Increase	Bankfull Area		X
5.4	No Change	Gradient	X	
5.5	No Change	Friction Factor	X	
5.6	No Change	Threshold Grain Size	X	
5.7	No Change	Sinuosity	X	
5.8	No Change	Mean Depth	X	

Step 2 (Multiple linear regression to explain the changes in channel morphology from Stillwater Creek to Deep Fork Creek)

The results of multiple linear regression models for width, bankfull area, and width depth ratio are summarized in Tables 5.23, 5.24, and 5.25. In the case of width, the value of R^2 (85.7 %) gave a significant explanation through different land cover types such as pervious area, impervious area, area under deciduous forest, grassland, pasture, cultivated area, and riparian trees. However, urbanization alone did not explain an increase in width from Stillwater to Deep Fork Creek. It clearly indicated the complexity and multiple land cover types leading to increasing width from Stillwater to Deep Fork Creek. Similar land cover types contributed to the changes in width depth ratio, as well as bankfull area. However, the relatively low values of R^2 for bankfull area (42.2 %) and width depth ratio (65.9 %) revealed that there is a large unexplained variation due to factors other than urbanization or other land cover types. Also, there is more area under cultivation in the case of Stillwater Creek than Deep Fork Creek, which is predominantly an urban watershed. The increasing trend of width, bankfull area, and width depth ratio from Stillwater Creek to Deep Fork Creek is therefore not due to urbanization alone.

Table 5.23: Multiple linear regression model to
explain increase in width from Stillwater Creek to Deep Fork Creek

Multiple Linear Regression
(Stillwater & Deep Fork Creeks)

Dependent Variable:	Transformation Used	R^2 = 85.7 % R^2 Adjusted = 84 % S (meters) = 0.0745204 PRESS = 0.298932
• Width	Cube Root	
Independent Variables: • Pervious Area	Untransformed	
• Impervious Area	Untransformed	
• Deciduous Forest	Natural log	
• Grassland	Reciprocal	
• Pasture	Reciprocal	
• Cultivated	Reciprocal	
• Total Tree	Sq Root	

The regression equation:
Width (meters) = 0.63 - 0.00448 Pervious Area (% of total area) - 0.00 Impervious Area (% of total area) - 0.04 Area Under Pasture (% of total area) - 0.00 Cultivated Area (% of total area) - 0.04 Riparian Trees (number of trees)

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	0.63	0.05	12.2	0.00	
Pervious Area	-0.00448	0.00126	-3.55	0.001	1.7
Impervious Area	-0.0000101	0.000623	-0.02	0.99	2.0
Area Under Pasture	-0.04	0.01	-6.83	0.00	1.5
Cultivated Area	-0.0008730	0.0001751	-4.99	0.00	1.9
Riparian Trees	-0.04	0.01	-4.07	0.00	2.0

S: Standard Deviation, Press: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

Table 5.24: Multiple linear regression model to explain increase in width depth ratio from Stillwater Creek to Deep Fork Creek

Multiple Linear Regression
(Stillwater & Deep Fork Creeks)

Dependent Variable:	Transformation Used	R^2 = 42.2% R^2 Adjusted = 35.9% S (meters) = 1.39 PRESS = 94.1
- Bankfull Area	Untransformed	
Independent Variables: - Pervious Area	Natural log	
- Impervious Area	Natural log	
- Deciduous Forest	Natural log	
- Grassland	Natural log	
- Pasture	Natural log	
- Cultivated	Natural log	
- Total Trees	Untransformed	

The regression equation:
Bankfull Area (square meters) = 4.99 - 1.56 Pervious Area (% of total area) + 0.28 Impervious Area (% of total area) - 0.9 Area Under Pasture (% of total area) - 0.1 Riparian Trees (number of trees)

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	4.99	0.88	5.67	0.00	
Pervious Area	-1.56	0.56	-2.8	0.01	5.3
Impervious Area	0.28	0.32	0.88	0.39	4.3
Area Under Pasture	-0.9	0.24	-3.80	0.001	2.1
Riparian Trees	-0.1	0.03	-3.76	0.001	1.5

S: Standard Deviation, Press: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

Table 5.25: Multiple linear regression model to
explain increase in width depth ratio from Stillwater Creek to Deep Fork Creek

Multiple Linear Regression
(Stillwater & Deep Fork Creeks)

Dependent Variable:	Transformation Used	R^2 = 65.9% R^2 Adjusted = 62.9% S (meters) = 0.66 PRESS = 19.9
- Width Depth Ratio	Natural Log	
Independent Variables:		
- Pervious Area	Reciprocal	
- Impervious Area	Reciprocal	
- Deciduous Forest	Reciprocal Root	
- Grassland	Reciprocal	
- Pasture	Cube Root	
- Cultivated	Reciprocal	
- Total Trees	Cube	

The regression equation:
Width Depth Ratio = - 1.02 + 0.61 Impervious Area (% of total area) - 1.86 Area Under Pasture (% of total area) + 0.00 Cultivated Area (% of total area)

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	-1.02	0.4	-2.54	0.02	
Impervious Area	0.61	0.38	1.61	0.12	1.1
Area Under Pasture	-1.86	0.27	-6.76	0.00	2.4
Cultivated Area	0.00398	0.00178	2.23	0.03	2.5

S: Standard Deviation, Press: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

Question 6: What is the change in channel morphology (channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size) from Skeleton Creek (rural) to Deep Fork Creek (urban)? Can this change be explained by increasing urbanization from a rural to an urban watershed?

The process of urbanization is expected to transform a rural watershed into an urban watershed. This urban transformation would lead to changes in channel width, mean depth, width depth ratio, bankfull area, sinuosity, gradient, friction factor, and threshold grain size.

Hypothesis 6.1: Channel width is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.2: Width depth ratio is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.3: Bankfull area is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.4: Gradient is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.5: Friction factor is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.6: Threshold grain size is greater in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.7: Sinuosity is less in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Hypothesis 6.8: Mean depth is less in Deep Fork Creek compared to Skeleton Creek as measured at a 0.05 level of significance.

Step 1 (comparison of Skeleton Creek and Deep Fork Creek)

The results of the Mann-Whitney non parametric test revealed that there is no change in sinuosity, gradient, mean depth, width depth ratio, friction factor, and threshold grain size between Skeleton and Deep Fork Creeks (Table 5.26). Only two variables changed from Skeleton Creek to Deep Fork Creek which were width and bankfull area. The two variables increased from Skeleton Creek to Deep Fork Creek. This means that Deep Fork Creek is relatively wider and has more capacity (bankfull area). Therefore, only two hypotheses (6.1 and 6.3) were accepted in the case of increasing width and bankfull area from Skeleton to Deep Fork Creek. All other hypotheses (6.2, 6.4, 6.5, 6.6, 6.7, and 6.8) were rejected (Table 5.27) at a 0.05 level of significance in case of other variables (width depth ratio, gradient, friction factor, threshold grain size, sinuosity, and mean depth). The next step involved multiple linear regression to explain possible causes for increase in width, and bankfull area from Skeleton Creek to Deep Fork Creek.

Table 5.26: Mann-Whitney results comparing Skeleton Creek and Deep Fork Creek

Comparison of Skeleton Creek and Deep Fork Creek	
Variable	**Change From Skeleton Creek To Deep Fork Creek** (α = 0.05)
	Change
Width	Increase
Width Depth Ratio	No Change
Bankfull Area	Increase
Gradient	No Change
Friction Factor	No Change
Threshold Grain Size	No Change
Sinuosity	No Change
Mean Depth	No Change

Table 5.27: Results of hypotheses testing of change from Skeleton Creek to Deep Fork Creek

Status of Hypotheses (Change From Skeleton Creek To Deep Fork Creek)				
Hypothesis	Change in the variable from Skeleton Creek to Deep Fork Creek	Variable Tested	Status of Hypothesis (at 0.05 level of significance)	
			Rejected	Accepted
6.1	Increase	Width		X
6.2	No Change	Width Depth Ratio	X	
6.3	Increase	Bankfull Area		X
6.4	No Change	Gradient	X	
6.5	No Change	Friction Factor	X	
6.6	No Change	Threshold Grain Size	X	
6.7	No Change	Sinuosity	X	
6.8	No Change	Mean Depth	X	

Step 2 (Multiple linear regression to explain the changes in channel morphology From Skeleton Creek to Deep Fork Creek)

The results of multiple linear regression models for width and bankfull area are summarized in Tables 5.28 and 5.29. In case of width, the high value of R^2 (91.1 %) provided a significant explanation through different land cover types such as grassland, pasture, and cultivated area. However, urbanization did not explain this increase in width from Skeleton to Deep Fork Creek. Similarly, the increasing channel capacity (bankfull area) from Skeleton to Deep Fork Creek was not due to urbanization. In fact, other types of land cover such as area under deciduous forest, area under grassland, and pasture provided possible explanations (R^2 = 91.1 %) for this change. Therefore, changing degrees (increasing) of urbanization from Skeleton to Deep Fork Creek did not explain any changes in the morphology of these two streams. In other words, conversion of a rural stream into an urban stream would not affect the channel morphology in this geomorphic province. At the same time channel morphology does not change radically as expected. Few changes observed in the channel morphology were due to the combined effects of multiple land cover types.

Table 5.28: Multiple linear regression model to
explain increase in width from Skeleton Creek to Deep Fork Creek

Multiple Linear Regression:
(Skeleton & Deep Fork Creeks)

Dependent Variable:	Transformation Used	
• Width	Natural Log	R^2 = 91.1% R^2 Adjusted = 90.5% S (meters) = 0.4 PRESS = 8.86
Independent Variables: • Pervious Area	Cube	
• Impervious Area	Square	
• Deciduous Forest	Cube Root	
• Grassland	Cube Root	
• Pasture	Square Root	
• Cultivated	Cube	
• Total Trees	Cube	

The regression equation:
Width (meters) = - 0.02 - 0.6 Area Under Grassland/Herbaceous (% of total area) - 0.58 Area Under Pasture/Hay (% of total area) + 0.00 Cultivated Area (% of total area)

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	-0.02	0.13	-0.13	0.9	
Area Under Grassland/Herbaceous	-0.6	0.05	-11.7	0.00	3.9
Area Under Pasture/Hay	-0.58	0.18	-3.26	0.002	2.5
Cultivated Area	0.00000001	0.00000000	6.22	0.000	2.3

S: Standard deviation, Press: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

Table 5.29: Multiple linear regression model to
explain increase in bankfull area from Skeleton Creek to Deep Fork Creek

<table>
<tr><td colspan="3">Multiple Linear Regression
(Skeleton & Deep Fork Creeks)</td></tr>
<tr><td>Dependent Variable:</td><td>Transformation Used</td><td rowspan="9">R^2 = 73.1%
R^2 Adjusted = 70.8%
S (meters) = 0.95
PRESS = 42.2</td></tr>
<tr><td>• Bankfull Area</td><td>Natural log</td></tr>
<tr><td>Independent Variables:
• Pervious Area</td><td>Reciprocal Root</td></tr>
<tr><td>• Impervious Area</td><td>Natural Log</td></tr>
<tr><td>• Deciduous Forest</td><td>Natural Log</td></tr>
<tr><td>• Grassland</td><td>Cube Root</td></tr>
<tr><td>• Pasture</td><td>Natural Log</td></tr>
<tr><td>• Cultivated</td><td>Natural log</td></tr>
<tr><td>• Total Trees</td><td>Cube</td></tr>
<tr><td colspan="3">The regression equation:
Bankfull Area (square meters) = - 2.28 + 0.88 Deciduous Forest (% of total area) - 0.54 Area Under Grassland /Herbaceous (% of total area) - 1.16 Area Under Pasture / Hay (% of total area)</td></tr>
</table>

Predictor	**Coef**	**SE Coef**	**T**	**P**	**VIF**
Constant	-2.28	0.5	-4.57	0.00	
Deciduous Forest	0.88	0.18	4.84	0.00	2.2
Grassland/Herbaceous	-0.54	0. 1	-5.71	0.0	1.7
Area Under Pasture/Hay	-1.16	0.25	-4.62	0.00	2.6

S: Standard Deviation, Press: Prediction Sum of Squares, Coef: Coefficient, SE Coef: Standard Error of the Coefficient, T: t-value, P: p-value, VIF: Variation Inflation Factor

5.6 Discussion of Results

This discussion clearly reveals that urbanization provided minimal explanation for any changes in geomorphic variables of the three streams. The three streams represent three distinct stages in time on the sediment curve due to changing land cover (Figs. 1.1 and 1.4) (Chin, 2006; Wolman, 1967). This involves the degree of urbanization ranging from rural stage to ex-urban and completely urban landscape. Such radical increase in imperviousness is followed by substantial increase in runoff and sediment production (Figs. 1.1, 1.3, and 1.4) (Chin, 2006; Chin and Gregory, 2001; Wolman, 1967). In order to accommodate the increased hydrologic regimes, stream channels adjust their morphology and acquire a new equilibrium (Arnold et al., 1982; Booth, 1990; Booth, 1991; Brierley and Fryirs, 2005; Chin, 2006; Hammer, 1971; Hollis, 1976; Wolman, 1967). Also, due to their location in the same geomorphic province, human activities such as urbanization should transform these rivers in similar ways (Marston, 2006). However, the hypotheses testing clearly revealed that very few variables changed among the three streams and also between upstream and downstream sections. Now the question arises: are the three streams really different? According to statistical analysis, field observations, and personal observations, these three streams are more similar than different.

Few statistical differences exist among the three streams and between their upstream and downstream sections. In addition, none of these differences are likely dominated by urbanization. In fact some of these are not due to urbanization at all. Any possible geologic variable is ruled out because the watersheds are situated in the same geomorphic province (Fig. 3.1). A complex mechanism (Walsh et al., 2005) involving different land cover types along with urbanization provided some explanation (with the help of multiple regression) for such differences. However, due to large unexplained variations such a combination did not explain these changes completely. This clearly shows the presence of convergence as a confounding factor (Schumm, 1991). Convergence is one of the fundamental forms of landscape evolution where a variety of initial conditions or starting points can lead to similar end-state (Phillips, 1999). At the same time, the three streams make a unique case where changing imperviousness is not able to make these streams significantly different from each other in most geomorphic variables. However, few changes that exist among the three streams are not explained by statistics and show the presence of singularity as another factor (Schumm, 1991).

Singularity refers to the specific characteristics of a stream that separate it from other similar streams (Schumm, 1991). These characteristics can make it difficult to predict attributes and response of such a stream even though it is classified as a similar type to other streams.

Informal discussion with a resident (Monte Humphrey) of Skeleton Creek Watershed suggests that the stream and the riparian corridor have not changed since 1948. Similar discussion with an older gentleman (Bud Payne), who spent most of his life in Stillwater, revealed that this stream has not changed substantially in the last five decades, despite urban growth.

Therefore the three streams in this geomorphic province present an ideal case of singularity and convergence as confounding factors as argued by Schumm (1991). One other possible reason for the unexplained variance can be the presence of the Central Oklahoma Aquifer under the sandstone bedrock of these entrenched streams (Fig. 5.8). It is possible that there is some complex interactions (Maddock and Vionnet, 2004) between this aquifer and the discharge of water in the three streams (personal communication, Dr. Paxton, School of Geology, Oklahoma State University). Overlaid on the sandstone bedrock with some shale, the three streams respond like flumes for the runoff. This would explain the entrenched response of the three streams.

Therefore, local conditions (Hession et al., 2002; Montgomery, 1997) such as thick riparian buffers, stable channel types, entrenched nature, low gradient, and cohesive silt-clay as bed materials counter urban impact on channel morphology of these three streams. Although Fryirs and Brierley (2000) suggested that there are irreversible alterations due to urbanization, such alterations are not occurring in three streams of this geomorphic province.

Another reason that channels in the Central Redbed Plains geomorphic province do not respond dramatically to urbanization may be related to the channel cross-sectional shape downstream from urban areas. A parabolic cross-sectional shape is common for streams in this region. A parabolic cross-section has been shown to be the equilibrium shape based on threshold theory (Stevens, 1989), models of lateral diffusion (Parker, 1978), minimum stream power (Chang, 1980), and minimum variance (Langbein, 1965). Moreover, streams in this geomorphic region experienced entrenchment during the early 20th century for reasons other than urbanization. At present, the entrenched, parabolic cross-sections, carved into cohesive shales and clay, with the soil-binding effect of streamside vegetation appear to be insensitive to the hydrologic and sediment impacts from urbanization. These results lay foundation for understanding the unique geomorphic behavior of the three streams.

These findings also present a solid base for future research to develop generalizations (Walsh et al., 2005) about geomorphic response of streams to urbanization in the Redbed Plains of Oklahoma.

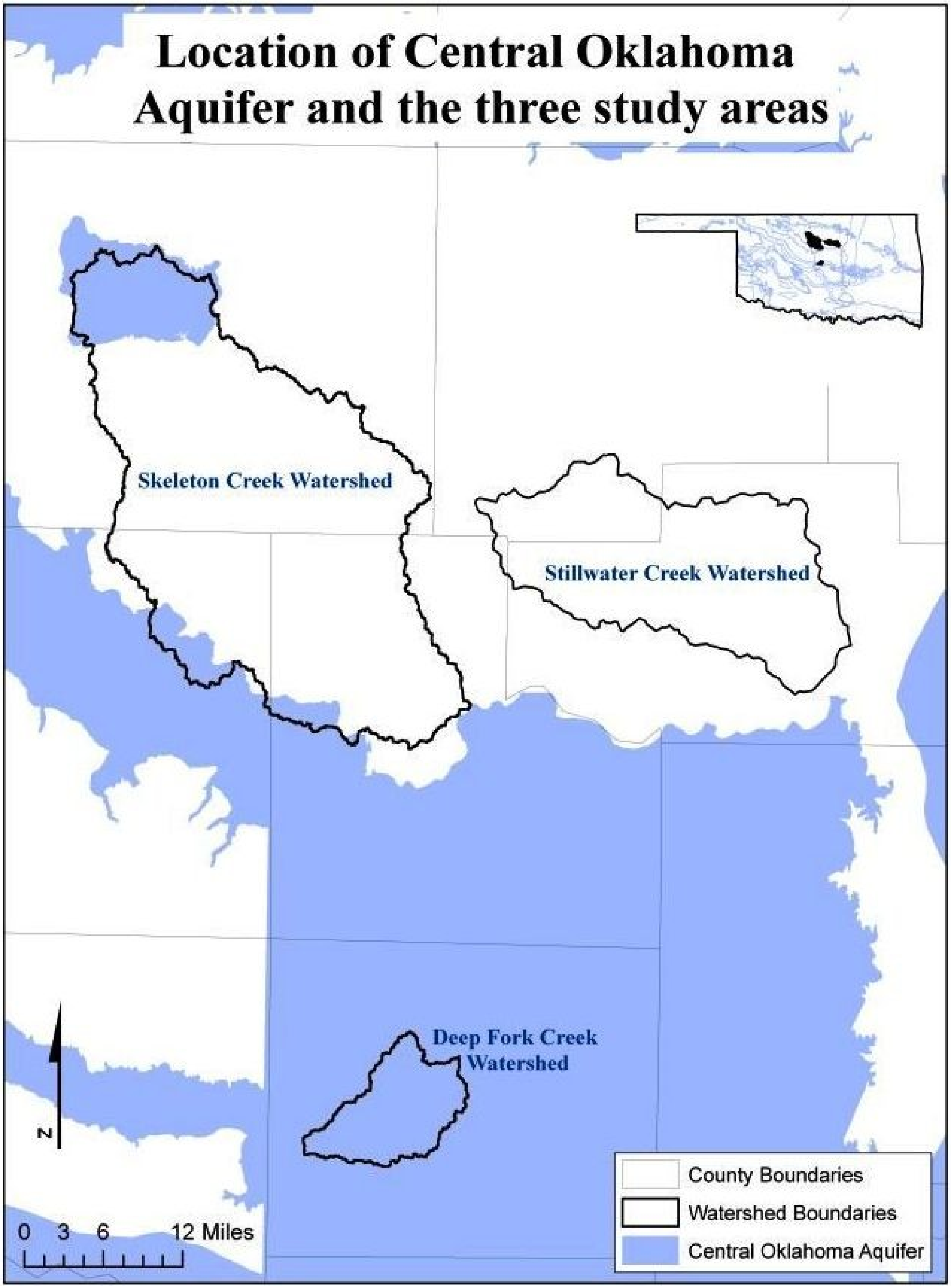

Figure 5.8: Location of the Central Oklahoma Aquifer and the three study areas. Due to non-availability of data, a portion of the left border of this aquifer stops along the county boundary. (produced from unpublished data provided by the Oklahoma Water Resources Board)

CHAPTER-6

SUMMARY AND CONCLUSIONS

6.1 Summary

This project involved a suite of parametric and non-parametric statistical methods to analyze channel morphology and land cover data sets for three watersheds. In the case of parametric methods, data sets were transformed for normality when needed. The comparison of upstream sections of three streams with their respective downstream sections revealed that the channel morphologies of the three streams do not change as one moves downstream for most geomorphic variables. There were few variables that changed, such as mean depth (decreases), width depth ratio (increases), and friction factor (increases) in the case of Stillwater Creek. In the case of Skeleton Creek, there was no statistically significant change as one moved downstream. In the case of Deep Fork Creek, change only occurred in the case of sinuosity (decreases) and width (increases). One can argue that any stream channel would change as one moves downstream due to an increasing drainage area (Downs and Gregory, 2004). Separating such changes from changes that would occur without human interference is critical in understanding the impact of urbanization on channel morphology. This was accomplished by normalizing channel morphology variables at every transect according to the drainage area contributing water to that transect in each stream.

It was expected that changes from upstream to downstream sections of Stillwater and Deep Fork Creeks are due to urbanization. In the case of Stillwater Creek, which is an ex-urban stream, there was a large unexplained variation indicated by a R^2 value of 50.7% for mean depth. However, increase in width depth ratio, as well as friction factor, was explained more by the regression model. One common factor in the case of all three variables that changed from upstream to downstream of Stillwater Creek was that urbanization alone does not explain all of the changes in these variables. These changes may be in part due to the presence of multiple land cover types in the watershed. At the same time, the local conditions (riparian trees, cohesive bed materials, occasional woody debris jams, stable Rosgen channel types, and entrenched nature) in this watershed may counter the possible effects of urbanization on channel morphology. Therefore, local conditions may be playing a decisive role (Hession et al., 2002).

In the case of the urban stream, Deep Fork Creek, a similar pattern was observed where only two variables (sinuosity and width) changed from the upstream to downstream sections. Although the Deep Fork Creek watershed is an urban watershed, urbanization did not explain any changes in these variables. Presence of other land cover types, such as deciduous forest, pasture, and some cultivated land provided possible explanations for decreasing sinuosity and increasing width downstream of Deep Fork Creek. At the same time, this stream lacked any woody debris jams, but the riparian corridor and bed materials along with an entrenched nature were similar to Stillwater Creek. Therefore, the presence of cohesive bed material, thick riparian corridor, entrenched nature, and stable Rosgen channel types are controlling the effects of urbanization on channel morphology of Deep Fork Creek.

Few conclusions were derived from the comparison of the upstream and downstream sections of the three streams. First, most geomorphic variables did not change from the upstream to downstream sections of these streams. Secondly, the few variables that did change were not due to urbanization, and if urbanization explained any change, it provided minimal explanation. Finally, local conditions played a critical role in controlling effects of urbanization on channel morphology (Hession et al., 2002). Such conclusions also raised a question: are these three streams really different from each other?

According to the space-for-time substitution method (Chin, 2006; Chin and Gregory, 2001), the three streams were compared by using the rural stream, Skeleton Creek, as the reference stream (Fryirs and Brierley, 2000). This involved the comparison (Mann-Whitney Non Parametric test) of Skeleton Creek with the ex-urban stream, Stillwater Creek, and the urban stream, Deep Fork Creek, followed by the comparison of Stillwater Creek with Deep Fork Creek as well.

According to this comparison, most geomorphic variables did not change among these three streams. Only a few variables changed, such as sinuosity (decreases) and bankfull area (increases) from Skeleton to Stillwater Creek; width (increases), bankfull area (increases), and width depth ratio (increases) from Stillwater to Deep Fork Creek; and width (increases) and bankfull area (increases) from Skeleton to Deep Fork Creek.

It was anticipated that these changes from a rural to an ex-urban and an urban stream are due to the changing degree of urbanization (Arnold et al., 1982; Arnold and Gibbons, 1996; Bavard and Petts, 1996; Booth, 1990; Fryirs and Brierley, 2000; Graf, 1976; Gregory, 1976; Hammer, 1971; Hammer, 1972; Hollis, 1976; Jeje and Ikeazota, 2002; Johnson, 2001; May et al., 2002; Morisawa and Laflure, 1979; Nanson, 1981; Neller, 1988; Nelson and Booth, 2002; Pizzuto et al., 2000; Trimble, 1997; Walsh et al., 2005; Wolman, 1967). At the same time, other types of current and historical land cover such as agriculture can also play a critical role in such geomorphic patterns (Quinn, 2000; Quinn and Hick, 1990).

The regression model for increasing bankfull area from Skeleton to Stillwater Creek showed a large unexplained variation due to a R^2 value of 54.9 %. However, decrease in sinuosity was explained more by the regression model (R^2 = 95.5 %). In both cases, urbanization alone did not explain all changes in these variables. These changes were due to the presence of multiple land cover types in the two watersheds, such as pervious area, impervious area (urbanization), area under deciduous forest, and area under grassland. Also, the Skeleton Creek watershed has some barren land (though substantially low area), whereas the Stillwater Creek watershed has no barren land. The presence of urban pervious areas such as parks, lawns, and playgrounds, along with occasional woody debris jams in Stillwater Creek provided a possible explanation for changes in channel capacity and sinuosity from Skeleton Creek to Stillwater Creek. However, urbanization was not primarily responsible for these changes. In spite of different degrees of urbanization, these two channels are similar in most respects.

In the case of increasing width from Stillwater to Deep Fork Creek, the regression model provided a strong explanation (R^2 = 85.75 %). However the regression models for increasing bankfull area (R^2 = 42.2 %) and width depth ratio (R^2 = 65.9 %) were relatively less strong due to large unexplained variation. Similar to the changes from Skeleton to Stillwater Creek, urbanization alone did not explain any changes in these variables from Stillwater to Deep Fork Creek. Various land cover types along with urbanization provided a possible explanation for such trends.

In the case of Skeleton and Deep Fork Creeks, the regression model showed that urbanization did not explain any changes from a rural stream (Skeleton Creek) to an urban stream (Deep Fork Creek). Increase in width and bankfull area from Skeleton to Deep Fork Creek was due to other types of land cover. The increase in width was explained (R^2 = 91.1 %) by areas under grassland, pasture, and cultivation. Whereas, the increase in bankfull area was explained (R^2 = 73.1 %) by areas under deciduous forest, grassland, and pasture.

The major difference between these two streams was the degree of urbanization. Skeleton Creek is a rural watershed whereas Deep Fork Creek is an urban watershed. However, in reality, Deep Fork Creek differed from Skeleton Creek only in the case of two variables, and this was not due to urbanization. Therefore, these two streams are more similar than dissimilar and those dissimilarities are not due to urbanization. At the same time, the local conditions (riparian trees, cohesive bed materials, stable Rosgen channel types, and entrenched nature) in these watersheds counter the possible effects of urbanization on channel morphology.

It was also anticipated that increasing urbanization encroaches on riparian areas and reduces the sources of woody debris to stream channels, affecting channel morphology (Booth, 1991). However, this did not happen in the three study areas. All three streams had thick riparian corridors dominated by trees along stream banks (Figs. 4.12, 5.1, and 5.2) which helped protect stream banks (Hession et al., 2002). A parabolic channel cross-sectional shape (equilibrium shape) downstream also helps explain why these stream channels do not change radically due to urbanization (Chang, 1980; Langbein, 1965; Parker, 1978; Stevens, 1989).

Table 6.1: Summary of results

Approach 1: Comparison of Upstream and Downstream Sections of Three Streams										
Stream	Change from upstream to downstream section (at 0.05 level) (Increase: ↑) (Decrease: ↓)	Possible land cover explaining the change								Does urbanization explain this change?
		IMPERVIOUS	PERVIOUS	BARREN	DECIDUOUS FOREST	GRASSLAND	PASTRUE	CULTIVATION	RIPARIAN TREES	
Change from upstream section of Skeleton Creek to downstream section	No Change									
Change from upstream section of Stillwater Creek to downstream section	Mean Depth (↓)	X			X				X	Minimally
	Width Depth Ratio (↑)					X			X	No
	Friction Factor (↑)	X				X			X	Minimally
Change from upstream section of Deep Fork Creek to downstream section	Sinuosity (↓)				X					No
	Width (↑)				X		X	X		No

Table 6.1 (Continued): Summary of results

Approach 2: Comparison of Three Streams										
Stream	Change between streams (at 0.05 level) (Increase: ↑) (Decrease: ↓)	Possible land cover explaining the change								Does urbanization explain this change?
		IMPERVIOUS	PERVIOUS	BARREN	DECIDUOUS FOREST	GRASSLAND	PASTRUE	CULTIVATION	RIPARIAN TREES	
Change from Skeleton Creek to Stillwater Creek	Sinuosity (↓)	X	X		X					Minimally
	Bankfull Area (↑)	X				X				Minimally
Change from Stillwater Creek to Deep Fork Creek	Width (↑)	X	X				X	X	X	Minimally
	Width Depth Ratio (↑)	X					X	X		Minimally
	Bankfull Area (↑)	X	X				X		X	Minimally
Change from Skeleton Creek to Deep Fork Creek	Width (↑)					X	X	X		No
	Bankfull Area (↑)				X	X	X			No

6.2 Conclusions

Lack of understanding of stream response to urbanization in the Central Redbed Plains Geomorphic Province served as the catalyst for this study. The findings of this project helped show the degree to which urbanization explains the expected downstream changes in channel morphology of an ex-urban stream, such as Stillwater Creek. It also explained whether changing degrees of imperviousness in the three watersheds can lead to any significant differences in their channel morphologies. Therefore, this project separated human effects (rural-to-urban land cover change) on the three streams from changes that would have occurred without human interference. This was accomplished by the integration of geomorphology and hydrology methods along with field work in all three streams.

The results of this study clearly indicate that local conditions are playing a decisive role in countering the effects of urbanization (Brierley and Fryirs, 2005; Hession et al., 2002). Riparian vegetation as one of the local conditions played a key role (Allmendinger et al., 2005; Goodwin et al., 1997) in countering the urban effects on channel morphology in this geomorphic province. Similar local conditions for all three study areas demonstrated the significance of geomorphic provinces in controlling the human impact on fluvial environments (Marston, 2006). At the same time, the concepts of singularity and convergence played a confounding role in the three streams (Schumm, 1991).

Contrary to many studies (Arthington, 1985; Charbonneau and Resh, 1992; Edward, 1972; Fusillo et al., 1977; Graf, 1977) urbanization within in the Stillwater Creek watershed is not leading to anticipated dramatic changes in geomorphic systems in this geomorphic province. These findings are consistent with Hession et al. (2002) and Montgomery (1997) who found that local conditions must be considered in any such analysis. Klein (Klein, 1979) addressed construction, the first stage of urbanization, as an environmental insult and argued various measures to limit the adverse effects of urbanization on streams. Such measures also included limiting watershed urbanization rates. However, in this geomorphic province, the decisive role of local conditions in countering such effects of urbanization advocates the place dependency of such measures. This means that such measures must be employed after detailed analysis of geomorphic conditions. This study provides a detailed foundation for deciding the applicability of such measures, setting conservation priorities, developing regional management strategies, and setting watershed objectives in this geomorphic province.

Based on ergodic reasoning (substitution of space-for-time), this research helps us understand how three similar streams in the same geomorphic province can be used to understand the response of a single stream to changing degrees of imperviousness through time. This study also offers the most detailed data set in the south-central United States, as a majority of similar studies have been conducted in the eastern or western United States (Arnold and Gibbons, 1996; Booth, 1990; Booth, 1991; Booth and Jackson, 1997; Chin, 2006; Chin and Gregory, 2001; Hammer, 1972; Morisawa and Laflure, 1979; Trimble, 1997). Intensive field data collected for this study provides information about the geomorphic characteristics of stream channels in this geomorphic province. The observed site specific geomorphic response of stream channels to imperviousness can be used as guidelines in devising river channel management practices in this geomorphic province. The analysis of stream response to urbanization from this research can also be used to test similar hypotheses in other streams in this region.

6.3 Recommendations for future research

The future research should focus on following areas:

(i). Use of computer modeling techniques to test the interaction of aquifer (Barringer et al., 1994) and stream channel morphology in the three watersheds.

(ii). The use of time series for statistical analysis.

(iii). A detailed land cover change in the three watersheds through different periods of time.

(iv). Use of SWAT (Soil and Water Assessment Tool) model to understand sediment budget in the three watersheds under different land management scenarios (Luzio et al., 2002).

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APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Side of Stream	Sinuosity	Relief (Mt)	Gradient
1.00	Right	1.30	7.02	0.12
2.00	Right	1.60	4.08	0.23
3.00	Right	1.29	9.14	0.42
4.00	Left	1.04	2.51	0.37
5.00	Right	1.37	0.91	0.10
6.00	Left	1.26	2.77	0.19
7.00	Left	1.11	2.56	0.83
8.00	Right	1.13	0.13	0.05
9.00	Right	1.49	7.52	0.16
10.00	Right	1.11	0.85	0.28
11.00	Left	1.13	0.16	0.03
12.00	Left	1.67	2.25	0.08
13.00	Left	1.24	2.20	0.19
14.00	Left	1.20	0.81	0.10
15.00	Left	1.23	1.89	0.22
16.00	Right	1.04	0.00	0.00
17.00	Right	1.27	0.00	0.00
18.00	Right	2.10	1.04	0.11
19.00	Right	1.37	0.00	0.00
20.00	Right	1.36	0.00	0.00
21.00	Left	1.57	0.09	0.01
22.00	Right	1.17	3.02	0.90
23.00	Right	1.49	0.00	0.00
24.00	Right	1.51	0.72	0.04
25.00	Right	1.31	0.00	0.00
26.00	Right	1.10	3.21	0.58
27.00	Right	1.26	0.05	0.00
28.00	Left	1.31	0.44	0.04
29.00	Right	1.58	0.00	0.00
30.00	Left	1.14	0.03	0.00

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Rosgen Channel Types	Channel Unit Type	Bankfull Mean Depth (Mt)	Bankfull Width (Mt)
1.00	E6b	Glide	0.64	3.38
2.00	E6b	Glide	0.46	3.66
3.00	E6b	Glide	0.58	5.58
4.00	C2b	Glide	0.55	8.20
5.00	E6b	Riffle	0.67	6.77
6.00	E6b	Glide	0.82	7.99
7.00	C4b	Glide	0.82	11.64
8.00	C1b	Riffle	0.24	11.37
9.00	C1b	Glide	0.30	12.68
10.00	C6b	Riffle	0.49	13.23
11.00	C6b	Riffle	0.98	20.24
12.00	C6b	Riffle	0.98	12.50
13.00	C6b	Glide	0.24	16.82
14.00	E6b	Riffle	0.76	8.60
15.00	C6b	Glide	0.18	10.45
16.00	C6b	Glide	0.18	8.26
17.00	C6b	Riffle	0.27	8.32
18.00	E6b	Pool	1.16	7.74
19.00	E6	Glide	0.82	5.33
20.00	C6c	Pool	0.91	9.81
21.00	C6b	Riffle	0.76	30.57
22.00	C6b	Riffle	0.61	25.73
23.00	C6b	Riffle	0.55	22.43
24.00	C6b	Run	1.16	15.03
25.00	C6b	Run	0.73	13.84
26.00	C6b	Run	0.58	33.28
27.00	C6b	Run	0.70	29.47
28.00	C6b	Riffle	0.61	15.88
29.00	C6b	Run	1.37	27.61
30.00	C6b	Glide	1.74	57.67

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Width Depth Ratio	Entrenchment Ratio	Manning's n	Bankfull Area (Sq Mt)
1.00	5.29	>2.2	0.03	2.18
2.00	8.00	>2.2	0.03	1.73
3.00	9.63	>2.2	0.03	3.22
4.00	14.94	>2.2	0.03	4.60
5.00	10.09	>2.2	0.03	4.48
6.00	9.70	>2.2	0.03	6.45
7.00	14.15	>2.2	0.03	9.42
8.00	46.63	>2.2	0.03	2.80
9.00	41.60	>2.2	0.03	3.72
10.00	27.13	>2.2	0.03	4.34
11.00	20.75	>2.2	0.03	19.65
12.00	12.81	>2.2	0.03	12.15
13.00	69.00	>2.2	0.03	4.09
14.00	11.28	>2.2	0.03	6.44
15.00	57.17	>2.2	0.03	1.90
16.00	45.17	>2.2	0.03	1.60
17.00	30.33	>2.2	0.03	2.29
18.00	6.68	>2.2	0.03	8.95
19.00	6.48	>2.2	0.03	4.41
20.00	10.73	>2.2	0.03	9.11
21.00	40.12	>2.2	0.03	23.36
22.00	42.20	>2.2	0.03	15.71
23.00	40.89	>2.2	0.03	12.27
24.00	12.97	>2.2	0.03	17.21
25.00	18.92	>2.2	0.03	9.98
26.00	57.47	>2.2	0.03	19.34
27.00	42.04	>2.2	0.03	20.72
28.00	26.05	>2.2	0.03	9.76
29.00	20.13	>2.2	0.03	37.72
30.00	33.19	>2.2	0.03	100.27

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Area Above Transect (Sq Kms)	Flood Prone Height (Mt)	Silt/Clay %	Sand %
1.00	14.63	1.65	60.00	0.00
2.00	18.32	1.46	60.00	0.00
3.00	33.18	1.65	90.00	0.00
4.00	43.16	1.71	30.00	0.00
5.00	44.41	2.32	80.00	0.00
6.00	45.63	2.19	80.00	0.00
7.00	45.96	2.01	10.00	20.00
8.00	46.25	0.91	0.00	0.00
9.00	184.87	0.79	0.00	0.00
10.00	198.50	0.98	40.00	30.00
11.00	198.78	2.26	80.00	20.00
12.00	202.28	2.38	60.00	0.00
13.00	203.43	0.73	50.00	0.00
14.00	230.72	2.93	50.00	0.00
15.00	274.42	0.55	50.00	50.00
16.00	321.11	0.67	100.00	0.00
17.00	429.99	1.10	80.00	20.00
18.00	495.59	3.35	100.00	0.00
19.00	593.87	3.17	100.00	0.00
20.00	601.42	2.74	90.00	0.00
21.00	808.87	2.38	100.00	0.00
22.00	815.24	1.83	100.00	0.00
23.00	876.81	1.95	100.00	0.00
24.00	879.05	3.41	100.00	0.00
25.00	881.00	1.95	80.00	0.00
26.00	881.90	2.01	100.00	0.00
27.00	889.83	2.13	50.00	0.00
28.00	1075.82	1.71	35.00	35.00
29.00	1427.07	3.84	90.00	5.00
30.00	1428.45	8.11	90.00	0.00

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Gravel %	Coble %	Bed Rock %	Boulder %
1.00	20.00	0.00	20.00	0.00
2.00	0.00	0.00	40.00	0.00
3.00	10.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	70.00
5.00	0.00	0.00	20.00	0.00
6.00	20.00	0.00	0.00	0.00
7.00	70.00	0.00	0.00	0.00
8.00	10.00	0.00	85.00	0.00
9.00	0.00	0.00	95.00	0.00
10.00	0.00	0.00	30.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	15.00	0.00	25.00	0.00
13.00	0.00	0.00	50.00	0.00
14.00	0.00	0.00	50.00	0.00
15.00	0.00	0.00	0.00	0.00
16.00	0.00	0.00	0.00	0.00
17.00	0.00	0.00	0.00	0.00
18.00	0.00	0.00	0.00	0.00
19.00	0.00	0.00	0.00	0.00
20.00	10.00	0.00	0.00	0.00
21.00	0.00	0.00	0.00	0.00
22.00	0.00	0.00	0.00	0.00
23.00	0.00	0.00	0.00	0.00
24.00	0.00	0.00	0.00	0.00
25.00	20.00	0.00	0.00	0.00
26.00	0.00	0.00	0.00	0.00
27.00	0.00	0.00	50.00	0.00
28.00	15.00	0.00	15.00	0.00
29.00	5.00	0.00	0.00	0.00
30.00	0.00	0.00	10.00	0.00

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Concrete/Riprap/Waste %	Wetted Perimeter (Mt)	Hydraulic Radius (Mt)	Bankfull Shear Stress (Kg/Mt Sq)
1.00	0.00	4.11	0.52	0.63
2.00	0.00	4.11	0.43	0.98
3.00	0.00	5.88	0.55	2.29
4.00	0.00	8.69	0.52	1.95
5.00	0.00	7.25	0.61	0.63
6.00	0.00	8.87	0.73	1.37
7.00	0.00	12.44	0.76	6.30
8.00	0.00	11.89	0.24	0.10
9.00	0.00	12.92	0.27	0.44
10.00	0.00	13.41	0.34	0.93
11.00	0.00	21.37	0.91	0.29
12.00	0.00	13.26	0.91	0.73
13.00	0.00	17.01	0.24	0.44
14.00	0.00	9.20	0.70	0.68
15.00	0.00	10.55	0.18	0.39
16.00	0.00	8.35	0.18	0.00
17.00	0.00	8.53	0.27	0.00
18.00	0.00	8.84	1.01	1.12
19.00	0.00	6.22	0.70	0.00
20.00	0.00	10.58	0.85	0.00
21.00	0.00	30.88	0.76	0.10
22.00	0.00	25.91	0.61	5.47
23.00	0.00	22.77	0.55	0.00
24.00	0.00	15.97	1.07	0.44
25.00	0.00	14.17	0.70	0.00
26.00	0.00	33.38	0.58	3.37
27.00	0.00	29.72	0.70	0.00
28.00	0.00	16.09	0.61	0.24
29.00	0.00	29.05	1.31	0.00
30.00	0.00	58.86	1.71	0.00

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Bankfull Shear Velocity (Mt/sec)	Bankfull Unit Stream Power (Kg/Mt/sec)	Threshold Grain Size (mm)	Friction Factor (u/u*)
1.00	0.08	0.53	8.10	8.70
2.00	0.10	0.88	11.50	8.40
3.00	0.15	3.19	28.60	8.80
4.00	0.14	2.50	24.00	8.70
5.00	0.08	0.46	7.90	8.90
6.00	0.12	1.64	15.50	9.20
7.00	0.25	15.43	118.90	9.20
8.00	0.03	0.03	2.00	7.60
9.00	0.07	0.25	6.20	7.90
10.00	0.09	0.69	10.90	8.00
11.00	0.05	0.14	4.10	9.50
12.00	0.09	0.63	9.10	9.50
13.00	0.07	0.24	6.20	7.60
14.00	0.08	0.56	8.80	9.10
15.00	0.06	0.18	5.50	7.30
16.00	0.00	0.00	0.00	0.00
17.00	0.00	0.00	0.00	0.00
18.00	0.10	1.29	12.90	9.70
19.00	0.00	0.00	0.00	0.00
20.00	0.00	0.00	0.00	0.00
21.00	0.03	0.02	1.40	9.20
22.00	0.23	11.31	90.00	8.90
23.00	0.00	0.00	0.00	0.00
24.00	0.06	0.29	5.90	9.80
25.00	0.00	0.00	0.00	0.00
26.00	1.62	5.40	43.70	8.80
27.00	0.00	0.00	0.00	0.00
28.00	0.05	0.11	3.60	8.90
29.00	0.00	0.00	0.00	0.00
30.00	0.00	0.00	0.00	0.00

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Froude Number	Shrub%	Grass %	Canopy %
1.00		56.67	20.00	50.00
2.00		23.33	53.33	0.00
3.00		6.67	83.33	5.00
4.00		10.00	90.00	0.00
5.00		40.00	60.00	0.00
6.00		10.00	90.00	0.00
7.00		0.00	100.00	0.00
8.00		30.00	70.00	20.00
9.00		3.33	93.33	0.00
10.00		16.67	66.67	0.00
11.00		0.00	96.67	0.00
12.00		0.00	96.67	0.00
13.00		0.00	76.67	0.00
14.00		0.00	70.00	15.00
15.00		3.33	86.67	0.00
16.00		23.33	0.00	100.00
17.00		20.00	60.00	60.00
18.00		3.33	53.33	0.00
19.00		43.33	6.67	0.00
20.00		73.33	0.00	0.00
21.00	0.01	13.33	40.00	100.00
22.00	0.71	20.00	56.67	0.00
23.00	0.00	6.67	53.33	10.00
24.00	0.04	6.67	40.00	50.00
25.00	0.00	10.00	36.67	60.00
26.00	0.45	20.00	36.67	80.00
27.00	0.00	20.00	23.33	30.00
28.00	0.03	0.00	43.33	75.00
29.00	0.00	0.00	91.67	10.00
30.00		0.00	100.00	0.00

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Shade On Stream%	Total Trees in Transect	Number of Trees with Diameter 3-15 cms (Zone 1)	Number of Trees with Diameter 16-30 cms (Zone 1)
1.00	0.00	25.00	7.00	1.00
2.00	0.00	14.00	6.00	3.00
3.00	0.00	4.00	1.00	0.00
4.00	0.00	0.00	0.00	0.00
5.00	0.00	2.00	0.00	2.00
6.00	0.00	1.00	1.00	0.00
7.00	0.00	1.00	0.00	0.00
8.00	0.00	17.00	5.00	0.00
9.00	0.00	4.00	4.00	0.00
10.00	0.00	7.00	1.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00
13.00	0.00	0.00	0.00	0.00
14.00	0.00	1.00	0.00	0.00
15.00	0.00	0.00	0.00	0.00
16.00	0.00	53.00	2.00	0.00
17.00	0.00	4.00	0.00	0.00
18.00	0.00	7.00	6.00	1.00
19.00	0.00	2.00	0.00	0.00
20.00	0.00	0.00	0.00	0.00
21.00	0.00	85.00	5.00	2.00
22.00	0.00	4.00	2.00	0.00
23.00	0.00	12.00	3.00	0.00
24.00	0.00	16.00	0.00	0.00
25.00	0.00	13.00	2.00	1.00
26.00	0.00	17.00	0.00	0.00
27.00	0.00	8.00	0.00	0.00
28.00	0.00	23.00	0.00	0.00
29.00	0.00	9.00	0.00	0.00
30.00	0.00	0.00	0.00	0.00

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Number of Trees with Diameter 31-50 cms (Zone 1)	Number of Trees with Diameter 51-90 cms (Zone 1)	Number of Trees with Diameter 91+ cms (Zone 1)	Total Basal Area of Trees in Zone 1 of Riparian Transect
1.00	0.00	0.00	0.00	3227.00
2.00	0.00	0.00	0.00	1682.91
3.00	0.00	0.00	0.00	63.62
4.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	867.47
6.00	0.00	0.00	0.00	63.62
7.00	0.00	1.00	0.00	3903.63
8.00	0.00	0.00	0.00	318.09
9.00	0.00	0.00	0.00	254.47
10.00	0.00	0.00	0.00	63.62
11.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00
13.00	0.00	0.00	0.00	0.00
14.00	0.00	0.00	0.00	0.00
15.00	0.00	0.00	0.00	0.00
16.00	0.00	0.00	0.00	127.23
17.00	0.00	0.00	0.00	0.00
18.00	0.00	0.00	0.00	815.44
19.00	0.00	0.00	0.00	0.00
20.00	0.00	0.00	0.00	0.00
21.00	1.00	0.00	0.00	2473.81
22.00	0.00	0.00	0.00	127.23
23.00	0.00	0.00	0.00	190.85
24.00	0.00	0.00	0.00	0.00
25.00	0.00	0.00	0.00	2155.72
26.00	0.00	0.00	0.00	0.00
27.00	0.00	0.00	0.00	127.23
28.00	0.00	0.00	0.00	0.00
29.00	0.00	0.00	0.00	0.00
30.00	0.00	0.00	0.00	1288.25

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Number of Trees with Diameter 3-15 cms (Zone 2)	Number of Trees with Diameter 16-30 cms (Zone 2)	Number of Trees with Diameter 31-50 cms (Zone 2)	Number of Trees with Diameter 51-90 cms (Zone 2)
1.00	3.00	0.00	1.00	0.00
2.00	5.00	0.00	0.00	0.00
3.00	2.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00
8.00	7.00	0.00	0.00	0.00
9.00	0.00	0.00	0.00	0.00
10.00	6.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00
13.00	0.00	0.00	0.00	0.00
14.00	0.00	0.00	0.00	0.00
15.00	0.00	0.00	0.00	0.00
16.00	20.00	5.00	1.00	0.00
17.00	0.00	0.00	0.00	0.00
18.00	0.00	0.00	0.00	0.00
19.00	2.00	0.00	0.00	0.00
20.00	0.00	0.00	0.00	0.00
21.00	25.00	3.00	0.00	0.00
22.00	0.00	0.00	2.00	0.00
23.00	1.00	5.00	3.00	0.00
24.00	4.00	3.00	0.00	1.00
25.00	0.00	4.00	1.00	0.00
26.00	6.00	4.00	1.00	0.00
27.00	2.00	0.00	0.00	0.00
28.00	5.00	2.00	4.00	1.00
29.00	4.00	3.00	1.00	0.00
30.00	0.00	0.00	0.00	0.00

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Number of Trees with Diameter 91+ cms (Zone 2)	Number of Trees with Diameter 3-15 cms (Zone 3)	Number of Trees with Diameter 16-30 cms (Zone 3)	Number of Trees with Diameter 31-50 cms (Zone 3)
1.00	0.00	4.00	4.00	5.00
2.00	0.00	0.00	0.00	0.00
3.00	0.00	1.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00
8.00	0.00	5.00	0.00	0.00
9.00	0.00	0.00	0.00	0.00
10.00	0.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00
13.00	0.00	0.00	0.00	0.00
14.00	0.00	0.00	1.00	0.00
15.00	0.00	0.00	0.00	0.00
16.00	0.00	20.00	3.00	1.00
17.00	0.00	0.00	4.00	0.00
18.00	0.00	0.00	0.00	0.00
19.00	0.00	0.00	0.00	0.00
20.00	0.00	0.00	0.00	0.00
21.00	0.00	40.00	9.00	0.00
22.00	0.00	0.00	0.00	0.00
23.00	0.00	0.00	0.00	0.00
24.00	0.00	8.00	0.00	0.00
25.00	0.00	3.00	2.00	0.00
26.00	0.00	1.00	2.00	3.00
27.00	0.00	5.00	0.00	0.00
28.00	0.00	11.00	0.00	0.00
29.00	0.00	1.00	0.00	0.00
30.00	0.00	0.00	0.00	0.00

APPENDIX – 1 (Channel Morphology Data for Skeleton Creek)

Reach Number	Number of Trees with Diameter 51-90 cms (Zone 3)	Number of Trees with Diameter 91+ cms (Zone 3)
1.00	0.00	0.00
2.00	0.00	0.00
3.00	0.00	0.00
4.00	0.00	0.00
5.00	0.00	0.00
6.00	0.00	0.00
7.00	0.00	0.00
8.00	0.00	0.00
9.00	0.00	0.00
10.00	0.00	0.00
11.00	0.00	0.00
12.00	0.00	0.00
13.00	0.00	0.00
14.00	0.00	0.00
15.00	0.00	0.00
16.00	1.00	0.00
17.00	0.00	0.00
18.00	0.00	0.00
19.00	0.00	0.00
20.00	0.00	0.00
21.00	0.00	0.00
22.00	0.00	0.00
23.00	0.00	0.00
24.00	0.00	0.00
25.00	0.00	0.00
26.00	0.00	0.00
27.00	0.00	1.00
28.00	0.00	0.00
29.00	0.00	0.00
30.00	0.00	0.00

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Side of Stream	Sinuosity	Relief (Mt)	Gradient
1.00	Left	1.32	1.22	0.08
2.00	Left	1.19	1.22	0.10
3.00	Right	1.61	1.22	0.08
4.00	Right	1.14	0.30	0.07
5.00	Left	1.54	0.30	0.03
6.00	Left	1.34	0.30	0.05
7.00	Right	1.07	0.00	0.01
8.00	Left	1.21	0.61	0.04
9.00	Right	1.28	0.91	0.06
10.00	Left	1.92	0.91	0.05
11.00	Right	1.30	0.61	0.07
12.00	Right	1.12	0.30	0.14
13.00	Right	1.04	0.30	0.09
14.00	Left	1.49	0.61	0.07
15.00	Left	1.03	0.00	0.01
16.00	Right	1.07	0.91	0.10
17.00	Right	1.25	0.61	0.06
18.00	Left	1.58	0.61	0.07
19.00	Right	1.18	0.30	0.12
20.00	Right	1.49	0.61	0.04
21.00	Left	1.16	1.22	0.06
22.00	Left	1.21	0.30	0.06
23.00	Left	1.42	0.61	0.04
24.00	Right	1.02	0.00	0.01
25.00	Left	1.43	0.00	0.01
26.00	Right	1.20	0.30	0.05
27.00	Right	1.04	0.30	0.04
28.00	Right	1.02	0.00	0.01
29.00	Left	1.16	0.30	0.02
30.00	Left	1.05	0.30	0.05

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Rosgen Channel Types	Channel Unit Type	Bankfull Mean Depth (Mt)	Bankfull Max. Depth (Mt)
1.00	C6b	Glide	1.10	2.16
2.00	E6b	Glide	1.40	2.35
3.00	E6b	Glide	2.07	2.90
4.00	E6b	Glide	27.58	30.18
5.00	E6b	Glide	4.21	6.07
6.00	E6b	Glide	2.23	4.18
7.00	E6b	Glide	2.83	4.24
8.00	E6b	Glide	2.44	3.66
9.00	E6b	Glide	30.91	35.27
10.00	E6b	Riffle	2.41	3.63
11.00	E6b	Glide	26.09	30.48
12.00	E6b	Glide	1.74	2.56
13.00	E6b	Glide	8.53	9.39
14.00	E6b	Riffle	3.32	4.85
15.00	E6b	Glide	3.51	5.30
16.00	E6b	Glide	27.28	31.15
17.00	E6b	Glide	23.84	30.48
18.00	E6b	Glide	2.01	4.30
19.00	E6b	Run	3.14	4.75
20.00	E6b	Glide	7.19	9.42
21.00	E6b	Glide	4.97	7.50
22.00	E6b	Glide	32.49	39.01
23.00	E6b	Glide	3.26	5.79
24.00	E6b	Run	6.58	3.93
25.00	E6b	Glide	2.93	3.63
26.00	E6b	Riffle	11.13	14.33
27.00	E6b	Glide	10.21	12.19
28.00	E6b	Glide	10.27	12.59
29.00	E6b	Glide	13.14	15.61
30.00	E6b	Glide	10.98	13.69

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Bankfull Width (Mt)	Width Depth Ratio	Entrenchment Ratio	Manning's n
1.00	29.57	26.94	>2.2	0.03
2.00	11.16	7.96	>2.2	0.03
3.00	12.16	5.87	>2.2	0.03
4.00	65.35	2.37	>2.2	0.03
5.00	17.34	4.12	>2.2	0.03
6.00	21.49	9.66	>2.2	0.03
7.00	18.81	6.63	>2.2	0.03
8.00	12.19	5.00	>2.2	0.03
9.00	64.83	2.10	>2.2	0.03
10.00	15.79	6.56	>2.2	0.03
11.00	63.98	2.45	>2.2	0.03
12.00	17.16	9.88	>2.2	0.03
13.00	20.21	2.37	>2.2	0.03
14.00	8.26	2.49	>2.2	0.03
15.00	19.90	5.68	>2.2	0.03
16.00	64.98	2.38	>2.2	0.03
17.00	63.79	2.68	>2.2	0.03
18.00	17.98	8.94	>2.2	0.03
19.00	13.78	4.39	>2.2	0.03
20.00	47.12	6.55	>2.2	0.03
21.00	31.39	6.32	>2.2	0.03
22.00	63.70	1.96	>2.2	0.03
23.00	22.43	6.88	>2.2	0.03
24.00	18.20	2.76	>2.2	0.03
25.00	8.23	2.81	>2.2	0.03
26.00	32.98	2.96	>2.2	0.03
27.00	31.00	3.04	>2.2	0.03
28.00	32.98	3.21	>2.2	0.03
29.00	44.78	3.41	>2.2	0.03
30.00	34.17	3.11	>2.2	0.03

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Bankfull Area (Sq Mt)	Area Above Transect (Sq Km)	Flood Prone Height (Mt)	Silt +Clay %
1.00	32.87	197.33	4.33	100.00
2.00	15.60	201.16	4.69	100.00
3.00	25.33	221.79	5.79	100.00
4.00	1802.01	325.43	60.35	100.00
5.00	72.87	330.51	12.13	100.00
6.00	48.01	332.12	8.35	100.00
7.00	53.04	335.05	8.47	100.00
8.00	29.75	337.38	7.32	100.00
9.00	2003.24	338.30	70.53	100.00
10.00	37.81	340.81	7.25	100.00
11.00	1670.22	375.13	60.96	100.00
12.00	29.96	392.14	5.12	100.00
13.00	172.75	399.74	18.78	100.00
14.00	27.52	417.98	9.69	95.00
15.00	69.80	420.85	10.61	100.00
16.00	1772.64	423.03	62.30	100.00
17.00	1519.40	424.65	60.96	100.00
18.00	36.32	473.63	8.60	100.00
19.00	43.08	475.49	9.51	100.00
20.00	338.70	563.27	18.84	100.00
21.00	156.43	570.57	15.00	100.00
22.00	2070.42	577.12	78.03	100.00
23.00	72.98	586.34	11.58	100.00
24.00	119.58	590.99	7.86	100.00
25.00	24.06	637.11	7.25	100.00
26.00	366.69	637.14	28.65	100.00
27.00	315.99	705.98	24.38	100.00
28.00	338.39	706.54	25.18	100.00
29.00	587.92	732.75	31.21	100.00
30.00	378.96	733.09	27.37	100.00

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Sand %	Gravel %	Coble %	Bed Rock %
1.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00
8.00	0.00	0.00	0.00	0.00
9.00	0.00	0.00	0.00	0.00
10.00	0.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00
13.00	0.00	0.00	0.00	0.00
14.00	5.00	0.00	0.00	0.00
15.00	0.00	0.00	0.00	0.00
16.00	0.00	0.00	0.00	0.00
17.00	0.00	0.00	0.00	0.00
18.00	0.00	0.00	0.00	0.00
19.00	0.00	0.00	0.00	0.00
20.00	0.00	0.00	0.00	0.00
21.00	0.00	0.00	0.00	0.00
22.00	0.00	0.00	0.00	0.00
23.00	0.00	0.00	0.00	0.00
24.00	0.00	0.00	0.00	0.00
25.00	0.00	0.00	0.00	0.00
26.00	0.00	0.00	0.00	0.00
27.00	0.00	0.00	0.00	0.00
28.00	0.00	0.00	0.00	0.00
29.00	0.00	0.00	0.00	0.00
30.00	0.00	0.00	0.00	0.00

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Boulder %	Concrete/Riprap/Waste %	Wetted Perimeter (Mt)	Hydraulic Radius (Mt)
1.00	0.00	0.00	30.14	1.10
2.00	0.00	0.00	12.44	1.25
3.00	0.00	0.00	14.36	1.77
4.00	0.00	0.00	68.46	26.33
5.00	0.00	0.00	20.36	3.57
6.00	0.00	0.00	23.38	2.04
7.00	0.00	0.00	20.73	2.56
8.00	0.00	0.00	14.75	2.01
9.00	0.00	0.00	72.57	27.61
10.00	0.00	0.00	18.38	2.04
11.00	0.00	0.00	69.68	23.99
12.00	0.00	0.00	19.05	1.58
13.00	0.00	0.00	21.09	8.20
14.00	0.00	0.00	13.87	1.98
15.00	0.00	0.00	23.62	2.96
16.00	0.00	0.00	71.75	24.72
17.00	0.00	0.00	76.54	19.84
18.00	0.00	0.00	21.06	1.74
19.00	0.00	0.00	18.71	2.32
20.00	0.00	0.00	48.89	6.92
21.00	0.00	0.00	36.12	4.33
22.00	0.00	0.00	102.41	20.21
23.00	0.00	0.00	28.68	2.53
24.00	0.00	0.00	20.63	5.79
25.00	0.00	0.00	9.94	2.41
26.00	0.00	0.00	40.05	9.14
27.00	0.00	0.00	37.55	8.41
28.00	0.00	0.00	37.73	8.96
29.00	0.00	0.00	47.34	12.41
30.00	0.00	0.00	43.89	8.63

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Bankfull Shear Stress (Kg/MtSq)	Bankfull Shear Velocity (Mt/sec)	Threshold Grain Size (mm)	Friction Factor (u/u*)
1.00	0.88	0.09	10.50	9.50
2.00	1.27	0.11	14.30	10.00
3.00	1.42	0.12	15.70	10.60
4.00	18.41	0.42		16.60
5.00	1.07	0.10	12.50	12.00
6.00	1.03	0.10	12.10	10.90
7.00	0.00	0.00		0.00
8.00	0.83	0.09	9.90	10.90
9.00	16.55	0.40		16.80
10.00	1.22	0.11	14.10	10.90
11.00	16.80	0.41		16.40
12.00	0.24	0.05	3.40	10.40
13.00	7.37	0.27		13.70
14.00	1.37	0.12	15.50	10.80
15.00	0.00	0.00		0.00
16.00	24.70	0.49		16.50
17.00	11.91	0.34		15.90
18.00	1.22	0.11	13.80	10.60
19.00	2.78	0.16	35.20	11.10
20.00	2.78	0.16	35.30	13.30
21.00	2.59	0.16	32.80	12.30
22.00	12.11	0.34		15.90
23.00	1.03	0.10	12.00	11.30
24.00	0.00	0.00		0.00
25.00	0.00	0.00		0.00
26.00	4.59	0.21	63.90	14.00
27.00	3.37	0.18	43.80	13.80
28.00	91.45	0.95		13.90
29.00	2.49	0.16	31.20	14.30
30.00	4.30	0.21	57.00	14.30

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Froude Number	Shrub %	Grass %	Canopy %
1.00		0.00	30.00	23.33
2.00		6.67	56.67	26.33
3.00		16.67	16.33	30.00
4.00		0.00	53.33	53.33
5.00		3.33	60.00	33.33
6.00		16.67	73.33	46.67
7.00		0.00	96.67	40.00
8.00		5.00	25.00	60.00
9.00		33.33	26.67	53.33
10.00	0.06	1.67	98.33	36.67
11.00		0.00	0.00	0.00
12.00		26.67	36.67	90.00
13.00		15.33	28.00	60.00
14.00	0.05	16.67	56.67	26.67
15.00		38.33	45.00	66.67
16.00		13.33	53.33	40.00
17.00		0.00	80.00	40.00
18.00		10.00	43.33	70.00
19.00	0.11	3.33	90.00	60.00
20.00		20.00	60.00	53.33
21.00		26.67	36.67	73.33
22.00		26.67	56.67	26.67
23.00		0.00	90.00	93.33
24.00	0.00	3.33	90.00	30.00
25.00		0.00	93.33	63.33
26.00	0.08	13.33	56.67	33.33
27.00		0.00	13.33	0.00
28.00		3.33	56.67	6.67
29.00		41.67	83.33	26.67
30.00		16.67	56.67	46.67

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Shade On Stream%	Total # Trees in Transect	Number of Trees with Diameter 3-15 cms (Zone 1)	Number of Trees with Diameter 16-30 cms (Zone 1)
1.00	40.00	24.00	19.00	2.00
2.00	60.00	32.00	8.00	3.00
3.00	100.00	10.00	10.00	0.00
4.00		7.00	4.00	0.00
5.00	90.00	13.00	3.00	0.00
6.00	60.00	19.00	15.00	0.00
7.00	70.00	23.00	12.00	1.00
8.00	60.00	34.00	11.00	2.00
9.00		3.00	0.00	1.00
10.00	90.00	12.00	3.00	3.00
11.00		0.00	0.00	0.00
12.00	70.00	40.00	15.00	2.00
13.00		21.00	1.00	2.00
14.00	30.00	13.00	0.00	0.00
15.00	40.00	35.00	14.00	1.00
16.00		3.00	1.00	0.00
17.00		11.00	0.00	1.00
18.00	50.00	13.00	1.00	0.00
19.00	60.00	9.00	0.00	0.00
20.00		3.00	0.00	0.00
21.00	0.00	8.00	0.00	0.00
22.00	60.00	6.00	1.00	1.00
23.00	0.00	15.00	3.00	0.00
24.00	0.00	6.00	0.00	0.00
25.00	50.00	9.00	1.00	0.00
26.00	30.00	3.00	0.00	1.00
27.00	20.00	2.00	0.00	1.00
28.00	0.00	2.00	0.00	1.00
29.00	0.00	6.00	0.00	0.00
30.00	0.00	20.00	5.00	4.00

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Number of Trees with Diameter 31-50 cms (Zone 1)	Number of Trees with Diameter 51-90 cms (Zone 1)	Number of Trees with Diameter 91+ cms (Zone 1)	Total Basal Area of Trees in Zone 1 of Riparian Zone
1.00	3.00	0.00	0.00	0.00
2.00	0.00	1.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00
8.00	0.00	0.00	0.00	0.00
9.00	0.00	0.00	0.00	0.00
10.00	2.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00
13.00	0.00	0.00	0.00	0.00
14.00	0.00	0.00	0.00	0.00
15.00	0.00	0.00	0.00	0.00
16.00	0.00	0.00	0.00	0.00
17.00	1.00	1.00	0.00	0.00
18.00	0.00	2.00	0.00	1288.25
19.00	0.00	0.00	0.00	0.00
20.00	0.00	0.00	0.00	0.00
21.00	0.00	0.00	0.00	0.00
22.00	1.00	0.00	0.00	1785.60
23.00	0.00	0.00	0.00	190.85
24.00	0.00	0.00	0.00	0.00
25.00	0.00	0.00	0.00	0.00
26.00	0.00	0.00	0.00	0.00
27.00	0.00	0.00	0.00	63.62
28.00	0.00	1.00	0.00	433.74
29.00	0.00	0.00	0.00	0.00
30.00	0.00	0.00	0.00	2053.03

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Number of Trees with Diameter 3-15 cms (Zone 2)	Number of Trees with Diameter 16-30 cms (Zone 2)	Number of Trees with Diameter 31-50 cms (Zone 2)	Number of Trees with Diameter 51-90 cms (Zone 2)
1.00	0.00	0.00	0.00	0.00
2.00	13.00	2.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00
5.00	7.00	3.00	0.00	0.00
6.00	4.00	0.00	0.00	0.00
7.00	10.00	0.00	0.00	0.00
8.00	7.00	2.00	0.00	0.00
9.00	1.00	0.00	0.00	0.00
10.00	2.00	2.00	0.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	6.00	1.00	0.00	1.00
13.00	12.00	2.00	4.00	0.00
14.00	5.00	1.00	0.00	0.00
15.00	13.00	1.00	0.00	0.00
16.00	0.00	0.00	0.00	0.00
17.00	0.00	4.00	1.00	1.00
18.00	3.00	1.00	1.00	0.00
19.00	4.00	4.00	1.00	0.00
20.00	0.00	0.00	1.00	0.00
21.00	4.00	0.00	0.00	1.00
22.00	0.00	0.00	0.00	0.00
23.00	4.00	0.00	0.00	0.00
24.00	2.00	2.00	2.00	0.00
25.00	2.00	2.00	1.00	0.00
26.00	2.00	0.00	0.00	0.00
27.00	0.00	0.00	0.00	0.00
28.00	0.00	0.00	0.00	0.00
29.00	0.00	0.00	0.00	0.00
30.00	6.00	5.00	0.00	0.00

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Number of Trees with Diameter 91+ cms (Zone 2)	Number of Trees with Diameter 3-15 cms (Zone 3)	Number of Trees with Diameter 16-30 cms (Zone 3)	Number of Trees with Diameter 31-50 cms (Zone 3)
1.00	0.00	0.00	0.00	0.00
2.00	0.00	5.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00
4.00	0.00	3.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00
8.00	0.00	10.00	2.00	0.00
9.00	0.00	1.00	0.00	0.00
10.00	0.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	0.00	14.00	0.00	1.00
13.00	0.00	0.00	0.00	0.00
14.00	0.00	5.00	1.00	0.00
15.00	0.00	4.00	2.00	0.00
16.00	0.00	2.00	0.00	0.00
17.00	0.00	1.00	1.00	0.00
18.00	0.00	0.00	4.00	0.00
19.00	0.00	0.00	0.00	0.00
20.00	0.00	0.00	1.00	1.00
21.00	0.00	2.00	1.00	0.00
22.00	0.00	3.00	0.00	0.00
23.00	0.00	8.00	0.00	0.00
24.00	0.00	0.00	0.00	0.00
25.00	0.00	1.00	2.00	0.00
26.00	0.00	0.00	0.00	0.00
27.00	0.00	0.00	0.00	0.00
28.00	0.00	0.00	0.00	0.00
29.00	0.00	5.00	1.00	0.00
30.00	0.00	0.00	0.00	0.00

APPENDIX – 2 (Channel Morphology Data for Stillwater Creek)

Reach Number	Number of Trees with Diameter 51-90 cms (Zone 3)	Number of Trees with Diameter 91+ cms (Zone 3)
1.00	0.00	0.00
2.00	0.00	0.00
3.00	0.00	0.00
4.00	0.00	0.00
5.00	0.00	0.00
6.00	0.00	0.00
7.00	0.00	0.00
8.00	0.00	0.00
9.00	0.00	0.00
10.00	0.00	0.00
11.00	0.00	0.00
12.00	0.00	0.00
13.00	0.00	0.00
14.00	0.00	1.00
15.00	0.00	0.00
16.00	0.00	0.00
17.00	0.00	0.00
18.00	0.00	1.00
19.00	0.00	0.00
20.00	0.00	0.00
21.00	0.00	0.00
22.00	0.00	0.00
23.00	0.00	0.00
24.00	0.00	0.00
25.00	0.00	0.00
26.00	0.00	0.00
27.00	0.00	1.00
28.00	0.00	0.00
29.00	0.00	0.00
30.00	0.00	0.00

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Side of Stream	Sinuosity	Relief (Mt)	Gradient
1.00	Left	1.03	0.00	0.00
2.00	Left	1.06	3.88	1.82
3.00	Left	1.16	3.42	0.75
4.00	Right	1.30	0.00	0.00
5.00	Left	1.23	1.50	0.33
6.00	Left	1.06	0.81	0.15
7.00	Left	1.11	4.81	1.37
8.00	Left	1.07	0.00	0.00
9.00	Left	1.16	2.78	0.46
10.00	Left	1.04	0.42	0.07
11.00	Left	1.06	0.00	0.00
12.00	Right	1.05	2.43	0.57
13.00	Right	1.09	0.64	0.15
14.00	Right	1.38	0.04	0.01
15.00	Left	1.04	0.00	0.00
16.00	Left	1.21	0.00	0.00
17.00	Right	1.26	1.52	0.45
18.00	Left	1.11	0.00	0.00
19.00	Right	1.91	0.08	0.01

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Rosgen Channel Types	Channel Unit Type	Bankfull Mean Depth (Mt)	Bankfull Width (Mt)
1.00	E6	Pool	5.27	37.19
2.00	E6b	Pool	4.79	36.00
3.00	E6b	Pool	3.17	28.10
4.00	E6	Glide	6.37	37.31
5.00	E6b	Glide	3.44	23.90
6.00	E6b	Glide	4.57	29.11
7.00	E6b	Glide	5.91	26.37
8.00	E6	Glide	5.67	45.66
9.00	E6b	Glide	4.63	26.64
10.00	E6b	Riffle	6.07	45.20
11.00	E6	Pool	6.74	48.59
12.00	E6b	Glide	3.99	30.24
13.00	C2b	Riffle	1.22	27.01
14.00	E6	Glide	4.57	21.31
15.00	E6	Glide	1.86	11.80
16.00	E6	Glide	1.65	14.42
17.00	C1b	Pool	0.82	10.97
18.00	C2c	Glide	0.52	10.15
19.00	E6b	Run	0.82	6.07

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Width Depth Ratio	Entrenchment Ratio	Manning's n	Bankfull Area (Sq Mt)
1.00	7.05	>2.2	0.03	19.57
2.00	7.52	>2.2	0.03	171.81
3.00	8.87	>2.2	0.03	88.75
4.00	5.86	>2.2	0.03	238.08
5.00	6.94	>2.2	0.03	82.54
6.00	6.37	>2.2	0.03	133.08
7.00	4.46	>2.2	0.03	156.23
8.00	8.05	>2.2	0.03	259.25
9.00	5.75	>2.2	0.03	123.80
10.00	7.45	>2.2	0.03	274.18
11.00	7.21	>2.2	0.03	328.07
12.00	7.57	>2.2	0.03	121.16
13.00	22.15	>2.2	0.03	32.82
14.00	4.66	>2.2	0.03	97.29
15.00	6.34	>2.2	0.03	22.08
16.00	8.76	>2.2	0.03	23.63
17.00	13.33	>2.2	0.03	9.05
18.00	19.59	>2.2	0.03	5.35
19.00	7.37	>2.2	0.03	5.04

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Area Above Transect (Sq Km)	Flood Prone Height (Mt)	Silt +Clay %	Sand %
1.00	36.58	14.45	50.00	50.00
2.00	36.60	13.17	30.00	70.00
3.00	43.27	7.62	100.00	0.00
4.00	55.61	19.08	50.00	50.00
5.00	55.89	10.79	30.00	40.00
6.00	56.43	16.40	50.00	50.00
7.00	56.60	17.98	20.00	50.00
8.00	56.64	16.82	20.00	50.00
9.00	64.10	12.74	60.00	40.00
10.00	82.56	19.02	10.00	80.00
11.00	88.39	23.77	30.00	10.00
12.00	111.57	11.95	0.00	0.00
13.00	111.77	3.96	10.00	10.00
14.00	119.35	12.98	0.00	0.00
15.00	120.61	4.57	90.00	0.00
16.00	120.76	3.90	90.00	0.00
17.00	121.42	2.38	0.00	0.00
18.00	161.46	1.46	0.00	0.00
19.00	171.53	2.32	0.00	0.00

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Gravel %	Coble %	Bed Rock %	Boulder %
1.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00
5.00	20.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00
8.00	0.00	0.00	0.00	0.00
9.00	0.00	0.00	0.00	0.00
10.00	10.00	0.00	0.00	0.00
11.00	0.00	0.00	10.00	10.00
12.00	25.00	5.00	70.00	0.00
13.00	10.00	0.00	0.00	70.00
14.00	20.00	0.00	0.00	80.00
15.00	0.00	0.00	10.00	0.00
16.00	0.00	0.00	10.00	0.00
17.00	0.00	0.00	60.00	0.00
18.00	0.00	0.00	0.00	100.00
19.00	0.00	50.00	0.00	0.00

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Concrete/Riprap/Waste %	Wetted Perimeter (Mt)	Hydraulic Radius (Mt)	Bankfull Shear Stress (Kg/MtSq)
1.00	0.00	41.00	4.79	0.00
2.00	0.00	39.14	4.39	79.88
3.00	0.00	30.30	2.93	21.97
4.00	0.00	43.37	5.49	0.00
5.00	0.00	28.10	2.93	9.67
6.00	0.00	35.57	3.75	5.61
7.00	30.00	34.78	4.48	61.52
8.00	0.00	51.11	5.06	0.00
9.00	0.00	31.85	3.90	17.87
10.00	0.00	50.54	5.43	3.81
11.00	0.00	57.82	5.67	0.00
12.00	0.00	33.22	3.66	20.80
13.00	0.00	27.98	1.16	1.76
14.00	0.00	26.73	3.63	0.34
15.00	0.00	14.30	1.55	0.00
16.00	0.00	16.76	1.40	0.00
17.00	40.00	11.43	0.79	0.00
18.00	0.00	10.58	0.52	0.00
19.00	50.00	6.77	0.76	0.00

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Bankfull Shear Velocity (Mt/sec)	Bankfull Unit Stream Power (Kg/Mt/sec)	Threshold Grain rain Size (mm)	Friction Factor (u/u*)
1.00	0.00	0.00	0.00	0.00
2.00	0.88	950.26		12.40
3.00	0.46	127.01		11.60
4.00	0.00	0.00		0.00
5.00	0.31	40.61		11.60
6.00	0.23	19.36	95.10	12.00
7.00	0.78	782.24		12.40
8.00	0.00	0.00		0.00
9.00	0.42	108.44		12.10
10.00	0.19	10.49	50.10	12.80
11.00	0.00	0.00		0.00
12.00	0.45	123.54		12.00
13.00	0.13	2.38	21.30	9.90
14.00	0.06	0.33	5.10	12.00
15.00	0.00	0.00		0.00
16.00	0.00	0.00		0.00
17.00	0.00	0.00		0.00
18.00	0.00	0.00		0.00
19.00	0.00	0.00		0.00

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Froude Number	Shrub%	Grass %	Canopy %
1.00		20.00	80.00	50.00
2.00		30.00	36.67	53.33
3.00		23.33	76.67	0.00
4.00		53.33	46.67	50.00
5.00		13.33	70.00	26.67
6.00		43.33	50.00	5.00
7.00		33.33	63.33	6.67
8.00		33.33	63.33	6.67
9.00		30.00	43.33	66.67
10.00	0.10	0.00	66.67	0.00
11.00		10.00	76.67	23.33
12.00		26.67	23.33	83.33
13.00	0.14	8.33	40.00	13.33
14.00		3.33	73.33	56.67
15.00		6.67	70.00	3.33
16.00		3.33	0.00	66.67
17.00		13.33	43.33	13.33
18.00		3.33	60.00	0.00
19.00	0.00	30.00	33.33	60.00

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Shade On Stream%	Number of Trees with Diameter 3-15 cms (Zone 1)	Number of Trees with Diameter 16-30 cms (Zone 1)	Number of Trees with Diameter 31-50 cms (Zone 1)
1.00	0.00	6.00	0.00	1.00
2.00	0.00	1.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00
4.00	90.00	4.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00
8.00	0.00	11.00	0.00	0.00
9.00	0.00	6.00	0.00	0.00
10.00	0.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00
13.00	50.00	2.00	0.00	0.00
14.00	5.00	6.00	0.00	0.00
15.00	0.00	1.00	0.00	0.00
16.00	0.00		1.00	0.00
17.00	20.00	5.00	0.00	0.00
18.00	0.00	0.00	0.00	0.00
19.00	40.00		4.00	0.00

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Number of Trees with Diameter 51-90 cms (Zone 1)	Number of Trees with Diameter 91+ cms (Zone 1)	Total Basal Area of Trees in Zone 1 of Riparian Zone	Number of Trees with Diameter 3-15 cms (Zone 2)
1.00	0.00	0.00	1672.53	0.00
2.00	0.00	0.00	65.42	0.00
3.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	256.87	0.00
5.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00
8.00	0.00	0.00	702.63	0.00
9.00	0.00	0.00	384.29	0.00
10.00	0.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00
13.00	0.00	0.00	129.34	0.00
14.00	0.00	0.00	384.29	0.00
15.00	0.00	0.00	65.42	0.00
16.00	0.00	0.00	0.00	0.00
17.00	0.00	0.00	320.59	0.00
18.00	0.00	0.00	0.00	0.00
19.00	0.00	0.00	0.00	0.00

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Number of Trees with Diameter 16-30 cms (Zone 2)	Number of Trees with Diameter 31-50 cms (Zone 2)	Number of Trees with Diameter 51-90 cms (Zone 2)	Number of Trees with Diameter 91+ cms (Zone 2)
1.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00
8.00	0.00	0.00	0.00	0.00
9.00	0.00	0.00	0.00	0.00
10.00	0.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00
13.00	0.00	0.00	0.00	0.00
14.00	0.00	0.00	0.00	0.00
15.00	0.00	0.00	0.00	0.00
16.00	0.00	0.00	0.00	0.00
17.00	0.00	0.00	0.00	0.00
18.00	0.00	0.00	0.00	0.00
19.00	0.00	0.00	0.00	0.00

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Number of Trees with Diameter 3-15 cms (Zone 3)	Number of Trees with Diameter 16-30 cms (Zone 3)	Number of Trees with Diameter 31-50 cms (Zone 3)	Number of Trees with Diameter 51-90 cms (Zone 3)
1.00	0.00	0.00	0.00	0.00
2.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00
4.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	0.00
6.00	0.00	0.00	0.00	0.00
7.00	0.00	0.00	0.00	0.00
8.00	0.00	0.00	0.00	0.00
9.00	0.00	0.00	0.00	0.00
10.00	0.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00	0.00
12.00	0.00	0.00	0.00	0.00
13.00	0.00	0.00	0.00	0.00
14.00	0.00	0.00	0.00	0.00
15.00	0.00	0.00	0.00	0.00
16.00	0.00	0.00	0.00	0.00
17.00	0.00	0.00	0.00	0.00
18.00	0.00	0.00	0.00	0.00
19.00	0.00	0.00	0.00	0.00

APPENDIX – 3 (Channel Morphology Data for Deep Fork Creek)

Reach Number	Number of Trees with Diameter 91+ cms (Zone 3)	Total # Trees in Transect
1.00	0.00	7.00
2.00	0.00	1.00
3.00	0.00	0.00
4.00	0.00	4.00
5.00	0.00	0.00
6.00	0.00	0.00
7.00	0.00	0.00
8.00	0.00	11.00
9.00	0.00	6.00
10.00	0.00	0.00
11.00	0.00	0.00
12.00	0.00	0.00
13.00	0.00	2.00
14.00	0.00	6.00
15.00	0.00	1.00
16.00	0.00	1.00
17.00	0.00	5.00
18.00	0.00	0.00
19.00	0.00	4.00

APPENDIX – 4 (Land Cover Data for Skeleton Creek)

Reach	Open Water Sq Km	Pervious Though Developed Sq Km	Developed High Intensity Sq Km	Barren Land Sq Km
1	0.0522	0.9675	1.2213	0
2	0.0891	1.8306	2.754	0
3	0.1944	2.6001	3.6936	0
4	0.2133	3.0456	4.1508	0
5	0.2133	3.0906	4.149	0
6	0.2133	3.1734	4.2048	0
7	0.2133	3.1815	4.2075	0
8	0.2133	3.1977	4.2939	0
9	0.4275	21.4173	42.7275	0
10	0.4464	21.8988	42.7302	0
11	0.4464	21.8988	42.7302	0
12	0.4464	21.9969	42.7302	0
13	0.4464	22.0374	42.7302	0
14	0.5517	23.0418	42.9858	0.0081
15	0.5832	24.6168	43.0119	0.0081
16	0.6156	26.847	43.2567	0.0081
17	0.8496	32.3028	44.5968	0.0081
18	1.2573	34.9758	44.712	0.0081
19	1.4517	38.9043	44.7129	0.0081
20	1.4562	39.2427	44.7093	0.0081
21	2.475	53.3394	45.1575	0.0081
22	2.475	53.604	45.1638	0.0081
23	2.6919	56.799	45.1647	0.0081
24	2.6919	56.916	45.1647	0.0081
25	2.6919	57.0969	45.1647	0.0081
26	2.6919	57.123	45.1647	0.0081
27	2.7648	57.5721	45.1647	0.0081
28	3.7422	66.2112	45.5472	0.0081
29	4.7331	80.1063	46.3221	0.0081
30	4.7331	80.2269		0.0081

APPENDIX – 4 (Land Cover Data for Skeleton Creek)

Reach	Deciduous Forest Sq Km	Grassland / Herbaceous Sq Km	Pasture / Hay Sq Km	Cultivated Crops Sq Km
1	0.4671	5.3982	0	6.4683
2	0.495		0.0612	6.9246
3	0.7497		0.4869	15.4701
4	0.9369		0.6174	22.5621
5	0.9666		0.6174	22.9995
6	1.0017		0.6174	23.6727
7	1.0017		0.6174	23.832
8	1.008		0.6174	23.9013
9	2.6721		0.6174	74.8827
10	2.7		0.6174	82.7766
11	2.7		0.6174	82.8882
12	2.7225		0.6264	85.6341
13	2.7729		0.6264	86.4603
14	2.8008		0.8127	106.5861
15	3.1194		0.9891	135.0108
16	3.5496		0.9891	162.5319
17	5.2164		1.0926	232.3845
18	6.2937		1.0926	269.1531
19	7.6095		1.0953	336.213
20	7.7913		1.0953	340.4106
21	11.9322		1.656	487.9323
22	12.0069		1.656	492.9381
23	13.8879		1.7505	521.0955
24	14.1759		1.7505	522.0549
25	14.2254		1.7505	522.7956
26	14.3136		1.7505	523.2006
27	14.76		1.7505	525.6117
28	24.84		2.1672	627.3
29	55.3329		3.4443	772.128
30			3.4524	773.6526

APPENDIX – 5 (Land Cover Data for Stillwater Creek)

Reach	Open Water Sq Km	Pervious Though Developed Sq Km	Developed High Intensity Sq Km	Deciduous Forest Sq Km
1	7.2945	7.1928	0.819	18.6048
2	13.7061	10.5471	1.1988	31.4559
3	13.7061	10.5471	1.1988	31.4559
4	18.8676	15.7158	1.5102	61.9137
5	18.9882	16.7067	1.7622	70.641
6	19.0134	16.8273	1.7721	71.3016
7	19.0134	16.8363	1.7721	71.316
8	19.1394	18.2835	3.3426	72.6939
9	19.1394	18.2835	3.3426	72.7425
10	19.1394	18.3303	3.3876	72.8361
11	19.2636	20.4579	4.7358	81.5202
12	19.4535	22.7403	5.6502	88.0965
13	19.4535	23.1282	6.0669	88.1586
14	19.5192	25.2	8.3754	94.5774
15	19.5192	25.7778	10.6425	94.7277
16	19.5327	26.1945	11.5101	95.1327
17	19.5606	26.2008	11.5992	95.2173
18	20.7657	32.8671	24.2433	100.3419
19	21.0924	37.0755	26.5365	116.1135
20	21.0924	37.2564	26.5464	116.7111
21	21.1455	38.5659	27.2745	121.2966
22	21.2004	39.1599	27.2844	123.966
23	21.2211	39.4344	27.2889	124.8786
24	21.2211	39.4344	27.2889	125.0442
25	21.2436	39.492	27.2934	125.496
26	21.8421	43.5951	27.6327	148.3425
27	21.8421	43.6257	27.6435	148.4514
28	21.8637	43.7706	27.6435	149.0238
29	21.8637	43.8831	27.6435	150.1614
30	21.9906	44.9451	27.6759	156.7206

APPENDIX – 5 (Land Cover Data for Stillwater Creek)

Reach	Grassland / Herbaceous Sq Km	Pasture / Hay Sq Km	Cultivated Crops Sq Km
1	106.5465	0.6606	9.0513
2	130.4163	1.1286	10.3356
3	130.4163	1.1286	10.3356
4	181.4652	1.7748	16.569
5	192.9771	2.2671	18.4959
6	194.8401	2.2689	18.6183
7	194.9175	2.2689	18.747
8	198.7389	2.4426	20.5452
9	198.7416	2.4426	20.5452
10	199.2492	2.4426	20.6694
11	203.2587	2.4849	20.8278
12	224.0955	3.4506	23.8131
13	224.1954	3.5271	24.0039
14	233.3952	4.3587	25.677
15	233.6976	4.3587	25.9029
16	234.5535	4.4847	26.2305
17	234.7812	4.5936	26.4528
18	253.5048	5.4225	27.7047
19	298.1592	7.1577	31.0005
20	300.7791	7.4655	32.1273
21	314.2089	8.5176	33.0498
22	321.5394	9.1647	34.3161
23	324.576	9.2493	35.5014
24	324.8388	9.2502	35.6643
25	325.5651	9.4446	35.7561
26	379.1205	15.6006	42.7131
27	379.1592	15.6006	42.9552
28	379.8117	15.6204	43.1433
29	380.6091	15.8382	43.902
30	391.059	18.4104	44.4384

APPENDIX – 6 (Land Cover Data for Deep Fork Creek)

Reach No.	Open Water Sq Km	Pervious Though Developed Sq Km	Developed High Intensity Sq Km	Barren Land Sq Km
1	0.1224	7.1334	35.91	
2	0.1224	7.1586	35.9631	
3	0.1224	9.4509	45.9297	
4	0.1224	9.5922	46.0701	
5	0.1224	9.7848	46.2249	
6	0.1224	9.801	46.2573	
7	0.1224	9.8172	46.2618	
8	0.1422	11.2581	50.0634	
9	0.2745	18.6912	62.8119	
10	0.2826	19.9062	63.8577	
11	0.3528	20.448	64.1286	
12	0.4734	22.1976	66.8871	
13	0.4734	22.2741	66.951	
14	0.4734	23.1498	67.2318	
15	0.4734	23.3325	67.464	
16	0.4734	23.3442	67.473	
17	0.4734	23.3856	67.4748	
18	0.6453	30.4272	77.4729	
19	0.7686	32.0103	78.2037	0.0099

APPENDIX – 6 (Land Cover Data for Deep Fork Creek)

Reach No.	Deciduous Forest Sq Km	Grassland / Herbaceous Sq Km	Pasture / Hay Sq Km	Cultivated Crops Sq Km
1	0.0117	0.0135	0	0
2	0.0117	0.0135	0	0
3	0.0396	0.0747	0	0.0036
4	0.0396	0.0747	0	0.0036
5	0.2106	0.0846	0	0.0036
6	0.3321	0.09	0	0.0036
7	0.3582	0.09	0	0.0036
8	1.1457	0.9342	0.0819	0.5049
9	4.203	1.7325	0.099	0.6102
10	5.8428	2.3877	0.1476	0.6408
11	6.9048	2.817	0.1845	0.6597
12	11.5767	7.308	1.1385	1.7064
13	11.7135	7.4745	1.1673	1.7604
14	15.8013	9.1809	1.5084	2.0358
15	16.3917	9.324	1.6191	2.0448
16	16.4475	9.3888	1.6191	2.0547
17	16.8102	9.585	1.6749	2.0619
18	26.2089	20.5821	2.6514	3.0951
19	30.3399	23.6115	3.2976	3.3129

VITA

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Candidate for the Degree of Doctor of Philosophy

Dissertation: EFFECTS OF URBANIZATION ON CHANNEL MORPHOLOGY OF THREE STREAMS IN THE CENTRAL REDBED PLAINS OF OKLAHOMA

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This research evaluates the impact of urbanization on channel morphology of three streams in the Central Redbed Plains geomorphic province (Central Great Plains ecoregion) of Oklahoma. The Deep Fork Creek watershed is largely urbanized; the Skeleton Creek watershed is largely rural; and the Stillwater Creek watershed is experiencing a rapid transition from rural to urban land cover. Each channel was divided into reaches based on tributary junctions, sinuosity, and slope. Field surveys were conducted at transects in a total of 90 reaches, including measurements of channel units, channel cross-section at bankfull stage, and riparian vegetation. Historical aerial photographs were available for only Stillwater Creek watershed, which were used to document land cover in this watershed, especially changes in the extent of urban areas (impervious cover).

The three streams have very low gradients (< 0.001), width-to-depth ratios < 10, and cohesive channel banks, but have incised into red Permian shales and sandstone. The riparian vegetation is dominated by cottonwoods, ash, and elm trees that provide a dense root mat on stream banks where the riparian vegetation is intact. Channels increased in the downstream direction as is normally expected, but the substrate materials and channel units remained unchanged. Statistical analyses demonstrated that urbanization provides minimal explanation for spatial patterns of changes in any variables. These three channels in the Central Redbed Plains are responding as flumes during peak flows, funneling runoff and the wash-load sediment downstream in major runoff events without any effect on channel dimensions. Therefore, local geological conditions (similar bed rock, cohesive substrates and similar riparian vegetation) are mitigating the effects of urbanization.

Advisor's Approval: Richard A. Marston and Daniel E. Storm