SPATIAL EXTENT, TIMING, AND CAUSES OF CHANNEL INCISION, BLACK VERMILLION WATERSHED, NORTHEASTERN KANSAS

by

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Abstract

The Black Vermillion River (watershed area = 1310 square kilometers) contributes runoff and sediment into Tuttle Creek Reservoir, a large federal reservoir (volume = 327 million cubic meters) northeast of Manhattan, Kansas. Tuttle Creek, completed in 1962, is filling with sediment faster than other federal reservoirs in the region. The Reservoir's conservation pool is about 40 percent full of sediment and is predicted to fill by 2023. Debate rages over the relative contribution of sediment from upland sources (largely croplands and pasture) versus channel incision. In the Black Vermillion watershed, bedrock is overlain in most of the watershed by pre-Illinoian age easily erodible glacial till and loess. Row crop agriculture is the most common land use in the watershed and stream channels are incised and prone to frequent flooding and channel instability. This research focused on the spatial extent, timing, and causes of channel incision in the Black Vermillion watershed. I conducted a watershed-wide survey of channel cross-sections in 56 locations repeated at sites that had been surveyed 45 years ago by the Soil Conservation Service. Further, I collected channel cross sections in 2008 at a total of 51 more locations for a total of 107 study sites. Channel depths between 1963 and 2008 increased by a mean of 1.6 meters (maximum = 5.2 meters). Most channels throughout the watershed have incised, are actively incising, or incising and widening. Statistical testing between channel depths as measured in 1963 and 2008 showed that the amount of incision was related to land use/land cover, riparian buffer widths, upstream drainage area, and geology. As channels incise, they progress through six stages of channel evolution, which complicates the relationship between channelization and incision. Channel stage, as identified in the field, was statistically related to geology, occurrence and timing of channelization, land use/land cover, and upstream drainage area. Channelization has reduced channel length by a significant portion and was identified as one of the leading causes of incision. This finding suggests that planting buffers and/or expanding existing buffers along streams should be encouraged in the watershed to alleviate flooding and channel instability.

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CHAPTER 1 - Introduction

Problem Statement

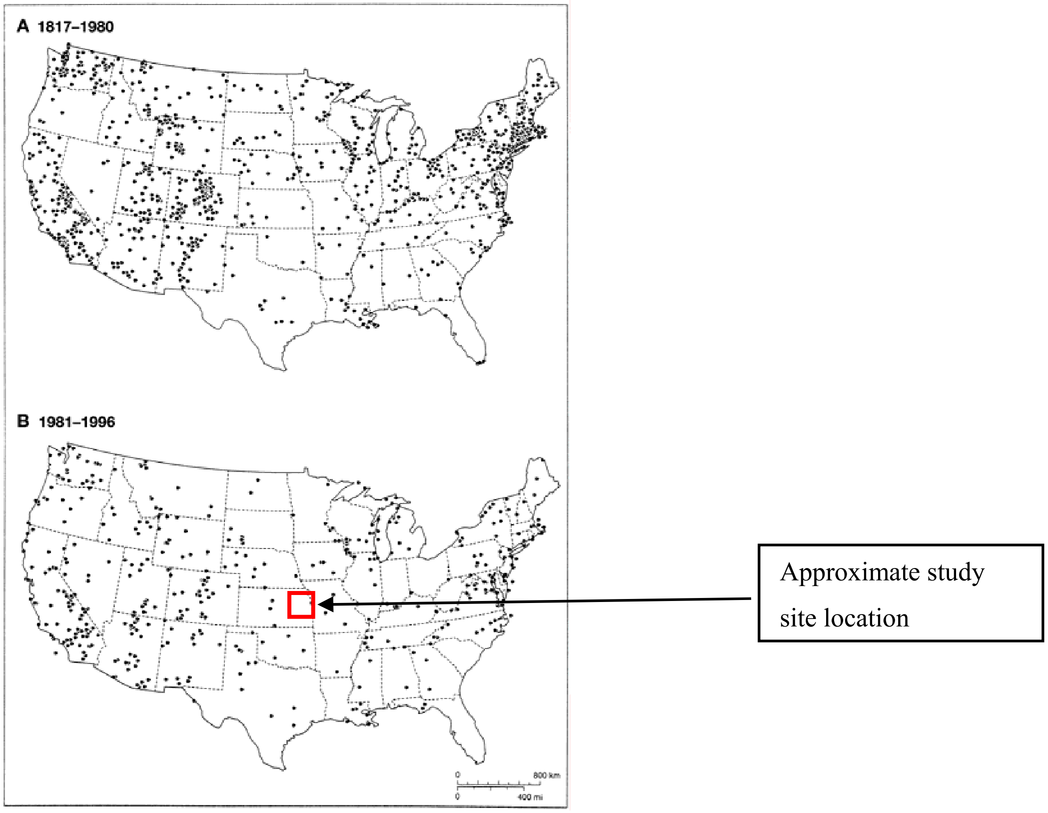
The Black Vermillion River drains an agricultural watershed in northeastern Kansas. This river system contributes a significant amount of sediment downstream into Tuttle Creek Reservoir northeast of Manhattan, Kansas. Similar to other reservoirs in Kansas, Tuttle Creek is infilling rapidly with sediment. In 2005, the USGS estimated that the Tuttle Creek Reservoir sediment pool was about 70 percent full and the reservoir's multipurpose pool water storage capacity is slated to completely fill with sediment by the year 2023 (Zeigler and Juracek, 2006). In 1970, eight years after being completed, Tuttle Creek Reservoir was 6474 hectares in size. According to Brian McNulty, Operations Manager of Tuttle Creek Reservoir, the acreage of water in the reservoir has been reduced to 5058 hectares currently, with the rest lost to sediment (Klusener, 2008). Much of the sediment deposited in the reservoir occurs in the upstream section of the reservoir. In 1970, water depths ranged from six to 10 meters. Today, this same area of the reservoir is completely filled with sediment (Klusener, 2008).

Debate continues over identifying the sources of this sediment from the Black Vermillion River watershed within Kansas and from the larger Big Blue River watershed that drains a more extensive area in both Nebraska and Kansas. This study will address the potential in-channel sources of this sediment by looking at the spatial extent, timing, and causes of channel incision in the Black Vermillion watershed. Simon and Rinaldi (2001) stated that sediments originating from incised stream channels can constitute a large proportion of the total sediment yield from a given landscape, with channel banks providing the majority of the sediment output. Simon and Rinaldi (2006) were more specific, citing several separate studies that described eroding channel banks as contributing up to 90% of the total sediment output from stream systems with incised channels. Questions of sediment delivery have not been previously investigated within this watershed. The identification of this sediment source could potentially assist with attempts to mitigate sediment output from the Black Vermillion River watershed and to prolong the usable life of Tuttle Creek Reservoir.

Significance:

The watershed selected for this study is located within the Great Plains region of the United States, an area dominated by agricultural land uses. Studies of the rivers of this area of the United States have been meager in comparison to other regions (Graf, 2001) despite the knowledge that streams in the Midwest have a unique suite of problems affecting them (Figure 1.1). These issues include channel instability, incision, and flooding. Furthermore, the largest and arguably the most commercially important rivers in the nation lie within the continental interior of the United States, including the Mississippi, Missouri, and Ohio Rivers. These larger rivers eventually collect the waters, sediment, and other effluent from smaller tributaries such as the Black Vermillion. Therefore, it is helpful to think of the river systems of the Midwest as a network where every component deserves greater attention. This study addresses the evident need for more research into the understanding of rivers of all sizes located in this region of the country. Specifically, this study contributes knowledge into the behavior of streams in the Midwest in relation to the natural and anthropogenic variables affecting them.

Knowledge of the sediment sources from this watershed would assist in efforts to limit the excessive sediment that is reaching Tuttle Creek Reservoir. If the sediment source was identified, whether from in-stream, riparian zone, or upland sources, potential rehabilitation actions could be identified in order to slow sedimentation of Tuttle Creek downstream. Currently, little is known about these topics. Further, rivers that contribute significant volumes of sediment into downstream areas are also likely suffering from other problems. Therefore, identification of sediment sources from this watershed might be jointly beneficial for Tuttle Creek Reservoir and also for the health of the Black Vermillion watershed.



Approximate study site location

Figure 1.1 Maps from Graf (2001) showing locations of research related to fluvial geomorphology.

The relative lack of research on rivers and streams of the Midwest adds some significance to this research because of the geographic location of the study. However, this study also combines some research objectives and approaches that other researchers have previously noted will prove to be valuable as the field of fluvial geomorphology progresses. For example, James and Marcus (2006) stated that research on rivers needs to focus on more integrative studies of watersheds. They suggest that past work on rivers as isolated features on the landscape should be abandoned and more studies on the interrelationships between rivers and their surrounding watersheds should be pursued. Gregory (2006) reported that the linkages between channel changes on a watershed scale need to be further addressed in future research. Gregory (2006) also mentioned that only since 1956 have questions regarding the human role in changing fluvial systems been approached in the scientific literature. In particular, Gregory (2006) also mentioned that questions of where, when, and why human changes to river systems occur have not been sufficiently answered.

This study on the Black Vermillion River and watershed of northeastern Kansas will address some of these gaping holes in the current research of fluvial geomorphology. The study focuses on issues affecting streams of the Midwest and it uses an integrated watershed approach as its research objective. Further, channel change on the watershed scale is studied and questions of why, when, and where channel changes occur in the watershed are central to the research. Lastly, the study has a distinct connection to the study of human impacts to fluvial systems and how those impacts influence the overall river environment.

Purpose and Objectives

The purpose of this study is to identify the spatial extent, timing, and causes of channel incision in the Black Vermillion watershed of northeastern Kansas.

Research Questions

The research questions to be addressed in this study are the following:

1) Do spatial patterns exist in the extent and severity of channel incision in the Black Vermillion watershed?

2) How long has channel incision been present in the Black Vermillion watershed?

3) Are human perturbations (including, but not limited to, channelization and land use/land cover change) the contributing factor(s) in the channel incision occurring to the streams of this watershed, or are natural factors (such as geology, watershed size, buffer width, or channel slope) more important?

Study Area

Location

The Black Vermillion watershed is located in parts of Marshall, Nemaha, and Pottawatomie Counties in northeastern Kansas. The watershed is primarily rural and no urban areas are present. The largest towns in the watershed are Frankfort with a population of 855 and Centralia with a population of 534 (U.S. Census Data, April 2000). Agriculture is the mainstay of the local economy and the land uses of the watershed exemplify this fact. Main, paved highways include Kansas Route 9 and U.S. Route 36, which extend East-West. Kansas Route 87 and Kansas Route 187 travel North-South. More minor county roads closely follow Township and Range boundaries throughout the watershed area. Most county roads are gravel or dirt.

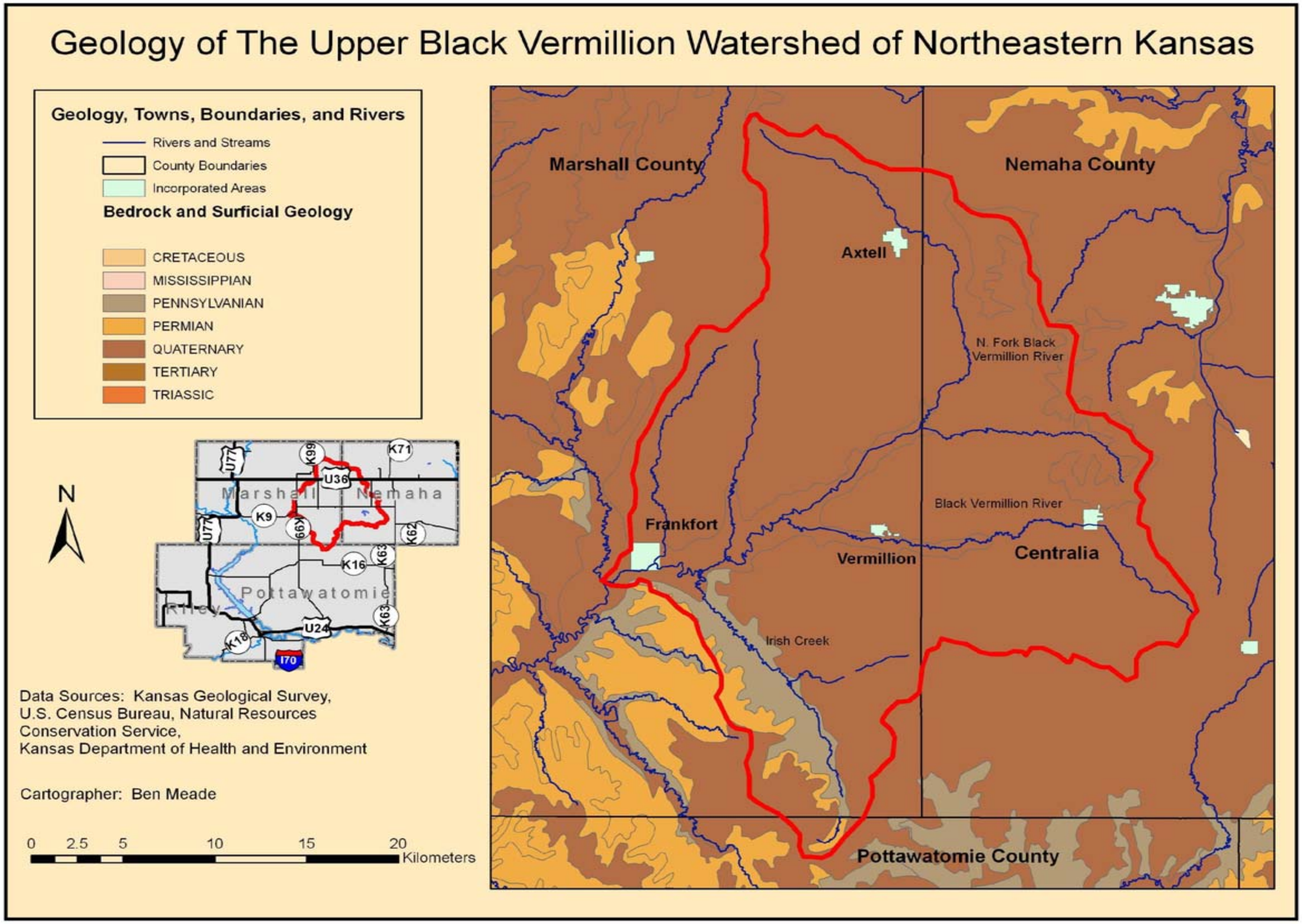
Bedrock and Surficial Geology

Upper Permian limestones and shales are the dominant bedrock types within the Black Vermillion watershed (Figures 1.2 and 1.3). However, bedrock outcrops and exposures are relatively uncommon because bedrock is overlain by a veneer of sediments and soils of differing ages and origins. Varying thicknesses of pre-Illinoian-age glacial till are present watershed-wide which were deposited by the pre-Illinoian continental ice sheet approximately 0.6 my B.P. (Merriam, 2003). Although the exact placing is not well understood, the southern boundary of this ice sheet extended approximately as far south as Douglas County, Kansas (Merriam, 2003). Subsequently, the Black Vermillion watershed lies near the southern limits of coverage by this continental ice sheet. The vestiges left by this Pleistocene glaciation are not always easily visible or identifiable because of extensive erosion of glacial deposits and debris. In the Black Vermillion watershed and elsewhere in northeastern Kansas, glacial erratics in the form of boulders and clasts (most commonly Sioux quartzite) are the most visible remnants of this glaciation (Merriam, 2003).

Wind-blown, fine-grained sediment known as loess was subsequently deposited towards the terminus of the later Wisconsinan glaciation. These loess deposits, known as the Peoria loess, were emplaced between about 25-30 ka and 12 ka ago (Rousseau et al., 2007).

While the exact source is not well understood, it is generally accepted that the Peoria loess originated from periglacial environments and spread widely throughout the Midwest (Luttenegger, 1987). Thickness of the deposits generally decrease southward (Rousseau et al., 2007) away from source areas to the north. In Nebraska and Iowa, the Peoria loess has been mapped at a depth of between 19 and 46 meters. This identifies the Peoria loess as having potentially the highest depositional rate for eolian deposits anywhere in the world (Rousseau et al., 2007).

In thousands of years, erosion has worked its way through these deposits of glacial till and eolian loess. Fluvial action, over time, has transported substantial volumes of material out of the Black Vermillion watershed and other watersheds of the Midwest. In the Black Vermillion watershed, some of this material is stored on floodplains as alluvium, and has been mapped as such (Figure 1.3). However, this blend of glacial, wind-borne, and fluvially-transported materials still has a thickness of at least 36 meters in locations within the Black Vermillion River watershed (Kansas Department of Transportation, 1978). Consequently, northeastern Kansas has been mapped as a separate Environmental Protection Agency (EPA) Level IV ecoregion known as the Loess and Glacial Drift Hills (Chapman, 2001). This Level IV ecoregion is considered separate from the remainder of Kansas due to the dominance of Quaternary-aged surface materials (Figures 1.2 and 1.3).



Data Sources: Kansas Geological Survey, U.S. Census Bureau, Natural Resources Conservation Service, Kansas Department of Health and Environment

Cartographer: Ben Meade

Figure 1.2 Geology map of the Black Vermillion watershed and surrounding region.

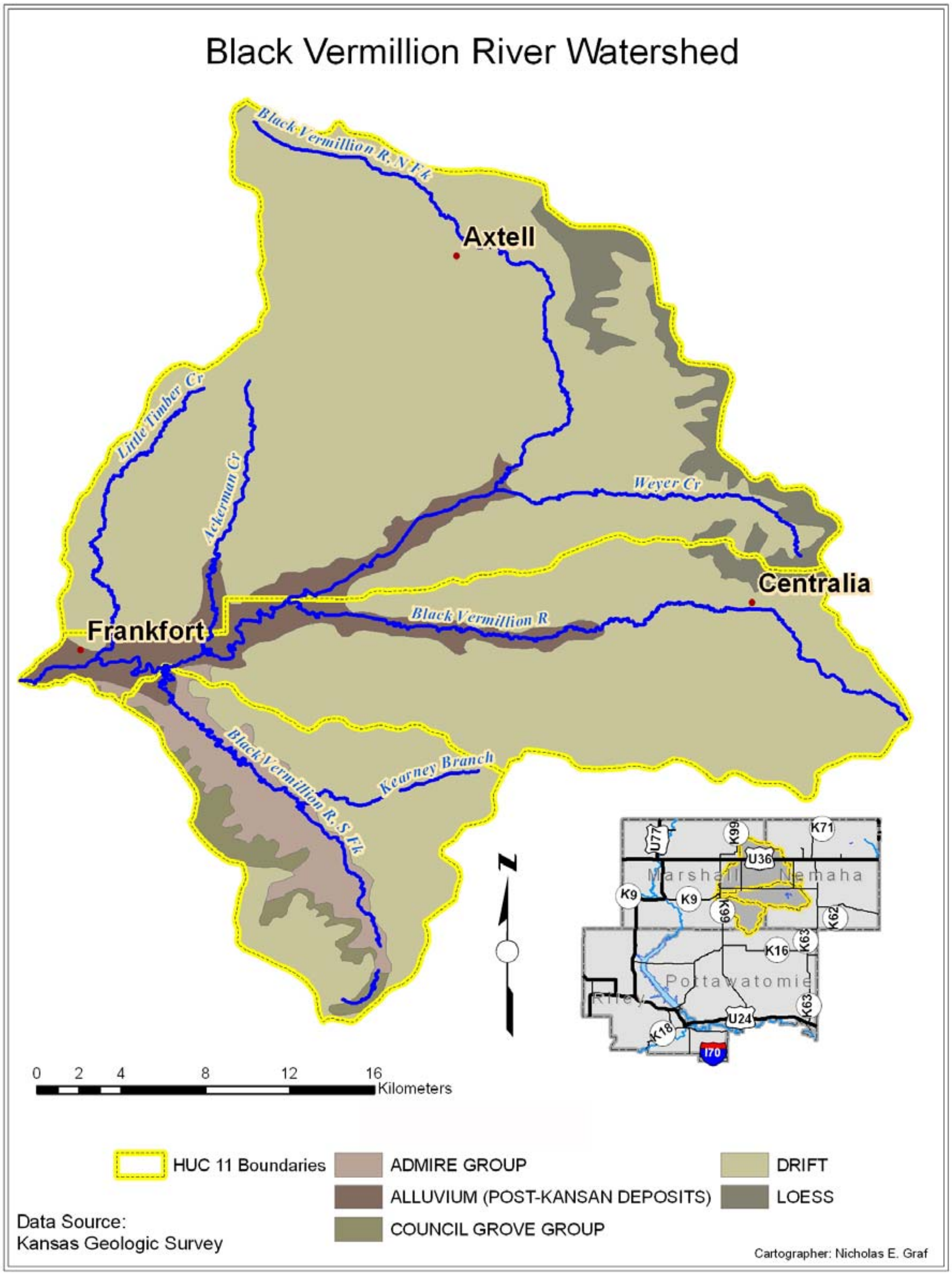


Figure 1.3 Detailed geology map of the Black Vermillion watershed.

Soils

The soils of the upland areas of the watershed have been classified as Wymore, Burchard, Morrill, Pawnee, and Steinauer series, which have consistently dark, deep topsoils and clayey subsoils (SCS, 1966). The soils along the streams of this region are largely classified as Kennebec silt loams, Wabash silty clay loams, and Nodaway silt loams. All three of these soil units are classified as alluvial silty loams, are frequently or occasionally flooded, and are located in floodplain areas (USDA-SCS, 1982). Defining characteristics of the soil types in the watershed area are available in Tables 1.1 and 1.2).

The fertility of the soils of the watershed is evident in both upland and floodplain areas because of the intensive farming efforts that are concentrated in the watershed. Soils are consistently derived from glacial till and loess, are predominantly very deep, and are composed of mostly silt and clay (Tables 1.1 and 1.2).

Table 1.1 Upland soils information. Source: Soil Survey of Nemaha County, Kansas - USDA and NRCS.

Upland Soils					
Soil Series Name	**% Sand**	**% Silt**	**% Clay**	**Drainage Class**	**Location/ Miscellaneous Characteristics**
Wymore	1.0	61.0	38.0	Moderately well drained	Uplands, formed in loess, slow to very slow permeability
Burchard	1.0	65.0	34.0	Well drained	Uplands, very deep, formed from calcareous glacial till, moderately slow permeability
Morrill	38.0	40.0	22.0	Well drained	Uplands, very deep, formed from loamy glacial till or outwash deposits
Pawnee	28.0	38.0	34.0	Moderately well drained	Uplands, formed in glacial till, slow or very slow permeability
Steinauer	32.0	40.0	28.0	Well drained	Uplands, very deep, formed in calcareous glacial till, moderately slow permeability

Table 1.2 Floodplains soils information. Source: Soil Survey of Nemaha County, Kansas - USDA and NRCS and the National Cooperative Soil Survey.

Floodplain Soils					
Soil Series Name	**% Sand**	**% Silt**	**% Clay**	**Drainage Class**	**Location/ Miscellaneous Characteristics**
Kennebec	5.0	70.0	25.0	Moderately well drained	Floodplains, very deep, formed in dark colored silty alluvium with low concentrations of fine to coarse sand
Wabash	6.0	58.0	36.0	Poorly and very poorly drained	Floodplains and upland drainageways, very deep, formed in alluvium, very slow permeability
Nodaway	8.0	70.0	22.0	Moderately well drained	Floodplains and upland drainageways, very deep, formed in alluvium

Topography

Topography in the Black Vermillion watershed consists of gently rolling hills and deeply entrenched drainages. Large variations in elevation are not present, stream gradients are generally gentle, and slopes range from two to 10 percent (SCS, 1966). Elevations range from approximately 300 to 450 meters above sea level throughout the watershed, with the lowest elevations being found near Frankfort, Kansas, within the valley of the lower reaches of the Black Vermillion River. The highest elevations are found in the northern portions of the watershed, near the Nebraska-Kansas state line.

Land Use

Agriculture is the dominant land use throughout the watershed. Approximately 61 percent of the watershed land area above Frankfort is in crops (ACOE, 1998). The percentage of land use in agriculture varies slightly by county and by time period. Between 1967 and 1977, 71 percent of the total land area of Nemaha County was in crops (USDA-SCS, 1982) while in 1967, approximately 60 percent of Marshall County was in crops (USDA-SCS, 1980).

The economy of the watershed and surrounding area is based on agriculture. Corn, grain sorghum, wheat, soybeans, and alfalfa are all produced in this region (SCS, 1966). Row crops are especially common in the sub-watersheds of the North Fork and Main Branches of the Black

Vermillion while the sub-watershed of the South Fork of the Black Vermillion (Irish Creek) contains higher levels of grazing land and woodlands (Figure 1.4). Such disparities in land use can be attributed to differences in the bedrock and surficial geology of varying regions of the watershed. The South Fork of the Black Vermillion (Irish Creek) flows out of hilly terrain similar to the Flint Hills topography to the south. Thinner soils and more bedrock exposure inhibit crop growth and therefore promote rangeland as a land use (Figures 1.2, 1.3, and 1.4). The North Fork and Main Branch of the Black Vermillion flow out of flatter terrain that is covered with thick deposits of glacial till and loess (Figures 1.2 and 1.3). These areas are more appropriate for row crops and land uses represent this as well (Figure 1.4).

Forested areas are present in the watershed where they have not been cleared or disturbed. Many such areas occur along streams (Figure 1.4). However, steep uplands and upland drainageways have some forested landcover as well. These forested areas represent small percentages of total land use in the watershed. For example, in Nemaha County, about 4,593 hectares - only 2.5 percent of the total county acreage - is woodland (Soil Survey of Nemaha County, Kansas). Tree species in these wooded areas are almost all hardwood species. These include black walnut, soft maple, bur oak, hackberry, green ash, elm, cottonwood, and sycamore (SCS, 1966). Scrub tree species such as osage orange and honeylocust are common in overgrazed pastures or upland areas.

Areas of pasture or ungrazed rangelands contain some of the native tallgrass prairie vegetation that was present before European cultivation was initiated in the region. Native grasses such as big bluestem, little bluestem, and Indiangrass exist in these areas (SCS, 1966). Approximately 25 percent of Marshall County is rangeland (Soil Survey of Marshall County, Kansas) while in Nemaha County about nine percent is rangeland (Soil Survey of Nemaha County, Kansas).

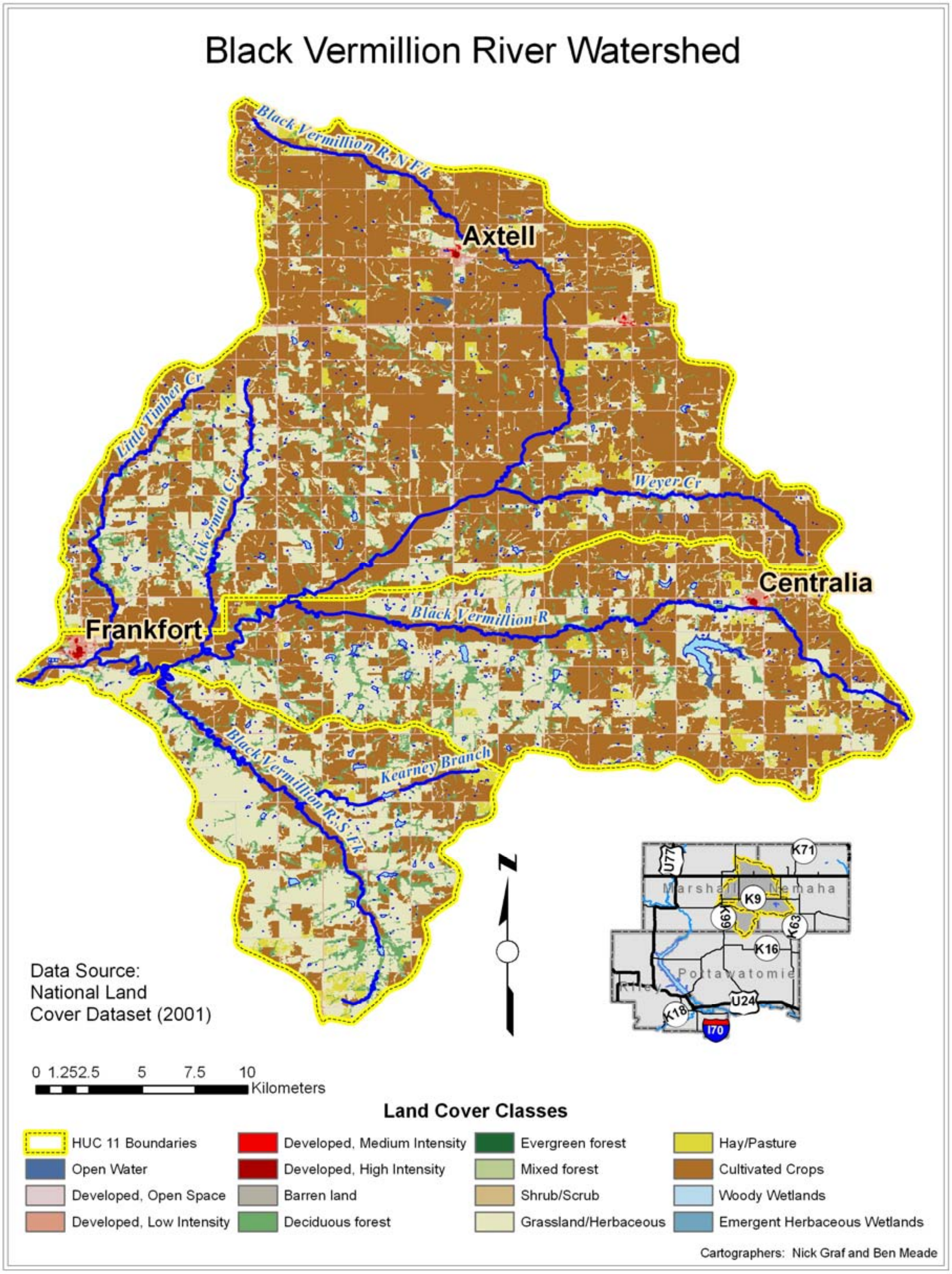


Figure 1.4 Land use map of the Black Vermillion watershed.

Climate

The Black Vermillion watershed is located in the Great Plains region of the United States, an area well known for its continental climate. Hot summers and cold winters predominate while large annual and daily changes in temperature are possible (USDA-SCS, 1980). Cold, dry air from polar regions to the North and warm, moist air from the South dominate based on the time of year. Warm temperatures predominate for about six months of the year while colder temperatures are mostly present from December through February (USDA-SCS, 1980). Average temperatures in winter hover slightly below freezing while summer temperatures average about 25 degrees Celsius (USDA-SCS, 1982). Transition seasons (spring and fall) are generally short. The growing season is approximately 170 days in length (Socolofsky and Self, 1988) which is considered to be of appropriate length for the crops grown in the region (USDA-SCS, 1982). For example, most types of corn require 140 frost-free days to mature before harvest (Socolofsky and Self, 1988).

Precipitation in the watershed area is highly seasonal and precipitation totals average between approximately 76 and 81 centimeters annually. However, overall precipitation in the state of Kansas increases in a west-to-east pattern at the rate of about 2.5 centimeters every 27 miles (Socolofsky and Self, 1988). Hence, the Black Vermillion watershed area at 1,310 square kilometers in size sees some spatial variability in the amount of precipitation that falls in any given year. For example, Marshall County sees an annual precipitation average of 79.5 centimeters (Soil Survey of Marshall County, Kansas) while Nemaha County, further east, has an average annual precipitation of 87.5 centimeters (Soil Survey of Nemaha County, Kansas).

Much of this moisture occurs as rainfall during the growing season. Approximately 76 percent of the precipitation in Marshall County, and 73 percent in Nemaha, falls as rain between April and September (Soil Survey of Marshall County and Soil Survey of Nemaha County, respectively). This timing of precipitation has important consequences for the growing of crops in the watershed area and little crop irrigation is present as a result. According to the U.S. Census of Agriculture in 1982, both Marshall and Nemaha Counties had less than one thousand acres of crops in irrigation (U.S. Census of Agriculture *in* Socolofsky and Self (1988).

CHAPTER 2 - Literature Review

This literature review contains four sections. The first section describes channel incision and the characteristics of incised streams. The second section reviews the natural and human characteristics of the American Midwest that make the streams in the region vulnerable to channel incision. The third section outlines the potential causes of channel incision in the American Midwest. The fourth section covers the harmful consequences of channel incision in the American Midwest.

All four of these sections are designed to put channel incision and unstable streams of the American Midwest (with emphasis on the Black Vermillion watershed) in broader context. A secondary purpose of this literature review is to validate the reasoning for the research described later in the thesis.

Channel Incision and Characteristics of Incised Streams

Incised channels vary in size, ranging from alluvial rills that can be measured in centimeters to bedrock canyons of a size that necessitate measurement on a kilometer scale (Darby and Simon, 1999). Dismissing their differences in scale, incised streams have undergone severe channel degradation. This is the result of systematic channel bed-level lowering that has occurred over an extended period of time (Mackin, 1948). Bed degradation is the universal and defining characteristic of incised stream channels (Simon and Darby, 1999) and is evidence of disturbance in which an excess of shear stress or stream power (sediment-transporting capacity) and flow energy is present relative to the volume of sediment being supplied to the stream (Simon and Darby, 1999). The characteristics of flow in the channel, the resistance to erosion, and bed material type all contribute to the amount and severity of bed degradation that is possible (Hanson and Simon, 2000).

Stream channels that have undergone this severe bed degradation are characterized under the umbrella term of "incised streams" and from this point forward will be labeled as such. Schumm et al., (1984) classified incised channels based on size. The following table illustrates their classification. Figure 2.1 (looking upstream) illustrates an incised stream where channelization has been completed in the past. Figure 2.2 (looking perpendicular to channel) shows the same incised stream and a gully in the same location as Figure 2.1.

Table 2.1 Classification of incised channels. Source: Schumm et al., (1984).

Channel Type	Description
Rill	Centimeter-scale ephemeral channel on a steep slope
Gully	Meter-scale incised channel that formed in a location where no previous channel existed previously.
Entrenched Stream	Incision of an existing channel. Deep, unstable channel results. Examples include arroyos and channelized streams.
Composite Incised Channel	Incised channel with reaches of different origin. For example, channel network might contain an entrenched stream and connected floodplain gullies.

Overall, channel incision is viewed as being indicative of a stream channel in disequilibrium (Simon and Rinaldi, 2006). Disregarding the contributing causes, the effects to river channel morphologies and associated hazards of channel incision can be very similar across a wide range of physiographic environments (Simon and Rinaldi, 2006).

Incised river channels have several defining characteristics. One such characteristic is an increase of bank heights as the channel bed degrades over time (Figure 2.1). Increasing bank heights decrease the stability of those same banks (Hanson and Simon, 2000). When a critical height and bank angle is reached, bank failure and erosion due to slumping can occur. This results in channel widening (Simon and Darby, 1999). Bank erosion is a natural process that creates and promotes wildlife habitats and the succession of riparian vegetation (Florsheim et al., 2008). However, in incised channels bank erosion is instigated by channel bed degradation and is considered to be a consequence of that rapid morphologic change (Simon and Darby, 1999). As noted by Simon (1992) channel widening is an important process for promoting the recovery of incised streams. This recovery occurs because widening helps to reduce available shear stress, lowers the sediment-transport capacity of the stream, and also reduces the depth of flows (Simon, 1992).

A second characteristic of incised channels is that they can contain flows of greater recurrence intervals than non-incised channels in similar hydrologic and natural environments (Simon and Rinaldi, 2006). Wolman and Leopold (1957) and Williams (1978) ascertained that the bankfull discharge of stable, non-incised streams occurs on the scale of 1 to 2-year recurrence interval flows. Because of their greater capacity and larger cross sections, incised channels more effectively transmit larger volumes of water downstream. As a result, the recurrence interval of bankfull discharge in the incised channel decreases to less than the 1 to 2-year recurrence interval established for a non-incised channel. Thus, the former floodplain becomes a terrace. This process has significant geomorphic consequences because flow energy of larger floods is no longer dissipated in the floodplain (Simon and Darby, 1999). Hence, these increased flows in incised channels contain higher shear stresses and are capable of transporting larger amounts of sediment than the same flows in the stream channel pre-incision (Simon, 1992; Simon and Darby, 1997a; Simon and Darby, 1999). In this way, further incision is encouraged within the channel and a positive feedback loop is initiated.

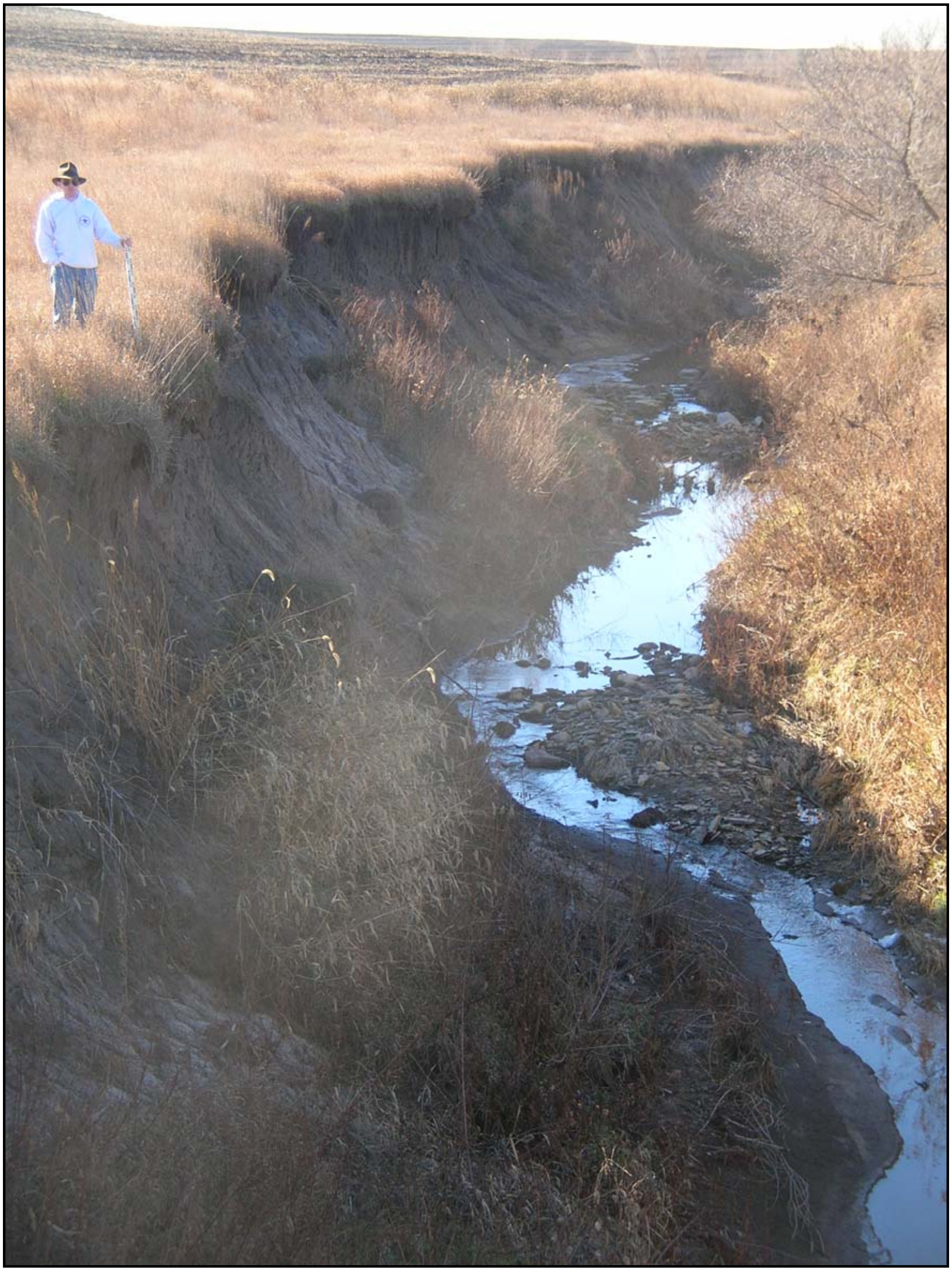


Figure 2.1 Site 13056 looking upstream (Northwest). Source: author, November, 2008.

Figure 2.2 Site 13056 looking perpendicular to channel (South). Source: author, May, 2008.

Vulnerability of the American Midwest and the Black Vermillion watershed to Channel Incision

In this section of the literature review, both the human and natural factors that make the American Midwest and the Black Vermillion watershed vulnerable to channel incision will be discussed.

Human-Induced Reasons for Vulnerability to Channel Incision

The American Midwest is particularly vulnerable to channel incision because of human-caused factors. Two primary reasons – land use change and channelization – will be discussed here. In the Midwest, these two factors are inextricably linked through time since European settlers first broke the prairie soils for row crops around the time of the Civil War. Widespread land clearing for farming occurred as a result, which decreased interception of precipitation and increased runoff as well. These changes and processes led to enhanced land erosion and gullying of terraces and floodplains (Simon and Rinaldi, 2000). In turn, the material eroded from the land was contributed as excess sediment into the meandering, low-gradient streams of the Midwest region. In turn, increased flooding occurred. This flooding led local drainage districts and private landowners to straighten and dredge (channelize) stream channels in order to alleviate problems with flooding. Channelization has been proven to be a trigger and widespread cause of channel incision (Simon and Rinaldi, 2006).

This combination of land use change, soil erosion, redistribution of sediment, increased flooding, and channelization caused channel instability. Incision of the streams of the Midwestern region was the primary result. A sequence of human-initiated changes to land use and hydrologic conditions of Midwestern watersheds ensued soon after European settlement and continue to the present day. Peterson (1991) described the same approximate sequence of events as occurring in the Black Vermillion watershed as Simon and Rinaldi (2000 and 2006) reported in their region-wide analysis of the American Midwest. The human-induced vulnerability of channel incision in the Black Vermillion watershed is potentially a good case study when looking at the streams of the Midwest in a more comprehensive analysis.

Natural Reasons for Vulnerability to Channel Incision

Compounding the potential human-induced vulnerability are the natural conditions of the Midwest and of the Black Vermillion watershed. Similar to sections of other states in the Midwest, northeastern Kansas is underlain by a veneer of loess, or windblown material, and glacial till. Both types of deposits are late Quaternary in age (Figures 1.2 and 1.3). As noted by Wood et al., (2001) and Heine and Lant (2009) the loess area of the Midwestern. U.S. is a region that is notorious for channel instability. Hanson and Simon (2001) stated that where loess deposits are present in areas of the Midwest, stream channel degradation (incision) has occurred extensively. A major reason given for this incision is that loess is relatively stable when dry, even when positioned in tall vertical cliffs along streams. However, loess becomes more erodible when wetted by rainfall or streamflow. As a result, stream channels in areas with deep loess deposits can become deeply incised and are very susceptible to bank erosion (Simon and Rinaldi, 2000).

Deeply weathered glacial deposits underlying these loess deposits are also potential sediments that may be easily eroded and transported by fluvial systems of the region. This loess and glacial till-covered area of the Midwest is considered to be a “worst-case scenario” for channel instability (Simon and Rinaldi, 2000). This results from the combination of highly erodible soils and extensive human disturbance. As such, the Black Vermillion watershed of northeastern Kansas contains loess and glacial deposits. These materials, and the silty and clayey soils that these materials weather into (Table 1.1 and Table 1.2) provide ample reserves of material that can be easily eroded and transported.

Potential Causes of Channel Incision in the American Midwest

The exact causes of channel incision vary widely and can be numerous (Darby and Simon, 1999). Channel incision is widely regarded as an excellent example of convergence in that many causes can create the same result (Schumm, 1991). Both human and natural factors make an area vulnerable to incision. Channel incision in the form of bed degradation is instigated if any of the following changes occur: a) changes that cause a decrease in sediment loads; b) an increase in annual or peak discharges; c) an increase in channel gradient and slope; and d) concentration of flows. Schumm (1999) identified six categories of triggers of channel incision: geologic, geomorphologic, climatic, hydrologic, animal-related, and human-related. Because of the wide combination of contributing factors, identifying the exact triggers of channel incision within a given region can be difficult. As mentioned by Schumm (1999), this is unfortunate because channel incision has a number of harmful consequences to natural systems and to human interests. More knowledge of the causes could help to lead to prevention. Further, Schumm (1999) noted identifying causes of channel incision is difficult because the incision itself has removed the geomorphic evidence of the original trigger of the initial incision. Various studies have identified or suggested possible causes in specific locations. For example, Heine and Lant (2009) studied channel incision in a wide area of the Missouri River watershed in southeastern Nebraska and southwestern Iowa. They concluded that channel incision was instigated in this region by base-level lowering of the Missouri River after the installation of several dams on this major river. However, whatever the contributing cause, Simon and Rinaldi (2006) noted that channel incision is overall a function of a disturbed landscape.

Land Use Change/Land Clearing/Conversion to Agriculture

It is well established that clearing of native vegetation (such as grasses, shrubs, and trees) within a given landscape lowers that region's ability to intercept runoff and that gullying and erosion of uplands can occur as a result (Simon and Rinaldi, 2006). Precipitation interception is a function of the type and density of vegetation or surface cover, as well as the volume and intensity of that precipitation. The potential for interception of precipitation varies depending on the type of vegetation present. Interception within an un-vegetated area is 0 mm and up to 0.5 mm in areas with corn planted. Conversely, prairie vegetation intercepts up to 7 mm. As a result, clearing of native prairie vegetation for the planting of crops decreases the ability of the landscape to intercept runoff and prevent it from infiltrating into the soil or running off as overland flow. Lau et al., (2006) stated that the planting of row crops after clearing has many harmful effects on nearby streams. Effects include increased erosion and sediment loads, the destruction of riparian areas and removal of naturally accumulated debris in the stream channel and natural factors influencing stream sinuosity. Faulkner (1998) inferred that in many regions of the Midwestern U.S., agricultural land use practices implemented since European settlement has caused greatly increased soil erosion and a subsequent inability of watercourses to transport increased sediment loads. Simon and Rinaldi (2006) concluded that land clearing for agriculture in western Iowa led to increased rates of surface runoff 2-3 times and peak streamflows 10-50 times when compared to pre-settlement amounts. Knox (1977) found that conversion of native forest/prairie vegetation to agriculture caused increased erosion, flooding, and sedimentation in the Platte River watershed of southwestern Wisconsin. A more comprehensive analysis by Knox (2001) showed that agricultural land uses in the Upper Mississippi River Valley led to an increase in peak discharges of 200-400% in high-frequency floods in the region compared to pre-agricultural discharges. Early tillage practices were reported to be most problematic in causing soil erosion and increased runoff before the Soil Conservation Service was formed in 1935 to combat these issues and to improve management of agricultural lands (Potter, 1991).

Land Use Change/Land Clearing/Conversion to Agriculture in the Black Vermillion Watershed

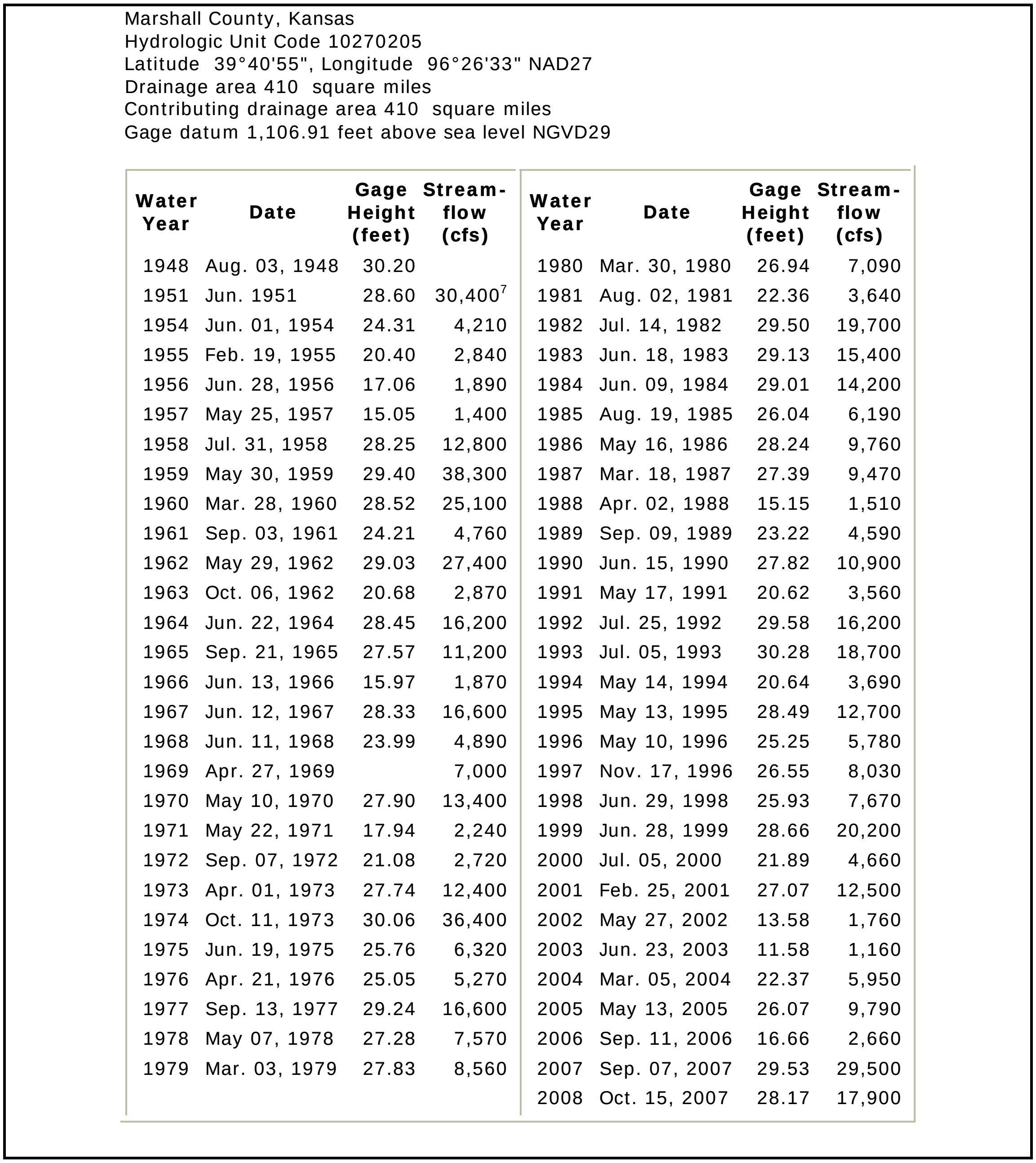
In northeastern Kansas, intense agricultural practices became more widespread as European settlement increased in the mid to late 1800's. As a result, the characteristics of land use and land cover changed drastically. Original prairie grassland was replaced with row crops and farming interests became the dominant economic factor in the watershed region (Peterson, 1991). Today, agriculture is the dominant land use within the Black Vermillion watershed (Figure 1.4).

In the Black Vermillion watershed, farming was initially concentrated in the river valleys until about 1880 (USDA-SCS-KAES, 1951). This was likely because of the flat topography and deep, fertile floodplain soils found adjacent to rivers (Table 1.2). After about 1880, farming efforts spread onto the surrounding hillslopes, divides, and slopes away from riparian areas (USDA-SCS-KAES, 1951). Currently, floodplain areas are still frequently under cultivation (author's observations, 2008).

As decades passed and crops became the dominant land use throughout the region, surface runoff occurred more rapidly than when prairie grassland was in place before farming began. This results because soils beneath cash crops are not as effective at absorbing precipitation and runoff as undisturbed prairie or riparian forest vegetation (Peterson, 1991). Others have quantified this phenomenon. Wolman and Schick (1967) discovered that exposure of erodible materials (soils) through agriculture and urbanization has the potential to increase sediment yields on the order of five to 700 times of what was previously normal. It has long been noted in the Black Vermillion watershed area that soil erosion is a significant problem. A report released in 1951 by the USDA, SCS (now NRCS) and Kansas Agricultural Experiment Station stated that the control of runoff water was the greatest single problem that the farmers of Nemaha County have to deal with. A similar report states that it is one of the major problems facing farmers in neighboring Marshall County as well.

As has been reported in other regions of the Midwest, increased runoff from agricultural lands entered into stream channels that soon became choked with sediment and exacerbated flooding problems (Simon and Rinaldi, 2006). For example, Moore (1917) reported that streams in nearby southeastern Nebraska were characterized by consistent channel aggradation. This resulted from eroded sediment from fields over-supplying nearby channels. Subsequently, the choked channels led to flooding of increasingly valuable agricultural lands during high flow events.

Table 2.2 Annual maximum streamflow data for the stream gauge on the Black Vermillion River at Frankfort. Source: United States Geological Survey.



Marshall County, Kansas
Hydrologic Unit Code 10270205
Latitude 39°40'55", Longitude 96°26'33" NAD27
Drainage area 410 square miles
Contributing drainage area 410 square miles
Gage datum 1,106.91 feet above sea level NGVD29

Water Year	Date	Gage Height (feet)	Stream-flow (cfs)
1948	Aug. 03, 1948	30.20	
1951	Jun. 1951	28.60	30,400[7]
1954	Jun. 01, 1954	24.31	4,210
1955	Feb. 19, 1955	20.40	2,840
1956	Jun. 28, 1956	17.06	1,890
1957	May 25, 1957	15.05	1,400
1958	Jul. 31, 1958	28.25	12,800
1959	May 30, 1959	29.40	38,300
1960	Mar. 28, 1960	28.52	25,100
1961	Sep. 03, 1961	24.21	4,760
1962	May 29, 1962	29.03	27,400
1963	Oct. 06, 1962	20.68	2,870
1964	Jun. 22, 1964	28.45	16,200
1965	Sep. 21, 1965	27.57	11,200
1966	Jun. 13, 1966	15.97	1,870
1967	Jun. 12, 1967	28.33	16,600
1968	Jun. 11, 1968	23.99	4,890
1969	Apr. 27, 1969		7,000
1970	May 10, 1970	27.90	13,400
1971	May 22, 1971	17.94	2,240
1972	Sep. 07, 1972	21.08	2,720
1973	Apr. 01, 1973	27.74	12,400
1974	Oct. 11, 1973	30.06	36,400
1975	Jun. 19, 1975	25.76	6,320
1976	Apr. 21, 1976	25.05	5,270
1977	Sep. 13, 1977	29.24	16,600
1978	May 07, 1978	27.28	7,570
1979	Mar. 03, 1979	27.83	8,560
1980	Mar. 30, 1980	26.94	7,090
1981	Aug. 02, 1981	22.36	3,640
1982	Jul. 14, 1982	29.50	19,700
1983	Jun. 18, 1983	29.13	15,400
1984	Jun. 09, 1984	29.01	14,200
1985	Aug. 19, 1985	26.04	6,190
1986	May 16, 1986	28.24	9,760
1987	Mar. 18, 1987	27.39	9,470
1988	Apr. 02, 1988	15.15	1,510
1989	Sep. 09, 1989	23.22	4,590
1990	Jun. 15, 1990	27.82	10,900
1991	May 17, 1991	20.62	3,560
1992	Jul. 25, 1992	29.58	16,200
1993	Jul. 05, 1993	30.28	18,700
1994	May 14, 1994	20.64	3,690
1995	May 13, 1995	28.49	12,700
1996	May 10, 1996	25.25	5,780
1997	Nov. 17, 1996	26.55	8,030
1998	Jun. 29, 1998	25.93	7,670
1999	Jun. 28, 1999	28.66	20,200
2000	Jul. 05, 2000	21.89	4,660
2001	Feb. 25, 2001	27.07	12,500
2002	May 27, 2002	13.58	1,760
2003	Jun. 23, 2003	11.58	1,160
2004	Mar. 05, 2004	22.37	5,950
2005	May 13, 2005	26.07	9,790
2006	Sep. 11, 2006	16.66	2,660
2007	Sep. 07, 2007	29.53	29,500
2008	Oct. 15, 2007	28.17	17,900

The majority of the precipitation that falls in the watershed area is highly seasonal. Approximately 76 percent of the precipitation in Marshall County, and 73 percent in Nemaha, falls as rain between April and September (Soil Survey of Marshall County and Soil Survey of Nemaha County, respectively). As can be inferred regarding the relationship between precipitation and streamflows, the majority of high flow events also occur during the warmer months.

As visible in the Table 2.2, many of the high flow events occur early in the spring. The timing of these floods make them potentially more erosive because they occur at a time of the year when land cover in the watershed area is particularly sparse. In March, April, and May, many fields have yet to be planted and are largely bare or nearly bare soil. At this time, high rain events may be more effective at eroding soil because there is little ground cover to protect it. Subsequently, runoff from surrounding upland areas likely reaches stream channels of the watershed quicker (Figure 2.3, Figure 2.4, and Figure 2.5). This further exacerbates flooding issues and increases the flashy nature of high flow events in the channels of the Black Vermillion watershed.

The flashy flow conditions and problems caused by flooding in the watershed were visible on May 22nd, 2008 when a rainstorm caused 108 mm of rain to fall in Axtell in the headwaters of the North Fork watershed. The flooding in Figure 2.3, Figure 2.4, and the hydrograph shown in Figure 2.5 all result from this same storm. Eventually, due to flooding problems and channel sedimentation, channelization practices began to be implemented in the Black Vermillion watershed.

Figure 2.3 Flooding on Weyer Creek. Source: author, May 22nd, 2008.

Figure 2.4 Flooding on the North Fork of the Black Vermillion River on Kansas route 9. Source: author, May 22nd, 2008.

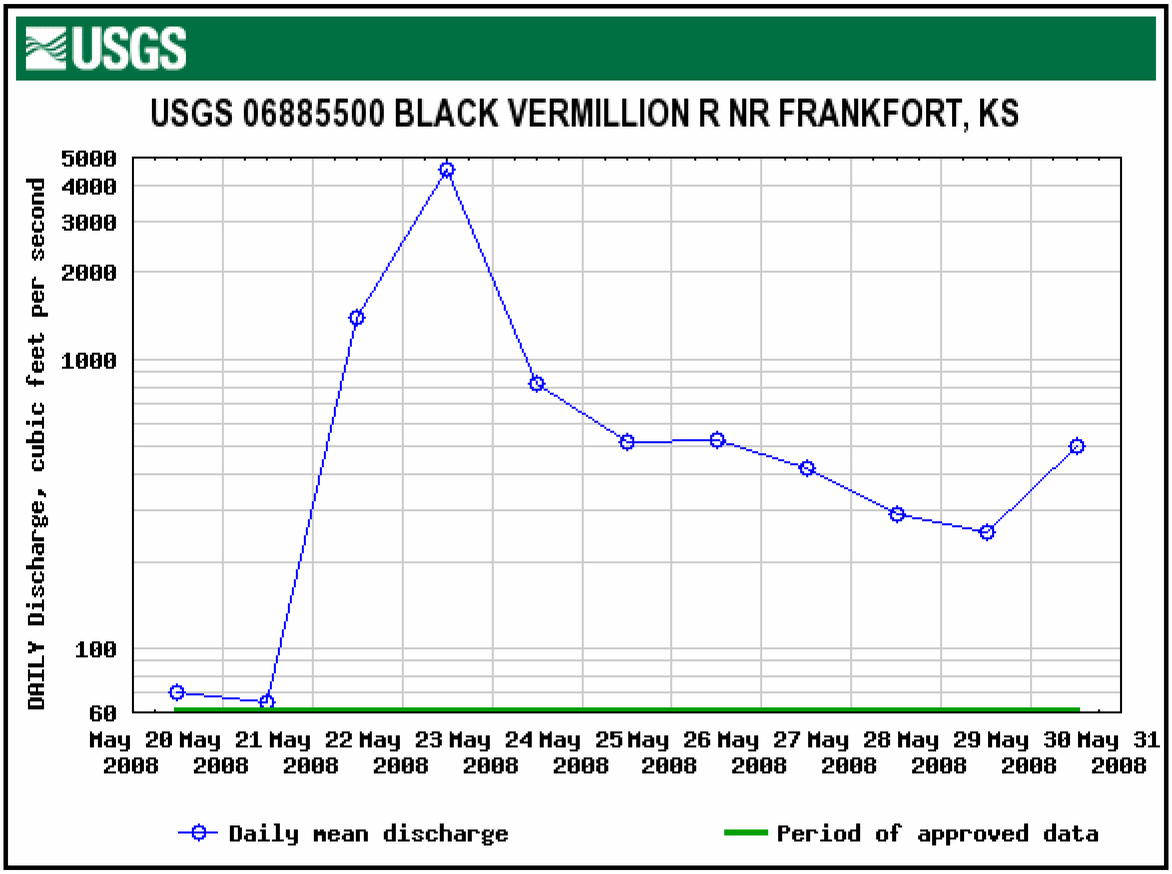


Figure 2.5 USGS hydrograph for the streamflow gauge at Frankfort, Kansas after a rainstorm caused 108 mm of precipitation in Axtell, Kansas and 11 mm of precipitation in Frankfort, Kansas. Source: USGS.

Channelization

Channelization is regarded as one of the most harmful anthropomorphic disturbances to fluvial systems (Davis, 2007) and is regarded as one of the most widespread human-caused triggers of channel incision (Simon and Rinaldi, 2006). Channelization is an engineering process in which attempts are made to physically re-align a channel in order to shorten or straighten that channel through dredging, excavation, etc. (Brookes, 1985) (Figure 2.4, Figure 2.5, and Figure 2.6). Channelization causes numerous negative effects to fluvial systems. These include lowering of the streambed through dredging, increased channel capacity, increased channel gradient, and increased velocity. Thus, rapid morphologic changes can occur within a fluvial system that has numerous harmful consequences. Such changes include unstable banks, upstream degradation, and downstream aggradation (Simon and Rinaldi, 2006). Stream channelization causes changes in nearly all hydrogeomorphic processes (Hupp, 1992). Importantly, characteristics both upstream and downstream of the channelized reach change rapidly when compared to most natural adjustments in a fluvial system (Hupp, 1992).

Landwehr and Rhoades (2003) explained that the primary purpose of channelization is to assist with the draining of agricultural lands. The practice of channelization in the Midwestern U.S. dates back about 150 years and can be directly correlated to the beginnings of intense agricultural practices that followed European settlement of the area that began around the time of the Civil War (Simon and Rinaldi, 2006).

Studies in the state of Iowa have been conclusive that channelization has severely altered the streams of that state. Zaimes et al., (2006) claimed that streams in Iowa are deeply incised due to accelerated streambank erosion that have been caused by human alterations to the stream channels. In Iowa, channelization that began in the late 1800's has decreased the original stream length of larger streams by dramatic amounts. Streams with drainage areas over 129 sq. km have been decreased in length by an average of 45%.

Channelization in the Black Vermillion Watershed

Historically, the stream channels of the Black Vermillion watershed meandered extensively (Peterson, 1991) and sinuosity on the main stream channels ranged from 1.5 to almost 2 (ACOE, 1998). Low channel gradients, erodible surface materials, and highly variable annual flows were likely contributing causes to the presence of serpentine stream channels. Similar to other streams in the Midwest, the channels of the Black Vermillion watershed also likely contained accumulations of large woody debris and beaver dams (Simon and Rinaldi, 2006).

These meandering, unaltered channels were likely subject to frequent flooding. Overall, flooding has been a constant occurrence both historically and currently in the Black Vermillion watershed (Peterson, 1991). However, residents of the Black Vermillion watershed area have recently noted increased bank instability and flooding in the region (ACOE, 1998).

Floods are an important and natural function of the fluvial system. However, human activities within the Black Vermillion watershed have likely increased the severity of flooding within the region. Because of the placement of crops in riparian areas, regularly occurring floods were likely viewed as a major nuisance by the area's farmers. Channelizing the stream channels became an effective method to contain floodflows within the channels to keep those flows from impacting crops being grown in the floodplain. Peterson (1991) found through mail-in surveys to river-adjacent landowners in the Black Vermillion watershed that their primary reason for channelizing was to keep flood flows from impacting their crops and to improve water drainage from their fields. A secondary benefit of channelization, as stated by many of these same farmers, was that the newly-straightened stream channels allowed for increased amounts of land to be put under cultivation (Peterson, 1991).

Channelization has occurred extensively to streams in the Black Vermillion watershed (Figure 2.7). Significant channelization practices in the Black Vermillion watershed began about 1950 (ACOE, 1998) and participation in the process has been undertaken by federal and local-level officials as well as individual farmers and landowners. In the late 1950's and early 1960's, channelization was done on the main stem of the Black Vermillion downstream of Frankfort in order to alleviate problems with flooding in the area (Barnes, personal communication, 2009). Channelization was subsequently completed jointly by the Soil Conservation Districts of both Marshall and Nemaha counties as well as the local watershed district on both the Main Branch and North Forks of the Black Vermillion (Barnes, personal communication, 2009). Concurrently, private farmers and landowners in the Black Vermillion watershed had been channelizing for years. As seen in Figure 2.7, channelization practices have not been completed consistently - temporally or spatially - in the Black Vermillion watershed. In fact, channelization has been completed in piecemeal fashion throughout the watershed (Figure 2.7). Since floodways and reservoirs require vast parcels of land (Barnard, 1977), channelization was likely seen as the cheapest method to eliminate or lessen the effects of flooding on adjacent agricultural lands in the Black Vermillion watershed.

Overall, channelization has shortened channel lengths in the Black Vermillion watershed. For the time period between the mid-1960's and the mid-1990's, channel lengths in the watershed were decreased by a total of 25.4 kilometers (ACOE - Table 2.3). Channel lengths have decreased approximately 23% on the North Fork of the Black Vermillion River, 26% on the main stem of the Black Vermillion River above Vliets, and 12% on the main stem of the Black Vermillion River from Vliets to Frankfort (ACOE, 1998). Exact numbers are found in Table 2.3.

Table 2.3 Channel length and sinuosity for rivers in the Black Vermillion watershed. Source: Army Corps of Engineers (1998).

River Reach	Base Channel Length	Historic Channel Length	Downvalley Distance (Constant)	Base (1998) Sinuosity	Historic Sinuosity
N. Fork Black Vermillion	39.4 km	51.2 km	34.1 km	1.15	1.50
Upper Black Vermillion	30.8 km	41.5 km	26.8 km	1.15	1.55
Lower Black Vermillion	19.3 km	21.9 km	12.2 km	1.58	1.80
Totals	89.4 km (55.5 miles)	114.6 km (71.3 miles)	73.2 km (45.5 miles)		

Using aerial photos from between the years 1956 and 1986, Peterson (1991) completed more specific measurements of the North Fork of the Black Vermillion as it became shortened by channelization. He stated that prior to most channelization activities in 1956, the North Fork was 59.9 kilometers in length. In 1986, the North Fork had been shortened through channelization to 40.7 kilometers in length. Peterson (1991) also noted that prior to 1956, the North Fork of the Black Vermillion River had 88.3 percent of natural (not channelized) channel remaining. Only 11.7 percent had been channelized by 1956. Conversely, in 1986, 88.7 percent of the channel had been altered through this method and only 11.3 percent of natural, unchannelized channel remained. Hence, it can be inferred that the vast majority of the channelization had been completed on the North Fork between 1956 and 1986. This is verified by the mapping efforts of Daniels (2008) – Figure 2.7.

The widespread presence of channelized streams throughout the Midwest (Simon and Rinaldi, 2006) and in the Black Vermillion watershed (Figure 2.7) suggests that the benefits of channelization practices are worthwhile for farmers. Peterson (1991) found that farmers in the Black Vermillion watershed channelized in order to reduce flooding on their land, to increase acreage for cultivation, and to make cultivation on their land more efficient. Peterson (1991) discovered that farmers, and especially those who owned greater acreages, did feel as though channelization was beneficial to their farming operations.

Today, channelized stream reaches are readily visible in the Black Vermillion watershed from the air (Figure 2.8, Figure 2.9, and Figure 2.10) and are also visible at ground level (Figure 2.6). The fragmented nature of the timing of channelization and the almost complete spatial coverage of channelization throughout the watershed are deserving of attention (Figure 2.7).

Many of the farmers who responded to the mail-in surveys of Peterson (1991) stated that if they had previously channelized, they were unlikely to do so again because of environmental concerns. Peterson (1991) also discovered that many farmers had noted that channelization practices upstream of their lands had increased both flooding and erosion on their lands downstream. This pattern might explain the almost complete spatial coverage of channelization on the larger channels of the Black Vermillion watershed. When upstream reaches were channelized earlier by other farmers, downstream farmers therefore channelized to decrease the effects of flooding on their lands. Siltation in channels further downstream, in conjunction with flooding, may also have led farmers further downstream to channelize in order to expedite floodwaters from their lands. This phenomenon of upstream channelization and downstream sediment overabundance has been noted by others. Examples include Emerson (1971) who studied the Blackwater River in Johnson County, Missouri, and Daniels (1960) who completed research on the Willow River in Harrison and Monona Counties, Iowa.

Figure 2.6 Channelized reach on site 14131 on Weyer Creek looking upstream. Source: author, June, 2008.

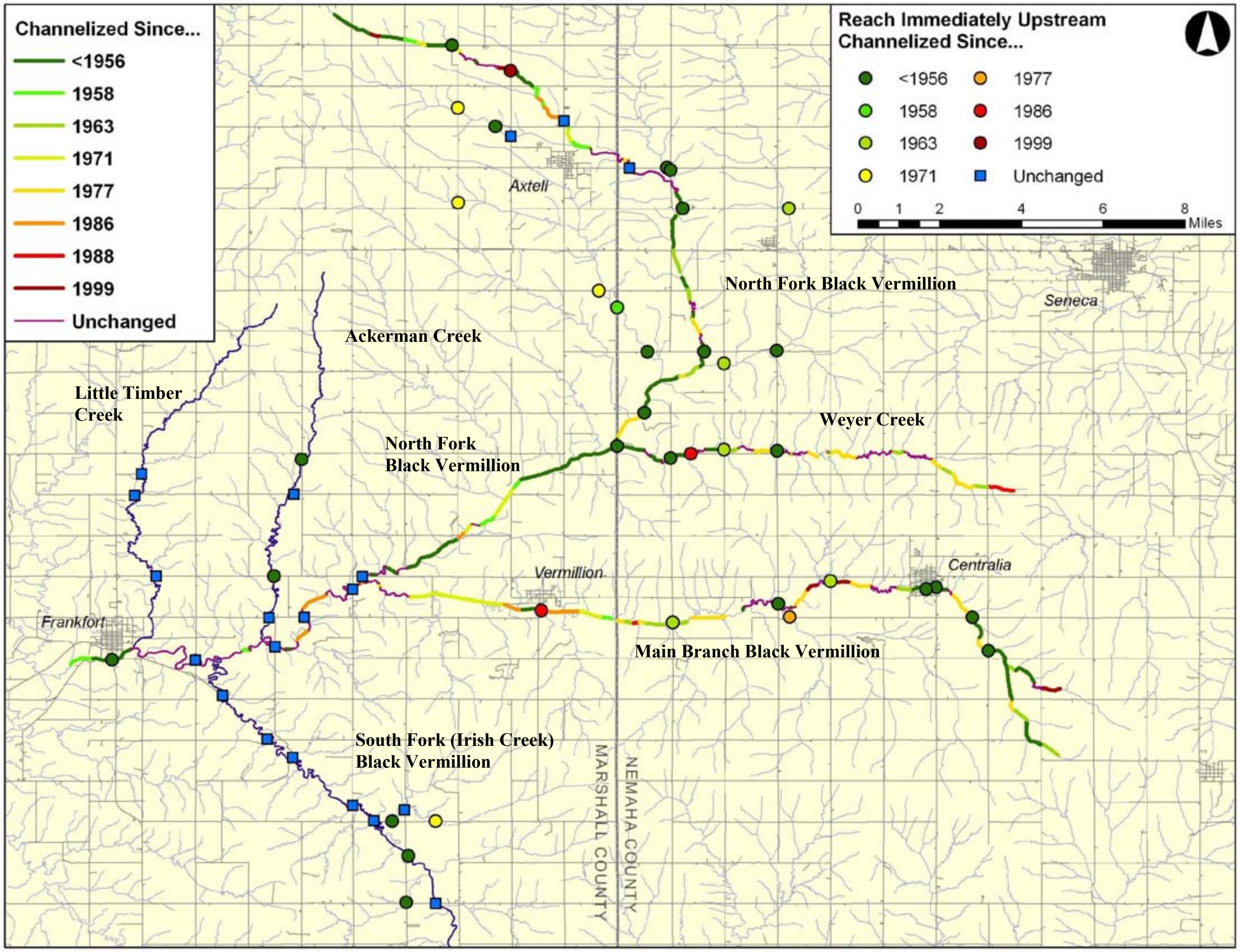


Figure 2.7 Map of timing of channelization in the Black Vermillion watershed. Created by Rob Daniels, 2008.

Figure 2.8 Channelization on the Main Branch of the Black Vermillion River near Vermillion, Kansas. Source: Erik Peterson, January, 1987.

Figure 2.9 Channelization on the Main Branch of the Black Vermillion River near Vermillion, Kansas. Source: Erik Peterson, January, 1987.

Figure 2.10 Channelization on the Main Branch of the Black Vermillion River near Vermillion, Kansas. Source: Erik Peterson, January, 1987.

Consequences of Channel Incision

The purpose of this section of the literature review is to illustrate the many negative consequences of channel incision in the fluvial environment. The section closes by showing how stream channels respond over time to channel incision and how, eventually, a potential recovery of the fluvial system can take place.

Hydrologic Effects of Channel Incision

The hydrologic effects of channel incision are many. Studies completed in Iowa by Schilling and Libra (2003) suggested that actively incising streams increased their baseflows because they more effectively captured inflowing groundwater. Shields et al., (1998) found slightly differing results in that incised streams flowed effectively with minimal baseflows for extended periods of time, however sharp, high flows more consistently occurred. Incised streams generally have an excess of stream power and channel capacity which then expedites further channel incision, bank erosion, and sediment transport and delivery processes (Darby and Simon, 1999).

Bank Erosion

As stated by Simon and Rinaldi (2006), channel incision contributes to the generation of higher and steeper streambanks. In turn, these banks are more susceptible to failure and are commonly found along streams that have been severely incised (Figure 2.11). According to Langendoen and Simon (2008) bank erosion occurs for two reasons. First, lateral erosion of the bank toe occurs because of the fluvial entrainment of in situ bank materials. This process is known as hydraulic erosion. Second, gravity can cause mass failure (slumping) of the upper part of the bank. Both of these processes can be triggered by channel incision since channel incision increases instability at the bank toe due to the lowering of the streambed. Hence, channel incision contributes to channel widening due to bank erosion and subsequent channel-width adjustment. Mass wasting of bank deposits can also result from increases in bank heights and angles, a direct result of channel incision (Darby and Simon, 1999). Decreases in shear strength of bank materials due to loss of matric suction are an attributed cause of bank erosion in incised channels as well. As a result, incised streams actively widen, triggering even more channel instability. Furthermore, past studies in nearby eastern Nebraska (Hanson and Simon, 2001) confirmed that channel bed materials that had originated from bank failures were found to have the weakest shear stresses, and subsequently, were the most easily erodible. Zaimes et al., (2005) found that bank erosion can contribute up to 50-90% of any given's stream sediment and phosphorous load. Simon and Rinaldi (2006) were more precise and stated that stream banks can contribute up to 80% of a stream's total suspended load. However, Simon (1992) found that channel widening and bank erosion are important processes in helping the incised channel to recover over time because these processes can effectively reduce flow depth, shear stress, and therefore slow the sediment transport capacity of the fluvial system.

Figure 2.11 Bank erosion on the North Fork of the Black Vermillion River. Source: Chris Sass, June, 2008.

Increased Sediment Yield

Sediment overload in streams in the United States is a major problem (Langendoen and Simon, 2008). The 1998 National Water Quality Inventory, published by the Environmental Protection Agency in 2000, shows that an overabundance of sediment is the main factor in the listing of water quality problems in the 1,350,000 km of rivers and streams that were studied. Excess sediment was discovered in 468,000 km (38%) of those rivers and streams, and was a more significant water-quality problem than both pathogens (36%) and excess nutrients (29% - USEPA, 2000).

Simon and Rinaldi (2006) concluded that sediments originating from incised channels can represent a significant proportion of the total sediment yield from a given landscape. They named erosion from the channel banks of incised streams as the dominant source of this increased sediment. They cited Simon and Thomas (2002) who calculated that streambank erosion contributes 90 percent of the total sediment load of the Yalobusha River in Mississippi. Simon and Hupp (1992) discovered that streambank erosion contributes 81 percent of the total sediment load in the Obion Forked Deer River in Tennessee. While the percentages of streambank-derived sediment listed here are substantial, Darby and Simon (1999) indicated that increased sediment loads and sediment transport capacities of incised streams are not static. They mention that these processes decrease asymptotically over time as the incised channels begin to recover. Further, increased channel cross sectional sizes that result from incision increase stream power and therefore have greater abilities to transport sediment loads.

Stream Channel Degradation and Aggradation

Stream channel degradation, or bed-level lowering, is a common response of unstable fluvial systems that have been affected by the factors that instigate channel incision. The severity of bed degradation is the result of the type of bed material and its subsequent resistance to erosion (Hanson and Simon, 2001). The flow characteristics of the stream also are a contributing factor (Hanson and Simon, 2001). The process of channel degradation will generally migrate upstream as a series of knickpoints or knickzones, depending on the bed substrate material and their cohesiveness and erosion resistance. The upstream progression of degradation will occur especially when bed-material mining or channelization have occurred because of the extreme disturbance to stream channels that have occurred (Simon and Rinaldi, 2006).

Simon and Rinaldi (2006) pointed out that downstream reaches of incised channels can become overwhelmed and oversupplied with sediment originating from upstream incising stream reaches. This leads to channel aggradation in those downstream reaches. This is a result of decreased channel gradients at downstream locations and an increased sediment load from upstream regions. An overabundance of sediment and decreased channel gradients at downstream locations can become problematic in their own right.

Stream Habitat Loss

Channel incision can have major negative impacts to the overall habitat qualities of a fluvial system. Such impacts include increased spatial habitat homogeneity, a greater temporal instability, less contact between the stream and its floodplain, and major shifts in fish community structure such as elimination of habitat for longer-lived fish species (Shields et al., 1998). Also, channel incision leads to major morphological changes within a fluvial system that remain in place for long periods of time. Furthermore, the longevity and severity of these impacts make them potentially more harmful than point or non-point source pollution (Shields et al., 1998).

Studies of wildlife populations in incised channels are commonly done concurrently between incised streams and incised streams that have been channelized. Negative consequences for wildlife are similar. For example, Shields et al., (1998) noted that stream habitat in incised streams becomes much more homogenous with decreasing channel characteristics such as riffles and pools. As stated by Brookes (1985) the most commonly stated reason for the loss of fish populations in channelized streams is the loss of riffle and pool sequences that provide varying habitats for fish. Prior to channelization, a given stream reach may have alternating pools and riffles. Post channelization, the same reach may consist of one long riffle. Unfortunately, quantitative analyses of wildlife populations impacted by channelization and/or incision are few. This is likely because very little baseline data was collected before incision and/or channelization took place. Emerson (1971) estimated that fish populations had been reduced to less than 20% of their pre-channelization numbers in the Blackwater River in Johnson County, Missouri.

Simon and Darby (1999) identified mobile and/or unstable streambeds in incised channels as being capable of destroying spawning areas and riffle-pool structures. Also, they note the negative effects to wildlife of bank erosion due to incision. These effects include higher water temperatures, decreased riparian vegetation, and increased turbidity. Overall, changes to streams due to channel incision and/or channelization can have potentially dire consequences for populations of fish and other wildlife in riparian corridors.

Sass (2008) reported that fish populations in streams of the Black Vermillion watershed have indeed been reduced due to channelization activities, channel incision, and overall channel instability. Sass (2008) stated that watershed landowners he talked to in casual conversation reported past healthy populations of bass, catfish, and crappie. Today, gar and minnows are the only fish with reportedly healthy populations in streams of the watershed. Two catfish, including a blue catfish of an estimated 2.2 kilograms in weight, were the only fish of significance seen during the fieldwork for this thesis in summer, 2008. This suggests that some populations of larger fish may still be present in the Black Vermillion system, albeit in reduced populations.

Negative Impacts to Human Interests

Incised channels contain flows that are more erosive than those same flows in a non-incised channel. Therefore, these incised channels are particularly difficult to manage because they are extremely dynamic (Darby and Simon, 1999). As a result, any in-channel structure such as bridges need to be designed for more increased flows, more erosive bed material, and greater amounts of in-channel morphological change such as scour and fill (Simon and Darby, 1999). Scour and fill can occur in very short lengths of time (hours to days) during higher flow events and can widely affect localized areas and bridges in response to those flows in incised channels (Simon and Rinaldi, 2000). Channel degradation due to incision can undermine abutments and piers while aggradation can create issues with trapping of large woody debris in the channel (Figure 2.12) as well as causing contraction and local scour around bridge pilings (Johnson and Simon, 1997). Baumel (1994) found that stream-channel degradation has resulted in the loss of agricultural lands since the turn of the century in western Iowa and damages to infrastructure that cost an estimated $1.1 billion. As noted by Simon and Rinaldi, (2000) 15 counties in northwestern Missouri identified 957 highway structures as being damaged by channel degradation.

Figure 2.12 Large woody debris upstream of bridge at Site 3210. Source: author, June, 2008.

Simon and Darby (1999) also wrote that materials such as large woody debris (LWD) that fall into incised channels due to bank failures can be hazardous to in-channel structures such as bridges (Figure 2.12). Such LWD can potentially cause bridge failures in incised channels (Simon and Darby, 1999).

Role of Riparian Vegetation

In the riparian zones of incised streams, vegetation provides many functions that can either help to alleviate or increase the effects of channel incision. Vegetation modifies flow and near-bank hydraulics, flow characteristics, and contributes to the quality of available habitat for wildlife. Streambank erosion is believed to occur as a result of hydraulic-induced bank-toe erosion and mass wasting, and riparian vegetation helps to mediate these processes (Simon and Collison, 2002). Riparian vegetation can also directly influence and reduce erosion rates due to its abilities to create hydraulic and geo-technical shear strength (Simon et al., 2004). Soil tends to be strong in compression but weak when subjected to tensional forces. Conversely, the fibrous roots of herbaceous plant species and trees are weak when subjected to compression forces. However, these roots are much stronger when exposed to tensional stresses. As a result, soil that contains roots has an enhanced strength that resists disturbance by fluvial erosional processes (Thorne, 1990).

Recovery from Channel Incision

Fluvial geomorphologists have long noticed that stream channels that have been perturbed by natural and human-induced changes follow through a somewhat predictable pattern of channel evolution (Davis, 1902), and Simon and Hupp, (1986). Several models have been developed to conceptualize these changes, such as Simon and Hupp (1986) and Schumm et al., (1984).

The model discussed here, and eventually used in the study of the Black Vermillion system, was developed by Simon and Hupp (1986). It was subsequently modified by Simon and Rinaldi (2006), Figure 2.13. This model was developed to illustrate the passage of time in channel adjustment and recovery after channelization. The model is segmented into stages numbered 1-6. Each stage represents dominant adjustment processes at that particular phase. Each stage is bordered by geomorphic thresholds that represent the geomorphic processes that result from the continuation of the stream recovery process through time (Simon and Rinaldi, 2006). One of these thresholds is the critical height of streambanks that is reached during incision. Prior to incision, banks are stable because bank heights are low enough that they haven't reached a critical height ($h<h_c$). Due to incision, that critical height is reached or exceeded, and the bank fails due to slumping ($h>h_c$). This threshold is important because of the significance of the process of bank erosion to the incision and widening process. Stage I represents the initial, pre-disturbance phase. Stage II represents channelization or the stream in another severely human-altered condition. Stage III shows subsequent channel degradation resulting from human disturbance. After a threshold was crossed in which bank slumping and channel widening was initiated, Stage IV shows degradation and widening. Stage V illustrates resulting aggradation and widening after the stream was able to adjust its bed level or deposition of sediment became possible. Stage VI shows that quasi-equilibrium may be the final outcome of a channelized stream reach (Figure 2.13).

Simon et al. (2004) stated that this model illustrates two potentially important "reference" channel conditions in Stages I and VI because both are considered to be channels in some type of equilibrium. However, as they noted, Stage I may never be reached again through recovery by some streams after a Stage II (channelization) event takes place. This most notably affects streams in the American Midwest because major land-clearing practices near the turn of the 20th century created major changes in land use and rain-fall to runoff ratios. Resulting changes in sediment storage and floodplain sedimentation may be irreversible (Simon et al., 2004). As a result, Stage VI may represent stream channel equilibrium, albeit not an originally natural one (Simon et al., 2004).

The amount of time required for streams to respond and to recover from channelization (Stage II) varies widely (Figure 2.14). Comparison studies done by Simon and Rinaldi (2006) between sand-bedded streams of West Tennessee and silt-bedded streams of western Iowa confirmed that wide discrepancies in response and recovery time exist in these differing environments (Figure 2.14). For example, in the sand-bedded streams of West Tennessee, Stage III (degradation) needed approximately 15 years to be reached post-channelization. Conversely, Stage III needed about 70 years to be attained in the silt-bedded streams of western Iowa. These discrepancies in time can also be related to discharge and precipitation.

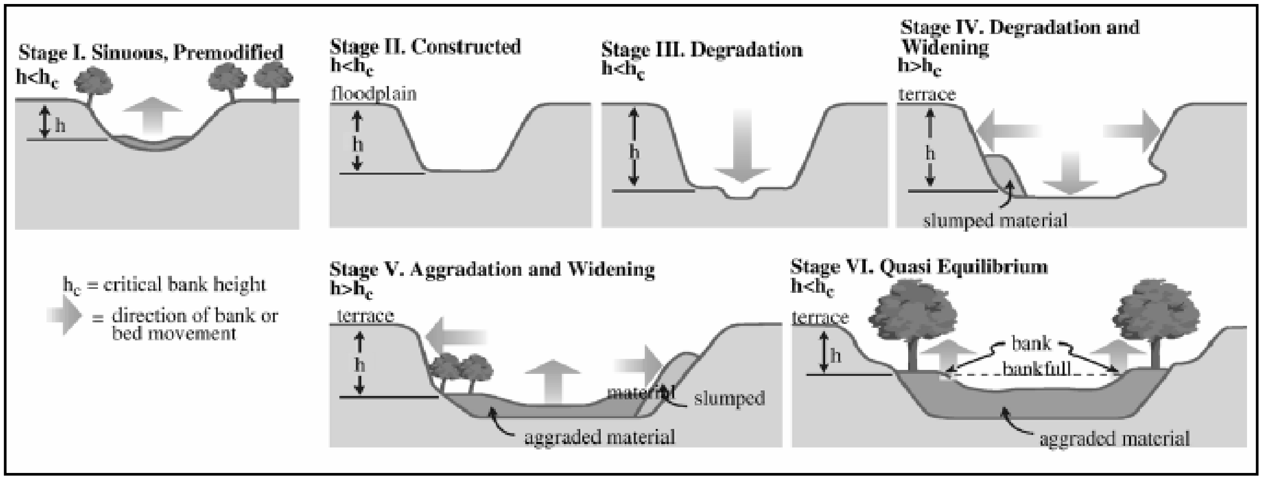


Figure 2.13. Stages of channel evolution following channelization. Source: Simon and Rinaldi (2006) as modified from Simon and Hupp (1986).

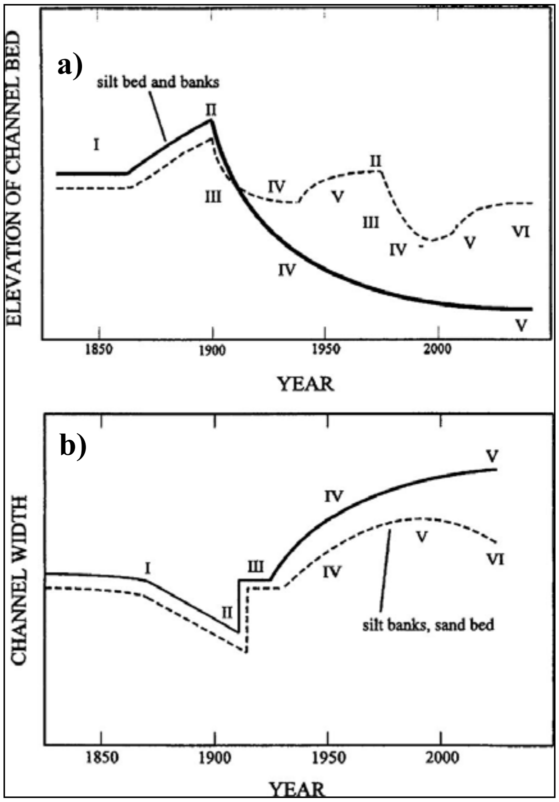


Figure 2.14 Channel adjustment through stages in the mid-continent of the U.S. Represents response of stream channels after channelization. Source: Simon and Rinaldi (2006).

The streams of the Black Vermillion watershed have been channelized at different times (Figure 2.7). So, depending on the timing of that channelization, Stage II would have been present at different times and in different areas of the watershed at a given time. About 70 years was required to reach Stage III in the silt-bedded streams of southwestern Iowa. However, the timing of the response of the silt-bedded channels in the Black Vermillion watershed has been complicated because of the varying time periods and spatial locations in which channelization took place.

Furthermore, it is important to note that streams are dynamic systems. Conceptual models, like Simon and Rinaldi's (Figure 2.13) or Rosgen's (1999, 2001b) while perhaps beneficial, may not always apply when analyzing the variable nature of the structure of fluvial environments and of the widely differing factors influencing them. This is particularly applicable to streams that have been dramatically altered by human activities. With this in mind, studies such as Landwehr and Rhoads (2003) have illustrated that streams vary in their responses to channelization and may not necessarily follow a conceptual model. For example, the Spoon River in Illinois, as studied by Landwehr and Rhoads (2003), did not undergo incision or major adjustments in gradient after channelization had occurred. Instead, this stream established a mode of recovery post-channelization through the creation of a stable inset channel with accompanying sediment deposition and channel aggradation. So, the unique nature of the fluvial system being studied should be kept in focus when analysis is being done.

Once stream incision has been initiated, the stoppage of the process is difficult. Conceptual models such as Simon and Rinaldi (2006) shown above assume that the affected stream can be allowed to respond on its own and that recovery is permitted to run its own independent course. Both natural factors and human-induced actions can help to stop or minimize the process and subsequent effects of stream channel incision. Natural factors include channel bed aggradation or the channel bed eroding into a more resistant lithologic material (Grissinger and Murphey, 1993). In-channel meandering (Figure 2.1) is another sign of natural adjustment.

Engineering and installing man-made structures or materials into the incised channel has been attempted. Examples of these include grade control structures, rip-rap, check dams, and retaining walls. Such objects or materials placed into the affected channel can also be done to help halt the process of stream incision (Watson et al., 1997; Simon and Darby, 2002). As noted by Simon and Darby (2002) mixed results can ensue as their results indicated that grade control structures are only effective when emplaced in incising channels soon after channel incision has been instigated.

CHAPTER 3 - Methods

The methods chapter is composed of four sections based on the three major research objectives of the study. The first section describes the process of site selection that was completed to identify study sites in the Black Vermillion watershed. The second section describes analysis needed to understand the spatial extent of channel incision within the watershed. The third section describes the processes undertaken to understand the timing of channel incision within the watershed. The fourth section shows the methods used to understand the causes of channel incision within the watershed.

Study Site Selection

Beginning in May, 2008, Geographic Information Systems (GIS) information was collected on the Black Vermillion watershed. Digital data layers were downloaded from the Kansas Geospatial Community Commons (KGCC), the state of Kansas's source for free GIS data. Data layers downloaded from this source were the following: a) soils, b) hydrologic unit code (HUC) 11 and 14 boundaries, c) stream flowlines, d) national land cover data (NLCD), e) state roads, f) non-state roads, g) state bridges, h) county bridges, i) bedrock geology, j) surficial geology, k) digital elevation model (DEM), and l) 2006 aerial photos.

Each of these data layers were downloaded into designated folders on personal computers or into a personal X:Drive on the KSU Geography computer server as compressed files. These compressed files were then unzipped using WinZip software. Following this, the data layers were opened in a Geographical Information System (GIS) software product developed, marketed, and sold by Environmental Systems Research Institute (ESRI). This software product, known as ArcMap 9.3, was accessed and utilized through the site license owned by the KSU Geography Department.

Following opening of the data layers in ArcMap, the layers were clipped to the HUC 14 watershed boundary of the Black Vermillion River. Clipping of the data layers provides a cleaner look at the data, shrank the size of the data necessary to be stored, and creates better looking maps (Figure 1.3 and Figure 1.4).

In conjunction with gathering background information and GIS data on the study area, a sampling methodology was developed for fieldwork. Since analysis of incision watershed-wide was a major objective of this study, a sampling methodology was needed in which the full extent of the watershed could be covered. For several reasons, bridge sites were chosen for study sites. Most importantly, bridge locations provide public access to stream channels and banks. Since Kansas state laws prohibit any public access to stream channels on private land (Associated Press - Kansas Supreme Court, 1990) study locations were sought that were legally accessible. Further, sampling near bridges made the fieldwork more effective and time efficient because of accessibility reasons. Finally, because of the extensive coverage of Township and Range roads throughout the watershed area, bridge locations were available throughout the watershed in a dense spatial pattern.

Bridge locations were identified throughout the watershed using aforementioned GIS information. Both state and county bridge locations are provided for free download in data layers included on the Kansas Geospatial Commons website. Each bridge was identified by state or county site-specific four or five digit number. These site numbers, such as 3183 or 14193, provided ideal values for identifying our own study sites and were utilized as such. Maps were created using these bridge data as well as data layers that showed the location of both state and county roads. These data layers also included labels that identified bridge numbers and road names. Maps were made and printed of the watershed that included this information. These maps became very useful in the field for navigating throughout the watershed and also for developing a sampling strategy in attempts to visit every bridge location.

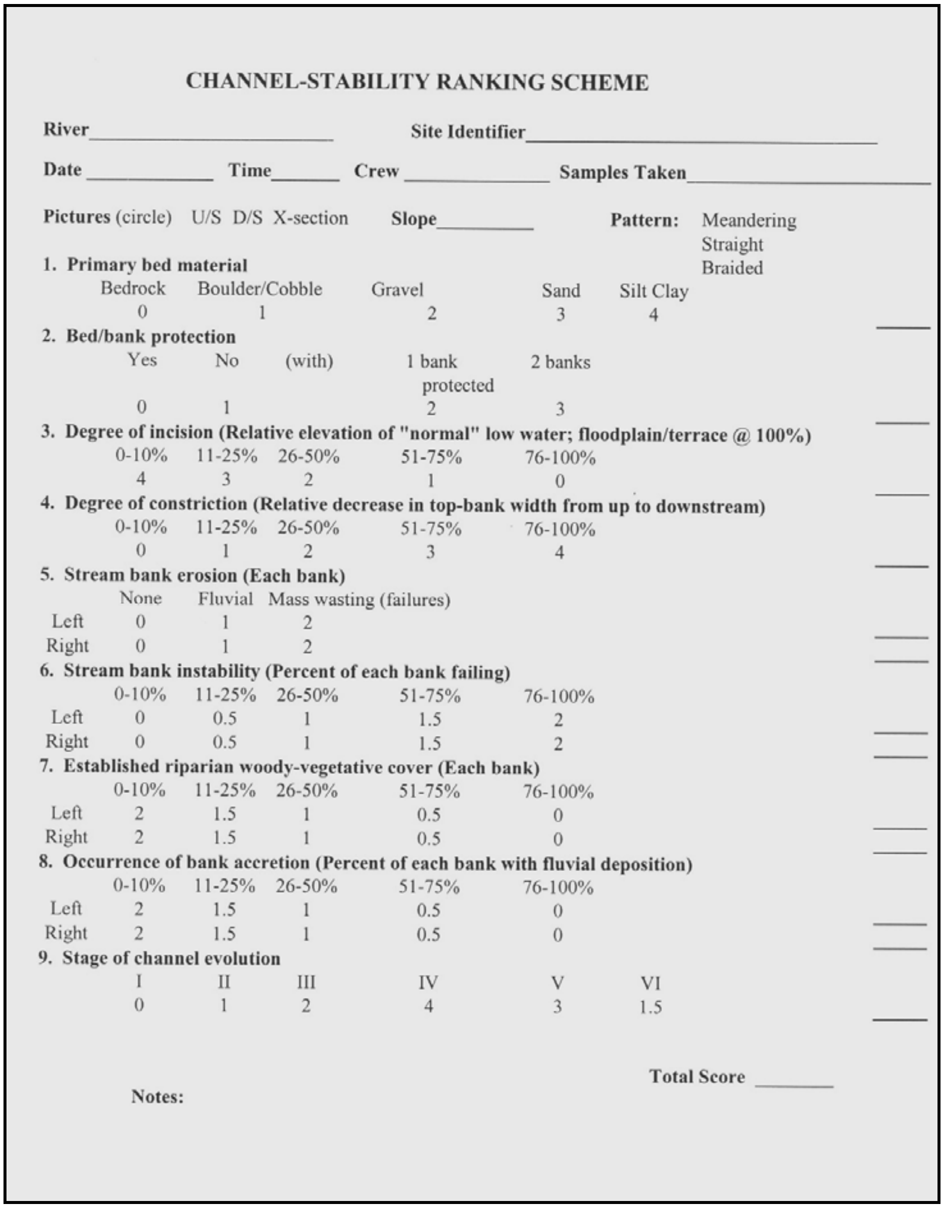
Once bridge locations were identified using GIS, the bridges were driven to and field collection of data began. At each bridge location (site), a GPS location in latitude and longitude was collected using a Garmin handheld GPS device. A waypoint was marked for each site. Each waypoint was site-specific and recorded on field data sheets. Photos were taken using a digital camera of the stream channel upstream and downstream of each bridge site as well as other features of interest. Examples of things of note include major bank slumping, evidence of tile drainage from fields, bank stabilization structures, or large woody debris (Figure 2.12).

Starting from the left bank (facing downstream) on the upstream side of each bridge, a 30.48 meter tape with a weight attached to the end were dropped from the bridge at every break in channel topography from one end of the bridge to the other. The depth to each channel feature was noted from the dropped tape and recorded. Also recorded was the distance on a second horizontal tape where each depth measurement was collected at. Depth measurements were collected at edges of floodplain, channel banks, water, in-channel structures such as sediment bars and the thalweg, and large woody debris. This same method of measurement was completed on the downstream side of the bridge as well. In this way, a channel cross section was created both upstream and downstream of the bridge and the characteristics of the channel were recorded as well.

After channel measurements were collected, a Channel Stability Ranking Scheme (a.k.a. Rapid Geomorphic Assessment, or RGA) was completed for each site, with a separate RGA completed for both upstream and downstream of the bridge (Figure 3.1). Almost every category of the RGA could be filled out in the field by making observations about the stream conditions present at that location. The exceptions were categories three (degree of incision) and four (degree of constriction). These two categories were calculated following entry of the RGA form into Microsoft Excel.

The purpose of the RGA is to use characteristics of the stream channel and riparian corridor at a given location in order to assess active channel processes and relative stability (Simon et al., 2007). As stated by Simon et al., (2007), tallying the values on the RGA form gives a stability-index value. Stability-index values greater than 20 are demonstrative of severe channel instability at that location. Values less than 10 are indicative of channels that are relatively stable. Use of the RGA's in combination with Channel Evolution Models such as that developed by Simon and Hupp (1986) is particularly helpful (Figure 2.13). Completion of the RGA form in the field involved assessing what stage of channel evolution present at that site. Thus, from the outset these two field assessment techniques were linked.

The joining of these two methodologies allow for channel instability to be mapped on a localized or a system-wide scale. Further, channel instability can also be identified on a localized or more regional scale (Simon et al., 2007). These assessment techniques provided an ideal methodology in which to analyze the streams of the Black Vermillion watershed and were utilized as a central data-gathering technique for this study.



CHANNEL-STABILITY RANKING SCHEME

River________________________ **Site Identifier**___________________________________

Date ____________ **Time**______ **Crew** ______________ **Samples Taken**_______________________

Pictures (circle) U/S D/S X-section **Slope**_________ **Pattern:** Meandering Straight Braided

1. Primary bed material

Bedrock	Boulder/Cobble	Gravel	Sand	Silt Clay	
0	1	2	3	4	_____

2. Bed/bank protection

Yes	No	(with)	1 bank protected	2 banks	
0	1		2	3	_____

3. Degree of incision (Relative elevation of "normal" low water; floodplain/terrace @ 100%)

0-10%	11-25%	26-50%	51-75%	76-100%	
4	3	2	1	0	_____

4. Degree of constriction (Relative decrease in top-bank width from up to downstream)

0-10%	11-25%	26-50%	51-75%	76-100%	
0	1	2	3	4	_____

5. Stream bank erosion (Each bank)

	None	Fluvial	Mass wasting (failures)	
Left	0	1	2	_____
Right	0	1	2	_____

6. Stream bank instability (Percent of each bank failing)

	0-10%	11-25%	26-50%	51-75%	76-100%	
Left	0	0.5	1	1.5	2	_____
Right	0	0.5	1	1.5	2	_____

7. Established riparian woody-vegetative cover (Each bank)

	0-10%	11-25%	26-50%	51-75%	76-100%	
Left	2	1.5	1	0.5	0	_____
Right	2	1.5	1	0.5	0	_____

8. Occurrence of bank accretion (Percent of each bank with fluvial deposition)

	0-10%	11-25%	26-50%	51-75%	76-100%	
Left	2	1.5	1	0.5	0	_____
Right	2	1.5	1	0.5	0	_____

9. Stage of channel evolution

I	II	III	IV	V	VI	
0	1	2	4	3	1.5	_____

Total Score _______

Notes:

Figure 3.1 Rapid Geomorphic Assessment (RGA) form, as cited by Simon et al., (2007).

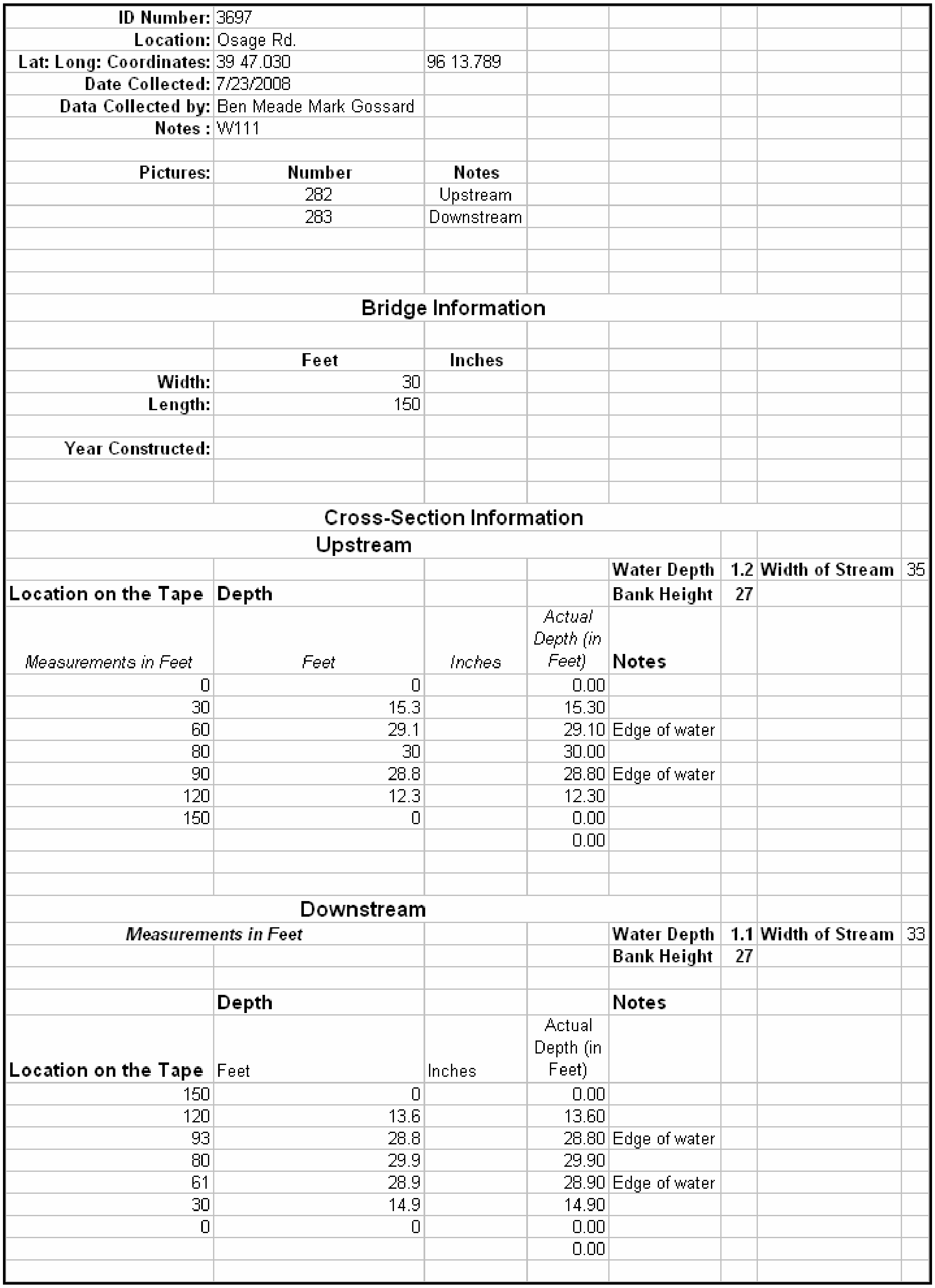
Data were collected at a total of 129 bridge sites throughout the Black Vermillion watershed during the summer of 2008. It should be noted that these 129 sites at which data were collected did not include every bridge location in the watershed. Some bridge locations were identified using GIS and visited in the field. However, for three major reasons were eliminated for data collection. The first reason for this elimination was that the channel under the bridge was very small and/or only contained a very small intermittent channel. Since channel incision was being studied for this thesis, any location where the stream channel was too small to actively incise is not necessary to be included. A second reason for this elimination was the bridge at the study site was a box culvert. Since box culverts are installed complete with a concrete channel bed lining, they successfully prevent the channel from downcutting at that location. The third reason for a site location being eliminated from this analysis was the presence of a low-water crossing at that location. Low water crossings completely alter the previous channel configurations and measurement of channel dimensions are not possible (Figure 3.2).

After field measurements had been collected at all 129 sites, further sites were eliminated after office review using 2006 aerial photos and photos taken in the field in the summer of 2008. A total of 22 more sites were removed for various reasons. These reasons included being immediately upstream or downstream of flood control structures, cattle ponds, or upon further review were deemed to have channels that were intermittent or too small to actively incise. A total of 107 sites were selected to be included as the remainder of the data for the rest of the project. These 107 sites are spread throughout the watershed and represent channels of all sizes in the Black Vermillion watershed.

Figure 3.2 Low water crossing at Site 13103. Source; author, July, 2008.

All information collected in the field was recorded on field data sheets for each site. The information from these sheets was then entered into Microsoft Excel spreadsheets for each study site, as labeled by bridge number. Each spreadsheet contained measurements for both upstream and downstream of each bridge site (Table 3.1, Appendix B). They also were designed to generate automatic channel cross sections for each site (Figure 3.3) and to create a chart showing the comparison between the cross sections from both up and downstream. Further, they were designed to automatically tally the total scores for the Channel Stability Ranking Scheme (a.k.a. Rapid Geomorphic Assessment - RGA) once that information had been entered. These data sheets also provided a convenient and organized way to store photos from each site as well. Shown below are examples of this electronic storage using site #3697, one of the final 107 study sites.

Table 3.1 Field data sheet for upstream of site 3697.



ID Number:	3697						
Location:	Osage Rd.						
Lat: Long: Coordinates:	39 47.030	96 13.789					
Date Collected:	7/23/2008						
Data Collected by:	Ben Meade Mark Gossard						
Notes :	W111						
Pictures:	**Number**	**Notes**					
	282	Upstream					
	283	Downstream					
Bridge Information							
	Feet	**Inches**					
Width:	30						
Length:	150						
Year Constructed:							
Cross-Section Information							
Upstream							
				Water Depth	**1.2**	**Width of Stream**	35
Location on the Tape	**Depth**			**Bank Height**	**27**		
Measurements in Feet	*Feet*	*Inches*	*Actual Depth (in Feet)*	**Notes**			
0	0		0.00				
30	15.3		15.30				
60	29.1		29.10	Edge of water			
80	30		30.00				
90	28.8		28.80	Edge of water			
120	12.3		12.30				
150	0		0.00				
			0.00				
Downstream							
Measurements in Feet				**Water Depth**	**1.1**	**Width of Stream**	33
				Bank Height	**27**		
	Depth			**Notes**			
Location on the Tape	Feet	Inches	Actual Depth (in Feet)				
150	0		0.00				
120	13.6		13.60				
93	28.8		28.80	Edge of water			
80	29.9		29.90				
61	28.9		28.90	Edge of water			
30	14.9		14.90				
0	0		0.00				
			0.00				

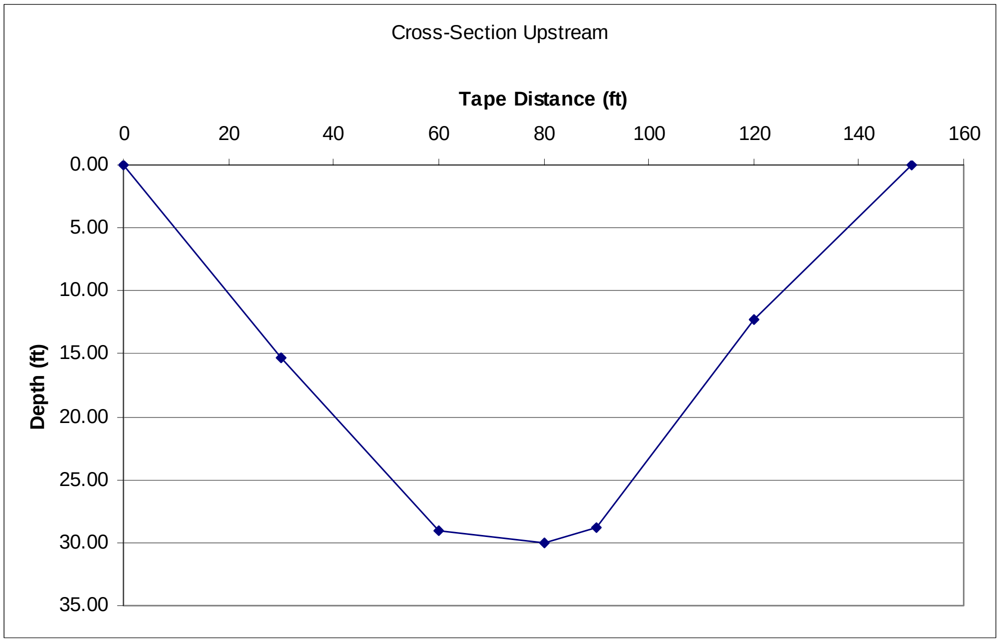


Figure 3.3 Channel cross section for site 3697, upstream of bridge.

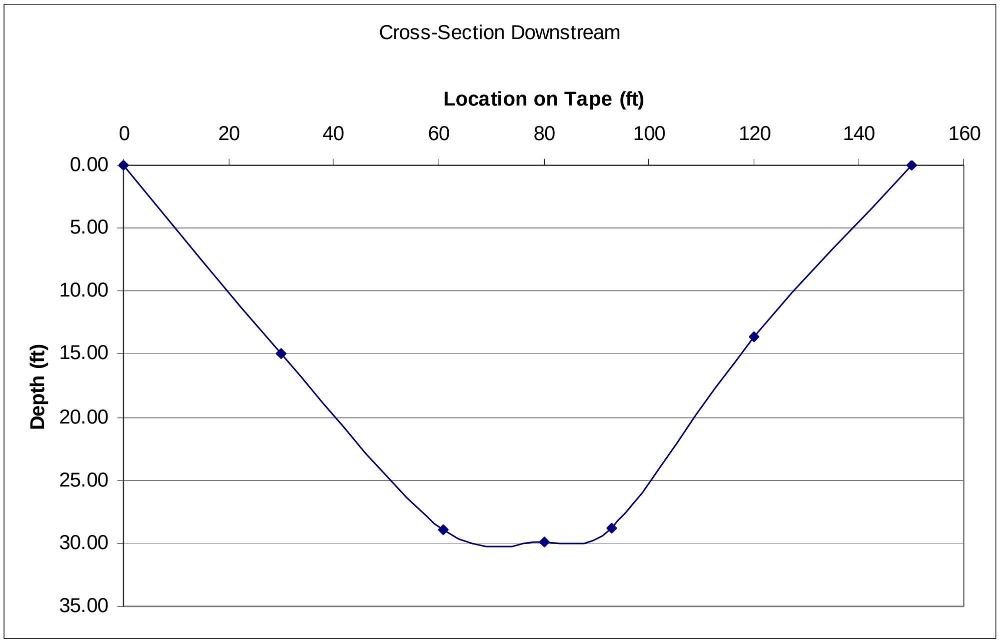


Figure 3.4 Channel cross section for site 3697, downstream of bridge.

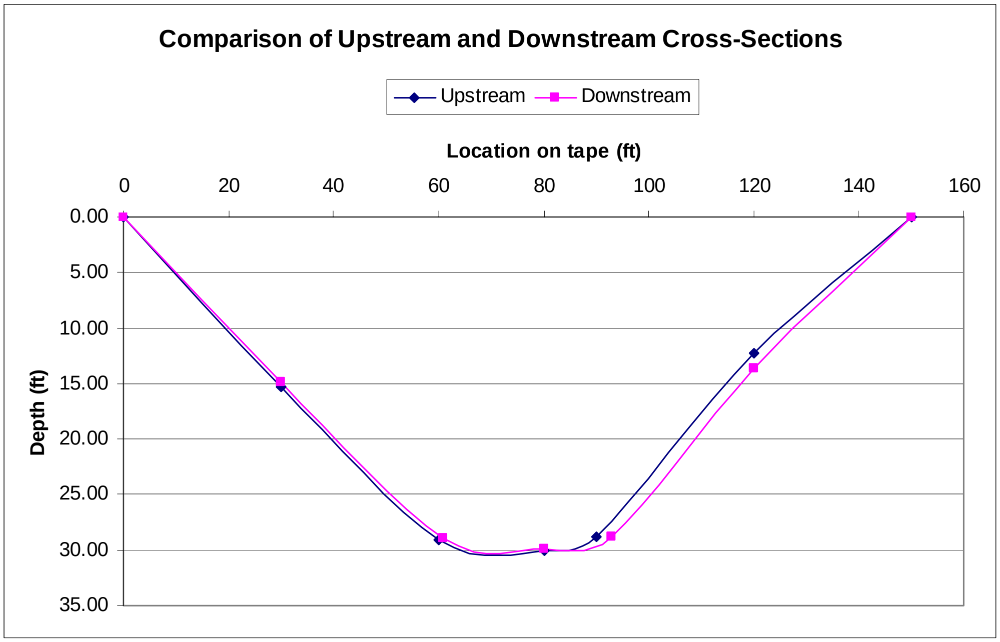
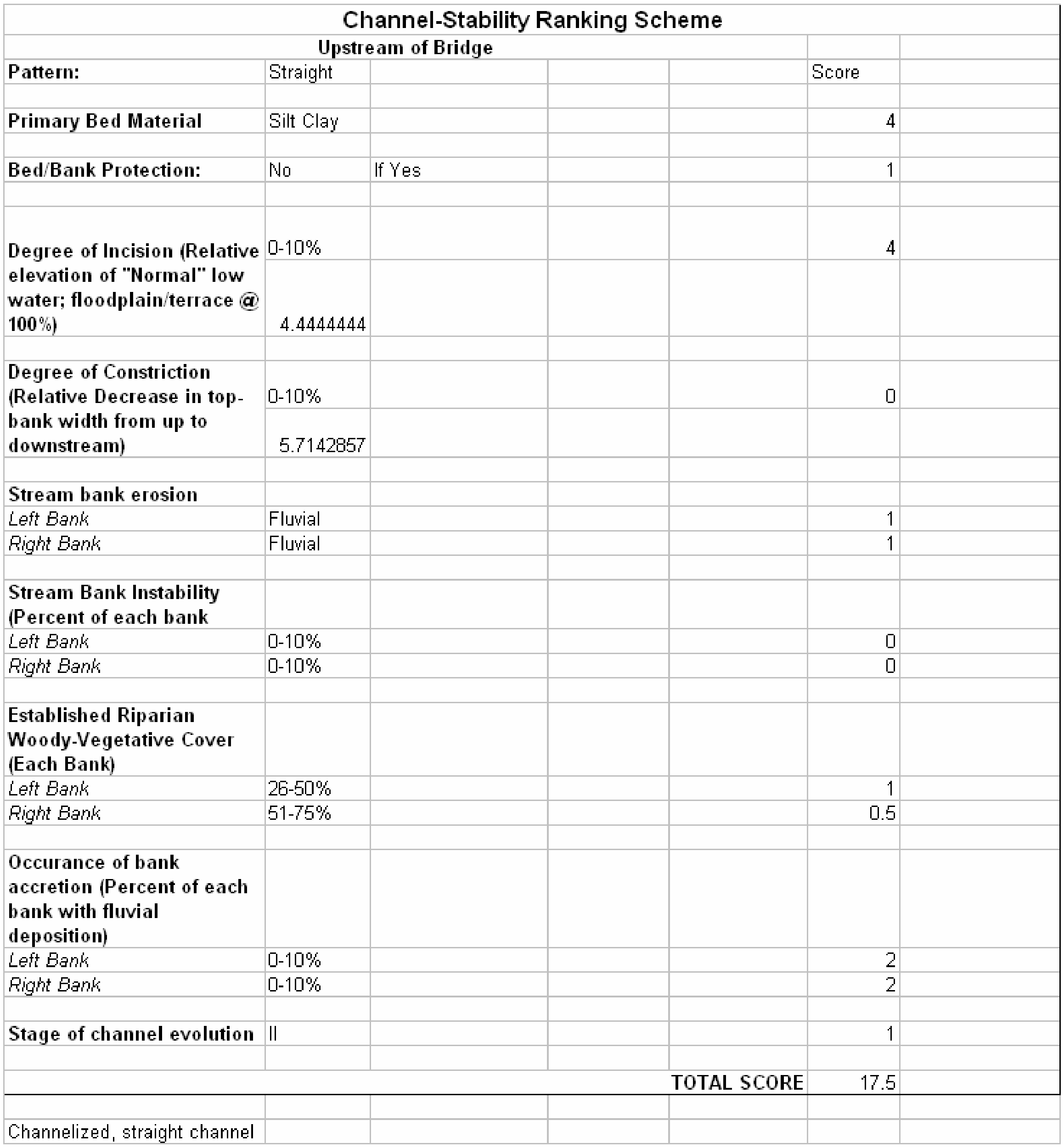


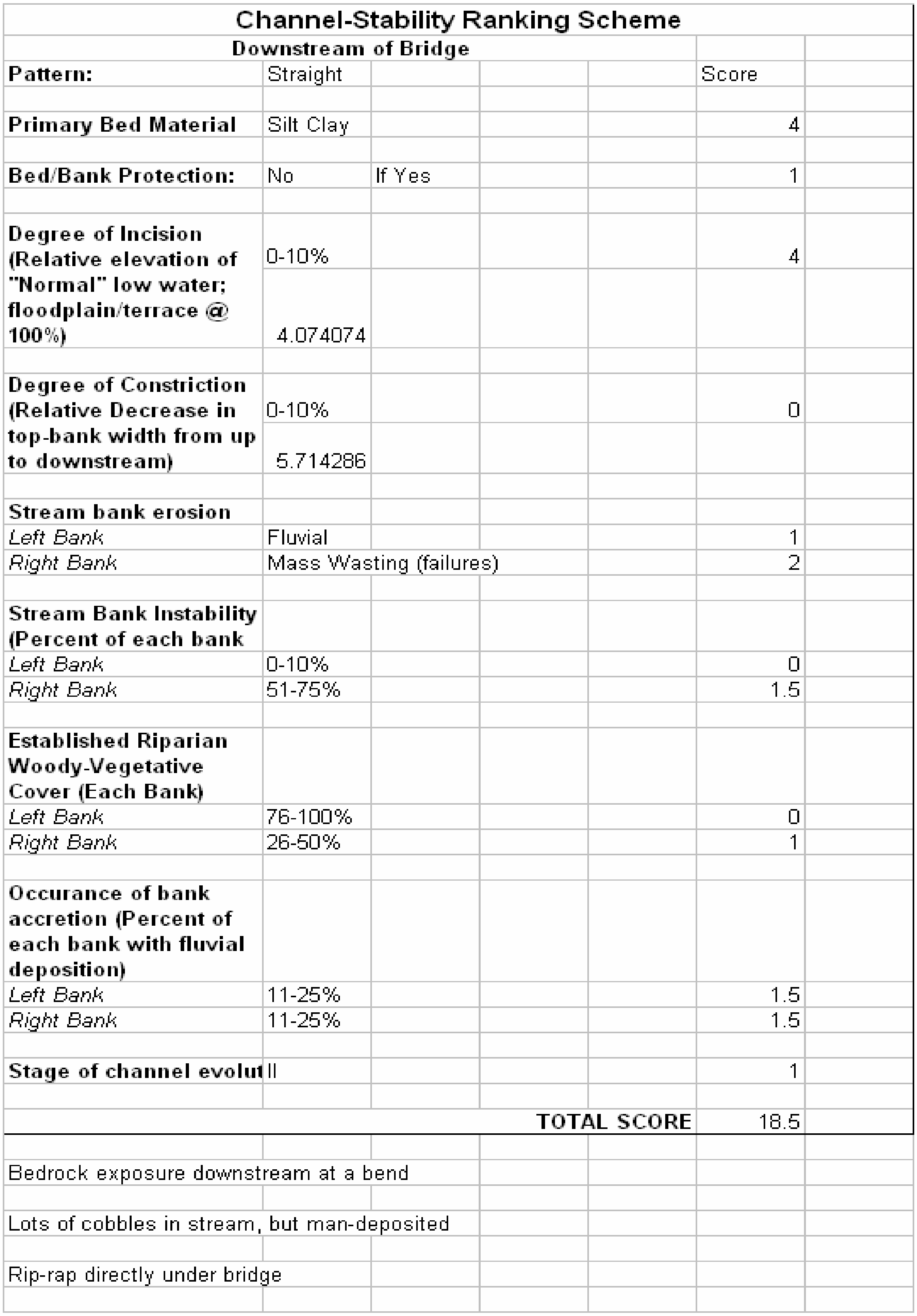
Figure 3.5 Comparison of cross sections upstream and downstream of bridge at site 3697.

Table 3.2 Channel Stability Ranking Scheme (RGA) for upstream of site 3697.



Channel-Stability Ranking Scheme						
Upstream of Bridge						
Pattern:	Straight				Score	
Primary Bed Material	Silt Clay				4	
Bed/Bank Protection:	No	If Yes			1	
Degree of Incision (Relative elevation of "Normal" low water; floodplain/terrace @ 100%)	0-10%				4	
	4.4444444					
Degree of Constriction (Relative Decrease in top-bank width from up to downstream)	0-10%				0	
	5.7142857					
Stream bank erosion						
Left Bank	Fluvial				1	
Right Bank	Fluvial				1	
Stream Bank Instability (Percent of each bank						
Left Bank	0-10%				0	
Right Bank	0-10%				0	
Established Riparian Woody-Vegetative Cover (Each Bank)						
Left Bank	26-50%				1	
Right Bank	51-75%				0.5	
Occurance of bank accretion (Percent of each bank with fluvial deposition)						
Left Bank	0-10%				2	
Right Bank	0-10%				2	
Stage of channel evolution	II				1	
				TOTAL SCORE	17.5	
Channelized, straight channel						

Table 3.3 Channel Stability Ranking Scheme (RGA) for downstream of site 3697.



Channel-Stability Ranking Scheme						
Downstream of Bridge						
Pattern:	Straight				Score	
Primary Bed Material	Silt Clay				4	
Bed/Bank Protection:	No	If Yes			1	
Degree of Incision (Relative elevation of "Normal" low water; floodplain/terrace @ 100%)	0-10%				4	
	4.074074					
Degree of Constriction (Relative Decrease in top-bank width from up to downstream)	0-10%				0	
	5.714286					
Stream bank erosion						
Left Bank	Fluvial				1	
Right Bank	Mass Wasting (failures)				2	
Stream Bank Instability (Percent of each bank						
Left Bank	0-10%				0	
Right Bank	51-75%				1.5	
Established Riparian Woody-Vegetative Cover (Each Bank)						
Left Bank	76-100%				0	
Right Bank	26-50%				1	
Occurance of bank accretion (Percent of each bank with fluvial deposition)						
Left Bank	11-25%				1.5	
Right Bank	11-25%				1.5	
Stage of channel evolut	II				1	
				TOTAL SCORE	18.5	
Bedrock exposure downstream at a bend						
Lots of cobbles in stream, but man-deposited						
Rip-rap directly under bridge						

This methodology of electronically storing all of the field data provided many advantages. First, it organized field information in an easily-accessible, easily-shared, and easily-reproducible format. Second, it allowed for automatic calculation of the RGA scores. Third, it provided cross sections that were automatically generated as width and depth values for each site were entered. Fourth, it provided an effective way in which to insure that our data were not lost as these data sheets were continually backed up in various computer hard drives, KSU Geography file server folders, and external hard drives. Fifth, site photos taken in the field could be included in the electronic data sheets as well. This made comparisons between sites relatively straightforward.

Following the collection of field data and organization of that information in Microsoft Excel, each of the cross section and channel measurements generated by fieldwork were added to a Microsoft Excel sheet that listed each site number (four or five digit bridge number) and that site's corresponding channel depth (in feet). After the depth values were recorded in Excel in feet, they were converted to meters. After the data conversion had taken place, the latitude and longitude values for each of the 107 sites throughout the watershed were then matched with the latitude and longitude measurements that were taken with the GPS unit in the field. These coordinates, and their associated channel depths, were imported into ArcMap. From these data, a data layer was created and then displayed in ArcMap. The data were then separated using the Jencks Natural Breaks method in ArcMap so that the depths could be illustrated in the ArcMap display. A symbology was then chosen in ArcMap that would effectively illustrate depth. In this way, the channel depths in the watershed would be visible when viewed. This map, therefore, would show channel depths at 107 separate locations throughout the Black Vermillion watershed for the year 2008. The sites where the channels were deeper would, in effect, be areas where more channel degradation (incision) had taken place.

With information on channel depths now available watershed-wide from the year 2008, historical baseline information on channel depths in the watershed became needed. For this project, a set of valley cross sections collected by the Soil Conservation Service (SCS) in 1963 were used (Figure 3.6). These valley cross sections were collected in a total of 243 locations throughout all three sub-watersheds of the Black Vermillion watershed upstream of Frankfort. Exact data collection techniques surrounding these valley cross sections are unclear. What little is known is that after elevation data was collected by surveyors in the field, their measurements were transcribed onto paper using a Kelsh plotter (SCS, 1966).

According to the SCS work plans published in 1966 for all three sub-watersheds, these cross sections were surveyed (in feet) in order to assist with the planning for floodwater retention structures, erosion control measures, grade-stabilization structures, and channel modification activities. As stated in these same reports, the valley cross sections were done with sufficient detail to show changes in topography, crop boundaries, roads, fences, and to show characteristics of the stream channel at the locations where the surveys were completed throughout the watershed.

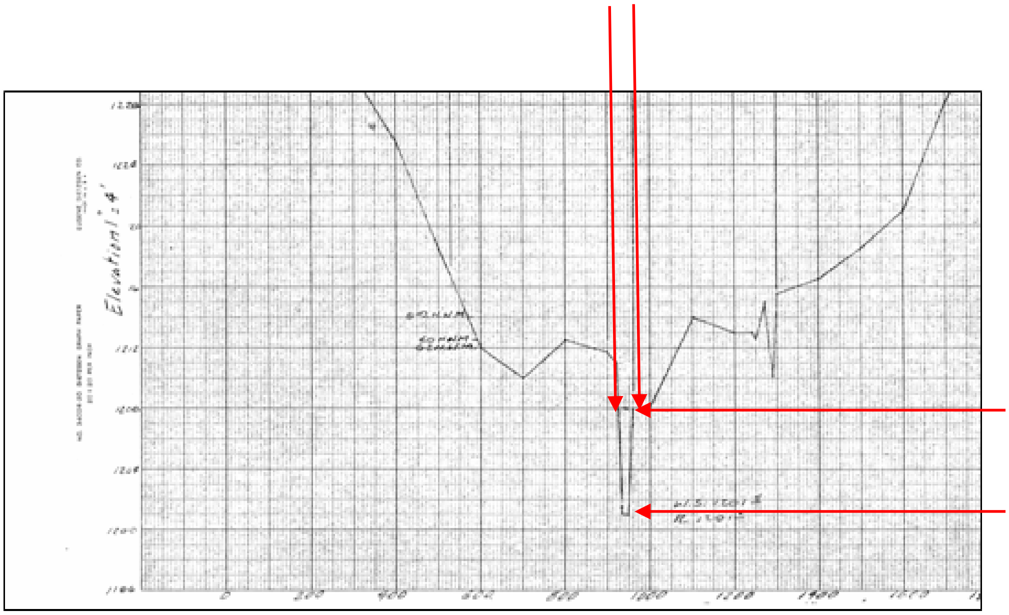


Figure 3.6 Example of valley cross section collected in 1963 by the SCS. Vertical exaggeration 50X.

For each of these 243 cross sections, channel width and depth were measured for this study. To complete this task, first the channel location on each had to be found. On these cross sections, the channels were visible as deep V-shaped structures (Figure 3.6). The deep V-shape of the channels is misleading; vertical exaggeration on these cross sections is 50 times. Also, despite the assertions of the SCS work plan reports (1966) details were not visible on the cross sections. This was attributable to the scale of the valley cross sections. Thousands of meters in length, they do not provide enough detail to show individual channel characteristics such as pools, riffles, bars, etc (Figure 3.6). In the case of this study, the extensive spatial coverage of these valley cross sections is a major advantage and is particularly rare. For what these cross sections lack in detail, they make up for in breadth of coverage throughout the watershed and they do provide overall channel depth. For this analysis, both channel width and channel depths were collected (Figure 3.6).

Channel depth was measured by identifying the elevation of the top of channel on the cross section. The elevation on the bottom of the channel was then measured as well (Figure 3.6). By subtracting the bottom elevation from the top, the approximate channel depth at that location in 1963 could be ascertained. These depths were then recorded in Microsoft Excel along with the corresponding number of the cross section.

Channel width was identified by measuring width of the deep V-shaped channels that were visible on each of the valley cross sections (Figure 3.6). These widths were then recorded in Microsoft Excel along with the corresponding number of the cross section.

When these cross sections were measured in 1963, they were labeled based on their location in each of the three sub-watersheds of the Black Vermillion watershed. The cross sections are paired with a set of aerial photos that have the cross section drawn as a line (Figure 3.7). These aerial photos, totaling 24 in all, show the locations of all of the cross sections used for this study. These aerial photos were originally in paper form. They were scanned at 600 dots per inch and saved on a computer as JPEG files. They were then cropped to the photo boundaries using Adobe Photoshop software. An example of one of these aerial photos is visible in Figure 3.7 with some of the valley cross sections labeled.

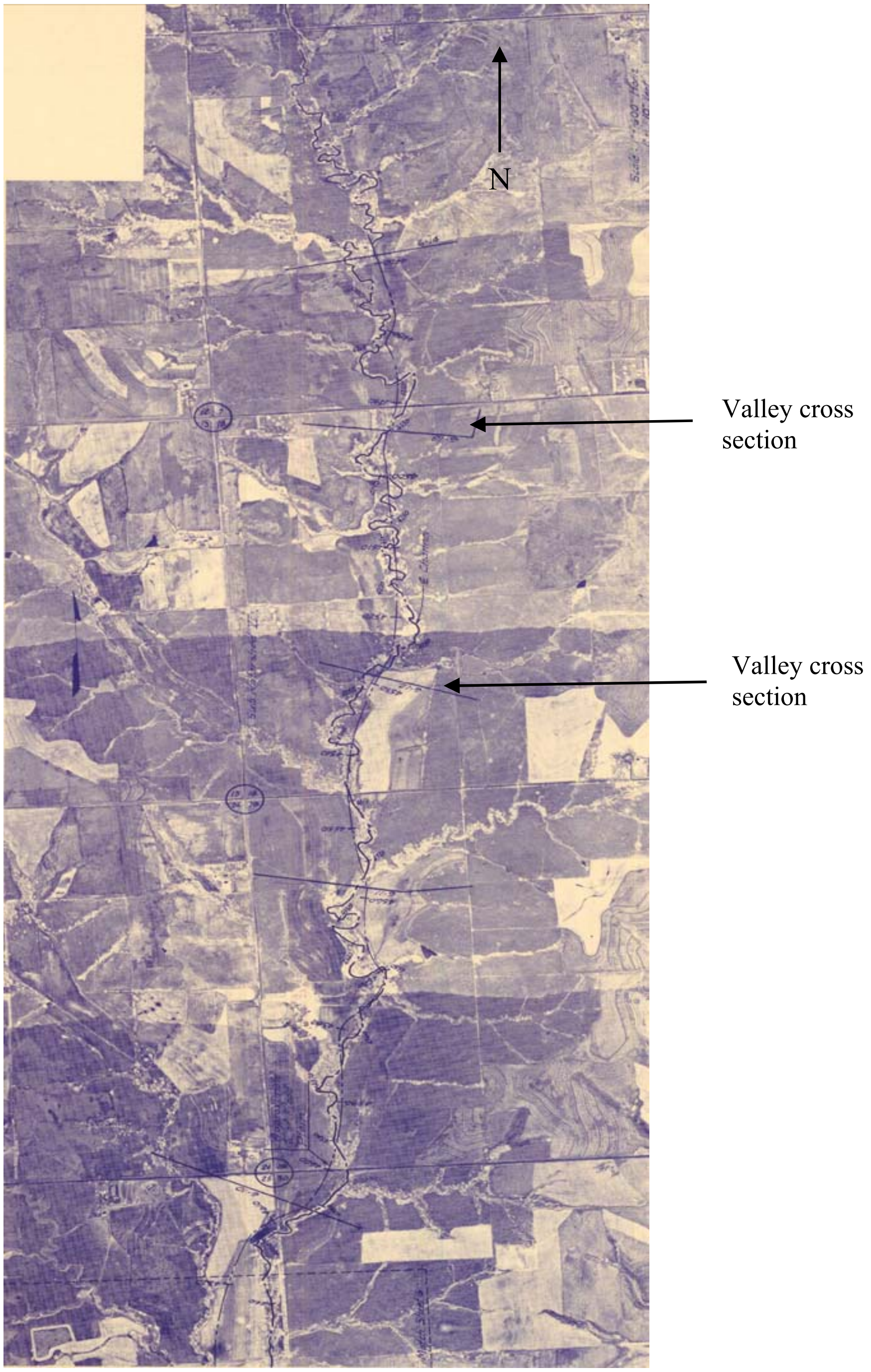


Figure 3.7 Example of aerial photo that accompanied the set of SCS valley cross sections. Showing locations of valley cross sections. Source: Soil Conservation Service (SCS).

All twenty four of these scanned, saved, and cropped aerial photos were entered into ArcMap 9.3 software as digital copies. Following this, a basemap was established by using a series of 2006 aerial photos in Digital Orthographic Quarter Quadrangles (DOQQ) form that were downloaded from the Kansas Geospatial Community Commons (KGCC) website. Using the geoprocessing toolbar in ArcMap, the aerial photos showing the valley cross sections were then georeferenced to this basemap of the watershed by using reference points. Reference points are positions on the ground that have not moved in the interim between the times the aerial photos (pre-1963) and 2006 were taken. Ideal reference points included street intersections, township and range boundary markers, old house locations, etc. Reference points were specifically chosen throughout the area of the pre-1963 aerial photos in order to reduce distortion and also to be as accurate as possible.

Once all twenty four of these pre-1963 aerial photos had been georeferenced to the basemap, the intersection points between all 243 of the valley cross sections and the stream that they cross were identified. Using ArcMap, a point in a data layer was assigned to each of the valley cross section/stream intersection locations. Each of these points were associated with a latitude and longitude location that was then entered into an Excel spreadsheet. The spreadsheet containing that latitude and longitude also had the associated valley cross section number and depth information as well. This numerical information, entered as XY coordinates into a table in ArcMap, allowed for the mapping of the locations and their associated channel depths to be completed. A map was then created using this method that showed these measurements. In this way, channel depths in 1963 throughout the watershed could be illustrated.

By measuring channel depths throughout the watershed in 1963, the extent to which those channel depths had changed between 1963 and 2008 could be measured. Sites of the 1963 cross sections had been located on aerial photos by the SCS. In 2008, 56 sites were resurveyed. To accomplish this, the data layers with the 1963 valley cross section locations, and the 2008 site locations, respectively (in latitude and longitude), were imported into ArcMap onto the watershed basemap that was previously established. Using the channel width information for each site that was collected in 1963, valley cross section locations located upstream within three channel widths (using 1963 widths) of 2008 sites were included for comparative analysis. Three channel widths were chosen in order to be consistent throughout the watershed area and also to account for inaccuracies inherent with the identification of the locations. Since the technology hadn't been developed yet, GPS locations were not collected in 1963 when the historical cross sections were surveyed. As a result, for this analysis the 1963 aerial photos (Figure 3.7) had to be used for accurate location of the valley cross sections.

Variables Tested

In order to answer questions about the causes of channel incision in the Black Vermillion watershed, statistical tests were used. A variety of dependent and independent variables were measured. Dependent variables are listed in Table 3.4. Independent variables are listed in Table 3.5. The independent variables were measured upstream of, or adjacent to, each of the study sites.

Dependent Variables

Dependent variables are those variables that are potentially influenced by the presence or condition of independent, or controlling variables, at that location or upstream. For example, it was tested if channel depth 2008 (a dependent variable) was related to watershed drainage area (an independent variable) for all 107 study sites. Similar tests were conducted for the remainder of the dependent and independent variables described here.

Table 3.4 Summary table of dependent variables.

Dependent Variables	Type of variable	Units of Measurement
Channel Depth 1963 (CD1963)	Continuous	meters
Channel Depth 2008 (CD2008)	Continuous	meters
Channel depth change 1963-2008 (DCNG)	Continuous	meters
Cross Section Area at Channel Capacity (XSACC)	Continuous	square meters
Discharge at Channel Capacity (QCC)	Continuous	cubic meters per second
Width/Depth Ratio	Continuous	meters
Simon & Rinaldi (2006) Geomorphic Stage Stage I = Sinuous, Premodified Stage II = Constructed Stage III = Degradation Stage IV = Degradation and Widening Stage V = Aggradation and Widening Stage VI = Quasi Equilibrium	Discrete (dummy)	

Channel depths from 1963 were measured from the 1963 Soil Conservation Service (SCS) cross sections. A total of 243 such depths were measured and recorded. Only 56 of these measurements were used for the comparison between the 1963 channel depths and the 2008 channel depths. As a result, these same 56 depth measurements were utilized in the statistical analysis.

Channel depths from 2008 were measured by generating channel cross sections at a total of 107 study sites throughout the watershed. Measurements collected upstream of these bridge site locations were used.

Channel depth change was measured between the years of 1963 and 2008 for the 56 comparison study sites. This was done using channel depths as measured from the 1963 cross sections and comparing them to channel depths as measured in the field in summer of 2008.

Channel cross section areas were calculated using RiverMorph 4.1© software. Calculation of this variable involved entering the width and depth information of the 56 comparison cross sections into the RiverMorph© software. The software automatically creates a cross section from those values and generates a series of values from the cross section as well. One of those values is cross section area.

Discharge at channel capacity is the measurement used to measure the volume of water that would pass through the cross section at a channel capacity flood. Obtaining these values is an identical process to the steps described previously using RiverMorph 4.1© software. These discharge values were also calculated for the 56 comparison cross sections.

Width to depth ratios were calculated for all 107 study sites at the channel full stage using the width and depth values from the 2008 channel measurements.

Geomorphic stage was determined in the field using the Simon and Rinaldi (2006) channel evolution diagram (Figure 2.13). The author of this thesis and his student colleague, Mark Gossard, collaborated on the identification of geomorphic stage in the field for each of the 107 study sites. Once consensus had been reached, the channel stage value was recorded. The values ranged from Stage I through Stage VI.

Independent Variables

Independent variables were measured that were believed to have influence on the dependent variables (Table 3.5). Some of these variables were measured for the 56 sites used for comparison of the channel depth between 1963 and 2008. Other variables were measured for the total of 107 sites throughout the watershed that were sampled in 2008.

Watershed area upstream of each of the 107 total study sites was delineated and measured in square kilometers using the Basins Version 4.0© program, free software that is available for download from the website of the U.S. Environmental Protection Agency (EPA).

Channel slope was measured for each study site. For the slope calculations completed for this study, a 30 meter resolution digital elevation model (DEM) and state bridge and non-state bridge GIS data layers were used. Also, flowline data layers were utilized to help identify stream channel locations. These data layers were downloaded from the Kansas Geospatial Community Commons (KGCC) website. These layers were then loaded into ArcMap Version 9.3 software. Using the identify tool available in ArcMap Version 9.3, with the DEM as the active layer, elevations were measured in meters above sea level upstream approximately 1,000 meters upstream of each study site.

Table 3.5 Summary table of independent variables.

Independent Variables	Number of Sites	Type of Variable	Unit of Measurement
Drainage Area (LDA)	107	Continuous	square kilometers
Unit Stream Power (SRP)	56	Continuous	watts per square meter
Channel Slope (SRS)	107	Continuous	decimal fraction
Occurrence of Channelization (CHZ)	107	Binomial (dummy)	0 = no 1 = yes
Timing of Channelization (CHZTIME)	86	Ordinal	Pre 1956 = 7 1958 = 6 1963 = 5 1971 = 4 1977 = 3 1986 = 2 1999 = 1

			Unchanged = 0
Stream Adjacent LULC (LULC) FORWET = Deciduous Forest/Woody Wetlands CROPS = cultivated crops GRASPAST= grassland/pasture	107	Binomial (dummy)	0 = no 1 = yes
Buffer Width (BUFFERW)	107	Continuous	meters
Geology (GEOL) ADMIRE DRIFT ALLUVIUM	107	Binomial (dummy)	0 = no 1 = yes
Channel Bed Material (BED) SILT/CLAY SAND GRAVEL	107	Binomial (dummy)	0 = no 1 = yes
Rapid Geomorphic Assessment (RGA) Total (LSIM)	107	Continuous	unitless

Unit stream power is the ability of a stream to transport sediment and to do geomorphic work. It was calculated for the 56 comparison cross sections. Although unit stream power can be calculated using the one equation stated here, numerous other measurements are necessary to successfully calculate it. All of the steps taken to calculate unit stream power are outlined here.

Unit stream power, in watts per square meter, is calculated by using the following equation:

$$\textbf{Unit Stream power} = \gamma * D * \mu * S \tag{1}$$

Where μ is velocity of the water flow (in meters/second), D is depth (in meters) of the deepest part of the channel, γ is the specific weight of water (9810 newtons/m^3), and S is channel slope.

The calculation of both velocity (included with Manning's roughness coefficient) and channel slope need further explanation. This is provided below.

The velocity of the stream was calculated for each of the 56 locations using the following equation:

$$\mu = (1.49/n) * (R^{2/3}) * (S^{1/2}) \quad (2)$$

Where n is Manning's roughness coefficient, R is hydraulic radius in meters, and S is channel slope as a decimal fraction.

The calculation of all three of these values is provided below.

Manning's roughness coefficient (n) was calculated for each location using the following equation, as developed by Cowan (1956)

$$n = (n_0 + n_1 + n_2 + n_3 + n_4) * m_5 \quad (3)$$

Where:

n0 = Bed material
earth = 0.020
rock = 0.025
fine gravel = 0.024
coarse gravel = 0.028

n1 = Degree of surface irregularity
smooth = 0.000
minor (only minor slumping) = 0.005
moderate (e.g. only moderate slumping) = 0.010
severe (e.g. badly slumped, or irregular rock surfaces) = 0.020

n2 = Variation of channel cross section
gradual = 0.000
alternating occasionally = 0.005
alternating frequently = 0.010-0.015

n3 = Relative effect of obstructions (e.g. debris, roots, boulders)

negligible = 0.000

minor = 0.010-0.015

appreciable = 0.020-0.030

severe = 0.040-0.060

n4 = vegetation

none = 0.000

low = 0.005-0.010

medium = 0.010-0.025

high = 0.025-0.050

very high = 0.050-0.100

m5=Degree of meandering (multiplier)

minor (sinuosity <1.2) = 1.00

appreciable (sinuosity 1.2-1.5) = 1.15

severe (sinuosity >1.5) = 1.30

Hydraulic radius was calculated by entering width and depth information into RiverMorph$^{©}$.

Stream adjacent land use/land cover type was identified immediately upstream of each study site based on two methods. First, field photos taken upstream of each site in the summer of 2008 allowed for current analysis of the stream adjacent land use and land cover for each site. National Land Cover Dataset (2001) data, downloaded from the Kansas Geospatial Commons was also used in a GIS interface in ArcMap 9.3 to assist in the identification of the land use/land cover type upstream of each site. For this analysis, land use/land cover was divided into four classes. These are:

1 = Deciduous Forest/Woody Wetlands
2 = Grassland/Pasture
3 = Cultivated Crops
4 = Forest One Bank, Crop the Other

Buffer widths were measured at all 107 study sites by using four main data layers in ArcMap 9.3. Buffer widths are defined for this study as areas with forest or grassland vegetation that border streams up to cropland, an urban area, etc. To do this, first the flowlines were used to help identify stream locations. Second, the state and county bridge layers were used to help identify locations of the study sites. Third, the 2006 aerial photos of the watershed study area were used to identify and measure the buffer areas. All of these data layers were available for free download from the Kansas Geospatial Community Commons (KGCC) website. After opening all of these data layers in ArcMap, the study sites were located. Then, a riparian buffer width (if present) would be measured upstream of the bridge, and perpendicular to the stream channel, using the measure tool in ArcMap. In many cases, riparian areas contain forest buffer which are the only consistently forested areas in the watershed area. However, even if present, the thicknesses of these forested buffers varied widely.

Timing of channelization was determined for the 56 comparison study sites. Using aerial photos obtained through the Marshall and Nemaha county conservation districts, the timing of channelization was mapped throughout the watershed (Figure 2.7). An ordinal scale was developed so that channelization timing could be used in statistical tests (Table 3.5).

Occurrence of channelization was also developed as a variable following the timing of channelization analysis described for the 56 comparison study sites. For this variable, the stream channel upstream of the remaining 51 study sites were examined using 2006 aerial photos downloaded for the Kansas Geospatial Community Commons (KGCC) website. By looking for unnaturally straight stream channels, channelization was easy to identify using aerial photos.

Geology as a variable was assessed as well. The bedrock and surficial geologic maps of the state of Kansas, as completed and published by the Kansas Geological Survey, have been digitized in the past. The formations and surficial materials represented on these maps are shapefiles that are available for free download from the Kansas Geospatial Community Commons (KGCC) website. The shapefiles for both surficial and bedrock geology were downloaded from this source, and opened in ArcMap, for the watershed study area. These geology data layers were then opened in conjunction with stream flowline, state bridge, and county bridge data layers. Using this information, the types of geologic material at, or near, the surface around each of the 107 study sites could be assessed. The geologic materials mapped at the surface at all of the study sites were one of three: a) Admire Group, a Permian-age limestone/shale alternating rock unit; b) alluvium, or material that had been eroded and deposited on floodplains by past river action; or c) drift, glacial material that was deposited due to continental glacier activity. Because of the digital form of the geology information, maps of the watershed area showing this information were also created (Figure 1.2 and Figure 1.3).

Channel bed material present at all 107 study sites was assessed and recorded in the field. This was done by looking at the channels at each study site and recording the dominant size fraction of material present in the channel.

Channel Stability Ranking Scheme (or Rapid Geomorphic Assessment – RGA) total values for each of the 107 study sites were also included in the statistical analysis. As stated by Simon et al., (2007), tallying the values on the RGA form gives a stability-index value. Stability-index values greater than 20 are demonstrative of severe channel instability at that location. Values less than 10 are indicative of channels that are relatively stable.

Data Organization and Transformations

Data were organized using Statistix 9$^{\copyright}$ software, a statistical software that can be utilized using a personal computer. Three statistical techniques were utilized for this study. These three techniques are the Pearson correlation, stepwise multiple regression, and the Kruskal-Wallis analysis of variance (ANOVA) test. The Pearson correlation and stepwise regression have an underlying assumption that the data are normally distributed. As a consequence, continuous variables needed to be transformed in order to achieve the normal distribution necessary to implement these two tests.

Depending on the skewness of the non-transformed data set, multiple options exist for the method of transformation to be utilized. As described by Helsel and Hirch (2002) eight main data transformations are possible. Five are for negative skewness, two are for positive skewness, and one for non-transformed data.

Table 3.6 Data transformations. Source: modified from Helsel and Hirch (2008).

Type of skewness	Equation	Transformation Name
For negative skewness	X^3	Cube
For negative skewness	X^2	Square
	X	Non-transformed
For positive skewness	$X^{1/2}$	Square root
For positive skewness	$X^{1/3}$	Cube root
For positive skewness	$\ln X$	Logarithmic
For positive skewness	$1 / X^{1/2}$	Reciprocal root
For positive skewness	$1 / X$	Reciprocal

When choosing which transformation technique to utilize, the objective was to choose the method that generated skewness and kurtosis values as close to zero as possible. Two positive transformation techniques were utilized for this study to achieve this objective. They were square root and logarithmic transformations. Based on which transformed variables were selected, these transformed variables were then used for the statistical techniques as described below.

Pearson Correlation

The first statistical method run for this study was a Pearson correlation. This method was used to test for correlation between the independent and dependent variables being utilized in this study. It was also used to identify variables that were autocorrelated. The variables tested using this analysis all are continuous in that all of these variables can take on any value within the maximum numerical limit of that variable. For Pearson correlations, an underlying assumption exists that the data is normally distributed. As a result, many of the variables tested using this method were transformed in order to achieve a normal distribution. Heine and Lant (2009) also used a Pearson correlation in their attempts to identify the causes of channel incision.

Variables Tested

The second statistical test that was run was multiple stepwise regression. The purpose of using multiple stepwise regression was to identify the influence of independent variables on each dependent variable. For this portion of the analysis, the channel depth measurements of 1963 and 2008, and the depth changes between the two years, were tested against the independent variables collected for this study. The overall objective of this analysis was to identify the variables influencing channel depth during these two years. Hence, the factors affecting channel incision could potentially be identified. Table 3.7 illustrates the variables tested and the statistical technique used in pursuing this objective.

Channel Stage vs. Independent Variables

The third statistical test completed for the analysis described here was the non-parametric Kruskal-Wallis analysis of variance (ANOVA) test in order to determine which independent variables varied by channel stage (Figure 2.13). Because of the ordinal nature of the data, channel stage had to be tested against independent variables using a statistical technique that accommodates these ordinal data. For this reason, the Kruskal-Wallis test was utilized (Moore, 2000). Also, channel stage was identified at all 107 study sites. So, it was verified that all of the independent variables tested for their influence on channel stage also had been collected at all 107 study sites. Table 3.8 illustrates the variables tested using this method. Also, since the Kruskal-Wallis test is a non-parametric test it is not necessary for the data tested to contain a normal distribution. As a result, the variables tested using this method did not need to be transformed.

Table 3.7 Variables tested using multiple stepwise regression.

Dependent Variable	Independent Variable(s)	Transformation Used	Abbreviation	Statistical Technique	Study Sites Used
Log channel depth 2008 (LCD08)	Drainage Area	Log	LDA	Stepwise	107 total
	Admire	None	ADMIRE	Linear	study sites
	Alluvium	None	ALLUVIUM	Regression	
	Drift	None	DRIFT		
	Channelization	None	CHZ		
	Timing of CHZ	None	CHZTIME		
	Crops	None	CROPS		
	Forest/Wetland	None	FORWET		
	Grass/Pasture	None	GRASPAST		
	Gravel	None	GRAVEL		
	Simon (RGA) #'s	Log	LSIM		
	Siltclay	None	SILTCLAY		
	Buffer Width	Square root	SRBW		
	Slope	Square root	SRS		
Depth change between 1963 and 2008 (DCNG)	Drainage Area	Log	LDA	Stepwise Linear Regression	56 comparison study sites
	Admire	None	ADMIRE		
	Alluvium	None	ALLUVIUM		
	Drift	None	DRIFT		
	Channelization	None	CHZ		
	Timing of CHZ	None	CHZTIME		
	Crops	None	CROPS		
	Forest/Wetland	None	FORWET		
	Grass/Pasture	None	GRASPAST		
	Gravel	None	GRAVEL		
	Simon (RGA) #'s	Log	LSIM		
	Siltclay	None	SILTCLAY		
	Buffer Width	Square root	SRBW		
	Slope	Square root	SRS		
Square root depth 1963 (SRD63)	ADMIRE	None	ADMIRE	Stepwise	56
	LDA	Log	LDA	Linear	comparison
	SRS	Square root	SRS	Regression	study sites
	DRIFT	None	DRIFT		

Table 3.8 Variables tested using the Kruskal-Wallis analysis of variance test.

Dependent Variable	**Independent Variables**	**Statistical Technique**	**Study Sites Used**
Stage I **Stage II** **Stage III** **Stage IV** **Stage V**	Geology	Kruskal-Wallis analysis of variance	107
	Bed Material		107
	Timing of Channelization		86 – timing of channelization information not known for some sites
	Occurrence of Channelization		107
	Land use/land cover		107
	Channel depth 1963		56 - only for comparison study sites
	Channel depth 2008		107
	Drainage area		107
	Unit stream power		56 – only for comparison study sites
	Simon #'s – Rapid Geomorphic Assessment		107
	Width/depth ratio		107
	Cross section area		56 - only calculated for comparison study sites

CHAPTER 4 - Results and Discussion

This chapter is composed of three sections based on the research objectives of the study. The first section describes the spatial extent of channel incision within the watershed. The second section identifies the timing of channel incision within the watershed. The third section identifies potential causes channel incision within the watershed.

The Spatial Extent of Channel Incision in the Black Vermillion watershed

The channel cross section measurements collected in the Black Vermillion watershed during the summer of 2008 show the current channel conditions of the streams in the watershed. The channel depth measurements at these 107 sites confirm that channel depths throughout the watershed vary widely (Figure 4.1). It is generally established that channel depth is directly related to stream discharge, stream order, and positioning in the watershed (Knighton, 1998). As stream discharge increases downstream, channel depths increase accordingly in order to accommodate those higher flows. Figure 4.1 reveals that in the case of the Black Vermillion watershed, this relationship largely holds true for the channel depths as measured in 2008. For example, Figure 4.1 shows a general increase of channel depths along the major trunk streams of the watershed – the North Fork of the Black Vermillion, the Main Branch, and the South Fork (Irish Creek). Thus, this pattern is consistent with established knowledge. Deserving of special note are the cluster of large channel depths downstream from the confluence of the North Fork and Main Branch. Based on observations made in the summer of 2008, the channels of the Main Branch and the North Fork experience large flows and frequent floods. Downstream of their confluence near Vliets, the conjoined flows of these two channels experience greater flow volumes than any location upstream of the confluence. The addition of the flows from the South Fork further contributes, especially during flooding events. As shown in Figure 2.5, floods occur very quickly in the Black Vermillion system. Further, is well established that the majority of geomorphic work done in fluvial systems is completed during flooding events (Knighton, 1998). As a result, the deeper channels in downstream reaches of the Black Vermillion River from Frankfort upstream to the North Fork/Main Branch confluence at Vliets potentially result from the accommodation of greater flows seen in these downstream reaches during floods.

The channel depths of smaller tributary streams of the watershed exhibit more variability in channel depth. While they too show a general pattern of increasing depths downstream, more spatial variability exists in the locations of shallower and deeper channels. Among the smaller tributary streams of all three sub-watersheds, locations exist where channel depths alternate between deeper and shallower.

Lacking in Figure 4.1 are any study site locations of the main trunk streams where significant decrease of the channel depths is seen. Depths becoming more shallow would indicate the presence of sediment storage, or aggradation. While the study site locations for this thesis do not cover every stretch of stream and some significant gaps are present, the dearth of measured aggradation is potentially significant since fluvial systems usually contain a balance between sediment storage and sediment transport out of the system. Based on increases in channel depths between 1963 and 2008, very little sediment storage is evidently occurring in the stream channels of the Black Vermillion system. This finding is corroborated with Figure 4.4, which shows overall channel degradation throughout the watershed between 1963 and 2008. This lack of sediment storage has been identified as a symptom of severely incised streams, and indicates an excess of stream power versus sediment contribution or channel storage capacity. Further, it is now known channel incision is widespread throughout the Black Vermillion system.

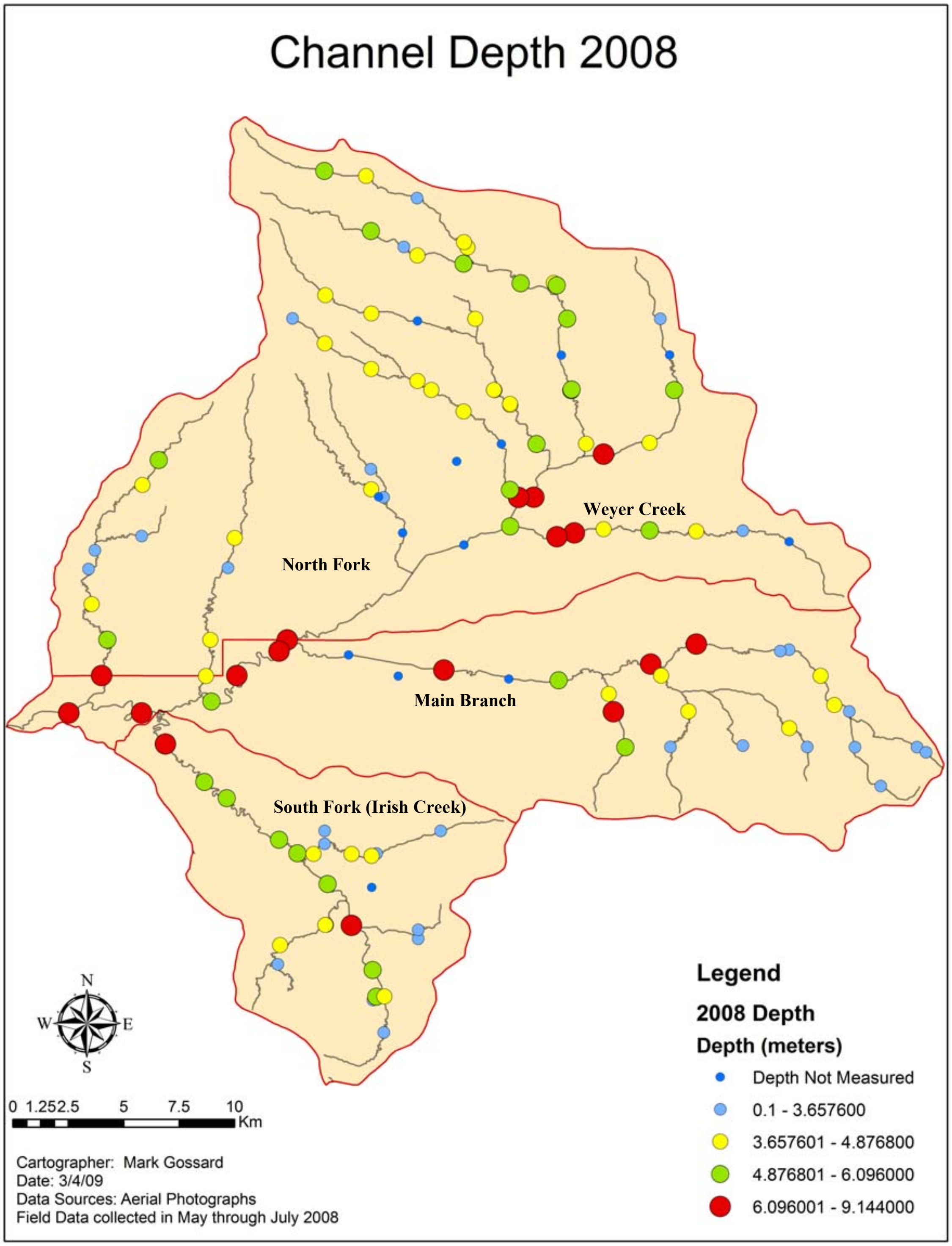


Figure 4.1 2008 channel depths, as measured from channel cross sections.

The Timing of Channel Incision in the Black Vermillion watershed

The 1963 measurements exhibit a more consistent pattern of channel depth throughout the watershed (Figure 4.3). As noted previously, channel depths tend to increase downstream throughout a stream network because of the necessity of the channels to accommodate higher flow volumes (Knighton, 1998). Figure 4.3 reveals that, in 1963, the stream channels of the Black Vermillion watershed exhibit a pattern that is somewhat consistent with that relationship. In general, the smaller tributary streams and the main stream channels in the upper reaches of the watershed contained shallower channel depths in 1963. Because of the presence of this pattern, it can be established that the stream channels in 1963 contained a worthwhile reference condition with channel depths consistent with naturally occurring conditions. These 1963 channel depths could then be accurately compared with stream channels in 2008.

Channels of the Black Vermillion watershed have changed extensively between 1963 and 2008. As shown in the box plot in Figure 4.2, median channel depths have increased from a little over 3 meters to approximately 5 meters during this time period. Furthermore, while the channels are undoubtedly deeper in 2008, the interquartile range also shows an increase in the variability of channel depths in 2008 (Figure 4.2). This result suggests that, overall, channel change in the form of channel incision has been extensive in a geomorphically short time frame in the Black Vermillion watershed.

Figure 4.4 illustrates channel change between 1963 and 2008. Stream channels in the Black Vermillion watershed have indeed changed considerably in this 45-year time frame. The stream channels throughout the watershed have deepened, or incised, through this time period. This finding was previously alluded to in Figure 4.2. However, visible in Figure 4.4 is the spatial extent of the widespread channel incision that has occurred in the Black Vermillion watershed over a specific period of time. Only five locations were measured as showing aggradation. Two of these are located on the Main Branch near Centralia, with one more on the South Fork (Irish Creek). The remaining two locations are on Ackerman Creek and Little Timber Creek (Figure 4.4).

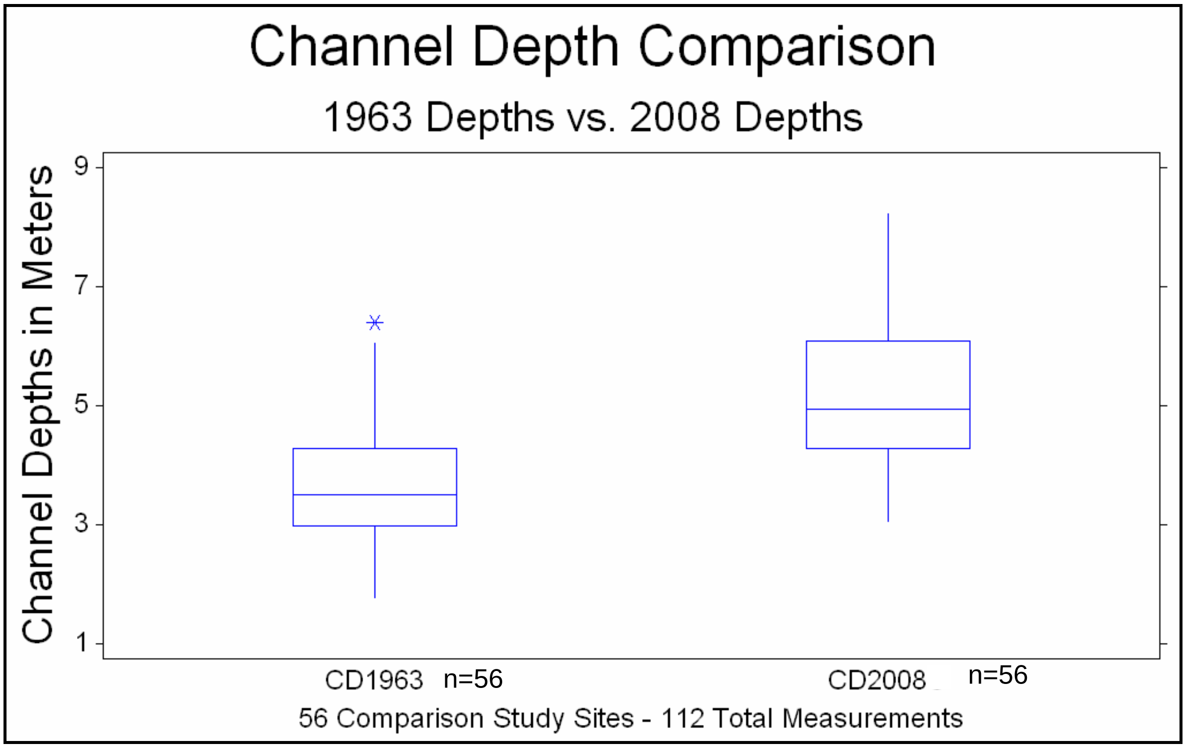


Figure 4.2 Box plot showing comparison between 1963 and 2008 channel depths for the 56 comparison study sites.

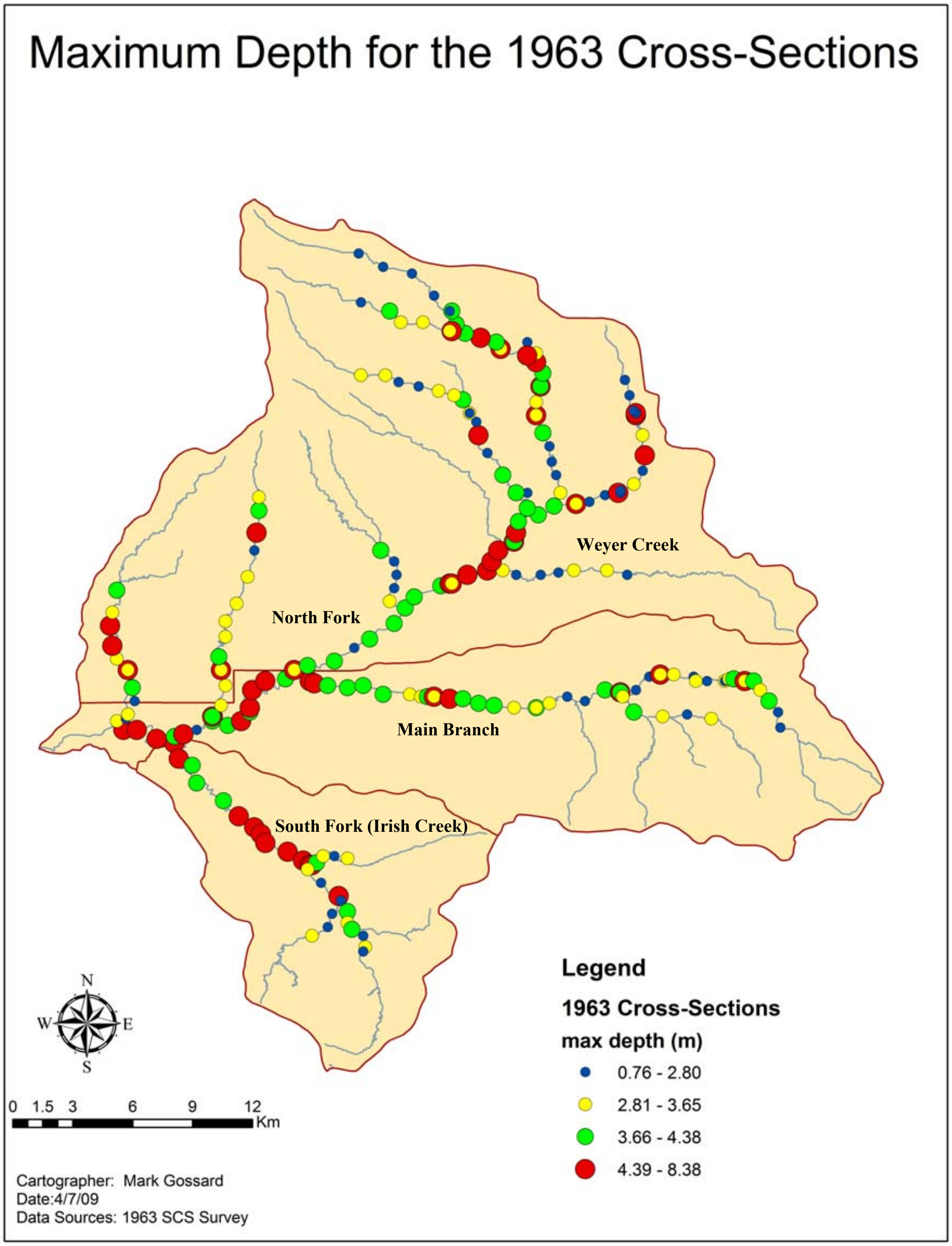


Figure 4.3 Cross-section location and depth.

A clustering of sites is apparent where extensive deepening occurs near the confluence of the North Fork and Weyer Creek (Figure 4.4). Field observation confirmed that all of these sites were severely impacted by channelization and were deeply incised in comparison to other locations in the watershed. Figure 4.4 shows no visible pattern of channel depth change elsewhere. Previous research (e.g., Simon and Rinaldi, 2006) claimed that, in general, channel incision tends to migrate upstream from the point of initial degradation. In some cases, the upstream migration of incision can move quickly if the knickpoint created from initial incision is allowed to move. Daniels (1960) mapped knickpoint migration on Willow Creek in western Iowa as moving about 0.8 km/year while Simon and Hupp (1992) identified knickpoint migration as occurring at the rate of about 2.4 km/year on the Obion-Forked Deer Rivers of Western Tennessee. Heine and Lant (2009) further researched movement of channel incision for streams in part of the Missouri River watershed in southwestern Iowa and southeastern Nebraska. They established that lowering of base levels on the mainstem of the Missouri River created the adjustment needed for channel incision to be instigated. Knickpoint migration was the primary method of channel incision movement through their study area.

The lack of a pattern of channel depths throughout the Black Vermillion watershed suggests that channel incision has been triggered in multiple locations and at different times. The spatial and temporal variability in channelization practices interrupt normal trends in channel depth. Further, as illustrated by Simon and Rinaldi (2006) some streams affected by channel incision do not contain knickpoints. Rather, they contain wider areas of degradation known as knickzones. Visual observation of streams in the Black Vermillion watershed during the summer of 2008 confirmed the lack of knickpoints. This can be attributed to the lack of resistant lithologies or other geologic materials in the channel beds while the silts and clays within the stream channels are uniformly susceptible to erosion. Therefore, knickzones are the likely cause of the channel incision migration on both the smaller tributaries and the main stems of the streams of the Black Vermillion watershed. The comparative analysis provided here for the years 1963 and 2008 confirms that incision watershed-wide has occurred in that geomorphically short time frame.

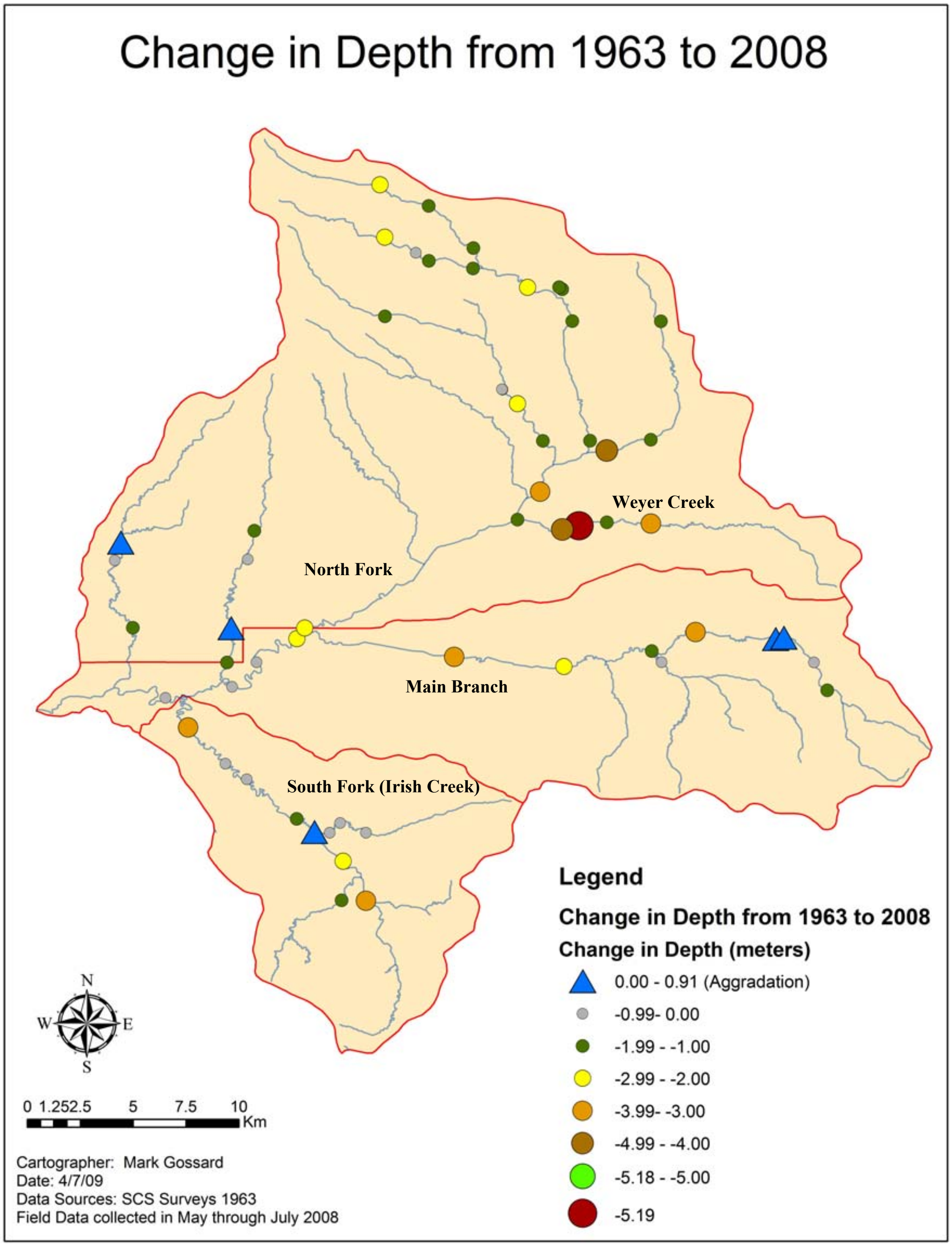


Figure 4.4 Cross sectional depth compared 1963 to 2008.

As shown in Figure 4.5, 63% of the 107 study sites were identified as either Stage III (degradation) or Stage IV (degradation and widening). Stage VI conditions (quasi equilibrium) were not found anywhere in the watershed. This finding further suggests that stream channels of the Black Vermillion watershed are still actively incising, or incising and widening, as they respond to past channelization disturbance. This finding, combined with the knowledge that very little sediment is being stored in the channels of the watershed, suggest that the stream channels have not finished responding to the factors that have caused channel incision. The amount of time required for streams to eventually recover from severe channel incision does vary (Simon and Rinaldi, 2006). Work done by Heine and Lant (2009) established a timeline of total incision for streams draining to the Missouri River in southeastern Nebraska and western Iowa. Their findings concluded that 99% of total incision occurred between 28 and 39 years after incision was initiated. Further, they reported that about half of total degradation occurs within five years after initial incision. The streams studied by Heine and Lant (2009) in southeastern Nebraska and western Iowa are similar to those of the Black Vermillion watershed. In both locations, the streams have been impacted by channelization, drain agricultural watersheds, and are underlain by glacial till or loess.

Two main points can be made that suggest that the streams of the Black Vermillion watershed are behaving similarly to those studied by Heine and Lant (2009). The first point is that 63% of the study sites have been identified in the Black Vermillion watershed as either Stage III (degradation) or Stage IV (degradation and widening). The second point is that the channels of the Black Vermillion watershed have deepened considerably since 1963. These two points infer that the 45 year time span analyzed for the Black Vermillion watershed in this study is long enough for considerable channel incision to have occurred. Further, depending on when channel incision was instigated at a given location, it is a long enough period for the vast majority of incision to have occurred (Heine and Lant, 2009). However, the abundance of Stage III, and especially Stage IV, conditions in the watershed suggest that the Black Vermillion fluvial system is still responding to the geomorphic changes imposed on the channels by severe incision.

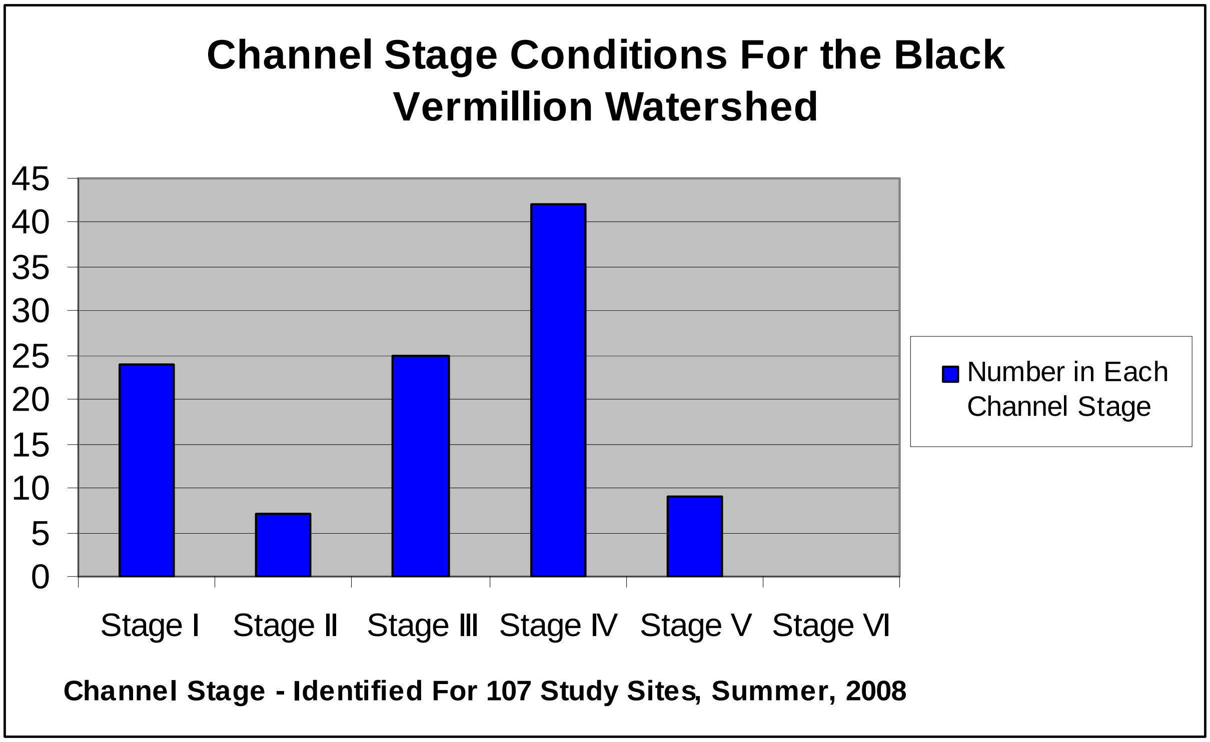


Figure 4.5 Histogram showing channel stage values as identified in the summer of 2008.

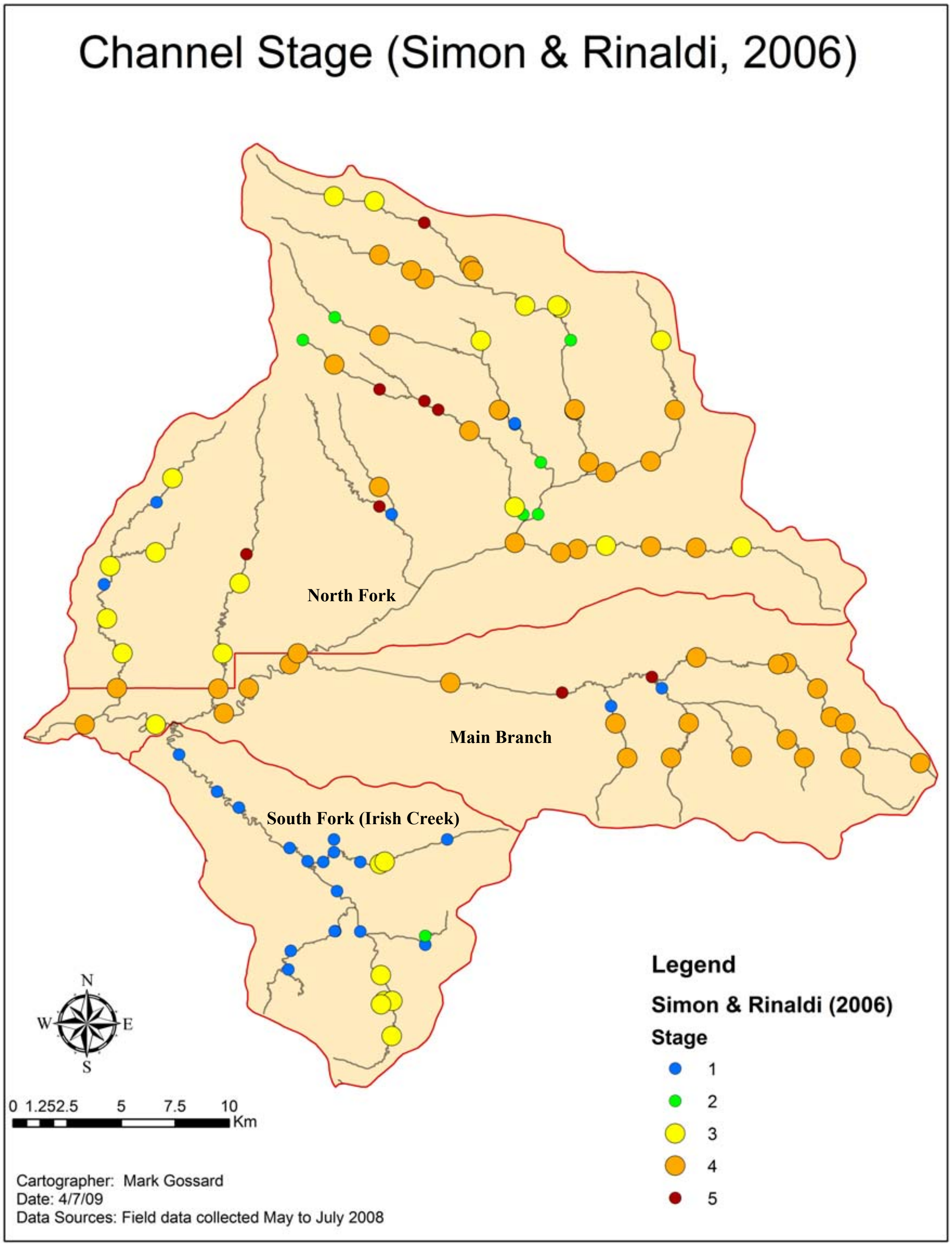


Figure 4.6 Channel stage as identified in summer, 2008, for the Black Vermillion watershed.

As shown in Figure 4.6, channel stages vary in location throughout the watershed. However, overall, channel stages cluster by their respective value. Stage I (sinuous, pre-modified) values are concentrated in the South Fork (Irish Creek) sub-watershed. This sub-watershed is the least impacted by channelization out of the three sub-watersheds of the Black Vermillion system being studied here. As a result, Stage I values would be expected to be found in this sub-watershed. Some Stage III (degradation) values are present in the headwaters region of the South Fork (Irish Creek) watershed. These values indicate response to past channelization practices. Some channelization had occurred prior to 1956 and around the mid-1970's in the headwaters area of the South Fork sub-watershed.

Field observations made in the summer of 2008 indicate some reasoning as to why channelization and, hence, Stage II-V values, are absent from the South Fork sub-watershed. This sub-watershed is predominantly pasture and grazing land while row crops are not as common as in the Main Branch and North Fork sub-watersheds (Figure 1.4). Hillier topography, shallower bedrock, and shallower, poorer soils in the South Fork (Irish Creek) sub-watershed contribute to the disparity in land use between this region and the other two sub-watersheds of the Black Vermillion system (Figure 1.2 and Figure 1.3).

Figure 4.7 confirms that channel stages III and IV are much more common in the sub-watersheds of the Main Branch and the North Fork. These two watersheds contain more active cropland (Figure 1.4) and have been more severely impacted by channelization activities (Figure 2.7). Of particular significance is the widespread presence of Stage IV (degradation and widening) values throughout the Main Branch and North Fork watersheds - from the most upstream reaches of the tributary streams to the main stem of the Black Vermillion in Frankfort (Figure 4.6). This finding confirms that channel instability is widespread throughout the Main Branch and South Fork watersheds. As noted by Simon (1994) channel widening is the primary mechanism in which silt-bedded streams (like those of the Black Vermillion system) can respond to increases in stream power that occur as a consequence of channel incision. This occurs because a distinct lack of course-grained material is present to contribute to aggradational processes. Simon and Rinaldi (2006) stated that silt-bedded streams in nearby western Iowa were among the deepest and widest of the streams in the mid-continent area that they observed for their study. Further, they ascertained that the process of channel incision (Stage III) through incising and widening (Stage IV) can take as long as 70 years as had been discovered on West Tarkio Creek in southwestern Iowa and northwestern Missouri.

The mapping and analysis of channel stage in the Black Vermillion watershed confirms that the streams of the watershed area have responded to past channelization practices. The mechanisms in which they are responding is consistent with what has been uncovered in the literature and what has been documented for streams in other areas of the Midwest. The response to channelization has been complex, with watershed-wide degradation and widening being the major processes. The multiple channelization projects in the watershed dominate the channels of the Black Vermillion fluvial system (Figure 2.7). Each individual channelization event has the potential to trigger the channel evolution process as shown. With the complex channelization history of the watershed now known, it can be inferred that channel evolution as described by Simon and Rinaldi (2006) and shown in Figure 2.13 has been instigated in numerous locations in the watershed and at various times. Channel depths compared between 1963 and 2008, as shown in Figure 4.4, reveal that degradation has indeed occurred extensively between these dates. Perhaps more importantly, that degradation does not appear to be consistent throughout the watershed area. This would suggest the presence of numerous locations where channelization practices and, hence, channel evolution from Stage II through Stage V had progressed.

Relatively few study sites assessed in the summer of 2008 show signs of a transgression from Stage IV to Stage V. Only nine out of 107 sites were recorded with a Stage V condition, while the 67 sites that contain Stage III (25 total) or Stage IV (42 total) conditions are still in a state where they are actively incising or incising and widening. No sites were observed where a Stage VI (recovered to quasi-equilibrium) condition was present. As a result, these Stage III and Stage IV channels may remain for many more years in their currently highly unstable state. Simon and Rinaldi (2006) ascertained that about 70 years was needed for channelized streams to reach a Stage III condition in silt-bedded streams in western Iowa. Following the establishment of a Stage III condition, a transgression to Stage IV can take a relatively short period of time (Simon and Rinaldi, 2006) and Stage V conditions persist for some time later (Figure 2.14). However, with very little channel sediment storage observed during fieldwork in the summer of 2008, it appears that Stage III and Stage IV conditions will be present for years or even decades to come in the Black Vermillion watershed. Simon and Rinaldi (2006) emphasized that if bank heights, increased due to incision, do not become reduced by channel aggradation, channel widening by bank slumping and other mass wasting conditions, will persist through the 21st century.

Others have used the Simon and Rinaldi (2006) model, or its predecessor (Simon and Hupp, 1986) to complete similar analyses in other fluvial environments. Hadish (1994) mapped channel stage along 2500 km of streams in western Iowa using the Simon and Hupp (1986) model. Their research uncovered that 56% of the streams observed were Stage IV while approximately 24% of those same streams were Stage V (aggradation and widening). Overall, 90% of the observed streams were categorized as being unstable for that region of western Iowa. The findings reported here for the Black Vermillion watershed agree with past research in other areas of the Midwest where loess and glacial till-derived soils exist and where agricultural land uses and channelization practices are prevalent.

The results outlined here have significant implications for the continuation of excessive volumes of sediment to be flushed out of the Black Vermillion watershed and ultimately downstream into Tuttle Creek Reservoir. As noted by Simon and Rinaldi (2006) bank slumping and other bank mass wasting processes can be the largest contributor of sediment from a watershed that contains incised channels. If Stage III and Stage IV conditions persist, it can be expected that the Black Vermillion watershed will continue to be a major supplier of sediment to Tuttle Creek Reservoir.

The Causes of Channel Incision in the Black Vermillion Watershed

It has been established in this thesis that channel incision is widespread throughout the Black Vermillion watershed and that this incision has been actively occurring since at least 1963. The task remaining is to identify the reasons as to why this has occurred. The primary approach used to complete this task is to implement statistical methods to test between independent and dependent variables of the stream channels and characteristics of the watershed.

The continuous variables collected for this portion of the thesis needed to be transformed in order to achieve a more normal distribution prior to statistical testing. Table 4.1 provides some of the original, un-transformed values for the continuous variables collected for this study.

Table 4.1 Original, un-transformed values for continuous variables.

Dependent Variables	**Units of Measurement**	**n (sample size)**	**Mean**	**Maximum Value**	**Minimum Value**
Channel Depth 1963 (CD1963)	meters	56	3.59	6.4	1.83
Channel Depth 2008 (CD2008)	meters	107	5.12	11.54	2.83
Channel depth change 1963-2008 (DCNG)	meters	56	1.64	5.18 (degradation)	-0.91 (aggradation)
Cross Section Area at Channel Capacity (XSACC)	square meters	56	115.15	327.2	28.5
Discharge at Channel Capacity (QCC)	cubic meters/second	56	253.80	975	47
Channel Width (LCW)	meters	107	17.91	46.02	4.87
Independent Variables					
Drainage Area (DAREA)	square kilometers	107	58.40	845	1.7
Unit Stream Power (POWER)	watts/square meter	56	236.60	970.2	11.6
Channel Slope (SLOPE)	n/a	107	0.0035	0.01	0.0002
Buffer Width (BUFFERW)	meters	107	29.68	228	0
(RGA) Rapid Geomorphic Assessment Total (SIMON)	n/a	107	20.47	33	9

Transformation of Data for Dependent Variables

Table 4.2 provides the comparison between the skewness and kurtosis values for the un-transformed and transformed (using the Log and Square root techniques) data for the dependent variables included in this analysis. All of these dependent variables have continuous data, so transformation was completed for them all.

Table 4.2 Skewness, kurtosis, and un-transformed values for dependent variables.

Dependent Variable	Un-transformed (skewness)	Log Transformation (skewness)	Square root transformation (skewness)	Un-transformed (kurtosis)	Log Transformation (kurtosis)	Square root transformation (kurtosis)
Channel Depth 1963 (CD1963)	0.3887	-0.3944	-0.0106	0.0709	-.2091	-0.2277
Channel Depth 2008 (CD2008)	0.9959	-0.1142	0.1144	2.2091	-0.8135	-0.8381
Channel depth change 1963-2008 (DCNG)	0.3493	-1.7372	-0.4649	-0.0455	3.1667	-0.2215
Cross Section Area at Channel Capacity (XSACC)	1.20	-0.0379	0.5757	1.14167	-0.6634	-0.1889
Discharge at Channel Capacity (QCC)	1.656	0.1914	0.9398	2.3718	-0.6392	0.3426
Channel Width (LCW)	1.1361	0.1315	0.6306	1.0281	-0.5538	-.1301

In Table 4.2, for each of the dependent variables, the values closest to zero for both skewness and kurtosis are underlined. These values are included in Table 4.3.

Table 4.3 Skewness and kurtosis values closest to zero with transformation techniques identified.

Dependent Variable	Skewness	Transformation used for skewness(if any)	Kurtosis	Transformation used for kurtosis (if any)
Channel Depth 1963 (CD1963)	-0.0106	Square root	0.0709	None
Channel Depth 2008 (CD2008)	-0.1142	Log	-0.8135	Log
Channel depth change 1963-2008 (DCNG)	0.3493	Un-transformed	-0.0455	Un-transformed
Cross Section Area at Channel Capacity (XSACC)	-0.0379	Log	-0.1889	Square root
Discharge at Channel Capacity (QCC)	0.1914	Log	0.3426	Square root
Channel Width (LCW)	0.1315	Log	-.1301	Square root

As shown in Table 4.2 and 4.3, transforming the variables did indeed assist in reducing the skewness and kurtosis values for many of the dependent variables with continuous data. The transformation techniques used are included as well. Transforming the data was therefore seen as a beneficial modification to these data sets in order to ready them for statistical testing.

Transformation of Data for Independent Variables

Table 4.4 provides the comparison between the skewness and kurtosis values for the un-transformed and transformed (using the log and square root techniques) data for the continuous independent variables included in this analysis. Only the independent variables with continuous data were transformed. As such, the independent variables listed in Table 4.4 are not all of the independent variables tested in this study.

Table 4.4 Skewness, kurtosis, and un-transformed values for independent variables.

Independent Variable	Un-transformed (skewness)	Log Transformation (skewness)	Square root transformation (skewness)	Un-transformed (kurtosis)	Log Transformation (kurtosis)	Square root transformation (kurtosis)
Drainage Area (DAREA)	2.9735	0.6945	2.0473	8.1351	0.1153	3.8510
Unit Stream Power (POWER)	1.6138	-0.8834	0.3990	3.4890	0.6789	0.3113
Channel Slope (SLOPE)	0.1766	-1.3616	-0.4480	-0.6464	-0.6464	-0.2578
Buffer Width (BUFFERW)	2.4839	0.1044	1.0293	6.0477	-0.6105	0.3967
(RGA) Rapid Geomorphic Assessment Total (SIMON)	-0.1239	-0.5244	-0.3107	-1.2121	-0.7323	-1.0600

Table 4.5 provides the skewness and kurtosis values closest to zero for the independent variables. The transformation technique utilized is listed as well.

Table 4.5 Skewness and Kurtosis values closest to zero for independent variables.

Independent Variable	**Skewness**	Transformation used for skewness(if any)	**Kurtosis**	Transformation used for kurtosis (if any)
Drainage Area (DAREA)	0.6945	Log	0.1153	Log
Unit Stream Power (POWER)	0.3990	Square root	0.3113	Square root
Channel Slope (SLOPE)	0.1766	None	-0.2578	Square root
Buffer Width (BUFFERW)	0.1044	Log	0.3967	Square root
(RGA) Rapid Geomorphic Assessment Total (SIMON)	-0.1239	None	-0.7323	Square root

As shown in Table 4.4 and 4.5, transforming the variables did indeed assist in reducing the skewness and kurtosis values for the independent variables with continuous data. The transformation techniques used are included as well in this table. Transforming the data was therefore seen as a beneficial modification to these data sets in order to ready them for statistical testing.

The dataset (whether un-transformed, log transformed, or square root transformed) for each of the independent and dependent variables was looked at. The improved skewness and kurtosis values achieved through transformation dictated which data set for each of the variables was used in statistical testing. For example, Table 4.4 shows that for the independent variable drainage area, skewness and kurtosis values closest to zero were achieved through transforming the data using the log transformation technique. The log transformed data set for the drainage area variable was used in the statistical analysis described below. This same selection technique was used for each of the dependent and independent variables used for the statistical analysis of this study.

When the transformations were being completed, separate columns in the Microsoft Excel and Statistix 9$^{©}$ spreadsheets were being generated to store these new data fields. Due to restrictions in the number of characters allowed to label each column in the Statistix 9$^{©}$ program, each of the transformed dependent and independent variables were given a separate, shortened name. When it was decided which of the datasets (un-transformed, log, or square root) for each of the variables was to be used, the names of the variables were shortened further. Each of these chosen data sets to be used in the statistical analysis (based on their skewness and kurtosis), and their shortened names, are given in Table 4.6.

Table 4.6 Summary of names given for the variables with continuous data.

Dependent Variables	**Transformation Technique (if needed)**	**Name given to variable in statistical analysis**
Channel Depth 1963	Square root	SRD63
Channel Depth 2008	Log	LCD08
Channel Depth Change 1963-2008	None needed	DCNG
Cross Section Area at Channel Capacity	Log	LXSA
Channel Width	Log	LCW
Width/Depth Ratio	Log	LWDR
Discharge at Channel Capacity	Log	LQCC
Independent Variables		
Drainage Area	Log	LDA
Unit Stream Power	Square root	SRP
Channel Slope	Square root	SRS
Buffer Width	Square root	SRBW
(RGA) Rapid Geomorphic Assessment Total	Log	LSIM

A Pearson correlation was run first between independent variables and dependent variables with continuous data to identify colinearity between these variables. Table 4.6 summarizes the variables tested using the Pearson correlation. The results from the Pearson correlation are shown in Table 4.7.

Table 4.7 shows strong colinearity between numerous variables. Discharge at channel capacity (LQCC), upstream drainage area (LDA), slope (SRS), depth in 1963 (SRD63), cross sectional area (LXSA) and channel width (LCW) are strongly correlated with many of the other variables and with each other. Because this method tests for the strength and direction of a linear relationship, the Pearson correlation matrix was primarily used to identify relationships between variables that could be further tested statistically using other methods (Moore, 2000). Further, in the case of the independent variables of unit stream power (SRP) and slope (SRS) it was decided that a strong colinearity between the two variables might prevent one of those variables from being used in further statistical tests. Square root stream power (SRP) was dropped because it was calculated for only the 56 comparison study sites while square root slope (SRS) was calculated for all 107 study sites.

Table 4.7 Pearson correlation coefficients and p values. Correlations significant at the p<0.05 significance level underlined and colored in red.

	SRD63	LCD08	DCNG	LXSA	LCW	LWDR	LQCC	LDA	SRP	SRS	SRBW
LCD08	0.3825										
P-VALUE	0.0036										
DCNG	-0.4273	0.6454									
P-VALUE	0.0010	0.0000									
LXSA	0.3867	0.7127	0.3947								
P-VALUE	0.0032	0.0000	0.0026								
LCW	0.2569	0.4319	0.2002	0.8048							
P-VALUE	0.0560	0.0009	0.1390	0.0000							
LWDR	0.0211	-0.2049	-0.2175	0.3933	0.7943						
P-VALUE	0.8776	0.1298	0.1073	0.0027	0.0000						
LQCC	0.2958	0.6375	0.3948	0.8445	0.6258	0.2496					
P-VALUE	0.0269	0.0000	0.0026	0.0000	0.0000	0.0635					
LDA	0.6560	0.6028	0.0526	0.6701	0.5275	0.1664	0.4464				
P-VALUE	0.0000	0.0000	0.7003	0.0000	0.0000	0.2204	0.0006				
SRP	-0.1496	-0.0585	0.0416	-0.2251	-0.2991	-0.2852	0.2593	-0.3916			
P-VALUE	0.2711	0.6685	0.7607	0.0953	0.0251	0.0331	0.0537	0.0028			
SRS	-0.2782	-0.3429	-0.1524	-0.5515	-0.4581	-0.2661	-0.2279	-0.6226	0.7799		
P-VALUE	0.0379	0.0097	0.2620	0.0000	0.0004	0.0475	0.0912	0.0000	0.0000		
SRBW	0.6357	0.2085	-0.3331	0.1937	0.1317	0.0024	0.1305	0.4922	-0.0866	-0.0929	
P-VALUE	0.0000	0.1231	0.0121	0.1525	0.3334	0.9857	0.3378	0.0001	0.5256	0.4958	
LSIM	-0.3654	-0.0912	0.2065	0.1268	0.1739	0.2502	0.1622	-0.1032	-0.0539	-0.1662	-0.5157
P-VALUE	0.0056	0.5036	0.1267	0.3515	0.1998	0.0629	0.2323	0.4490	0.6932	0.2209	0.0000

Three of the variables shown in the Pearson correlation matrix were not included in the statistical tests to test for the causes of channel incision. These three variables are channel width (LCW), cross section at channel capacity, (LXSA), and discharge at channel capacity (LQCC).

They will be potentially used in future work on the Black Vermillion fluvial system, however they were not utilized further for the study described here.

Following completion of the Pearson correlation, stepwise linear regression was used to test the significance of independent variables influencing the following dependent variables; a) channel depth in 2008; b) channel depth change between 1963 and 2008; and channel depths from 1963. Some of the variables had to be transformed for stepwise regression and the names of the variables were shortened and changed accordingly (Figure 4.5).

Table 4.8 Stepwise linear regression analysis to identify significant variables affecting channel depth 2008.

Stepwise Linear Regression of Log Channel Depth 2008 (LCD08)					
Unforced Variables: Admire, Log transformed drainage area (LDA), Alluvium, Drift, Channelization (CHZ), Timing of CHZ (CHZTIME), Crops, Forest/Wetland (FORWET), Grass/Pasture (GRASPAST), Gravel, Log transformed Simon(RGA) #'s (LSIM), Siltclay, Square root transformed slope (SRS)					
Stepwise Model at P = 0.05 Significance Level					
Ind. Variable	**Coefficient**	**Std Error**	**T**	**P**	**VIF**
Constant	0.53167	0.03015	17.63	**0.0000**	
LDA	0.12119	0.01961	6.18	**0.0000*** **	1.0
GRASPAST	-0.11729	0.04888	-2.40	**0.0187** **	1.0
Cases Included 86		**R Squared 0.3670**		Mse 0.00899	
Missing Cases 21		**Adjusted R Squared 0.3518**		SD 0.09480	
*** denotes statistical significance at the p<0.01 level ** denotes statistical significance at the p<0.05 level					
Variables Not in the Model – Correlations					
Ind. Variable	**Multiple**	**Partial**	**T**	**P**	
ADMIRE	0.0694	0.1352	1.24	0.2201	
ALLUVIUM	0.4891	-0.0675	-0.61	0.5419	
DRIFT	0.2685	-0.0807	-0.73	0.4656	
CHZ	0.2457	0.0352	0.32	0.7505	
CHZTIME	0.2709	0.0809	0.74	0.4642	
CROPS	0.1953	-0.0020	-0.02	0.9858	
FORWET	0.3018	-0.0707	-0.64	0.5229	

GRAVEL	0.0668	0.0091	0.08	0.9348	
LSIM	0.1140	0.0383	0.35	0.7294	
SILTCLAY	0.0883	0.1183	1.08	0.2839	
SRBW	0.3837	-0.1097	-1.00	0.3205	
SRS	0.6316	0.1763	1.62	0.1087	

Table 4.9 Stepwise linear regression analysis of channel depth change between 1963 and 2008.

Stepwise Linear Regression of Channel Depth Change 1963-2008 (DCNG)					
Unforced Variables: Admire, Log transformed drainage area (LDA, Alluvium, Drift, Channelization (CHZ), Timing of CHZ (CHZTIME), Crops, Forest/Wetland (FORWET), Grass/Pasture (GRASPAST), Gravel, Log transformed simon(RGA) #'s (LSIM), Siltclay, Square root transformed slope (SRS)					
Stepwise Model at P = 0.05 Significance Level					
Ind. Variable	**Coefficient**	**Std Error**	**T**	**P**	**VIF**
Constant	2.23853	0.23509	9.52	**0.0000**	
GRASPAST	-1.52603	0.65531	-2.33	**0.0237****	1.1
SRBW	-0.13191	0.04129	-3.19	**0.0024*****	1.1
*** denotes statistical significance at the p<0.01 level ** denotes statistical significance at the p<0.05 level					
Cases Included 56		**R Squared 0.1935**		MSE 1.49667	
Missing Cases 51		**Adjusted R Squared 0.1631**		SD 1.22338	
Variables Not in the Model – Correlations					
Ind. Variable	**Multiple**	**Partial**	**T**	**P**	
ADMIRE	0.4245	0.1791	1.31	0.1950	
ALLUVIUM	0.2048	-0.1105	-0.80	0.4263	
DRIFT	0.4658	-0.0534	-0.39	0.7016	
CHZ	0.4811	0.0013	0.01	0.9925	
CHZTIME	0.5124	0.0416	0.310	0.7653	
CROPS	0.6895	-0.0045	0.03	0.9741	
FORWET	0.7866	-0.0628	-0.45	0.6518	

GRAVEL	0.0871	-0.1137	-0.83	0.4130	
LSIM	0.5161	0.0377	0.27	0.7868	
SILTCLAY	0.1665	0.1083	0.79	0.4355	
SRS	0.3111	-0.1149	-0.83	0.4079	
LDA	0.5087	0.2323	1.72	0.0910	

Table 4.10 Stepwise linear regression analysis of channel depths in 1963.

Stepwise Linear Regression of Channel Depths in 1963					
Unforced Variables: Admire, Log transformed drainage area (LDA), Drift, Square root transformed slope (SRS)					
Stepwise Model at P = 0.05 Significance Level					
Ind. Variable	**Coefficient**	**Std Error**	**T**	**P**	**VIF**
Constant	1.28876	0.09349	13.79	**0.0000**	
Admire	0.16007	0.07605	2.10	**0.0401****	
LDA	0.35431	0.05682	6.24	**0.0000*****	1.0
*** denotes statistical significance at the p<0.01 level ** denotes statistical significance at the p<0.05 level					
Cases Included 56		**R Squared 0.4743**		MSE 0.04287	
Missing Cases 51		**Adjusted R Squared 0.4545**		SD 0.20705	
Variables Not in the Model – Correlations					
Ind. Variable	**Multiple**	**Partial**	**T**	**P**	
SRS	0.6704	0.1451	1.06	0.2952	
Drift	0.7437	-0.1225	-0.89	0.3776	

Discussion of Variables Influencing Channel Depths and Channel Depth Changes

Table 4.8 shows the results from using stepwise linear regression to test for significant variables influencing channel depth in 2008. One independent variables (drainage area) is significant at the p<0.01 level. Another independent variables (grass/pasture) is significant at the p<0.05 level. About 35% of the variance in the model is explained here. The remaining variables are not significant at the p<0.05 level.

The significant variables identified by this test can be explained geomorphically. It is well established that larger stream channels exist in downstream areas of a watershed as those channels accommodate higher flows from the watershed upstream (Knighton, 1998). The larger the watershed size upstream, the greater the size of the channel will be. Even with highly modified stream channels in the Black Vermillion watershed (Daniels, 2008), this relationship statistically holds true (Figure 2.7). Grassland/pasture, as an adjacent land use that was identified in the field, appears to influence channel depth as well. This could potentially result from the increased shear stress that tree roots contribute to bank stability. Further, it has been noted by Thorne (1990) that soil containing roots has an enhanced strength that resists disturbance by fluvial erosional processes. The deeper roots of tree species in the riparian zone may assist in maintaining bank heights that are not possible when grassland or pasture vegetation is present. Stream channels at locations with grassy vegetation are shallower due to the lack of stabilizing roots in the streambanks. This relationship seems solidified for the Black Vermillion watershed by the stepwise linear regression test undertaken here.

Table 4.9 illustrates the results from using stepwise linear regression to test for significant variables influencing channel depth change between 1963 and 2008. One independent variable (buffer width) is significant at the $p<0.01$ level. Another independent variable, grassland/pasture, is significant at the $p<0.05$ level. About 16% of the variance is accounted for in this model. These two significant variables, and their influence on channel depth change between 1963 and 2008, might be explained geomorphically similar to the reasons stated for channel depths for 2008. Grassland/pasture and buffer width appear to be variables that influence the behavior of the overall incision process. This influence may be derived from the ability of vegetation to anchor material in streambanks and to prevent it from failing.

Table 4.10 demonstrates the results from completing stepwise regression on the variables potentially affecting channel depths in 1963. Because of the historical nature of these data, only independent variables that would have remained unchanged between 1963 and 2008 could be included in this analysis. One of these variables, upstream drainage area, is significant at the $p<0.01$ level. A second variable, the Admire Group geology type, is statistically significant at the $p<0.05$ level. About 45% of the model's variance is explained by the variables tested.

What is shown by this result is that the type of geology present was an important factor in determining the depths of stream channels in 1963. As shown in Figures 1.2 and 1.3, areas with the Admire Group geology underlying them are located within the South Fork (Irish Creek) watershed. Also as seen in Figure 1.4, this sub-watershed contains more pastureland, but less agricultural land, when compared to the sub-watersheds of the Main Branch and North Fork. Historically, this has been the case as well (Sass, 2008). More extensive forested riparian buffers are also present along the streams of this watershed. The difference in geology likely influenced the depths of stream channels in this area by making the South Fork sub-watershed less conducive to row crop agriculture. Hence, less channelization took place prior to 1963, and riparian buffers were allowed to remain (Figure 2.7). The importance of both riparian buffers and adjacent land use were confirmed using stepwise linear regression for both channel depths in 1963 and 2008. Further, the significance of channelization on channel stage was shown to be significant using the Kruskal-Wallis statistical test. These other variables, while related to geology, could not be tested in 1963. However, they have been recognized to be significant variables that influence channel conditions in later years. The importance of geology in relation to channel depths in 1963 can therefore be understood. The importance of geologic conditions have also been noted by Heinen and Lant (2009) who stated differing geological conditions present in a watershed would affect channel incision because of variability in the erodibility of surficial materials.

Upstream drainage area also returned as a significant independent variable affecting channel depths in 1963, as it did for channel depths in 2008. It is known that upstream drainage area affects channel dimensions with stream channels further downstream being larger to accommodate larger flows (Knighton, 1998). This relationship is again proven here for stream channels for the Black Vermillion watershed in 1963.

This discovery of the importance of upstream drainage area in both 1963 and 2008 is significant because it is a purely natural variable and not influenced by human activities. It has already been established that extensive land use change has occurred in the watershed (Figure 1.4) and that channelization has impacted many of the major streams of the watershed (Figure 2.7). Despite these findings, a natural variable is still significant in influencing channel depths, both historically and in modern times. The importance of upstream drainage area on determining channel dimensions has been noted by others, including Anderson (1957).

Following completion of the Pearson correlation and stepwise regression analyses, the Kruskal-Wallis analysis of variance (ANOVA) test was utilized to identify the independent variables influencing channel stage (Figure 2.13). This was done because the importance of channel stage, its occurrence, and its location within the watershed have been determined to be important components of the story of the stream channels of the Black Vermillion watershed (Figure 4.6). The results of this test are shown in Table 4.11.

Table 4.11 Results from Kruskal-Wallis Analysis of Variance (ANOVA).

Dependent Variable	**Independent Variables**	**Statistical Technique**	**Study Sites Used (Cases included)**	**P Value**
Stage I **Stage II** **Stage III** **Stage IV** **Stage V**	**Geology**	**Kruskal-Wallis analysis of variance**	**107**	**0.0000*****
	Bed Material		107	0.3904
	Timing of Channelization		**86 – timing of channelization information not known for some sites**	**0.0741***
	Channelization		**107**	**0.0157****
	Land use/land cover		**107**	**0.0120****
	Channel depth 1963		56 - only calculated for comparison study sites	0.2357
	Channel depth 2008		107	0.6777
	Drainage area		**107**	**0.0819***
	Unit stream power		56 - only calculated for comparison study sites	0.6931
	Cross section area		56 - only calculated for comparison study sites	0.3905

*** denotes statistical significance at the $p<0.01$ level

** denotes statistical significance at the $p<0.05$ level

* denotes statistical significance at the $p<0.1$ level

Discussion of Variables Influencing Channel Stage

Table 4.11 shows the results of testing channel stage against the independent variables collected for this study. One variable (geology) returned as being statistically significant at the $p<0.01$ level. Two variables (channelization and land use/land cover) returned as being statistically significant at the $p<0.05$ level. Two more variables (timing of channelization and drainage area) returned as being statistically significant at the $p<0.1$ level. All five variables can be explained geomorphically. Geology - whether a site was located within alluvial or glacial deposits, or had bedrock close to the surface – appears to influence the condition of stream channels and the stage that they are found in. In the Black Vermillion watershed, glacial deposits dominate the landscape, contributing to the fertile, fine-grained soils that cover the region. Alluvium is river-deposited material, with much of it found on floodplains. As such, alluvium is material that has been carried by a stream, reworked, and deposited in the riparian zone or floodplain. Many sites along the streams of the Black Vermillion watershed contain this material. Bedrock, the third type of geology, lies close to the surface only within the South Fork (Irish Creek) watershed. While statistically significant, what is not determined by this statistical test is exactly which of the three geology types is the most important in influencing channel stage. However, stepwise linear regression indicated the Admire (bedrock) geology type influenced channel depths in 1963. Therefore, the Admire geology type may also influence channel stage. However, about 75% of the study sites are mapped as overlying glacial till (Figure 1.2 and Figure 1.3) . The widespread presence of this erodible glacial till as the primary surficial material within the watershed area likely does indeed have a geomorphic relationship to channel stage. This could potentially result from erodible glacial till being easily scoured out from degrading channel beds (Stage III) and also being prone to bank failure (Stage IV). However, what is shown is that geology as a natural variable does influence channel stage. It has been previously well established that incised streams and the consequences thereof (specifically bed degradation and bank erosion) are found in areas with erodible surficial geologic materials. However, this relationship has been quantified and illustrated here for the Black Vermillion watershed using channel stage and geologic characteristics.

Both channelization and timing of channelization were identified as statistically significant independent variables as well. Because the Simon and Rinaldi (2006) model was developed to illustrate transgression of stream channels through post-channelization adjustment and recovery, the statistical relationship exhibited here is justified. Also deserving of note again is that 63% of the study sites in the watershed were identified as either Stage III (degradation) or Stage IV (degradation and widening). As such, the majority of locations in the watershed studied for this thesis exhibit response to previous channelization events. This knowledge further strengthens the cause for a statistically significant relationship between these two variables.

Simon and Rinaldi (2006) emphasized the importance of identifying the amount of time that had passed since channelization disturbance when attempting to understand channel stage (Figure 2.14). With this in mind, the liberal statistical relationship shown between channel stage and timing of channelization should be considered in comparison with the map of channel stages shown in Figure 4.6. There is a definite spatial relationship between Stage III's (degradation) and Stage IV's (degradation and widening) and the more agricultural areas of the watershed (Figure 1.4). These more agriculturally-dominated areas of the watershed are more likely to have streams that have been channelized and, hence, more locations where Stage III, Stage IV, or Stage V channels are present (Figure 2.7).

Channelization and timing of channelization were identified as significant variables influencing channel stage. However, it is interesting that these variables did not return as statistically significant when tested against channel depths in 2008 or channel depth change between 1963 and 2008 using multiple regression. These findings suggest that the response and recovery from channelization of stream channels in the Black Vermillion watershed do not follow a consistent pattern. It is known that channelization practices throughout the watershed are ubiquitous (Figure 2.7), suggesting that channelization has impacted almost every major stream channel in the majority of the watershed. However, the spatially and temporally variable occurrence of the channelization activities has potentially clouded the statistical relationship with channel depths. As shown in the model by Simon and Rinaldi (2006 - Figure 2.13) the response to channelization in the fluvial system is complex. Deepening, widening, and eventual aggradation of the affected channels occurs over time. As a result, the dependent variable stage was tested against channelization, and timing of channelization. These two independent variables returned as statistically important. The lack of a statistical relationship between channelization and timing of channelization, and channel depths in 2008 and channel depth change between 1963 and 2008 does confirm the presence of a complex response to channelization.

Further, the analysis undertaken here has been done on a watershed scale. Therefore, for each study site the conditions present in the drainage area upstream of that site have to be considered as potential influences. In sites further downstream, the cumulative effect of all channelization practices in reaches upstream have to be considered. This cumulative effect may be exerting a lot of influence on channels of the watershed, however channel depth may not be directly affected at locations where channel depth could be measured. For example, even if channelization had not been done specifically at a study site where channel depths were measured, upstream channelized reaches would potentially still help alter flow and sediment transport conditions at that site since it lies downstream. In further downstream locations, the response may be even more complex because of the wider variability in upstream conditions. This phenomenon of a cumulative affect is strengthened by the hydrograph shown in Figure 2.5. That hydrograph, from the USGS gauging station in Frankfort, shows a high intensity flooding event where the flows from the watershed quickly accumulated in the channel. The channelization-shortened channels of the Black Vermillion watershed do not allow much water storage. Hence, flooding occurs more rapidly at that location even if channelization had not been completed directly at that location (Table 2.3). This cumulative effect of all upstream channel and watershed conditions can therefore have a major effect on the conditions seen at a given location in the watershed. As a result, channelization, as an anthropomorphic disturbance to stream channels, has been identified as a significant cause of channel incision. This is largely because of the widespread presence of channelization in the watershed and its direct and far-reaching impacts to in-channel processes and conditions.

Upstream drainage area also appears as an important independent variable. Its influence on stage is likely due to its apparent relationship on channel depths in both 1963 and 2008, as shown using stepwise regression. Illustrated by these results is the importance of the location of a study site in the watershed and its upstream watershed area. Anderson (1957) labeled upstream drainage area as a “devil’s variable” in that it has an influence on many characteristics of streams. This relationship between channel conditions and upstream drainage area is further strengthened by the findings reported here.

Land use/land cover as an independent variable also resulted in being statistically significant in influencing channel stage. Since the land use/land cover variable was identified in the riparian zone adjacent to each study site, the presence of this statistically significant relationship is potentially meaningful. About 64% of the 107 study sites had forest buffers in their riparian zones. This is encouraging because of the documented benefits of riparian vegetation buffers in agricultural watersheds and their particular value on increasing streambank stability (Simon and Collison, 2002). Despite the widespread presence of riparian buffers, Stage III (degradation) and Stage IV (degradation and widening) conditions dominate in the Black Vermillion watershed (Figure 4.6). These conditions might be either encouraged or hindered by the presence of riparian vegetation. Streambanks created more stable by the presence of riparian vegetation might lead to deeper stream channels since those streambanks might hold together better vertically. Conversely, in locations where little to no riparian forested buffer is present (about 35%) triggering of mass wasting through channel widening and bank erosion could ensue. However the exact processes are occurring, it is clear that riparian vegetation is influencing channel stages in the Black Vermillion watershed.

This finding about the significance of adjacent land use/land cover is corroborated with previous findings of this thesis. Stepwise multiple regression confirmed that grass/pasture, as a land use, has a statistically significant relationship with channel depths as measured in 2008 and the channel depth change between 1963 and 2008. These results from two separate statistical tests indicate that adjacent land use/land cover does indeed influence the condition of the stream channels of the Black Vermillion watershed.

Further, this relationship has significant implications in consideration of possible remedial strategies for the streams of the Black Vermillion watershed. Observations made in the watershed area in the summer of 2008 confirm that many farmers are specifically leaving riparian vegetation buffers adjacent to the streams on their lands. Exactly how much the vegetation buffers are helping to control channel instability has not been determined. However, considering the channel instability problems of the watershed, the potential benefits of streamside buffers should be strongly considered in thinking about the future of the watershed. The statistical relationships described here should help to emphasize the importance of buffer strips, since they are one independent variable influencing channel conditions that humans can manage.

It is important to note that both of these variables affecting channel stage are somewhat natural, especially geology. The geological materials present at each site are not human-controlled. On the other hand, land use/land cover is partially controlled by human activity. Sass (2008) established that riparian vegetation has changed extensively throughout the Black Vermillion watershed since the time of early human settlement in the area. Much of this has been due to clearing of riparian areas for cultivation, especially since the mid-1950's (Sass, 2008). However, the ways in which riparian vegetation influence fluvial erosional processes and behaviors are natural. So, their presence is both natural and human-influenced.

The occurrence and timing of channelization practices upstream of each study site also has a statistically significant relationship with channel stage. As a purely human-caused disturbance and agent of geomorphic change, this is a particularly poignant finding. It proves statistically that human activities through channelization have undoubtedly altered the condition of the streams of the Black Vermillion watershed. While the channelization history of the watershed detailed in this thesis strongly suggested this relationship, it is now known to be statistically significant.

At this point, questions arise about what can be done to improve the health of the streams of the Black Vermillion system. Questions of stream and watershed health have been addressed in previous research (Marston and Anderson, 1991). With that said, the extensive human impacts and vulnerable natural conditions of the Black Vermillion watershed cause questions of overall watershed condition to arise. Further, questions of overall watershed health and condition tie into inquiries surrounding remedial actions to potentially reduce the negative affects of channel incision in the watershed. These questions have been asked and addressed previously and past work has been completed in the Black Vermillion watershed in order to reduce flooding issues and to help improve channel stability. As shown by Sass (2008) the Soil Conservation Service in 1966 instituted a watershed-wide work plan to help address pressing land management issues in the Black Vermillion watershed. Actions undertaken included the construction of flood and sediment detention ponds and channelization to existing channels of the watershed. Despite this past work, many issues with flooding and channel instability remain in the Black Vermillion watershed.

The literature on specific management restoration and rehabilitation options of incised streams are relatively meager considering the widespread presence and negative consequences of channel incision in this watershed and throughout the American Midwest. Simon and Darby (2002) outlined three main strategies for managing incised streams. First, restoration and rehabilitation are considered. This approach involves focusing on the causes of incision, and attempting to change management policies to eliminate or reduce sediment output from a watershed. Shields et al., (1999) couple rehabilitation and remediation of incised streams with a similar approach to the overall stream corridor habitat. However, as they note, complete restoration (return to pre-degradation form) of incised streams and their riparian corridors is usually not feasible. This is due to the impracticalities of changing land uses in watersheds, restoring natural stream sinuosity to pre-channelization values, and restoring stream channel morphologies to pre-widened and deepened conditions. Further, extensive encroachment of human structures and interests into floodplains would make restoring the fluvial system to its original, unaltered state impossible. With these limitations, Shields et al., (1999) emphasize that rehabilitation, or a limited return to pre-incision channel form, should be the preferred management strategy for incised streams. They cited examples such as installing flood storage reservoirs as a potentially helpful solution to restore pre-incision flow regimes. Further, they mentioned the possibility of installing in-channel structures to slow or stop the progression of channel incision. Simon and Darby (2002) comment on this further as their second method for the management of incised streams.

Grade control structures, weirs, spurs, or drop structures have been installed in some incised streams in order to stop or slow bed degradation and channel incision. Analysis of their benefits indicates that their effectiveness is mixed (Shields et al., 1998). Watson and Biedenharn (1999) outlined the effectiveness of grade control structures on the rehabilitation of incised streams. They described several of these structures, including channel linings, concrete drop structures, and simple bed control structures. Most of these features are constructed using concrete, rip-rap, or other erosion-resistant material. Simon and Darby (1999) documented the competence of grade-control structures on Hotophia Creek in Mississippi, a severely incised stream. Their detailed analysis concurs with the findings of other researchers, including Watson and Biedenharn (1999) and Shields et al., (1999) that multiple factors have to be considered when assessing the feasibility and effectiveness of grade control structures in incised streams. Perhaps most significant are the findings of Simon and Darby (1999) who showed that grade control structures are only useful in stopping or slowing channel incision when they are installed early in the progression of the channel incision process. Further, these same structures inhibited the downstream movement of sediment from upstream incised reaches. This led to increased incision and bank erosion downstream on Hotophia Creek. Also, as shown by Simon and Rinaldi (2006), these sediments from upstream incised reaches are an important component of downstream recovery from channel incision.

The third and final management option for incised streams as outlined by Simon and Darby (2002) is to use drastic methods such as floodplain excavation to re-establish the relationship between the floodplain and the incised river. Another example listed by them includes installing structures in the incised channel in order to improve stream habitat.

Overall, these three options as shown by Simon and Darby (2002) are all potentially impractical when considering the Black Vermillion watershed. Because of the large size of the watershed, treatment of the whole fluvial system would be an expensive and significant undertaking. Two of the options, drastic floodplain excavation or installation of grade control structures as listed by Simon and Darby (2002), are likely to be exceedingly expensive if eventually implemented for the Black Vermillion watershed. The effectiveness of both of the options deserves doubt as well. Based on what this thesis has shown, grade control structures would likely have very limited effectiveness. As shown by Simon and Darby (2002), grade control structures are only effective at stopping or slowing incision early in the adjustment process. This thesis has shown that channel depth changes between 1963 and 2008 have increased considerably. Further, Stage III (degradation) and Stage IV (degradation and widening) conditions are present watershed-wide. These findings suggest that the process of channel incision in the Black Vermillion watershed has been occurring for an extended period of time. Building on the findings of Simon and Darby (2002), it is doubtful that grade control structures installed in the near future would be effective because they would have been emplaced at least 45 years too late. Further, from observations made in the field during the summer of 2008, it is doubtful that any in-channel erosion control structures would be effective at controlling either channel bed degradation or bank erosion. Bank slumping and channel incision are so widespread, and the bed materials are so consistently erodible silt and clay, that in-channel structures would likely be rendered useless.

However, what this thesis has also shown is that channel depths and channel stages throughout the watershed are statistically related to adjacent land use and land cover. Using this knowledge, the planting of thicker and more extensive riparian buffers in the watershed should be encouraged. Currently, the NRCS does encourage the planting of riparian buffers in the Black Vermillion watershed area (Sass, 2008). The research described here could provide further emphasis on the importance of these buffers as farmers of the watershed continue to till their lands in future decades. However, little is known about the overall effectiveness of riparian vegetation in the prevention of further channel incision. Therefore, while installation of new riparian buffers or improvement of existing riparian buffers is likely beneficial for the rehabilitation of the streams of the Black Vermillion watershed, it is not known exactly how beneficial they would be.

Chapter 5 - Conclusions

The objectives of this study were threefold. The first objective was to identify the spatial extent and pattern of channel incision in the Black Vermillion watershed. The second objective was to uncover the timing of channel incision in the Black Vermillion watershed. The third objective was to discern the causes of channel incision in the Black Vermillion watershed.

The analysis of channel measurements collected at 107 points throughout the watershed in summer of 2008 revealed that channel incision is widespread, and, at times, severe throughout the Black Vermillion watershed. While natural variables such as riparian buffers, adjacent land use, slope, and upstream watershed size vary for each of the study sites, channel incision continues to persist at the majority of the sites throughout the watershed. As seen in the field in the summer of 2008 and recorded in Figure 4.1, both small tributary streams and the main stem channels of the Black Vermillion fluvial system have experienced channel incision. This conclusion suggests that channel incision has been instigated in numerous locations throughout the watershed and that one location cannot be pinpointed as the origin of the channel incision seen throughout the watershed. Further, the wide spatial extent of channel degradation in the study area suggests that the Black Vermillion fluvial system has been responding to the factors causing channel incision for an extended period of time.

Other researchers have noted that channel incision migrates upstream as stream reaches upstream attempt to adjust to lowered base levels downstream. In turn, the channel downstream of the incised reach accumulates sediment because of the sediment overabundance being supplied from upstream. In this way, channel incision migrates throughout the channel network and can potentially influence the whole watershed. Analysis of the spatial extent of incision in the Black Vermillion watershed has shown that out of the 56 locations where channel depths were compared between 1963 and 2008, only five showed aggradation. At the remaining 51 locations, channels have deepened, some of them considerably, between those years. These sites that showed aggradation were not located in downstream reaches of the watershed. This finding confirms that very little sediment storage is occurring in the portion of the Black Vermillion watershed analyzed for this study.

Using the 1963 Soil Conservation Service (SCS) cross sections as a baseline, analysis of the timing of channel incision in the Black Vermillion watershed confirmed that between the years 1963 and 2008, stream channels in the Black Vermillion watershed deepened by an average of 1.6 meters. Geomorphically speaking, the 45 years between those dates is a very short time period and the channel incision seen throughout the watershed during that time is significant. That said, it can be concluded that during the last four and a half decades, the channels of the Black Vermillion watershed have undergone major change in the form of bed degradation, or channel incision.

The third and final objective of this study was to attempt to understand the causes of channel incision in the Black Vermillion watershed. The evaluation of the spatial extent and timing of channel incision within the Black Vermillion watershed has shown that human impacts to the stream channels have indeed been very influential to the morphology of channels within the watershed. Conversely, the results from statistical analyses of the causes indicate that the natural variables of the watershed and the channels themselves are controls on channel morphology as well. Stepwise regression showed that upstream drainage area, and adjacent land use/land cover (especially grassland/pasture) are influencing channel morphology as measured in 2008. For channel depth change between 1963 and 2008, adjacent land use/land cover and buffer widths are shown to be significant controls. However, after completion of the statistical analysis described here, it is clear that channel depths for both 1963 and 2008 seem to be very dependent on their location in the watershed. Deeper channels are generally in downstream reaches while shallower channels are located in upstream reaches.

Analysis of the drivers of channel stage showed that channel stages are partially dependent on the same factors that influence channel depths. Land use/land cover at each site has a potentially significant relationship with channel stage as well as with channel depths in 1963 and 2008. Geology and upstream drainage area also influences channel stage. However, channel stage is also affected by the occurrence and timing of channelization. Further, channel stage is a dependent variable that has the capacity to change over time. This fact also complicates the process of identification of the factors that influence it.

Channelization has potentially the most direct and far-reaching impacts on stream channels because of its ability to severely alter sediment delivery, floodflow attenuation, and other fluvial processes. The majority of the larger stream channels of the Black Vermillion watershed have been altered due to channelization practices. Each site is likely to be affected not only by the channelization at the site, but also by the cumulative impact of channelization upstream and downstream. Past research and this study have only examined the impact of channelization at each site. Therefore, it is not surprising that channelization was not identified as a statistically significant variable in regression analysis with 2008 channel depths and 1963-2008 channel depth change. Occurrence and timing of channelization were identified as statistically significant when tested against channel stage. In turn, channel stage was developed to model the complex response of stream channels to channelization disturbance. This complex response indicates that stream channels follow through a sequence of channel conditions following channelization. Not all of these responses involve channel degradation. Aggradation and widening are responses as well. As a result, not uncovering a statistical relationship between occurrence/timing of channelization and channel depths in 2008 or channel depth change between 1963 and 2008 does not mean that a relationship does not exist. Instead, it suggests that the complex response of stream channels to channelization masks the relationship between the variables. This relationship is strengthened with the knowledge that channel stage is statistically related with the timing and occurrence of channelization.

The findings of this study confirm what has been a central tenet of this thesis throughout the process: that channel incision, and channel stage, cannot be accredited to only one source, one cause, or one contributing variable. Schumm (1991) emphasized that channel incision is a great example of convergence in that many causes create the same result. Further, channel incision can also be attributed to Schumm's (1991) definition of multiplicity; that multiple variables acting in combination create a result. This thesis has shown these two relationships to hold true for the Black Vermillion watershed of northeastern Kansas.

What this study has established is that the stream channels of the Black Vermillion watershed have incised throughout the watershed area and are still actively incising and widening. Further, it has been shown that this channel instability has been occurring since at least 1963, with extensive channel change having occurred between 1963 and 2008. Heine and Lant (2009) showed that this 45 year time frame is sufficient to allow for substantial channel incision in similar agricultural streams. Through analysis of the spatial extent and timing of channel incision, it can be concluded that human impacts to the stream channels and the region have significantly altered the streams of the watershed area. Land use change, intense farming practices, and channelization all have played a role in causing channel incision. However, statistical analysis revealed that the natural variables of the watershed have been contributors as well. At this point, it is difficult to confirm which of these two sets of variables…human-caused vs. naturally occurring…is more significant. However, an undisputable finding of this study is that the stream channels of the Black Vermillion watershed have been heavily altered by human activity (channelization) while natural variables such as riparian land cover types, upstream drainage area, and geology are potential contributors to their instability as well. Simon and Rinaldi (2000) stated that areas of the Midwest where intense agriculture and erodible soils are present, like the Black Vermillion watershed, are a “worst case scenario” for channel instability and that the combination of human and natural factors forms the basis for this instability.

These findings are significant as attempts continue to understand the volume and origin of sediment emanating from the watershed and eventually reaching Tuttle Creek Reservoir. What is clear is that channel incision has been initiated by a variety of causes, and that the streams of the watershed are still responding and adjusting to changes in their channel morphology. However, as previous research has shown, the adjustment period of streams to severe channel incision takes many years, and sometimes many decades. Further, streams in this type of disequilibrium cause greater volumes of sediment to leave the watershed due to bank slumping, larger channel capacities, and lack of sediment storage. As a result, Tuttle Creek Reservoir will likely continue to receive excessive volumes of sediment from the Black Vermillion watershed well into the future.

Future work on the Black Vermillion River system should benefit from this study. It provides analysis of channel change between 1963 and 2008 while also attempting to establish linkages between the complex cause and effect relationships present in this watershed. Future researchers could also use it as a baseline for how the stream channels of the watershed have changed over time. For example, in several decades it might be beneficial to re-survey the study sites and identify channel stages. In this way, the channel stage analysis and channel depth information should be particularly helpful as conditions in 2008 have been well recorded.

This study offers much potential for future research. While well studied, channel incision in agricultural watersheds will be a continuing issue with streams in the American Midwest. It has many negative consequences that affect human, wildlife, natural, and environmental interests. Greater research into the causes and behavior of incised streams may yield insight into how they can be remedied. The importance of riparian buffers in this watershed has been identified, and this finding is important as a future potential management tool. However, in other watersheds other variables might be more important, and this topic deserves future work. Further, it is clear that little research has been completed on channel incision on the watershed scale. Future studies that integrate channel incision with other environmental issues in Midwestern watersheds are likely to be beneficial and enlightening.

The findings reveal that the watershed is suffering from the effects of intense human disturbance to both uplands and stream channels. Further, land use and surficial geology have made it highly susceptible to these disturbances. Also, the health of this watershed is adversely affecting Tuttle Creek Reservoir downstream. Stream and riparian restoration would likely prove costly. Installation of in-channel structures would probably be ineffective because channel incision has already occurred, and the streams throughout the watershed are already too severely impacted. Lastly, the highly erodible nature of the channel beds and banks of the streams of the Black Vermillion watershed would also likely limit the effectiveness of other in-channel structures. However, all may not be lost for potential management improvements. This study has documented the importance of riparian buffers to channel incision and channel stage. It is reasonable to advocate for watershed improvement through future plantings and protection of riparian buffers.

This study has further revealed the importance of understanding stream response to change on the watershed scale. More research needs to be completed to help us understand our rivers, and hence, our place in the world. Human activities, coupled with sensitive watershed conditions, work together to degrade streams of the Black Vermillion watershed. With much urgency, forward thinking and preventative measures should be pursued in our watersheds and our world in order to prevent further environmental damage. As growing human needs continue to be balanced with global environmental health, we should learn from past mistakes and remember that human and environmental well-being are inextricably intertwined. Streams of the Black Vermillion watershed provide examples of how human actions, when imposed on sensitive natural conditions, create persistent consequences to our environments, and therefore to ourselves.

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Appendix A - 1963 Soil Conservation Service (SCS) Cross Section Measurements

Table A.1 Upper Black Vermillion watershed cross sections S1 to S6.

Reach (SCS labeled by locale in watershed)	Road Cross Section	Maximum Depth of Channel (Feet)	Width of channel (feet)	Width to depth ratio
S1	1	15.8	60.0	3.8
S1	2	14.6	100.0	6.8
S1	2A	10.7	50.0	4.7
S1	2B	17.3	30.0	1.7
S1	2C	23.6	20.0	0.8
S1	2D	15.3	260.0	17.0
S1	3	14.3	110.0	7.7
S1	4	13.8	40.0	2.9
S1	5	14.0	90.0	6.4
S1	6	18.0	220.0	12.2
S2	1	16.5	100.0	6.1
S2	2	16.4	100.0	6.1
S2	3	16.5	170.0	10.3
S2	4	14.5	80.0	5.5
S2	5	19.0	140.0	7.4
S3	1	14.9	100.0	6.7
S3	2	21.7	115.0	5.3
S3	3	10.5	50.0	4.8
S3	4	12.8	70.0	5.5
S3	5	9.8	50.0	5.1
S3	6	7.8	120.0	15.4
S3	7	11.1	110.0	9.9
S4	0	11.8	60.0	5.1
S4	1	8.1	100.0	12.3
S4	3	14.5	70.0	4.8

S4	4	8.2	80.0	9.8
S4	5	8.9	200.0	22.5
S5	1	6.5	45.0	6.9
S5	2	8.6	40.0	4.7
S5	3	10.9	100.0	9.2
S6	1	12.4	40.0	3.2
S6	2	11.3	45.0	4.0
S6	3	12.2	80.0	6.6
S6	4	9.2	60.0	6.5
S6	5	9.9	50.0	5.1
S6	6	7.8	70.0	9.0
S3	3	10.5	50.0	4.8
S3	4	12.8	70.0	5.5

Table A.2 Upper Black Vermillion cross sections sub-watersheds 3 to 14.

Reach (SCS labeled by locale in watershed)	Road Cross Section	Maximum Depth of Channel (Feet)	Width of channel (feet)	Width to depth ratio
3	1	23.5	220.0	9.4
3	2	25.6	200.0	7.8
3	3	19.8	120.0	6.1
3	4	13.0	110.0	8.5
3	5	14.7	80.0	5.4
3	6	9.0	180.0	20.0
3	7	13.8	60.0	4.3
4	1	10.0	60.0	6.0
4	2	8.6	40.0	4.7
4	3	9.8	60.0	6.1
4	4	8.3	130.0	15.7
4	5	12.4	80.0	6.5
4	6	7.0	50.0	7.1
4	7	18.9	160.0	8.5
4	8	9.5	40.0	4.2
4	9	11.8	50.0	4.2
4	10	16.2	50.0	3.1

4	11	15.0	40.0	2.7
4	12	9.9	40.0	4.0
4	13	12.3	60.0	4.9
5	1	14.4	60.0	4.2
5	2	14.5	120.0	8.3
5	2A	14.3	80.0	5.6
5	3	19.6	120.0	6.1
5	4	27.5	200.0	7.3
5	5	16.0	70.0	4.4
5	6	14.6	100.0	6.8
5	7	14.9	100.0	6.7
5	8	14.1	140.0	9.9
6	A	13.5	70.0	5.2
6	B	18.4	160.0	8.7
6	C	13.5	80.0	5.9
6	1	10.0	60.0	6.0
6	2	9.9	50.0	5.1
6	3	13.8	90.0	6.5
6	4	23.1	180.0	7.8
6	5	9.8	80.0	8.2
6	6	13.6	60.0	4.4
6	7	10.2	80.0	7.8
6	8	10.1	50.0	5.0
6	9	11.3	80.0	7.1
6	10	9.7	80.0	8.2
6	11	7.5	130.0	17.3
6	12	21.3	100.0	4.7
6	13	14.0	80.0	5.7
6	14	9.5	70.0	7.4
7	1	16.9	80.0	4.7
7	2	20.0	110.0	5.5
7	3	14.6	60.0	4.1
7	4	15.8	90.0	5.7
7	5	12.8	100.0	7.8
7	6	13.7	80.0	5.8
7	6A	13.2	80.0	6.1

7	7	12.5	40.0	3.2
7	8	11.6	70.0	6.0
8	1	11.0	40.0	3.6
8	2	12.3	100.0	8.1
8	3	9.8	190.0	19.4
8	4	20.4	230.0	11.3
8	5	11.9	60.0	5.0
8	6	14.5	100.0	6.9
9	1	13.8	80.0	5.8
9	2	13.2	60.0	4.5
9	3	12.5	50.0	4.0
9	5	10.7	100.0	9.3
9	4	11.6	100.0	8.6
10	1	12.5	60.0	4.8
10	2	9.5	60.0	6.3
10	3	10.7	60.0	5.6
10	4	7.0	65.0	9.3
10	5	8.9	50.0	5.6
10	6	13.0	200.0	15.4
10	7	12.2	90.0	7.4
10	8	23.0	180.0	7.8
10	9	13.0	110.0	8.5
10	10	10.0	100.0	10.0
11	1	13.3	100.0	7.5
11	2	11.4	80.0	7.0
11	3	7.7	40.0	5.2
11	4	10.0	40.0	4.0
12	1	8.6	60.0	7.0
12	2	8.4	80.0	9.5
12	3	8.4	50.0	6.0
12	4	14.5	60.0	4.1
12	5	11.0	80.0	7.3
12	6	11.8	60.0	5.1
12	7	8.0	100.0	12.5
12	8	9.5	70.0	7.4
12	9	7.8	35.0	4.5

12	10	11.0	35.0	3.2
13	1	11.9	35.0	2.9
13	2	9.0	40.0	4.4

Table A.3 Upper Black Vermillion watershed cross-sections sub-watersheds N1 to N12.

Reach (SCS labeled by locale in watershed)	Road Cross Section	Maximum Depth of Channel (Feet)	Width of channel (feet)	Width to depth ratio
N1	1	12.2	60.0	4.9
N1	2	19.7	200.0	10.2
N1	3	10.7	50.0	4.7
N1	4	13.0	100.0	7.7
N1	5	12.5	100.0	8.0
N1	6	6.2	180.0	29.0
N1	7	12.8	70.0	5.5
N1	8	12.5	80.0	6.4
N1	9	13.0	70.0	5.4
N2	1	12.2	60.0	4.9
N2	2	13.8	70.0	5.1
N2	3	18.0	90.0	5.0
N2	4	20.7	140.0	6.8
N2	5	12.0	100.0	8.3
N2	6	16.5	80.0	4.8
N2	7	18.0	100.0	5.6
N3	1	10.5	60.0	5.7
N3	2	8.5	50.0	5.9
N3	3	8.4	45.0	5.4
N3	4	9.0	60.0	6.7
N3	5	12.9	55.0	4.3
N4	1	11.5	30.0	2.6
N4	2	8.0	100.0	12.5
N4	3	7.0	60.0	8.6
N4	4	6.0	120.0	20.0
N4	5	10.8	90.0	8.3

N4	6	11.3	50.0	4.4
N4	7	8.6	30.0	3.5
N5	1	17.5	120.0	6.9
N5	2	14.5	150.0	10.3
N5	3	15.4	55.0	3.6
N5	4	18.8	45.0	2.4
N5	5	13.6	100.0	7.4
N5	6	16.4	70.0	4.3
N5	7	13.5	80.0	5.9
N5	8	14.4	50.0	3.5
N5	9	12.3	100.0	8.1
N6	1	13.3	40.0	3.0
N6	2	8.5	40.0	4.7
N6	3	13.5	70.0	5.2
N6	4	12.3	70.0	5.7
N6	5	6.2	80.0	12.9
N6	6	15.0	120.0	8.0
N6	7	8.5	130.0	15.3
N6	8	10.0	70.0	7.0
N6	10	9.2	100.0	10.9
N6	11	13.2	100.0	7.6
N6	12	9.4	140.0	14.9
N6	13	9.5	100.0	10.5
N6	14	5.5	50.0	9.1
N6	15	2.5	50.0	20.0
N6	16	10.3	100.0	9.7
N6	17	9.5	60.0	6.3
N7	1	8.0	70.0	8.8
N7	2	15.0	100.0	6.7
N7	3	9.4	100.0	10.6
N7	4	7.0	50.0	7.1
N7	5	5.5	80.0	14.5
N7	6	7.5	100.0	13.3
N7	7	16.8	120.0	7.1
N7	8	2.5	40.0	16.0
N7	8A	3.0	50.0	16.7

N7	9	11.0	60.0	5.5
N7	10	8.6	80.0	9.3
N7	11	14.5	110.0	7.6
N7	12	10.5	50.0	4.8
N7	13	7.2	50.0	6.9
N7	14	21.9	100.0	4.6
N7	15	21.0	100.0	4.8
N7	16	8.5	160.0	18.8
N7	16A	5.6	160.0	28.6
N7	17	8.3	40.0	4.8
N7	18	6.5	65.0	10.0
N8	1	10.5	50.0	4.8
N8	2	8.9	100.0	11.2
N8	3	8.5	65.0	7.6
N8	4	9.0	40.0	4.4
N8	5	13.0	80.0	6.2
N8	6	8.5	70.0	8.2
N8	7	23.0	200.0	8.7
N8	8	9.7	50.0	5.2
N8	9	12.0	60.0	5.0
N8	10	13.7	50.0	3.6
N8	11	19.7	90.0	4.6
N8	12	12.3	70.0	5.7
N8	13	13.7	60.0	4.4
N8	14	14.5	100.0	6.9
N9	1	12.0	80.0	6.7
N9	2	8.6	100.0	11.6
N10	1	16.0	150.0	9.4
N10	2	11.6	100.0	8.6
N10	3	15.7	100.0	6.4
N10	4	11.5	50.0	4.3
N10	5	13.0	90.0	6.9
N10	6	15.2	140.0	9.2
N10	7	13.0	50.0	3.8
N11	1	12.7	80.0	6.3
N11	2	8.6	100.0	11.6

N11	3	14.0	100.0	7.1
N11	4	7.0	100.0	14.3
N11	5	5.0	65.0	13.0
N11	6	5.8	100.0	17.2
N11	7	7.0	70.0	10.0
N11	8	6.0	50.0	8.3
N12	1	10.2	190.0	18.6
N12	2	16.3	200.0	12.3
N12	3	12.0	120.0	10.0
N12	4	10.0	120.0	12.0
N12	5	9.5	150.0	15.8
N12	6	12.4	30.0	2.4
N12	7	8.4	120.0	14.3
N1	1	12.2	60.0	4.9
N1	2	19.7	200.0	10.2
N1	3	10.7	50.0	4.7
N1	4	13.0	100.0	7.7
N1	5	12.5	100.0	8.0
N1	6	6.2	180.0	29.0
N1	7	12.8	70.0	5.5
N1	8	12.5	80.0	6.4
N1	9	13.0	70.0	5.4
N2	1	12.2	60.0	4.9
N2	2	13.8	70.0	5.1
N2	3	18.0	90.0	5.0
N2	4	20.7	140.0	6.8
N2	5	12.0	100.0	8.3
N2	6	16.5	80.0	4.8
N2	7	18.0	100.0	5.6
N3	1	10.5	60.0	5.7
N3	2	8.5	50.0	5.9
N3	3	8.4	45.0	5.4
N3	4	9.0	60.0	6.7
N3	5	12.9	55.0	4.3
N4	1	11.5	30.0	2.6
N4	2	8.0	100.0	12.5

N4	3	7.0	60.0	8.6
N4	4	6.0	120.0	20.0
N4	5	10.8	90.0	8.3
N4	6	11.3	50.0	4.4
N4	7	8.6	30.0	3.5

Appendix B - Data Tables for Dependent Variables

Table B.1 Dependent variables.

SITE	SRD63	CW	LCW	LQCC
3179	-	12.4968	1.096799	-
3180	2.10238	20.7264	1.316524	2.285557
3181	2.024846	46.0248	1.662992	2.756636
3183	2.109502	18.288	1.262166	2.367356
3187	-	13.1064	1.117483	-
3202	-	10.0584	1.002529	-
3203	1.92873	27.432	1.438258	2.886491
3207	-	7.3152	0.864226	-
3211	1.732051	30.48	1.484015	2.232996
3665	2.213594	24.384	1.387105	2.641474
3666	1.618641	33.2232	1.521442	2.264818
3667	1.516575	33.528	1.525408	2.431364
3696	-	22.5552	1.353247	-
3697	2.213594	27.432	1.438258	2.898725
3705	1.974842	30.48	1.484015	2.428135
3706	1.913113	13.1064	1.117483	1.880814
3723	-	24.384	1.387105	-
3724	1.949359	35.052	1.544713	2.017033
12979	1.737815	9.4488	0.975377	1.819544
12980	-	18.288	1.262166	-
12984	1.936492	14.0208	1.146773	1.812913
12988	-	25.908	1.413434	-
12993	-	12.4968	1.096799	-
12994	-	8.8392	0.946413	-

12995	2.457641	35.9664	1.555897	2.269513
13010	1.746425	18.288	1.262166	2.117271
13011	2.066398	28.6512	1.457143	2.4133
13012	2.095233	28.0416	1.447803	2.20412
13016	2.343075	18.8976	1.276407	2.404834
13018	1.854724	11.8872	1.07508	1.897627
13019	1.720465	16.764	1.224378	2.004321
13022	2.529822	34.7472	1.54092	2.989005
13025	-	7.0104	0.845743	-
13026	-	12.4968	1.096799	-
13027	2.406242	25.6032	1.408294	2.432969
13028	-	8.2296	0.915379	-
13032	2.144761	21.6408	1.335273	2.230449
13036	-	12.192	1.086075	-
13037	-	12.8016	1.107264	-
13038	-	9.4488	0.975377	-
13042	-	10.9728	1.040318	-
13043	1.729162	10.3632	1.015494	1.812913
13044	1.870829	13.716	1.137228	2.324283
13045	1.618641	13.1064	1.117483	2.396199
13049	1.838478	10.0584	1.002529	1.78533
13052	1.352775	14.9352	1.174211	2.060698
13056	1.6	12.4968	1.096799	2.376577
13057	1.702939	12.4968	1.096799	2.056905
13058	-	12.4968	1.096799	-
13059	-	9.7536	0.989165	-
13060	-	11.8872	1.07508	-
13061	-	9.144	0.961136	-
13064	-	18.5928	1.269345	-
13065	-	17.3736	1.23989	-
13068	-	12.4968	1.096799	-
13069	-	12.192	1.086075	-
13070	-	10.668	1.028083	-
13071	-	9.144	0.961136	-
13073	-	4.8768	0.688135	-
13077	1.81659	10.668	1.028083	2.127105

13081	1.330414	22.2504	1.347338	1.934499
13082	1.702939	16.4592	1.216409	2.053078
13084	-	15.24	1.182985	-
13087	-	17.3736	1.23989	-
13088	-	7.3152	0.864226	-
13091	-	9.7536	0.989165	-
13095	-	18.288	1.262166	-
13097	-	8.5344	0.931173	-
13102	2.137756	15.24	1.182985	1.982271
13105	-	14.9352	1.174211	-
14114	-	19.812	1.296928	-
14114	1.374773	17.6784	1.247443	2.056905
14115	1.873499	18.288	1.262166	2.190332
14119	2.027314	7.3152	0.864226	1.672098
14124	1.760682	10.3632	1.015494	1.886491
14125	1.459452	30.48	1.484015	2.660866
14126	1.81659	21.336	1.329113	2.130334
14130	2.044505	21.9456	1.341348	2.255273
14131	1.352775	32.3088	1.509321	2.600973
14133	-	21.6408	1.335273	-
14134	1.788854	23.4696	1.370506	2.340444
14140	1.81659	19.2024	1.283356	2.501059
14141	1.813836	19.2024	1.283356	2.7348
14142	-	17.9832	1.254867	-
14145	-	18.5928	1.269345	-
14148	-	10.9728	1.040318	-
14152	1.407125	15.24	1.182985	2.176091
14153	2.012461	17.3736	1.23989	1.724276
14156	-	20.4216	1.31009	-
14157	-	7.62	0.881955	-
14160	-	18.5928	1.269345	-
14162	-	15.24	1.182985	-
14163	1.843909	23.4696	1.370506	2.399674
14168	-	10.0584	1.002529	-
14169	-	12.4968	1.096799	-
14173	1.989975	29.5656	1.470787	2.507856

14187	-	12.8016	1.107264	-
14188	1.989975	16.1544	1.208291	2.445604
14193	1.469694	13.716	1.137228	2.176091
14196	-	9.4488	0.975377	-
14197	-	8.5344	0.931173	-
14212	-	7.62	0.881955	-
103022	1.897367	27.7368	1.443056	2.706718
103023	2.167948	30.48	1.484015	2.677607
103038	2.073644	13.716	1.137228	2.885361
103039	-	45.72	1.660106	-
103041	2.073644	45.72	1.660106	2.534026

Table B.2 Dependent variables continued.

SITE	LXSA	LCD08	CD1963	CD2008
3179	-	0.705008	-	5.07
3180	2.122544	0.78533	4.42	6.1
3181	2.50637	0.881955	4.1	7.62
3183	2.202761	0.873321	4.45	7.47
3187	-	0.761176	-	5.77
3202	-	0.606381	-	4.04
3203	2.308137	0.881955	3.72	7.62
3207	-	0.783904	-	6.08
3211	2.021189	0.68842	3	4.88
3665	2.313867	0.826723	4.9	6.71
3666	2.069298	0.78533	2.62	6.1
3667	2.158965	0.630428	2.3	4.27
3696	-	0.882525	-	7.63
3697	2.379849	0.9154	4.9	8.23
3705	2.159567	0.78533	3.9	6.1
3706	1.671173	0.71433	3.66	5.18
3723	-	0.691965	-	4.92
3724	1.843233	0.528917	3.8	3.38
12979	1.454845	0.525045	3.02	3.35
12980	-	0.756636	-	5.71
12984	1.693727	0.4843	3.75	3.05

12988	-	0.880814	-	7.6
12993	-	0.667453	-	4.65
12994	-	0.52763	-	3.37
12995	2.047275	0.845718	6.04	7.01
13010	1.807535	0.659916	3.05	4.57
13011	2.057286	0.701568	4.27	5.03
13012	2.200577	0.69897	4.39	5
13016	2.059185	0.739572	5.49	5.49
13018	1.664642	0.563481	3.44	3.66
13019	1.772322	0.597695	2.96	3.96
13022	2.448861	0.836324	6.4	6.86
13025	-	0.503791	-	3.19
13026	-	0.634477	-	4.31
13027	2.123852	0.71433	5.79	5.18
13028	-	0.576341	-	3.77
13032	1.899273	0.68842	4.6	4.88
13036	-	0.783904	-	6.08
13037	-	0.681241	-	4.8
13038	-	0.640481	-	4.37
13042	-	0.686636	-	4.86
13043	1.542825	0.525045	2.99	3.35
13044	1.889302	0.762679	3.5	5.79
13045	1.723456	0.659916	2.62	4.57
13049	1.474216	0.597695	3.38	3.96
13052	1.732394	0.630428	1.83	4.27
13056	1.928396	0.71433	2.56	5.18
13057	1.810904	0.68842	2.9	4.88
13058	-	0.710117	-	5.13
13059	-	0.656098	-	4.53
13060	-	0.673021	-	4.71
13061	-	0.599883	-	3.98
13064	-	0.779597	-	6.02
13065	-	0.800717	-	6.32
13068	-	0.786041	-	6.11
13069	-	0.670246	-	4.68
13070	-	0.474216	-	2.98

13071	-	0.550228	-	3.55
13073	-	0.699838	-	5.01
13077	1.522444	0.525045	3.3	3.35
13081	1.746634	0.4843	1.77	3.05
13082	1.895423	0.68842	2.9	4.88
13084	-	0.683947	-	4.83
13087	-	0.456366	-	2.86
13088	-	0.515874	-	3.28
13091	-	0.691965	-	4.92
13095	-	0.706718	-	5.09
13097	-	0.689309	-	4.89
13102	1.878522	0.659916	4.57	4.57
13105	-	0.798651	-	6.29
14114	-	0.761176	-	5.77
14114	1.97174	0.597695	1.89	3.96
14115	1.944976	0.739572	3.51	5.49
14119	1.553883	0.739572	4.11	5.49
14124	1.657056	0.659916	3.1	4.57
14125	2.203577	0.845718	2.13	7.01
14126	2.175802	0.762679	3.3	5.79
14130	2.115943	0.78533	4.18	6.1
14131	2.223756	0.845718	1.83	7.01
14133	-	0.794488	-	6.23
14134	2.14239	0.659916	3.2	4.57
14140	2.069298	0.881955	3.3	7.62
14141	1.981819	0.659916	3.29	4.57
14142	-	0.728354	-	5.35
14145	-	0.897627	-	7.9
14148	-	0.836957	-	6.87
14152	1.755875	0.545307	1.98	3.51
14153	1.84136	0.630428	4.05	4.27
14156	-	0.836957	-	6.87
14157	-	0.52763	-	3.37
14160	-	0.634477	-	4.31
14162	-	0.728354	-	5.35
14163	2.045714	0.816241	3.4	6.55

14168	-	0.58995	-	3.89
14169	-	0.451786	-	2.83
14173	2.083503	0.4843	3.96	3.05
14187	-	0.603144	-	4.01
14188	1.900367	0.68842	3.96	4.88
14193	1.841985	0.597695	2.16	3.96
14196	-	0.644439	-	4.41
14197	-	0.515874	-	3.28
14212	-	0.634477	-	4.31
103022	2.272538	0.71433	3.6	5.18
103023	2.274389	0.659916	4.7	4.57
103038	2.388279	0.826723	4.3	6.71
103039	-	1.062206	-	11.54
103041	2.514813	0.80618	4.3	6.4

Table B.3 Dependent variables continued.

SITE	DCNG	XSACC	QCC
3179	-	-	-
3180	2.13	132.6	193
3181	3.52	320.9	571
3183	3.09	159.5	233
3187	-	-	-
3202	-	-	-
3203	3.9	203.3	770
3207	-	-	-
3211	1.88	105	171
3665	1.5	206	438
3666	3.47	117.3	184
3667	1.97	144.2	270
3696	-	-	-
3697	3.33	239.8	792
3705	1.89	144.4	268
3706	1.37	46.9	76
3723	-	-	-
3724	-0.58	69.7	104
12979	0.49	28.5	66

12980	-	-	-
12984	-0.55	49.4	65
12988	-	-	-
12993	-	-	-
12994	-	-	-
12995	0.98	111.5	186
13010	1.55	64.2	131
13011	0.76	114.1	259
13012	0.55	158.7	160
13016	0	114.6	254
13018	0.06	46.2	79
13019	1.01	59.2	101
13022	0.31	281.1	975
13025	-	-	-
13026	-	-	-
13027	-0.46	133	271
13028	-	-	-
13032	0.12	79.3	170
13036	-	-	-
13037	-	-	-
13038	-	-	-
13042	-	-	-
13043	0.52	34.9	65
13044	2.44	77.5	211
13045	1.95	52.9	249
13049	0.43	29.8	61
13052	2.29	54	115
13056	2.62	84.8	238
13057	2.29	64.7	114
13058	-	-	-
13059	-	-	-
13060	-	-	-
13061	-	-	-
13064	-	-	-
13065	-	-	-
13068	-	-	-

13069	-	-	-
13070	-	-	-
13071	-	-	-
13073	-	-	-
13077	0.21	33.3	134
13081	1.58	55.8	86
13082	2.29	78.6	113
13084	-	-	-
13087	-	-	-
13088	-	-	-
13091	-	-	-
13095	-	-	-
13097	-	-	-
13102	0.46	75.6	96
13105	-	-	-
14114	-	-	-
14114	2.38	93.7	114
14115	1.37	88.1	155
14119	1.22	35.8	47
14124	1.78	45.4	77
14125	4.72	159.8	458
14126	2.8	149.9	135
14130	2.23	130.6	180
14131	5.18	167.4	399
14133	-	-	-
14134	1.83	138.8	219
14140	4.17	117.3	317
14141	1.58	95.9	543
14142	-	-	-
14145	-	-	-
14148	-	-	-
14152	1.6	57	150
14153	0.21	69.4	53
14156	-	-	-
14157	-	-	-
14160	-	-	-

14162	-	-	-
14163	2.33	111.1	251
14168	-	-	-
14169	-	-	-
14173	-0.91	121.2	322
14187	-	-	-
14188	1.53	79.5	279
14193	2.41	69.5	150
14196	-	-	-
14197	-	-	-
14212	-	-	-
103022	1.74	187.3	509
103023	0.02	188.1	476
103038	2.41	244.5	768
103039	-	-	-
103041	2.25	327.2	342

Table B.4 Dependent variables continued.

SITE	LWDR	WRDR
3179	0.391791	2.464852
3180	0.531194	3.397771
3181	0.781037	6.04
3183	0.388846	2.448193
3187	0.356308	2.271473
3202	0.396148	2.489703
3203	0.556303	3.6
3207	0.080323	1.203158
3211	0.795595	6.245902
3665	0.560382	3.633979
3666	0.736112	5.446426
3667	0.89498	7.851991
3696	0.470722	2.956121
3697	0.522858	3.333171
3705	0.698685	4.996721
3706	0.403154	2.530193
3723	0.69514	4.956098

3724	1.015796	10.37041
12979	0.450332	2.820537
12980	0.50553	3.202802
12984	0.662473	4.596984
12988	0.53262	3.408947
12993	0.429346	2.687484
12994	0.418783	2.622908
12995	0.710179	5.130728
13010	0.60225	4.001751
13011	0.755575	5.696064
13012	0.748833	5.60832
13016	0.536834	3.442186
13018	0.511599	3.247869
13019	0.626683	4.233333
13022	0.704596	5.06519
13025	0.341952	2.197618
13026	0.462322	2.89949
13027	0.693965	4.942703
13028	0.339037	2.182918
13032	0.646854	4.43459
13036	0.302171	2.005263
13037	0.426023	2.667
13038	0.334895	2.162197
13042	0.353681	2.257778
13043	0.490449	3.093493
13044	0.374549	2.368912
13045	0.457567	2.867921
13049	0.404834	2.54
13052	0.543783	3.497705
13056	0.382469	2.41251
13057	0.408379	2.56082
13058	0.386682	2.436023
13059	0.333067	2.153113
13060	0.402059	2.523822
13061	0.361253	2.297487
13064	0.489748	3.088505

13065	0.439173	2.748987
13068	0.310758	2.045303
13069	0.415829	2.605128
13070	0.553867	3.579866
13071	0.410908	2.575775
13073	-0.0117	0.973413
13077	0.503038	3.184478
13081	0.863038	7.295213
13082	0.527989	3.372787
13084	0.499038	3.15528
13087	0.783524	6.074685
13088	0.348352	2.230244
13091	0.2972	1.982439
13095	0.555448	3.592927
13097	0.241864	1.745276
13102	0.523069	3.334792
13105	0.37556	2.374436
14114	0.535753	3.433622
14114	0.649748	4.464242
14115	0.522594	3.331148
14119	0.124654	1.332459
14124	0.355578	2.267659
14125	0.638297	4.348074
14126	0.566434	3.684974
14130	0.556018	3.597639
14131	0.663603	4.608959
14133	0.540785	3.473644
14134	0.71059	5.13558
14140	0.401401	2.52
14141	0.623439	4.201838
14142	0.526513	3.361346
14145	0.371718	2.353519
14148	0.203361	1.597205
14152	0.637678	4.34188
14153	0.609462	4.068759
14156	0.473133	2.972576

14157	0.354325	2.261128
14160	0.634868	4.313875
14162	0.454631	2.848598
14163	0.554264	3.583145
14168	0.412579	2.585707
14169	0.645012	4.41583
14173	0.986487	9.693639
14187	0.50412	3.192419
14188	0.519871	3.310328
14193	0.539532	3.463636
14196	0.330938	2.142585
14197	0.415299	2.601951
14212	0.247478	1.767981
103022	0.728727	5.354595
103023	0.824099	6.669584
103038	0.310505	2.044113
103039	0.5979	3.961872
103041	0.853926	7.14375

Table B.5 Dependent variables continued.

SITE	STAGE	STAGE 1	STAGE 2	STAGE 3
3179	1	1	0	0
3180	1	1	0	0
3181	4	0	0	0
3183	1	1	0	0
3187	4	0	0	0
3202	1	1	0	0
3203	1	1	0	0
3207	3	0	0	1
3211	4	0	0	0
3665	5	0	0	0
3666	4	0	0	0
3667	4	0	0	0
3696	2	0	1	0
3697	2	0	1	0
3705	3	0	0	1

3706	3	0	0	1
3723	4	0	0	0
3724	4	0	0	0
12979	1	1	0	0
12980	3	0	0	1
12984	3	0	0	1
12988	4	0	0	0
12993	1	1	0	0
12994	3	0	0	1
12995	3	0	0	1
13010	4	0	0	0
13011	1	1	0	0
13012	4	0	0	0
13016	1	1	0	0
13018	3	0	0	1
13019	5	0	0	0
13022	4	0	0	0
13025	1	1	0	0
13026	1	1	0	0
13027	1	1	0	0
13028	2	0	1	0
13032	1	1	0	0
13036	3	0	0	1
13037	2	0	1	0
13038	4	0	0	0
13042	1	1	0	0
13043	1	1	0	0
13044	1	1	0	0
13045	1	1	0	0
13049	1	1	0	0
13052	3	0	0	1
13056	4	0	0	0
13057	4	0	0	0
13058	5	0	0	0
13059	4	0	0	0
13060	5	0	0	0

13061	3	0	0	1
13064	3	0	0	1
13065	3	0	0	1
13068	3	0	0	1
13069	3	0	0	1
13070	1	1	0	0
13071	3	0	0	1
13073	3	0	0	1
13077	4	0	0	0
13081	5	0	0	0
13082	4	0	0	0
13084	5	0	0	0
13087	2	0	1	0
13088	1	1	0	0
13091	5	0	0	0
13095	4	0	0	0
13097	3	0	0	1
13102	4	0	0	0
13105	3	0	0	1
14114	1	1	0	0
14114	1	1	0	0
14115	4	0	0	0
14119	2	0	1	0
14124	3	0	0	1
14125	4	0	0	0
14126	5	0	0	0
14130	2	0	1	0
14131	4	0	0	0
14133	4	0	0	0
14134	5	0	0	0
14140	4	0	0	0
14141	3	0	0	1
14142	1	1	0	0
14145	4	0	0	0
14148	4	0	0	0
14152	3	0	0	1

14153	1	1	0	0
14156	4	0	0	0
14157	4	0	0	0
14160	4	0	0	0
14162	4	0	0	0
14163	4	0	0	0
14168	3	0	0	1
14169	4	0	0	0
14173	4	0	0	0
14187	4	0	0	0
14188	4	0	0	0
14193	4	0	0	0
14196	4	0	0	0
14197	4	0	0	0
14212	4	0	0	0
103022	3	0	0	1
103023	3	0	0	1
103038	4	0	0	0
103039	4	0	0	0
103041	4	0	0	0

Table B.6 Dependent variables continued.

SITE	**STAGE 4**	**STAGE 5**
3179	0	0
3180	0	0
3181	1	0
3183	0	0
3187	1	0
3202	0	0
3203	0	0
3207	0	0
3211	1	0
3665	0	1
3666	1	0
3667	1	0
3696	0	0

3697	0	0
3705	0	0
3706	0	0
3723	1	0
3724	1	0
12979	0	0
12980	0	0
12984	0	0
12988	1	0
12993	0	0
12994	0	0
12995	0	0
13010	1	0
13011	0	0
13012	1	0
13016	0	0
13018	0	0
13019	0	1
13022	1	0
13025	0	0
13026	0	0
13027	0	0
13028	0	0
13032	0	0
13036	0	0
13037	0	0
13038	1	0
13042	0	0
13043	0	0
13044	0	0
13045	0	0
13049	0	0
13052	0	0
13056	1	0
13057	1	0
13058	0	1

13059	1	0
13060	0	1
13061	0	0
13064	0	0
13065	0	0
13068	0	0
13069	0	0
13070	0	0
13071	0	0
13073	0	0
13077	1	0
13081	0	1
13082	1	0
13084	0	1
13087	0	0
13088	0	0
13091	0	1
13095	1	0
13097	0	0
13102	1	0
13105	0	0
14114	0	0
14114	0	0
14115	1	0
14119	0	0
14124	0	0
14125	1	0
14126	0	1
14130	0	0
14131	1	0
14133	1	0
14134	1	0
14140	1	0
14141	0	0
14142	0	0
14145	1	0

14148	1	0
14152	0	0
14153	0	0
14156	1	0
14157	1	0
14160	1	0
14162	1	0
14163	1	0
14168	0	0
14169	1	0
14173	1	0
14187	1	0
14188	1	0
14193	1	0
14196	1	0
14197	1	0
14212	1	0
103022	0	0
103023	0	0
103038	1	0
103039	1	0
103041	1	0

Appendix C - Data Tables for Independent Variables

Table C.1 Independent variables.

SITE	WTSD	CUMCHZ	CHZSEG	SRP
3179	1	-	-	-
3180	1	52.9	0	9.782638
3181	2	66.6	14.3	5.656854
3183	1	62.2	0	8.660254
3187	3	-	-	-
3202	1	-	-	-
3203	1	28.3	28.3	23.92488

3207	2	-	-	-
3211	3	42.2	13.8	13.25896
3665	2	46.1	4.72	14.91979
3666	3	18.7	18.7	9.423375
3667	3	-	-	8.56738
3696	3	-	-	-
3697	3	109	23.7	14.28286
3705	3	51.2	8.99	16.81071
3706	3	-	-	13.94633
3723	2	-	-	-
3724	2	30	5.93	8.933085
12979	2	-	-	15.30686
12980	2	-	-	-
12984	2	-	-	11.24278
12988	2	-	-	-
12993	2	-	-	-
12994	2	-	-	-
12995	2	397	5.48	8.185353
13010	2	23.8	3.11	14.49828
13011	1	62.2	0	16.83152
13012	2	305	2.35	4.301163
13016	1	62.2	9.3	13.33792
13018	2	17.1	6.19	10.52616
13019	2	10.9	10.9	13.37535
13022	2	303	2	21.10924
13025	1	-	-	-
13026	1	-	-	-
13027	1	52.9	10.1	13.29286
13028	3	-	-	-
13032	1	-	-	18.4038
13036	3	-	-	-
13037	3	-	-	-
13038	3	-	-	-
13042	1	-	-	-
13043	1	-	-	15.46932
13044	1	42.8	14.4	24.85961

13045	1	-	-	31.14803
13049	1	-	-	17.30029
13052	3	25.3	25.3	17.79326
13056	3	-	-	20.69783
13057	3	-	-	20.07735
13058	3	-	-	-
13059	3	-	-	-
13060	3	-	-	-
13061	1	-	-	-
13064	1	-	-	-
13065	1	-	-	-
13068	1	-	-	-
13069	1	-	-	-
13070	3	-	-	-
13071	1	-	-	-
13073	1	-	-	-
13077	3	-	-	24.84351
13081	3	28.4	3.16	10.31504
13082	3	-	-	15.75754
13084	3	-	-	-
13087	1	-	-	-
13088	1	-	-	-
13091	3	-	-	-
13095	3	-	-	-
13097	3	-	-	-
13102	3	-	-	12.57378
13105	3	-	-	-
14114	3	-	-	-
14114	3	-	-	9.359487
14115	3	43.2	10.5	11.88276
14119	3	-	-	12.80234
14124	3	-	-	15.70032
14125	3	32.7	4.09	18.17691
14126	2	52.3	6.27	5.709641
14130	3	56.4	5.17	3.405877
14131	3	28.6	4.53	15.0333

14133	3	-	-	-
14134	3	85.2	28.8	8.006248
14140	3	-	-	17.82975
14141	3	24.1	5.38	25.26262
14142	2	-	-	-
14145	2	-	-	-
14148	2	-	-	-
14152	3	-	-	16.44992
14153	2	-	-	4.393177
14156	3	-	-	-
14157	2	-	-	-
14160	2	-	-	-
14162	3	-	-	-
14163	2	41.3	9.26	14.83914
14168	3	-	-	-
14169	2	-	-	-
14173	2	32.1	2.12	19.05256
14187	2	-	-	-
14188	2	24	8.25	15.94992
14193	2	15.8	15.8	13.51666
14196	2	-	-	-
14197	2	-	-	-
14212	2	-	-	-
103022	2	-	-	19.10759
103023	2	-	-	14.90637
103038	2	301	18.9	13.53514
103039	2	402	5.01	-
103041	2	216	63.5	6.292853

Table C.2 Independent variables continued.

SITE	LSIM	SRS	LDA	DAREA
3179	1.130334	0.057446	1.053078	11.3
3180	1.113943	0.046904	1.950852	89.3
3181	1.217484	0.02	2.1959	157
3183	1.130334	0.03873	2.056905	114
3187	1.414973	0.054772	1.274158	18.8

3202	1.176091	0.089443	0.578639	3.79
3203	1.113943	0.054772	1.50515	32
3207	1.371068	0.087178	0.724276	5.3
3211	1.414973	0.056569	1.136721	13.7
3665	1.342423	0.054772	1.943495	87.8
3666	1.423246	0.042426	1.450249	28.2
3667	1.454845	0.033166	1.503791	31.9
3696	1.255273	0.04899	1.414973	26
3697	1.243038	0.034641	2.184691	153
3705	1.278754	0.06	1.526339	33.6
3706	1.230449	0.05831	1.060698	11.5
3723	1.332439	0.054772	1.252853	17.9
3724	1.40654	0.05099	1.423246	26.5
12979	1.190332	0.05831	1.332439	21.5
12980	1.255273	0.06245	1.382017	24.1
12984	1.230449	0.052915	1.252853	17.9
12988	1.380211	0.045826	1.518514	33
12993	1.113943	0.06	0.954243	9
12994	1.322219	0.064807	0.230449	1.7
12995	1.255273	0.036056	2.840733	693
13010	1.267172	0.054772	1.49693	31.4
13011	1.079181	0.056569	2.041393	110
13012	1.462398	0.022361	2.724276	530
13016	1.146128	0.041231	2.029384	107
13018	1.311754	0.041231	1.271842	18.7
13019	1.176091	0.057446	1.133539	13.6
13022	1.414973	0.05	2.710117	513
13025	1.20412	0.093274	0.732394	5.4
13026	1.255273	0.074162	0.90309	8
13027	1.041393	0.041231	1.92993	85.1
13028	1.322219	0.079373	0.361728	2.3
13032	0.954243	0.066333	1.332439	21.5
13036	1.431364	0.072801	0.900367	7.95
13037	1.255273	0.069282	0.755875	5.7
13038	1.414973	0.042426	0.672098	4.7
13042	1.20412	0.060828	1.012837	10.3

13043	1.230449	0.06245	0.976808	9.48
13044	1.079181	0.064031	1.772322	59.2
13045	1.20412	0.072111	1.049218	11.2
13049	1.161368	0.070711	0.893762	7.83
13052	1.423246	0.064807	0.697229	4.98
13056	1.454845	0.064807	1.037427	10.9
13057	1.431364	0.067082	0.956168	9.04
13058	1.39794	0.070711	0.857333	7.2
13059	1.130334	0.083666	0.740363	5.5
13060	1.146128	0.06245	1.201397	15.9
13061	1.255273	0.070711	0.857333	7.2
13064	1.255273	0.052915	1.383815	24.2
13065	1.190332	0.076812	0.792392	6.2
13068	1.322219	0.083666	0.832509	6.8
13069	1.230449	0.091104	0.832509	6.8
13070	1.079181	0.069282	1.20412	16
13071	1.230449	0.089443	0.897627	7.9
13073	1.176091	0.072111	0.838849	6.9
13077	1.447158	0.070711	1.152288	14.2
13081	1.40654	0.052915	0.871573	7.44
13082	1.342423	0.06245	1.164353	14.6
13084	1.20412	0.083666	1.120574	13.2
13087	1.30103	0.070711	0.414973	2.6
13088	1.113943	0.042426	0.763428	5.8
13091	1.332439	0.05099	1.184691	15.3
13095	1.454845	0.1	1.281033	19.1
13097	1.30103	0.05	0.857333	7.2
13102	1.423246	0.05099	1.480007	30.2
13105	1.267172	0.05831	1.38739	24.4
14114	1.311754	0.051962	1.49693	31.4
14114	1.311754	0.041231	1.510545	32.4
14115	1.431364	0.041231	2.354108	226
14119	1.113943	0.05099	1.60206	40
14124	1.278754	0.05831	1.679428	47.8
14125	1.462398	0.052915	1.613842	41.1
14126	1.20412	0.03	2.11059	129

14130	1.447158	0.014142	1.70757	51
14131	1.462398	0.046904	1.558709	36.2
14133	1.454845	0.054772	1.926342	84.4
14134	1.462398	0.026458	1.820202	66.1
14140	1.431364	0.04899	1.607455	40.5
14141	1.39794	0.047958	1.539076	34.6
14142	1.079181	0.046904	1.130334	13.5
14145	1.39794	0.05831	1.079181	12
14148	1.431364	0.063246	0.929419	8.5
14152	1.342423	0.052915	0.974972	9.44
14153	1.146128	0.028284	1.645422	44.2
14156	1.352183	0.053852	1.494155	31.2
14157	1.380211	0.046904	0.919078	8.3
14160	1.278754	0.068557	1.158363	14.4
14162	1.389166	0.05	1.523747	33.4
14163	1.380211	0.045826	1.584331	38.4
14168	1.041393	0.066333	1.440909	27.6
14169	1.361728	0.069282	0.672098	4.7
14173	1.439333	0.05831	1.419956	26.3
14187	1.414973	0.041231	1.201397	15.9
14188	1.518514	0.03873	1.262451	18.3
14193	1.431364	0.041231	1.170262	14.8
14196	1.380211	0.084262	1.40654	25.5
14197	1.311754	0.092195	1.502427	31.8
14212	1.380211	0.076812	0.544068	3.5
103022	1.278754	0.053852	1.509203	32.3
103023	1.361728	0.044721	1.453318	28.4
103038	1.352183	0.04	1.943495	87.8
103039	1.20412	0.047958	2.926857	845
103041	1.352183	0.03	2.69897	500
SITE	LSIM	SRS	LDA	DAREA

Table C.3 Independent variables continued.

SITE	**AREACLASS**	**POWER**	**SLOPE**	**CHZ**
3179	2	-	0.0033	1
3180	2	95.7	0.0022	0

3181	3	32	0.0004	1
3183	3	75	0.0015	0
3187	2	-	0.003	0
3202	1	-	0.008	1
3203	2	572.4	0.003	0
3207	1	-	0.0076	0
3211	2	175.8	0.0032	0
3665	2	222.6	0.003	1
3666	2	88.8	0.0018	1
3667	2	73.4	0.0011	1
3696	2	-	0.0024	1
3697	3	204	0.0012	1
3705	2	282.6	0.0036	0
3706	2	194.5	0.0034	1
3723	2	-	0.003	1
3724	2	79.8	0.0026	1
12979	2	234.3	0.0034	0
12980	2	-	0.0039	0
12984	2	126.4	0.0028	0
12988	2	-	0.0021	1
12993	1	-	0.0036	0
12994	1	-	0.0042	1
12995	3	67	0.0013	0
13010	2	210.2	0.003	0
13011	3	283.3	0.0032	0
13012	3	18.5	0.0005	0
13016	3	177.9	0.0017	0
13018	2	110.8	0.0017	0
13019	2	178.9	0.0033	1
13022	3	445.6	0.0025	0
13025	1	-	0.0087	0
13026	1	-	0.0055	0
13027	2	176.7	0.0017	0
13028	1	-	0.0063	1
13032	2	338.7	0.0044	1
13036	1	-	0.0053	1

13037	1	-	0.0048	1
13038	1	-	0.0018	1
13042	2	-	0.0037	0
13043	1	239.3	0.0039	0
13044	2	618	0.0041	1
13045	2	970.2	0.0052	1
13049	1	299.3	0.005	1
13052	1	316.6	0.0042	1
13056	2	428.4	0.0042	1
13057	1	403.1	0.0045	1
13058	1	-	0.005	1
13059	1	-	0.007	1
13060	2	-	0.0039	1
13061	1	-	0.005	0
13064	2	-	0.0028	0
13065	1	-	0.0059	0
13068	1	-	0.007	0
13069	1	-	0.0083	0
13070	2	-	0.0048	1
13071	1	-	0.008	0
13073	1	-	0.0052	0
13077	2	617.2	0.005	1
13081	1	106.4	0.0028	1
13082	2	248.3	0.0039	0
13084	2	-	0.007	1
13087	1	-	0.005	0
13088	1	-	0.0018	0
13091	2	-	0.0026	0
13095	2	-	0.01	1
13097	1	-	0.0025	1
13102	2	158.1	0.0026	1
13105	2	-	0.0034	1
14114	2	-	0.0027	1
14114	2	87.6	0.0017	1
14115	3	141.2	0.0017	1
14119	2	163.9	0.0026	1

14124	2	246.5	0.0034	1
14125	2	330.4	0.0028	1
14126	3	32.6	0.0009	1
14130	2	11.6	0.0002	1
14131	2	226	0.0022	1
14133	2	-	0.003	1
14134	2	64.1	0.0007	1
14140	2	317.9	0.0024	0
14141	2	638.2	0.0023	1
14142	2	-	0.0022	1
14145	2	-	0.0034	0
14148	1	-	0.004	1
14152	1	270.6	0.0028	1
14153	2	19.3	0.0008	1
14156	2	-	0.0029	1
14157	1	-	0.0022	0
14160	2	-	0.0047	0
14162	2	-	0.0025	0
14163	2	220.2	0.0021	1
14168	2	-	0.0044	0
14169	1	-	0.0048	1
14173	2	363	0.0034	1
14187	2	-	0.0017	1
14188	2	254.4	0.0015	1
14193	2	182.7	0.0017	1
14196	2	-	0.0071	1
14197	2	-	0.0085	1
14212	1	-	0.0059	1
103022	2	365.1	0.0029	0
103023	2	222.2	0.002	1
103038	2	183.2	0.0016	0
103039	3	-	0.0023	1
103041	3	39.6	0.0009	0

Table C.4 Independent variables continued.

SITE	CHZTIME	CHZ63	LULC	FORWET
3179	7	1	1	1
3180	0	0	1	1
3181	2	0	1	1
3183	0	0	1	1
3187	0	0	2	0
3202	-	-	1	1
3203	0	0	1	1
3207	0	0	1	1
3211	0	0	2	0
3665	7	1	1	1
3666	7	1	2	0
3667	7	1	2	0
3696	-	-	2	0
3697	7	1	1	1
3705	0	0	1	1
3706	7	1	1	1
3723	-	-	2	0
3724	7	1	1	1
12979	0	0	1	1
12980	0	0	1	1
12984	0	0	1	1
12988	-	-	1	1
12993	0	0	1	1
12994	-	-	1	1
12995	0	0	1	1
13010	0	0	2	0
13011	0	0	1	1
13012	0	0	1	1
13016	0	0	1	1

13018	0	0	1	1
13019	7	1	1	1
13022	0	0	1	1
13025	0	0	1	1
13026	0	0	1	1
13027	0	0	1	1
13028	-	-	2	0
13032	7	1	1	1
13036	7	1	2	0
13037	-	-	1	1
13038	-	-	1	1
13042	0	0	1	1
13043	0	0	1	1
13044	7	1	1	1
13045	7	1	3	0
13049	4	0	1	1
13052	7	1	2	0
13056	4	0	2	0
13057	4	0	1	1
13058	-	-	1	1
13059	-	-	1	1
13060	-	-	1	1
13061	0	0	1	1
13064	0	0	1	1
13065	0	0	1	1
13068	0	0	1	1
13069	0	0	1	1
13070	-	-	1	1
13071	0	0	1	1
13073	0	0	1	1
13077	7	1	3	0
13081	1	0	1	1
13082	0	0	2	0
13084	-	-	1	1
13087	0	0	1	1
13088	0	0	1	1

13091	0	0	1	1
13095	6	1	2	0
13097	-	-	1	1
13102	4	0	2	0
13105	-	-	1	1
14114	6	1	1	1
14114	6	1	2	0
14115	7	1	1	1
14119	7	1	2	0
14124	7	1	1	1
14125	7	1	2	0
14126	5	1	1	1
14130	7	1	2	0
14131	2	0	2	0
14133	7	1	2	0
14134	7	1	2	0
14140	5	1	2	0
14141	5	1	2	0
14142	7	1	1	1
14145	0	0	1	1
14148	-	-	2	0
14152	5	1	3	0
14153	3	0	1	1
14156	-	-	1	1
14157	0	0	1	1
14160	0	0	2	0
14162	0	0	2	0
14163	5	1	1	1
14168	0	0	1	1
14169	-	-	3	0
14173	7	1	3	0
14187	-	-	2	0
14188	7	1	2	0
14193	7	1	2	0
14196	7	1	1	1
14197	-	-	2	0

14212	-	-	2	0
103022	0	0	1	1
103023	7	1	2	0
103038	0	0	1	1
103039	7	1	1	1
103041	0	0	2	0

Table C.5 Independent variables continued.

SITE	CROPS	GRASPAST	BUFFERW	SRBW
3179	0	0	49.5	7.035624
3180	0	0	26	5.09902
3181	0	0	51	7.141428
3183	0	0	38.5	6.204837
3187	1	0	45.5	6.745369
3202	0	0	40	6.324555
3203	0	0	64	8
3207	0	0	0	0
3211	1	0	0	0
3665	0	0	100	10
3666	1	0	0	0
3667	1	0	0	0
3696	1	0	0	0
3697	1	0	8	2.828427
3705	0	0	16.5	4.062019
3706	0	0	16	4
3723	1	0	23.5	4.84768
3724	0	0	16.5	4.062019
12979	0	0	117	10.81665
12980	0	0	0	0
12984	0	0	30.5	5.522681
12988	0	0	13.5	3.674235
12993	0	0	21	4.582576
12994	0	0	0	0
12995	0	0	114.5	10.70047
13010	1	0	0	0
13011	0	0	61.5	7.842194

13012	1	0	90.5	9.513149
13016	1	0	157	12.52996
13018	1	0	4.5	2.12132
13019	0	0	19	4.358899
13022	0	0	225	15
13025	0	0	27	5.196152
13026	0	0	31.5	5.612486
13027	0	0	228	15.09967
13028	1	0	20.5	4.527693
13032	0	0	25.5	5.049753
13036	1	0	0	0
13037	0	0	27.5	5.244044
13038	0	0	60	7.745967
13042	0	0	0	0
13043	0	0	32	5.656854
13044	0	0	34	5.830952
13045	0	1	0	0
13049	0	0	29	5.385165
13052	1	0	0	0
13056	1	0	0	0
13057	0	0	15	3.872983
13058	0	0	16	4
13059	0	0	20.5	4.527693
13060	0	0	152.5	12.34909
13061	0	0	42	6.480741
13064	0	0	32	5.656854
13065	0	0	51	7.141428
13068	0	0	22	4.690416
13069	0	0	0	0
13070	0	0	95	9.746794
13071	0	0	30.5	5.522681
13073	0	0	0	0
13077	0	1	0	0
13081	1	0	6	2.44949
13082	1	0	0	0
13084	0	0	60	7.745967

13087	0	0	0	0
13088	0	0	24	4.89898
13091	0	0	94	9.69536
13095	1	0	105.5	10.27132
13097	0	0	15	3.872983
13102	1	0	0	0
13105	0	0	24.5	4.949748
14114	0	0	11.5	3.391165
14114	1	0	0	0
14115	0	0	11.5	3.391165
14119	1	0	0	0
14124	0	0	10	3.162278
14125	1	0	0	0
14126	0	0	32	5.656854
14130	1	0	0	0
14131	1	0	0	0
14133	1	0	0	0
14134	1	0	0	0
14140	1	0	0	0
14141	1	0	0	0
14142	0	0	0	0
14145	0	0	17.5	4.1833
14148	1	0	0.5	0.707107
14152	0	1	0	0
14153	0	0	41.5	6.442049
14156	0	0	27	5.196152
14157	0	0	27.5	5.244044
14160	1	0	0	0
14162	1	0	40	6.324555
14163	1	0	5.5	2.345208
14168	0	0	0	0
14169	0	1	12	3.464102
14173	0	1	0	0
14187	1	0	54.5	7.382412
14188	1	0	0	0
14193	1	0	0	0

14196	0	0	43.5	6.595453
14197	1	0	67	8.185353
14212	1	0	17.5	4.1833
103022	0	0	21.5	4.636809
103023	1	0	0	0
103038	0	0	38	6.164414
103039	0	0	28	5.291503
103041	1	0	0	0

Table C.6 Independent variables continued.

SITE	GEOL	ADMIRE	DRIFT	ALLUVIUM
3179	1	1	0	0
3180	1	1	0	0
3181	2	0	1	0
3183	1	1	0	0
3187	2	0	1	0
3202	2	0	1	0
3203	1	1	0	0
3207	2	0	1	0
3211	2	0	1	0
3665	2	0	1	0
3666	2	0	1	0
3667	2	0	1	0
3696	2	0	1	0
3697	2	0	1	0
3705	2	0	1	0
3706	2	0	1	0
3723	2	0	1	0
3724	2	0	1	0
12979	2	0	1	0
12980	2	0	1	0
12984	2	0	1	0
12988	2	0	1	0
12993	2	0	1	0
12994	2	0	1	0
12995	3	0	0	1

13010	3	0	0	1
13011	1	1	0	0
13012	3	0	0	1
13016	1	1	0	0
13018	2	0	1	0
13019	2	0	1	0
13022	3	0	0	1
13025	1	1	0	0
13026	1	1	0	0
13027	1	1	0	0
13028	2	0	1	0
13032	1	1	0	0
13036	2	0	1	0
13037	2	0	1	0
13038	2	0	1	0
13042	2	0	1	0
13043	2	0	1	0
13044	1	1	0	0
13045	1	1	0	0
13049	2	0	1	0
13052	2	0	1	0
13056	2	0	1	0
13057	2	0	1	0
13058	2	0	1	0
13059	2	0	1	0
13060	2	0	1	0
13061	2	0	1	0
13064	1	1	0	0
13065	1	1	0	0
13068	2	0	1	0
13069	1	1	0	0
13070	2	0	1	0
13071	1	1	0	0
13073	1	1	0	0
13077	2	0	1	0
13081	2	0	1	0

13082	3	0	0	1
13084	2	0	1	0
13087	2	0	1	0
13088	2	0	1	0
13091	2	0	1	0
13095	2	0	1	0
13097	2	0	1	0
13102	2	0	1	0
13105	3	0	0	1
14114	2	0	1	0
14114	2	0	1	0
14115	3	0	0	1
14119	2	0	1	0
14124	2	0	1	0
14125	2	0	1	0
14126	2	0	1	0
14130	2	0	1	0
14131	2	0	1	0
14133	2	0	1	0
14134	2	0	1	0
14140	2	0	1	0
14141	2	0	1	0
14142	2	0	1	0
14145	2	0	1	0
14148	2	0	1	0
14152	2	0	1	0
14153	2	0	1	0
14156	2	0	1	0
14157	2	0	1	0
14160	2	0	1	0
14162	2	0	1	0
14163	2	0	1	0
14168	2	0	1	0
14169	2	0	1	0
14173	2	0	1	0
14187	2	0	1	0

14188	2	0	1	0
14193	2	0	1	0
14196	2	0	1	0
14197	2	0	1	0
14212	2	0	1	0
103022	2	0	1	0
103023	3	0	0	1
103038	3	0	0	1
103039	3	0	0	1
103041	2	0	1	0

Table C.7 Independent variables continued.

SITE	BED	SILTCLAY	GRAVEL	SIMON
3179	1	1	0	13.5
3180	2	0	0	13
3181	1	1	0	16.5
3183	1	1	0	13.5
3187	1	1	0	26
3202	1	1	0	15
3203	1	1	0	13
3207	1	1	0	23.5
3211	1	1	0	26
3665	1	1	0	22
3666	1	1	0	26.5
3667	1	1	0	28.5
3696	1	1	0	18
3697	1	1	0	17.5
3705	1	1	0	19
3706	1	1	0	17
3723	1	1	0	21.5
3724	1	1	0	25.5
12979	1	1	0	15.5
12980	1	1	0	18
12984	1	1	0	17
12988	1	1	0	24
12993	1	1	0	13

12994	1	1	0	21
12995	1	1	0	18
13010	1	1	0	18.5
13011	2	0	0	12
13012	1	1	0	29
13016	2	0	0	14
13018	1	1	0	20.5
13019	1	1	0	15
13022	1	1	0	26
13025	1	1	0	16
13026	1	1	0	18
13027	1	1	0	11
13028	1	1	0	21
13032	3	0	1	9
13036	1	1	0	27
13037	1	1	0	18
13038	1	1	0	26
13042	1	1	0	16
13043	1	1	0	17
13044	1	1	0	12
13045	1	1	0	16
13049	1	1	0	14.5
13052	1	1	0	26.5
13056	1	1	0	28.5
13057	1	1	0	27
13058	1	1	0	25
13059	1	1	0	13.5
13060	1	1	0	14
13061	1	1	0	18
13064	1	1	0	18
13065	1	1	0	15.5
13068	1	1	0	21
13069	1	1	0	17
13070	1	1	0	12
13071	1	1	0	17
13073	1	1	0	15

13077	1	1	0	28
13081	2	0	0	25.5
13082	3	0	1	22
13084	1	1	0	16
13087	1	1	0	20
13088	1	1	0	13
13091	1	1	0	21.5
13095	1	1	0	28.5
13097	1	1	0	20
13102	1	1	0	26.5
13105	1	1	0	18.5
14114	1	1	0	20.5
14114	1	1	0	20.5
14115	1	1	0	27
14119	1	1	0	13
14124	1	1	0	19
14125	1	1	0	29
14126	1	1	0	16
14130	1	1	0	28
14131	1	1	0	29
14133	1	1	0	28.5
14134	1	1	0	29
14140	1	1	0	27
14141	1	1	0	25
14142	1	1	0	12
14145	1	1	0	25
14148	1	1	0	27
14152	1	1	0	22
14153	1	1	0	14
14156	1	1	0	22.5
14157	1	1	0	24
14160	1	1	0	19
14162	1	1	0	24.5
14163	1	1	0	24
14168	1	1	0	11
14169	1	1	0	23

14173	1	1	0	27.5
14187	1	1	0	26
14188	1	1	0	33
14193	1	1	0	27
14196	1	1	0	24
14197	1	1	0	20.5
14212	1	1	0	24
103022	1	1	0	19
103023	1	1	0	23
103038	1	1	0	22.5
103039	1	1	0	16
103041	1	1	0	22.5