UNDERSTANDING GULLY PROCESS IN TWO KANSAS LANDSCAPES

by

KATHERINE J. BURKE

B.S., Kansas State University, Manhattan, Kansas, 2015

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Environmental Design and Planning
College of Architecture, Planning and Design

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2015

Abstract

Gullies often form as a result of land use changes and associated factors such as soil compaction, vegetation removal and changes in rainwater infiltration. Gully erosion creates human safety hazards, soil loss, and sediment and nutrient pollution downstream. Across the globe, researchers have found a wide variety of gully growth rates and drivers (Poesen, Nachtergaele, Verstraeten, & Valentin, 2003), but after the late 1900s, very few published gully studies have been done in the United States, and fewer studies have been done in the Midwest and Great Plains regions.

This gully study was conducted in two heavily-used Kansas landscapes: Fort Riley military training areas and agricultural fields in McPherson County. The purpose of the study was to quantitatively measure rates and patterns of gully erosion, as well as identify main drivers of gully initiation and growth. Results and conclusions add Kansas gully characteristics to the growing knowledge of gully erosion in other areas of the world.

Gullies in both landscapes were surveyed in the field multiple times per year over three consecutive years (2012-2014) to capture patterns and rates of change. Rainfall data and land characteristics such as soils, vegetative cover, slope, and drainage area were compiled into a database to be compared to gully erosion rates in an attempt to correlate gully erosion not only to rainfall but to other land-based factors. Results show that for most Fort Riley gullies, beds are filling and banks are widening, and consistent drivers of erosion could not be determined from the data. In McPherson, gully channels are storing large amounts of sediment, though gully networks in the upper areas of the gully channels are actively widening and advancing headward. Drivers of channel change in McPherson County seem to be related to vegetative cover, slope, and early spring freeze/thaw processes. At both study locations, land use changes related to linear disturbance and reduced vegetative cover are suspected to have more of an influence on gully growth than rainfall events during the study timeframe. Objectives for best management practices are proposed for both Fort Riley and McPherson County.

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Major Professor
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Acknowledgements

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Chapter 1 - Introduction and Study Background

Introduction

Gully erosion is a world-wide problem that creates human safety hazards, soil loss, and sediment and nutrient pollution downstream (Piest & Spomer, 1968). Economic losses from gully erosion and downstream sedimentation have been quantified and are impressive (Hargrove, Johnson, Snethen, & Middendorf, 2010). Yet a comprehensive understanding of gully process is lacking, especially in the Midwestern United States. Gullies are a result of high-energy flow paths; as gullies concentrate water runoff, scour the land surface and mobilize large quantities of soil, they dissect the landscape and quickly transport rainwater runoff away from vegetation.

To understand gully erosion, one must first understand hillslope hydrological processes, because gullies form due to water flowing above or below the soil surface. Several conditions must be met for gully formation: First, there must be concentrated flow, either above or below the soil surface. Second, the concentrated flow must be strong enough and last long enough to overcome the resistance of the soil by detaching and transporting particles; erode enough material to form a channel considered larger than a rill; and in order to grow, gullies must be able to transport away sediment at a rate faster than the accumulation of sediments from uphill. Initial processes of gully formation often create a headcut, or a vertical or nearly vertical drop in channel elevation (Poesen, Vandekerckhove, Nachtergaele, Oostwoud Wijdenes, Verstraeten, & Van Wesemael, 2002).

There are natural factors and processes that can create gullies: intense rainstorms, steep slopes, large drainage areas, topographic location and soil characteristics such as crusting of the soil surface (Valentin, Poesen, & Li, 2005). However, land use change that has increased impermeable or less-permeable surfaces has decreased infiltration, causing storm water to accumulate and flow on the soil surface (sometimes sub-surface) with great energy, potentially causing erosive damage. The National Research Council (2010) warns of the effects of land use change: “The environmental impacts of human activity are expected to increase as the climate continues to warm and as the world becomes progressively more populated, industrialized, and urbanized” (p. 21). As climate changes and development expands, the risks for accelerated erosion surge. The literature has proven that driving factors of gully development and rates of erosion are highly variable. For instance, when considering rill, interrill, and gully erosion, data from across the world shows erosion rates from gullies can range from 10% to 94% of total sediment yield from water erosion in a given basin (Poesen, Nachtergaele, Verstraeten, & Valentin, 2003). The variety of driving factors and erosion rates suggests that regional understanding with quantitative and qualitative observations is critical if we are to prevent or slow the rate of soil lost from gullies and transported downstream.

Driving factors of gully erosion that have been reported in the literature usually relate to land use change, such as the introduction of man-made linear elements in the landscape that concentrate runoff (Vanwalleghem, Poesen, Nachtergaele, & Verstraeten, 2005), direct physical disturbance to the soil surface, and the removal of vegetation (Poesen et al., 2002; Poesen et al., 2003; Prosser & Slade, 1994). Two types of land use – agricultural lands and military training areas – directly damage the soil surface with heavy machinery, remove or reduce protective vegetation, and create altered flow paths such as tillage lines and tank tracks. When gullies form in agricultural fields, they remove topsoil and limit water availability for plant growth by transporting water away quickly (Valentin et al., 2005). Gullies in agricultural fields can also deliver large amounts of sediment, nitrogen, phosphorus, and other pollutants downstream, which damages stream habitat, alters stream flow due to added sediment load, and contributes to reservoir sedimentation and eutrophication of lakes and streams (Hargrove et al., 2010). Consequences are similar for gullies in military training areas – heavy equipment create tracks and decrease vegetative cover due to soil compaction (See Figure 1.1). In military training areas, there are added risks of soldier safety. There have been reports of soldiers driving tanks into deep gullies hidden by tall grasses – one incident on Fort Riley caused injury to the soldier and a large equipment bill for the military. As for training and land sustainability, if money is less available to repair and prevent gullies successfully, the military may be required to expand their training exercises onto new ground, further spreading potential ecological and hydrologic damage.

Figure 1.1 Tank track soil damage and compaction after a rain event. Photo by author.

The literature has documented that a single global solution to gully erosion is not possible, and that in every region studied, different factors are at play. For example, a study in eastern Ethiopia found that stream power and a topographic wetness index were good predictors of gully erosion (Daba, Rieger, & Strauss, 2003). In Italy, the geological substratum and slope angle were good predictors (Zucca, Canu, & Della Peruta, 2006); another study in Italy found a good relationship between antecedent moisture, rainfall and gully erosion (Capra, Porto, & Scicolone, 2009). A study in the Mediterranean found that vegetative cover was more critical than mean annual rainfall (Vandekerckhove, Poesen, Oostwoud Wijdenes, Nachtergaele, Kosmas, Roxo, & de Figueiredo, 2000). The majority of recent (post-2000) gully research in the world is being done in the Mediterranean (e.g. Capra et al., 2009; De Santisteban, Casalí, & López, 2006; Di Stefano & Ferro, 2011; Gómez-Gutiérrez, Schnabel, Berenguer-Sempere, Lavado-Contador, & Rubio-Delgado, 2014; Gómez-Gutiérrez, Schnabel, & Lavado-Contador, 2009; Nachtergaele, Poesen, Sidorchuk, & Torri, 2002; Oostwoud Wijdenes, Poesen, Vandekerckhove, Nachtergaele, & De Baerdemaeker, 1999; Zucca et al., 2006), with other hotspots of research in Belgium (e.g. Gyssels & Poesen, 2003; Nachtergaele et al., 2002; Vanwalleghem et al., 2005), Australia (e.g. Hancock & Evans, 2010; Prosser & Slade, 1994), and China (e.g. Gao, Wu, Zhao, Shi, Wang, & Zhang, 2011; Wu & Cheng, 2005). A lack of gully research in the United States, and a significant gap in the research community for gullies on military training land, calls for detailed, region-specific studies.

The Midwestern United States has conditions prone to gully initiation and growth: deep, erodible soils, sporadic intense rainfall events, and land uses that usually increase the rates of erosion. The Midwest is also a valuable resource for food production and military training. Few gully studies have been conducted in the greater Midwestern U.S. (i.e. Beer, 1963; Piest & Spomer, 1968; Spomer & Hjelmfelt Jr., 1986; Thomas, Iverson, Burkart, & Kramer, 2004), and only one was done after the year 2000. Very few, if any studies have been done in Kansas, a state that produces 15 percent of the United States' wheat, 42 percent of the nation's sorghum, and 19 percent of the nation's beef (Kansas Department of Agriculture, 2015); and is home to Fort Riley, a 2,331 hectare (101,000 acre) military base. Because of the lack of gully research in the Midwest and on military bases, a comprehensive understanding of gully growth rates and processes, including data collection on driving factors contributing to initiation and growth, is needed. Innovation in land rehabilitation methods and accurate communication of those strategies to land managers will then be possible.

Goals, Questions, Hypotheses and Significance

This research project's overall goal was to examine gully erosion process in the Midwestern United States in order to contribute to current gully literature, and to add value to gully mitigation efforts in agricultural fields and military training areas. Research questions and hypotheses include:

Rates of growth:

1. What are the rates and patterns in which gullies are growing, and if gullies expand once certain thresholds are met, what are those thresholds? How are the rates of growth related to rainfall volumes/intensities?

Hypothesis 1a: A direct, linear correlation between gully erosion rates and rainfall intensity is not likely due to specific field conditions preceding each rainfall event. As field conditions vary, such as antecedent soil moisture, vegetative cover, and direct disturbances such as tire tracks or tillage lines, the likelihood of erosion events will also vary.

Hypothesis 1b: The threshold rainfall event for gully erosion on agricultural fields and military training areas will be between 40 and 60 millimeters of rainfall over a 24-hour period, depending on site-specific conditions such as slope, drainage area and vegetative cover. Overland flow will not be required for gully growth in areas with a plow pan or other restrictive subsurface layer. For unprotected soils such as tilled agricultural fields, a lower threshold for erosion is expected.

Drivers of growth:

2. Which factors, natural or anthropogenic, are the main drivers of gully growth in agricultural fields and military training areas in Kansas?

Hypothesis 2a: Both high and very low antecedent soil moisture conditions will cause increases in gully erosion; soils that are saturated preceding a rainfall event will be more mobile due to decreases in soil strength, and very dry, shrink-swell clay soils surrounding gullies will form vertical cracks, causing failure events when rainfall fills those cracks.

Hypothesis 2b: Healthy grassland cover in military training areas and dense residue/continuous cover in agricultural fields will provide the best defense against gully erosion due to vegetation's effectiveness in slowing runoff volumes through friction, decreasing runoff volumes through infiltration, and distributing the runoff energy through interruptions in the flow path. Remote sensing of vegetation biomass in the gullied area will illustrate low leaf density correlation with higher gully growth rates.

Methods Overview

"Rates of growth" methods:

Measurements of gully area change, sediment movement, and uphill migration of gully headcuts are possible with accurate field data collection. Though many researchers choose to monitor gully growth remotely with aerial photography (i.e. Daba et al., 2003), spatial resolution would need to be precise at the sub-half meter to detect gully growth rates over short time periods. Accurate field-based gully monitoring is required for more accurate data and model development. To measure gully erosion rates and patterns, field survey equipment with a centimeter-level of accuracy was used. By surveying longitudinal profiles and cross sections of each gully, and resurveying after rainfall/runoff events, changes in gully dimension and profile, and thus growth rates related to rainfall/runoff events can be detected.

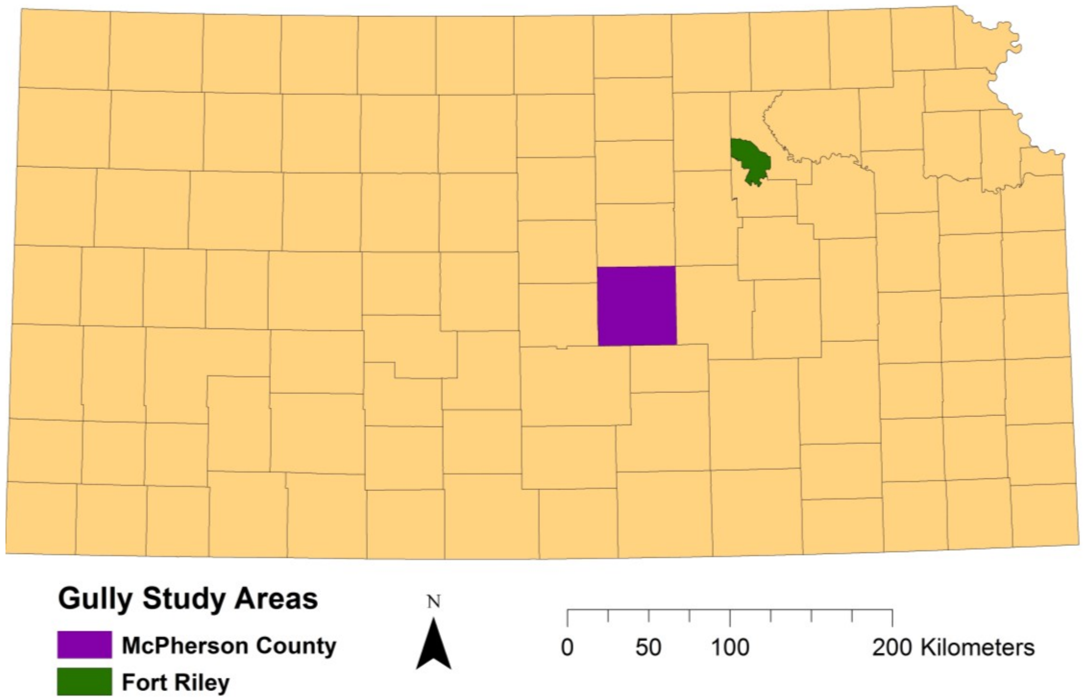
"Drivers of growth" methods:

As noted, drivers of gully erosion vary worldwide. In Kansas, cohesive shrink-swell clay soils and long periods of dry weather followed by intense rainfall events create high erosion potential. In natural, historic settings, dense Midwestern tallgrass prairie and undisturbed soil structure slowed runoff volumes, protecting against gully erosion. The reductions in vegetative cover due to changing land use compared to previous natural settings, along with widely varying antecedent moisture conditions, are likely major driving factors in present-day gully formation and accelerated growth in the Midwest. It may seem obvious that vegetation will be an important controlling factor in erosion, but not all gully studies have come to that conclusion, as noted. The literature shows that gully erosion can be dependent on various factors, most of which are inter-dependent and related to land use change. Slope, drainage area, topographic location, inherent soil conditions and rainfall intensity are natural factors that can drive gully initiation and growth. Anthropogenic drivers of gully erosion can be 1) infiltration impairments due to soil compaction and vegetation removal; 2) the creation of a "plow pan" in the soil subsurface also due to repeated compaction; 3) increases in surface and subsurface flow energy due to vegetation removal including roots and shoots; 4) increased concentration of flow over a hillslope due to the creation of linear elements in the landscape by vehicle tracks or tillage lines; and 5) direct physical disturbance/dislodging of soil aggregates at the soil surface creating vulnerability to rainsplash erosion and further soil dislodging. The research goal was to observe and monitor each of these drivers of erosion to determine which play the largest role in gully growth on military training lands and agricultural fields in Kansas.

Study Areas

This research focuses on the Fort Riley military base in northeast Kansas and agricultural fields in McPherson County, Kansas. Gullies formed in both locations before the study began, and gullies in both locations differ due to different land and land-use characteristics. Figure 1.2 is a map of Kansas with Fort Riley and McPherson county locations indicated. Both locations and land uses provide different processes for study within the same general region.

Figure 1.2 Fort Riley and McPherson in Kansas



McPherson field sites

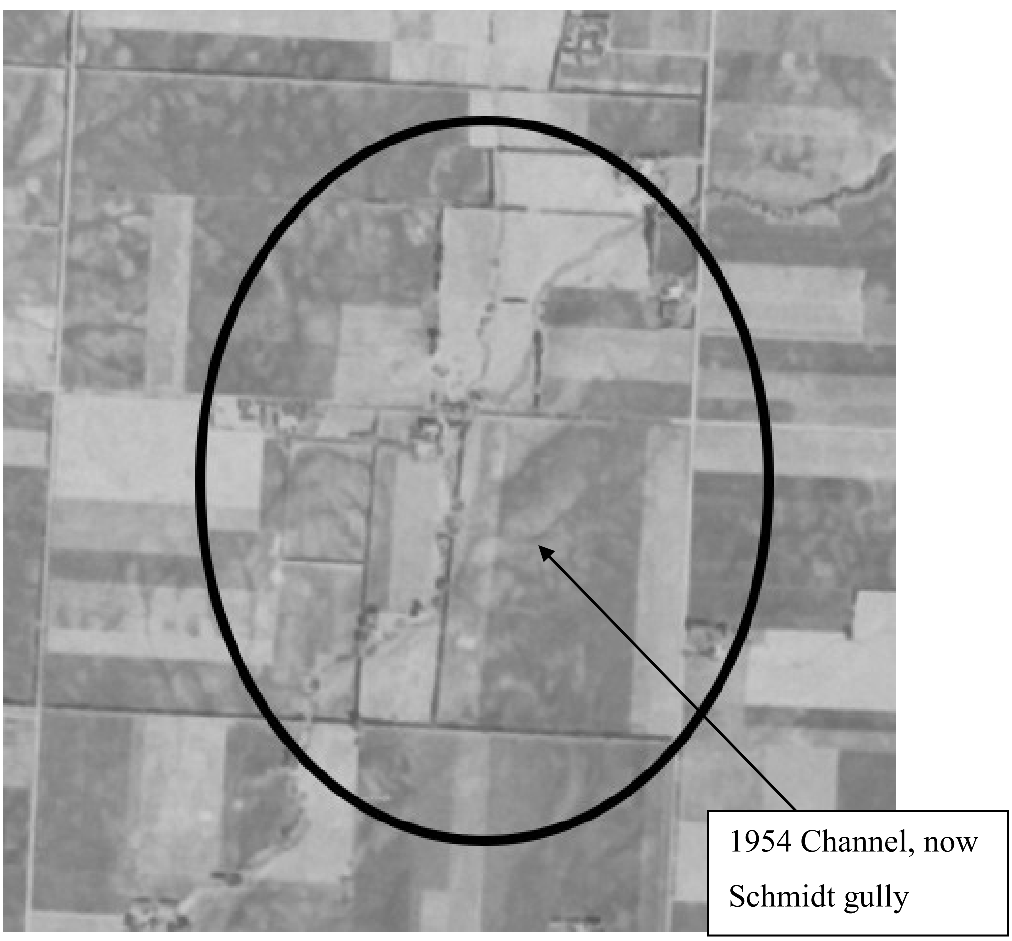
The McPherson gully study was funded by the National Institute of Food and Agriculture (NIFA) through the United States Department of Agriculture and a Conservation Innovation Grant (CIG) through the Natural Resource Conservation Service (USDA-NIFA under Agreement No. 2011-51130-31128 and Kansas NRCS-CIG grant number 69-6215-13-0003). Principal Investigators chose McPherson for gully studies because other stream and watershed studies had already been done there, and they had extensive data from the larger watersheds that the gullies are located in: the Emma Creek and Turkey Creek watersheds.

Central Great Plains ecoregion and McPherson area characteristics

McPherson County is located in the Central Great Plains Wellington-McPherson Lowlands Ecoregion, a landscape with gentle, rolling topography and expanses of flat land. The lowlands are formed from alluvial deposits of sand, silt and gravel transported from the High Plains one to two million years ago. Inactive sand dunes, formed by wind and water, are found throughout the region. In the subsurface are silt, sand and gravel deposits that contain a valuable ground water resource, named the "Equus beds" (Kansas Geological Survey, 1997; Kansas Geological Survey, 2005). The shale, gypsum and salt subsurface layers are products of a Permian sea (Chapman, 2001). The area is largely cropland for winter wheat and grain sorghum – soybeans and corn are also typical crops. Gully type in McPherson County depends on whether or not the farmer tills the land. Tilled fields have ephemeral gullies that are eliminated each year after tillage, and gullies in no-till fields vary in response to cropping and soil conservation practices.

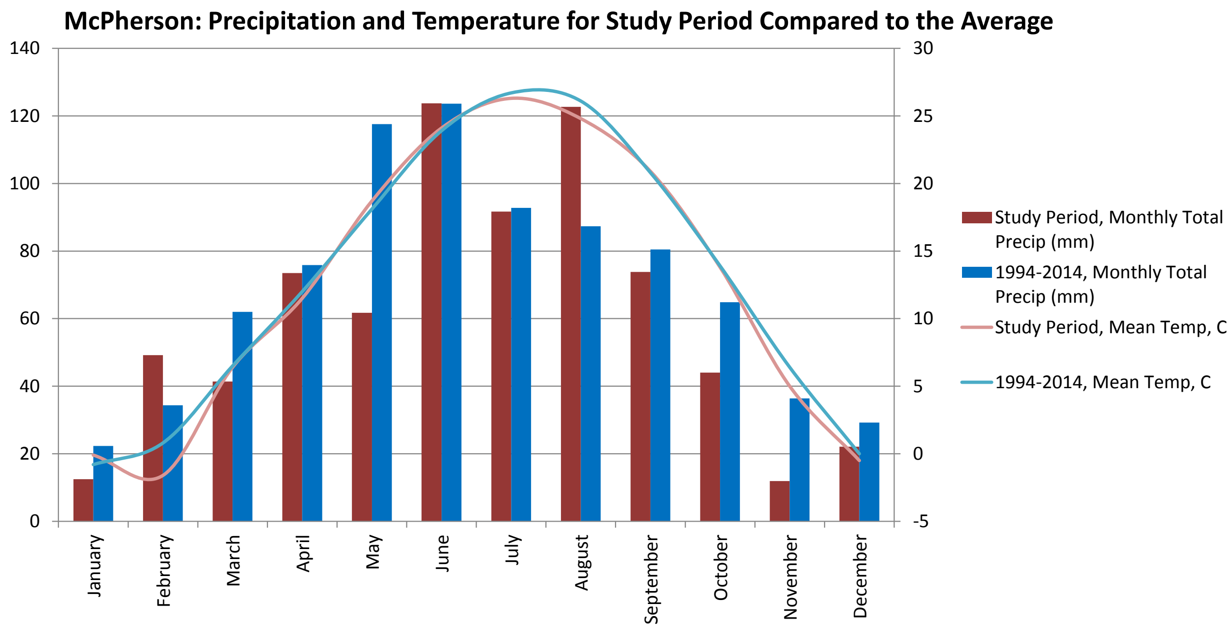
Before European settlement, McPherson County was 99 percent prairie and 1 percent forest. Even in the early days of agriculture, McPherson County was recognized as a valuable wheat-producing area (Cutler, 1883). Aerial photos from the 1950s show active agriculture, and they also illustrate that the gully networks studied in this project existed at that time (See Figure 1.3), suggesting that they have long been a part of the surface drainage network.

Figure 1.3 Gully network in the Schmidt field in 1954 aerial photo. Courtesy of USGS.



The McPherson study area receives 830 mm of rain yearly, on average (1981-2010 average, U.S. Climate Data, 2015a). The chart below (Figure 1.4) shows the 20-year monthly averages for rainfall and temperatures (in blue) compared to averages for the 2012-2014 study period (in red). The wettest season is typically in late spring during the months of May and June. The summer months that follow (July through September) are typically hot with less rainfall than the spring. Spring and summer months do bring occasional intense thunderstorm systems, which often correspond to increased runoff and erosion rates compared to the fall and winter seasons. Winters are cold and harsh, with an average snowfall depth of 35 cm (1981-2010 average, U.S. Climate Data, 2015a). Wind in McPherson County generally comes from the south – the average 2014 wind speed for the city of McPherson was 15.6 km/hour with a maximum of 88.8 km/hour (Kansas Mesonet, 2014a).

Figure 1.4 20-year rainfall and temperature averages versus study period averages. Data courtesy of NOAA/NCEI



Descriptions of individual McPherson gully fields

The McPherson agricultural gully sites are spread across four fields, two of which are no-till and two of which are traditionally tilled. Two of the sites are located in the Turkey Creek watershed, and are a mile apart. The other two sites are approximately 14 kilometers to the east, and are in the Emma Creek watershed. The four field sites were chosen for study as part of a larger gully research project, involving not only gully erosion measurements but also phosphorous and sediment loading and educational products for the farming community and for Kansas State University. A year into the gully study, one of the traditionally-tilled fields, named the Ratzlaff Field, was excluded from data collection. The producer works the land frequently enough with tillage equipment that data from that field would be difficult to compare to the other studied fields. Additionally, a defined gully channel did not form in the selected location of the Ratzlaff Field after the first year. The remaining three fields were studied throughout the whole project and are referred to by the landowners' names: Wedel, Goerhing, and Schmidt. Table 1.1 lists characteristics of each field, and Figure 1.5 is a map of field locations. Table 1.2 gives soil family classifications at each field. Table 1.3 provides soil property descriptions.

Table 1.1 McPherson gully fields' characteristics

Field name	Management Practices	Typical cover
Wedel	No-till	Medium to low residue
Schmidt	No-till	Heavy residue
Goerhing	Tillage	Low residue

Figure 1.5 McPherson gully site locations

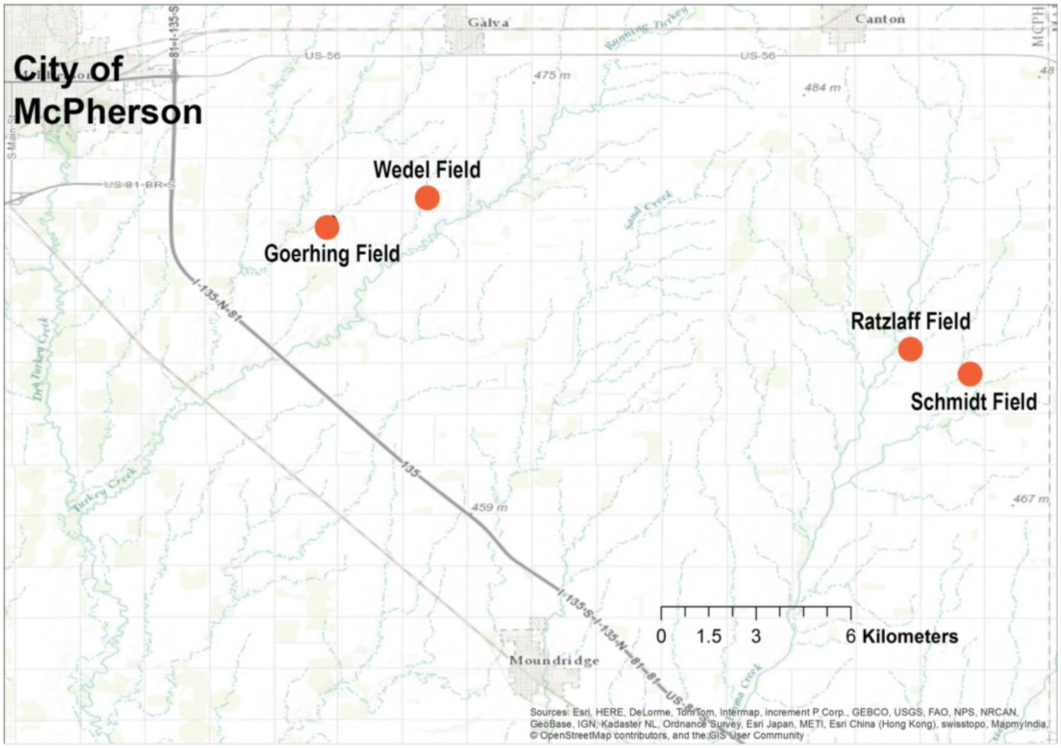


Table 1.2 McPherson soils descriptions

Site Identification	Latitude/ Longitude	Soil location at site	Soil Mapping Unit	+Family Classification
Wedel Field	97°32'58.19"W 38°20'9.28"N	*Primary soil	Crete silt loam, 1-3 % slopes (3825)	Crete, Fine, smectitic, mesic Pachic Udertic Argiustolls
		**Secondary soil	Crete silty clay loam, 1-3 % slopes, eroded (3829)	Crete, Fine, smectitic, mesic Pachic Udertic Argiustolls
Schmidt Field	97°23'40.62"W 38°17'13.00"N	Primary soil	Farnum loam, 1 to 3 % slopes (5893)	Farnum, Fine-loamy, mixed, superactive, mesic Pachic Argiustolls
		***Secondary soil	Crete silt loam, 0-1 % slopes (3824)	Crete, Fine, smectitic, mesic Pachic Udertic Argiustolls
Goerhing Field	97°34'30.81"W 38°19'47.68"N	Primary soil	Longford silty clay loam, 3-7% slopes (3403)	Longford, Fine, smectitic, mesic Udic Argiustolls
		***Secondary soil	Crete silt loam, 1-3 % slopes (3825)	Crete, Fine, smectitic, mesic Pachic Udertic Argiustolls
**primary soil type at gully channel location*				
***soil type in lower elevations*				
****soil type in headwater areas, above headcuts*				
+ Source: United States Department of Agriculture, www.soils.usda.gov				

Table 1.3 McPherson sites - Soil properties

McPherson soil descriptions	Farnum	Longford	Crete
Mapping Number	5893	3403	3825
Surface texture	loam	silty clay loam	silt loam/silty clay loam
Parent Material	loess	loess	loess
Slopes	1-3%	3-7%	1-3%
Depth to restrictive feature (cm)	>200	>200	>200
A horizon	0-30 cm	0-25 cm	0-25 cm
Color	dark grayish brown	dark grayish brown	dark grayish brown
Structure	granular	granular	granular
B horizon	30-124 cm	25-119 cm	25-109 cm
Color	brown/pale brown	reddish brown	dark grayish brown
Structure	subangular blocky	subangular blocky	blocky
C horizon	30-152 cm	119-152 cm	109-152 cm
Color	brown	brown	pale brown
Structure	N/A	massive	massive
pH (Weighted average)	7.2	7.0	7.2
Data source: U.S. Department of Agriculture, www.soils.usda.gov			

Wedel Field description

The Wedel field is 1/8 of a section (in the United States land surveying system), or about 32 hectares. The main gully channel in the field, which flows the length of the field from north to south, begins its flow path at least 2 kilometers northeast of the Wedel field. The gully channel enters the field through a road culvert at the north end, and exits the field into a road ditch at the south end. The channel flows into a culvert under the south road, and then into another field where a producer contains the gully within a grassed waterway. The road culvert at the outlet of the Wedel field was reworked and replaced in 2014 – two older culverts still exist under the road, but have been clogged with sediment from the Wedel field over time. The total watershed area for the Wedel field outlet is 66 hectares. Both fields to the west and the east of the Wedel field use grassed waterways and terracing for soil conservation.

During the study period, the field was no-till with very little residue cover and was left fallow for months at a time with very little cover. The 2012 summer season was an exception, with good wheat residue cover. Crop rotations after summer 2012 were grain sorghum and soybeans. The main, north-south channel in the Wedel field has been named the A Channel, or A Tributary. A large second channel branches to the east mid-way through the field – named the B Tributary (Trib B). At the head end of the B Tributary, bordering the field to the east, is a drop structure that seems to have fed the channel in past years. Currently though, the headwaters for Trib B run north to south along the east edge of the field. Two smaller channels that enter Tributary B from the north are named the C and D tributaries. Figure 1.6 is an overview photo of the field and channels. Figure 1.7 is an example of channel conditions.

Figure 1.6 Overview of the Wedel field. ESRI imagery modified by author.

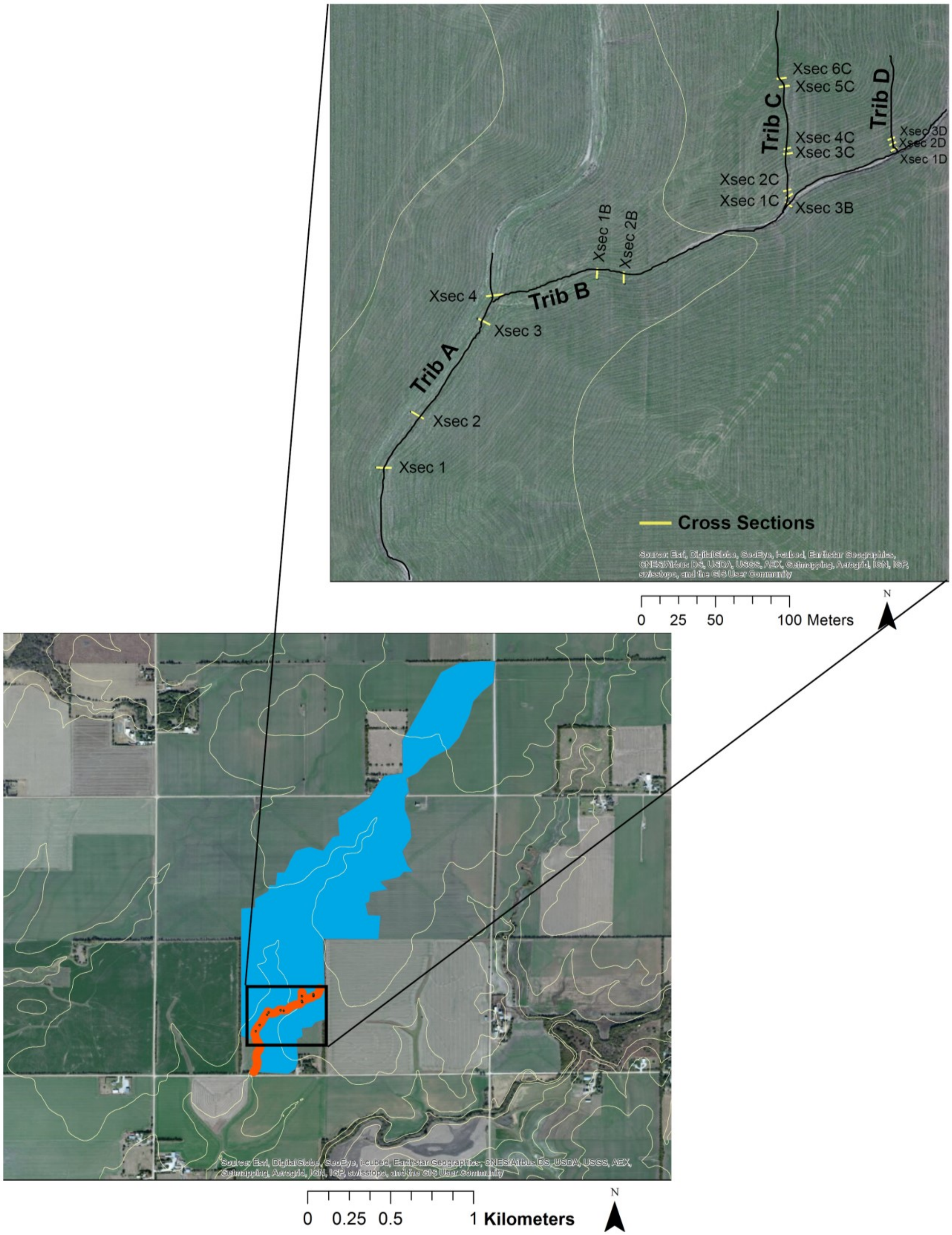
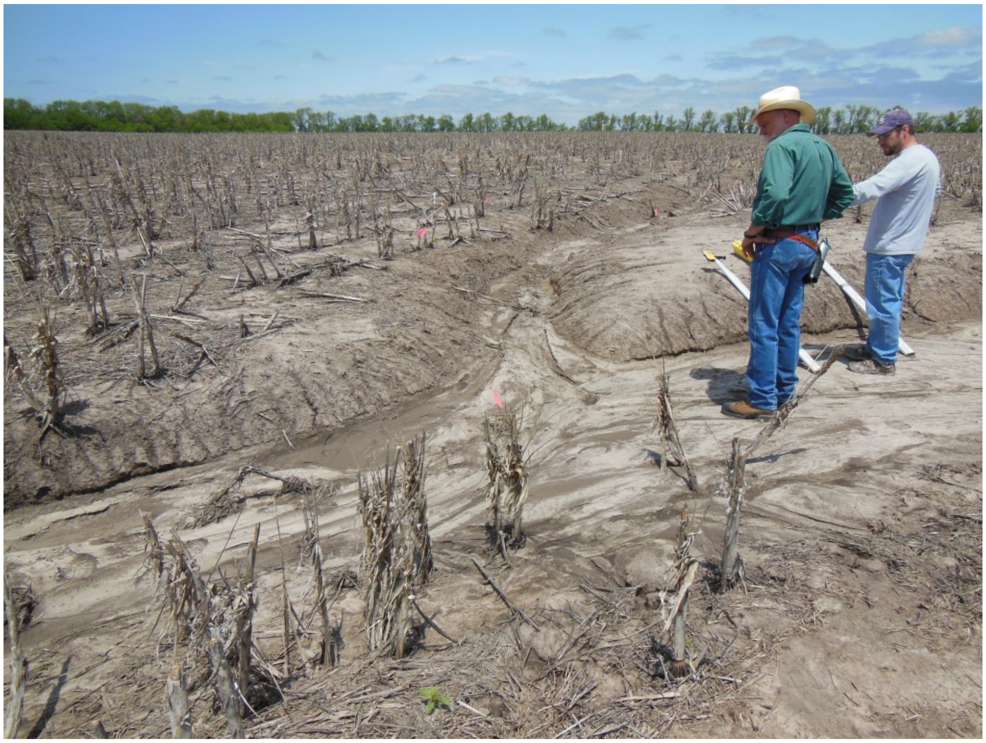


Figure 1.7 Example conditions of the Wedel field gully. Photo by author.



Schmidt Field description

The Schmidt field is nearly a quarter section (in the United States land surveying system) or about 48 hectares. The gully network consists of two smaller tributaries: one that originates in the northeast corner of the field and flows southwest, and one that originates in the center of the field and flows northwest. The tributaries join to form a larger channel that flows to the west. The lower end of the gully channel flattens out and deposits sediment along the west field edge before reaching a perennial stream. The watershed size at the gully outlet or depositional area is about 13 hectares.

The Schmidt field is a no-till field. The field was planted to wheat for most of the study period, but was in corn at the very beginning and the very end of the study. The field had excellent residue cover for most of the off-season, with knee-high wheat stubble in 2012. Figure 1.8 is an overview of the field and channel. Figure 1.9 is an example of channel conditions.

Figure 1.8 Schmidt field and gully channel. ESRI imagery modified by author.

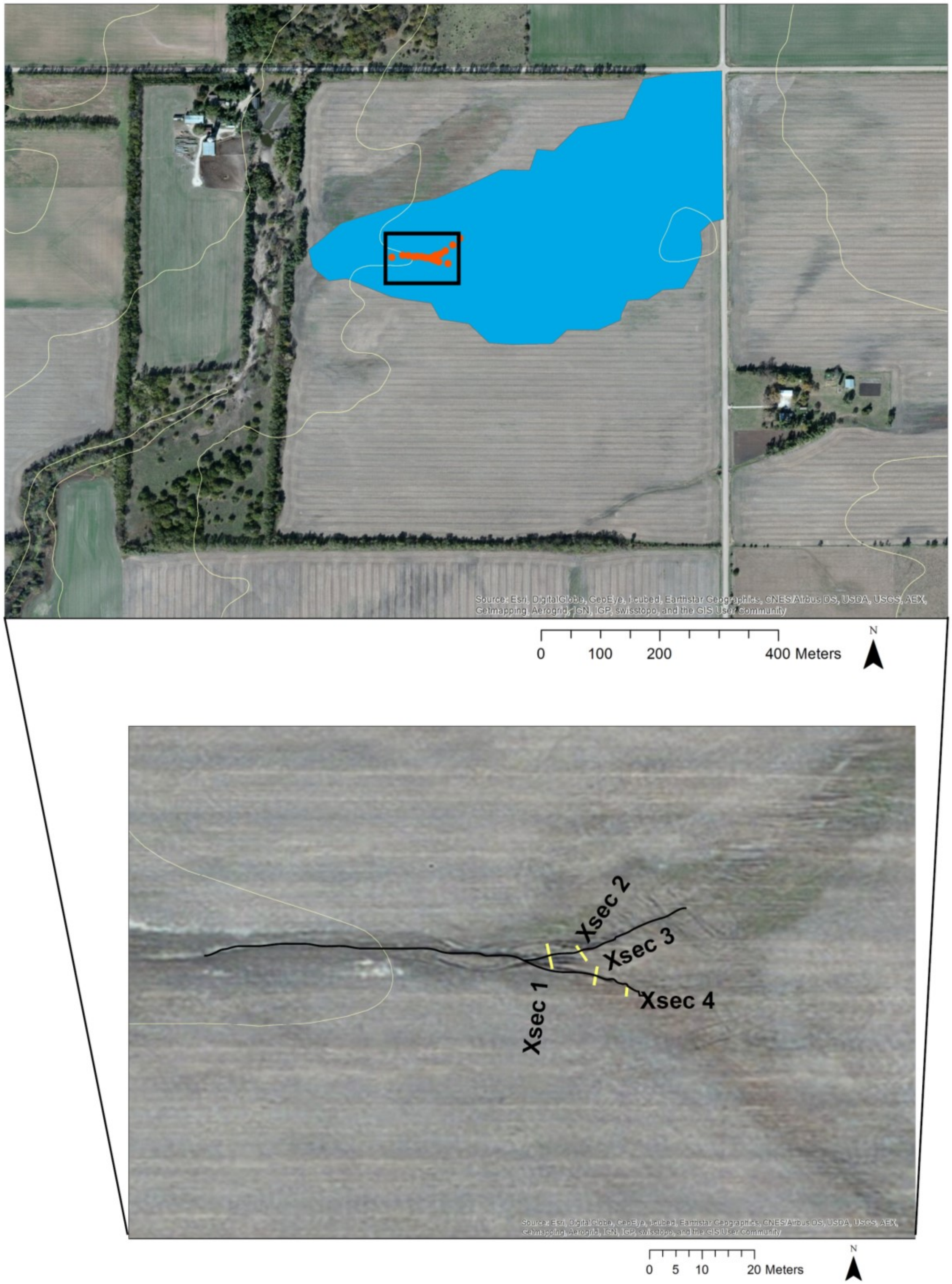


Figure 1.9 Example conditions of Schmidt field gully. Note heavy residue cover. Photo by author.

Goerhing Field description

The Goerhing field is about 6 hectares in size. One gully channel was studied, which flows from the south end of the field and enters a larger, meandering channel at the northern end of the field, which drains to the west. The Goerhing gully channel is fed by the adjacent field from the south, and some of the runoff comes from a road ditch. The watershed size at the channel outlet is 5 hectares. Prior to 2003, the Goerhing field was larger – but the meandering channel at the current gully outlet was created and separated the field into two sections.

During the study period, the field was planted as continuous wheat and was conventionally tilled multiple times per year. When the gully was initially chosen as a study location, the channel location was easily identified. After tillage, the gully channel location was not as easily distinguishable, but a low spot in the landscape was always present. Figure 1.10 is an overview photo of the field and channel. Figure 1.11 is an example of channel conditions.

Figure 1.10 Goerhing field and gully channel. ESRI imagery modified by author.

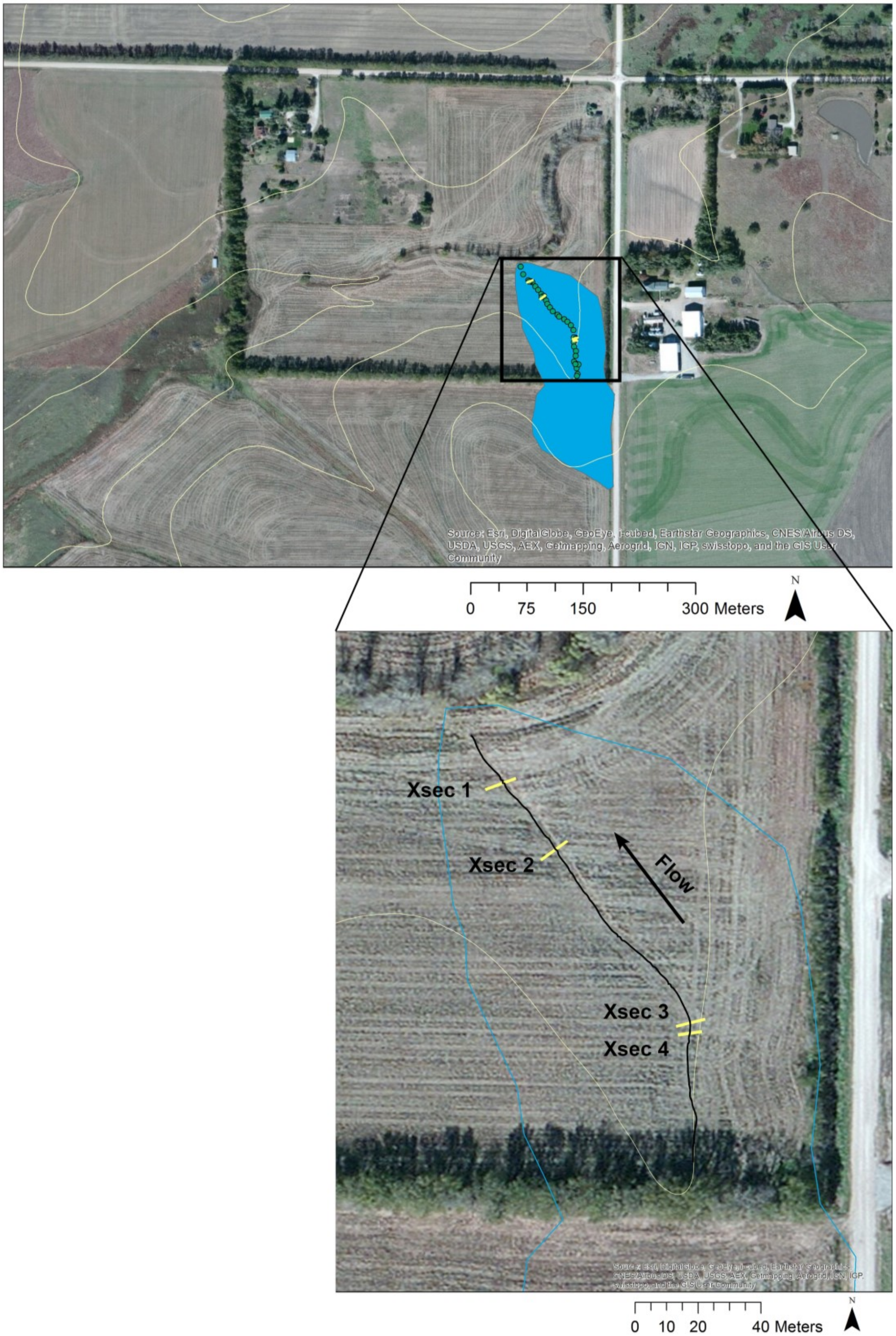


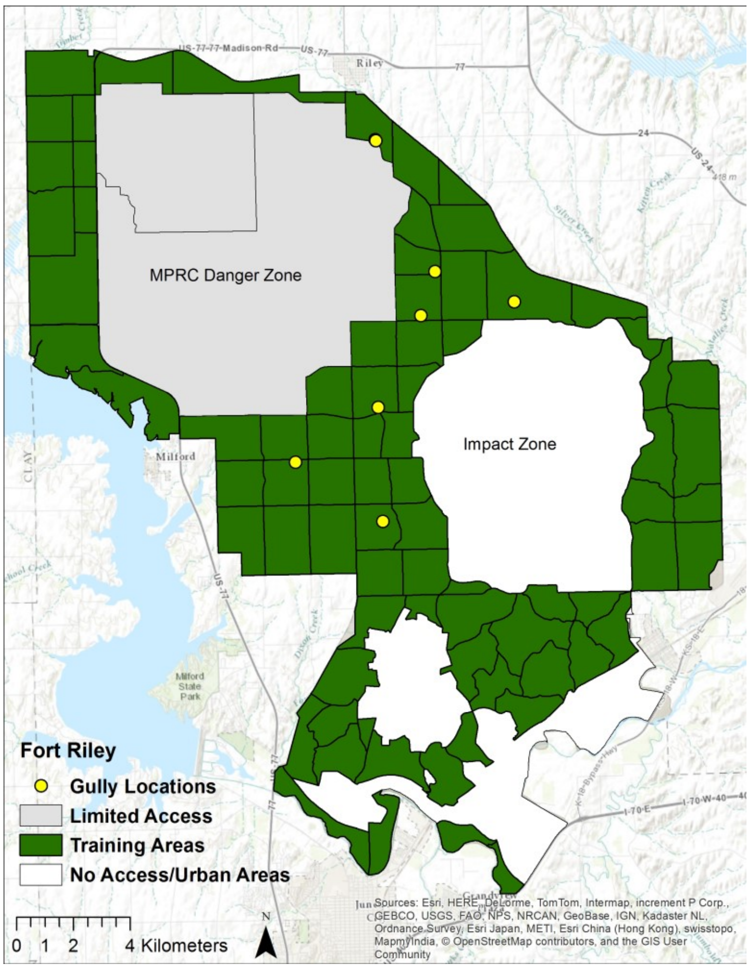
Figure 1.11 Example conditions of Goerhing field gully after tillage. A swale rather than defined channel. Photo by author.

Fort Riley field sites

The Fort Riley study was funded through the Great Plains (GP) Cooperative Ecosystems Studies Unit (CESU) Agreement No./ W9132T-11-2-0012. Fort Riley is a 2,331-hectare military base located in the Kansas Flint Hills. The Fort has large expanses of prairie land used for training activities ranging from tank maneuvers to firing ranges. Fort Riley gullies commonly form in tank tracks, in low-lying areas, or alongside roads, and are generally considered classic or deep gullies as opposed to ephemeral gullies that are found in agricultural fields. The Fort Riley portion of this study built upon two previous studies conducted by K-State Biological and Agricultural Engineering Masters students Katie Handley and Chelsea Corkins, who located gullies throughout the Fort and gathered coarse measurements of erosion and growth rates.

Fort Riley gullies vary greatly from site to site depending on how and where they formed, their soil materials, and their landscape position. To provide consistency, the gullies measured in this study were either tank-track related or in low-lying areas, and not affected by road drainage (concentrated flow alongside a road). Originally, six gullies were studied in six different training areas. In 2013, one of the gullies being studied (Training Area 36 gully) was filled with rock and soil under direction of the military because a soldier drove a vehicle into it during training and was injured. That gully could not be studied afterwards, so a new gully was instrumented in a different location (Training Area 98 gully). Seven total gullies were studied, but only five of them were measured throughout the entire 3 years. Figure 1.12 shows Fort Riley boundaries and gully locations.

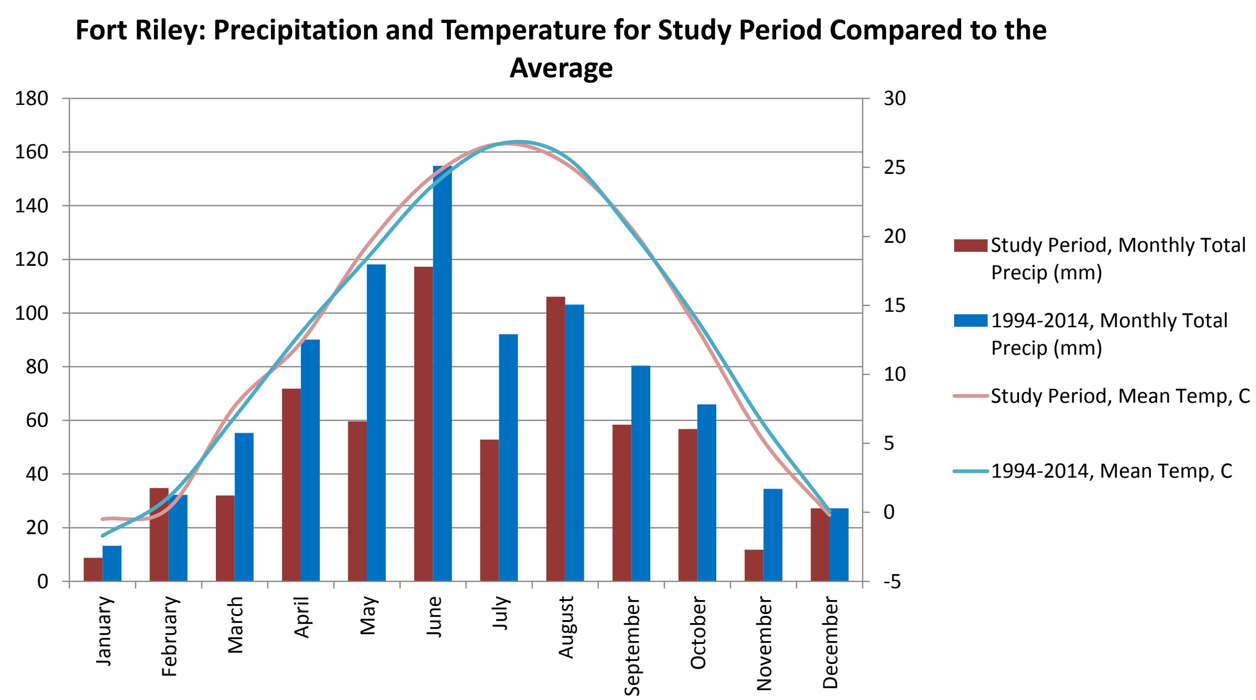
Figure 1.12 Fort Riley gully locations



Flint Hills ecoregion characteristics and Fort Riley history

The Flint Hills are composed of rolling hills with steep valleys, and contain “the largest remaining area of unplowed tallgrass prairie in North America” (Konza Prairie Biological Station, 2014). Water has shaped the landscape slowly over time through erosion. Prairie vegetation with roots as deep as 2 meters grows densely when undisturbed by changes in land use, paired with soils from 0.5 to greater than 2 meters deep; both allow for deep infiltration of rain water. The region surrounding Fort Riley receives about 900 mm of rain each year, and 43 cm of snowfall (1981-2010 average, U.S. Climate Data, 2015b), and the most rain typically falls in late spring during the months of May and June. The summer months that follow (July through September) are typically hot with less rainfall than the spring. Spring and summer months do bring occasional intense storm systems, which often correspond to increased runoff and erosion rates compared to the fall and winter seasons. Figure 1.13 shows a 20-year average for temperature and precipitation (in blue) compared to the 2012-2014 study period (in red). Wind at Fort Riley generally comes from the south, and the average wind speed for 2014 was 10 km/hour with a maximum speed of 91 km/hour (Kansas Mesonet, 2014b).

Figure 1.13 20-year temperature and precipitation average versus the 2012-2014 study period. Data courtesy of NOAA/NCEI



Fort Riley was established in 1853 as a military post, serving travelers along the Oregon and Santa Fe trails. The surrounding areas were used as farmland – old farm terraces can still be seen in aerial photos. In the 1940s, approximately 13,000 hectares were added to Fort Riley for training purposes, and in 1966 an additional 20,000 hectares, much of it farmland, was also acquired for training purposes (MyBaseGuide, 2014). Most of the gully sites for this study were farmland areas in the early and mid-1900s.

The Flint Hills are used mostly as rangeland (Chapman, 2001), and military training land at Fort Riley has sometimes been compared to rangeland because of similarities in compaction and associated limits of vegetation growth due to traffic and overgrazing. The vegetation community at Fort Riley went from pre-settlement tallgrass prairie to farmland, and back to an altered prairie as a result of training purposes. Though there is no current vegetation species data for each of the gully sites, data collected by Lantz and Devienne (unpublished data) suggests dominant Fort Riley grass species to be Big Bluestem *(Andropogon gerardii*), Little Bluestem *(Schizachyrium scoparium*), Prairie Junegrass *(Koeleria macrantha)* and Yellow Indian Grass *(Sorghastrum nutans*). Switchgrass *(Panicum virgatum*) and Dropseed (tall and prairie) *(Sporobolus compositus* and *Sporobolus heterolepis*) are also common. Common woody species noted through field observations, some of them encroaching on the training areas, include Eastern cottonwood *(Populus deltoides)*, roughleaf dogwood *(Cornus drummondii)*, osage orange *(Maclura pomifera)*, smooth sumac *(Rhus glabra)* and honey locust *(Gleditsia triacanthos)*. Soil classifications for each gully site are presented in Table 1.4. Table 1.5 gives detailed descriptions of the soil types.

Table 1.4 Fort Riley gully sites soils

Site Identification	Latitude/ Longitude	Soil location at site	Soil Mapping Unit	+Family Classification
TA 36 Gully	96°49'10.444"W 39°9'19.363"N	*Primary soil	Irwin silty clay loam 3-7% slopes, eroded (4674)	Irwin, fine, mixed, superactive, mesic Pachic Argiustolls
		Secondary soil	N/A	
TA 42 Gully	96°49'15.011"W 39°11'29.124"N	Primary soil	Irwin silty clay loam 3-7% slopes (4673)	Irwin, Fine, mixed, superactive, mesic Pachic Argiustolls
		**Secondary soil	Clime-sogn complex 3-20% slopes (4590)	Clime, Fine, mixed, active, mesic Udorthentic Haplustolls Sogn, Loamy, mixed, superactive, mesic Lithic Haplustolls
TA 51 Gully	96°51'15.652"W 39°10'30.34"N	Primary soil	Clime-sogn complex 3-20% slopes (4590)	Clime, Fine, mixed, active, mesic Udorthentic Haplustolls Sogn, Loamy, mixed, superactive, mesic Lithic Haplustolls
		***Secondary soil	Crete silty clay loam 3-7% slopes (3830)	Crete, Fine, smectitic, mesic Pachic Udertic Argiustolls
TA 89 Gully	96°48'8.095"W 39°13'11.797"N	Primary soil	Wymore-Kennebec complex 0-17% slopes (7690)	Wymore, Fine, smectitic, mesic Aquertic Argiudolls Kennebec, Fine-silty, mixed, superactive, mesic Cumulic Hapludolls
		***Secondary soil	Irwin silty clay loam 3-7% slopes (4673)	Irwin, fine, mixed, superactive, mesic Pachic Argiustolls
TA 91 Gully	96°45'50.346"W 39°13'26.336"N	Primary soil	Clime-sogn complex 3-20% slopes (4590)	Clime, Fine, mixed, active, mesic Udorthentic Haplustolls Sogn, Loamy, mixed, superactive, mesic Lithic Haplustolls
		Secondary soil	N/A	
TA 94 Gully	96°47'45.689"W 39°14'1.908"N	Primary soil	Irwin silty clay loam 3-7% slopes, eroded (4674)	Irwin, fine, mixed, superactive, mesic Pachic Argiustolls
		Secondary soil	N/A	
TA 98 Gully	96°49'8.079"W 39°16'32.203"N	Primary soil	Irwin silty clay loam 3-7% slopes, eroded (4674)	Irwin, fine, mixed, superactive, mesic Pachic Argiustolls
		***Secondary soil	Clime-sogn complex 3-20% slopes (4590)	Clime, Fine, mixed, active, mesic Udorthentic Haplustolls Sogn, Loamy, mixed, superactive, mesic Lithic Haplustolls

**soil type at gully location*

***soil type immediately to the east of gully*

****soil type in gully watershed, above headcut*

+ Source: United States Department of Agriculture, www.soils.usda.gov

Table 1.5 Fort Riley sites - Soil properties

Fort Riley soil descriptions	**Irwin**	**Clime-sogn complex**	**Crete**	**Wymore-Kennebec complex**
Mapping Number	4674	4590	3830	7690
Surface texture	Silty clay loam	Silty clay	Silty clay loam	Silty clay loam
Parent Material	residuum weathered from shale	residuum weathered from shale	loess	loess
Slopes	3-7%	3-20%	3-7%	0-17%
Depth to restrictive feature (cm)	140 to >200	78	>200	>200
A horizon depth	0-28 cm	0-25 cm	0-15 cm	0-15 cm
Color	very dark gray	dark gray/grayish brown	dark grayish brown	dark gray
Structure	Subangular blocky	granular	Granular to blocky	granular
B horizon depth	28-127 cm	25-48 cm	15-117 cm	15-135 cm
Color	brown	grayish brown	brown	grayish brown
Structure	Blocky	subangular blocky	blocky	blocky
C horizon depth	127-140 cm	48-79 cm	117-152 cm	135-200 cm
Color	reddish brown	pinkish gray/light gray	dark brown	light brownish gray
Structure	Massive	subangular blocky	blocky	blocky
pH (Weighted average)	6.9 - 7.5	7.8	7.2	7.0
Data source: U.S. Department of Agriculture, www.soils.usda.gov				

Descriptions of individual Fort Riley gully sites

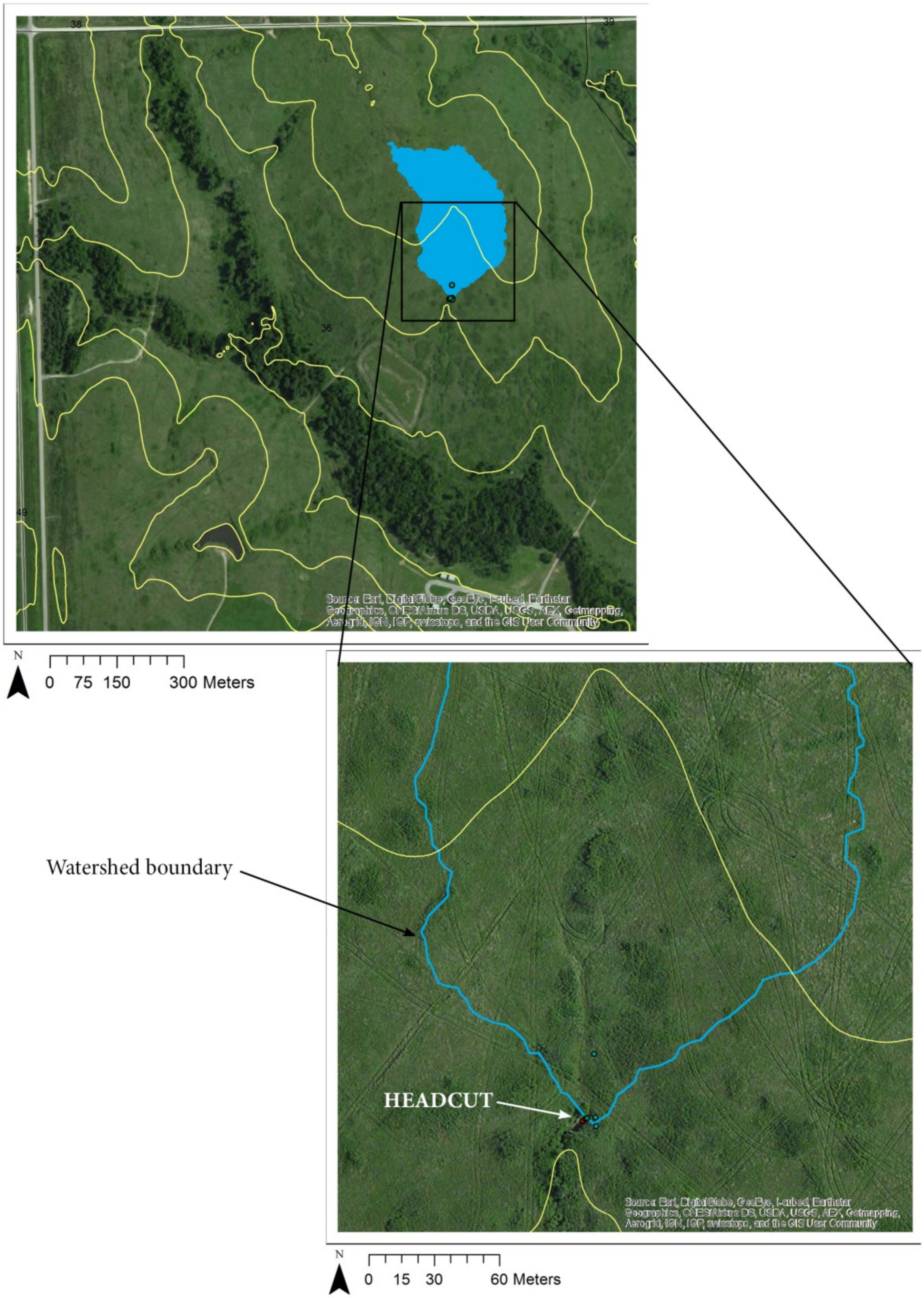
The following section describes in more detail the landform and vegetation of each gully site, along with any significant field observations as to what may influence runoff and erosion.

Training Area 36 Gully

Figure 1.14 is an example of Gully 36 conditions, and Figure 1.15 shows Gully 36 (indicated by the arrow), along with the gully's watershed and 3-meter contour lines. A study of Google Earth aerial photos suggested this is one of the oldest gullies in the Fort Riley study – it may have formed in the 1990s. The two-track paths in the photo, and in all subsequent gully photos, were made by military tanks or Humvees (High Mobility Multipurpose Wheeled Vehicles – HMMWV). The gully in Training Area 36 flows into a natural draw, and the gully headcut may have formed by branching from the natural draw. Though the gully did not form directly inside tank tracks, the imagery suggests that tank tracks concentrate flow from more than one direction above the headcut. Just below the headcut, the gully is 3.5 meters wide and 1.6 meters deep. The gully is immediately surrounded by young woody vegetation, and most of the training area consists of prairie vegetation and patches of woody trees.

Figure 1.14 Training Area 36 Gully, looking downstream from top of headcut. Photo by author.

Figure 1.15 Training Area 36 gully and surroundings. ESRI imagery modified by author.

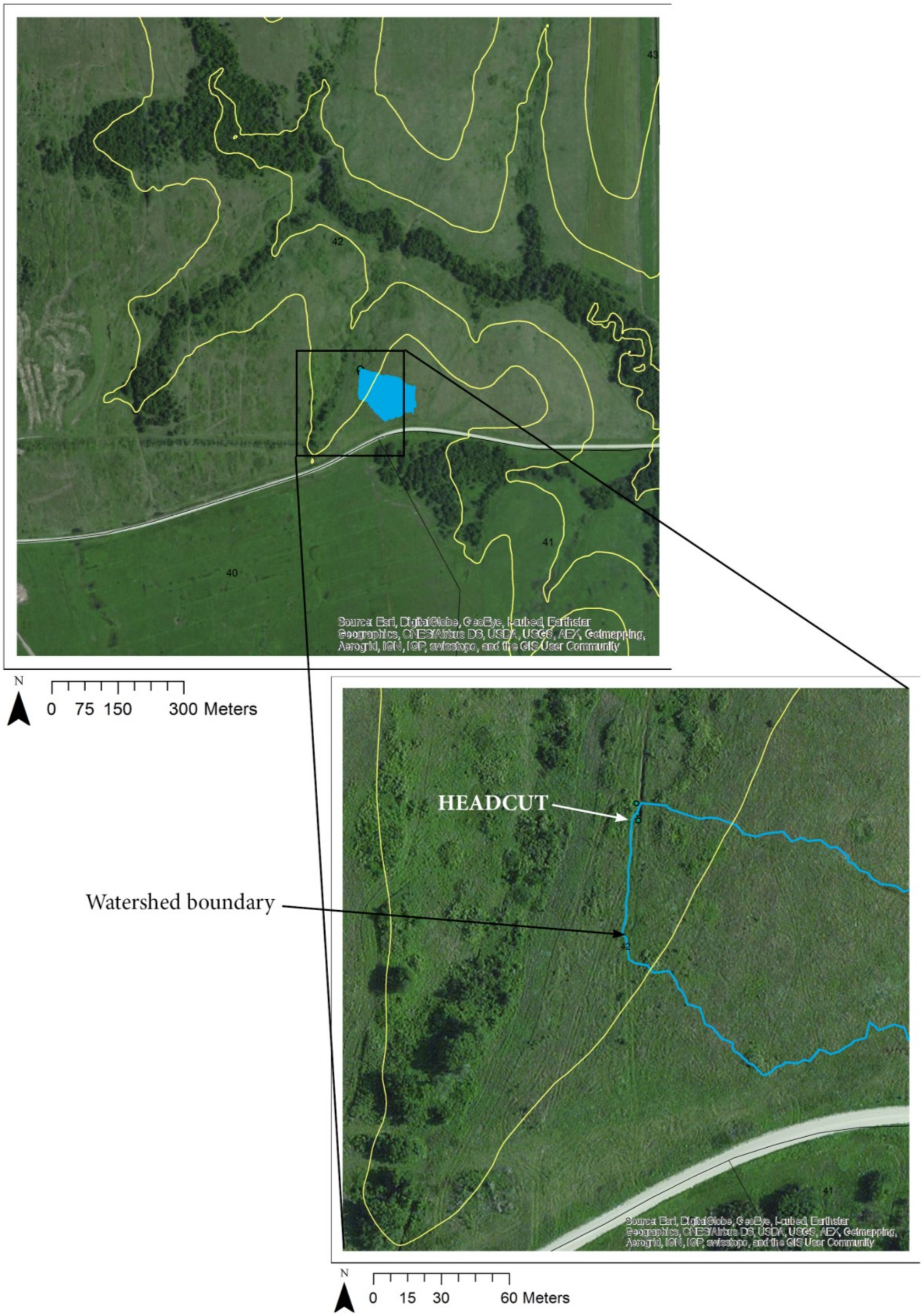


Training Area 42 Gully

Figure 1.16 is an example of Gully 42 conditions, and Figure 1.17 shows Gully 42 (indicated by the arrow), along with the gully's watershed and 3-meter contour lines. It is 2 meters wide and 0.5 meters deep just below the headcut, and becomes larger downslope. A study of Google Earth imagery suggests that the gully formed between 2005 and 2006. This gully formed inside tank tracks, and is a well-used thoroughfare for tank traffic. There is a steep slope toward the gully coming from the south road, and there are two main routes that tanks travel through the gully. In 2013, at least one tank drove over the gully in wet conditions, and a new tributary and headcut formed, entering the main channel from the east. The gully area is relatively wet, and many woody species are encroaching on the area.

Figure 1.16 Training Area 42 Gully, looking downstream at Cross Section 2. Photo by author.

Figure 1.17 Training Area 42 Gully. ESRI imagery modified by author.

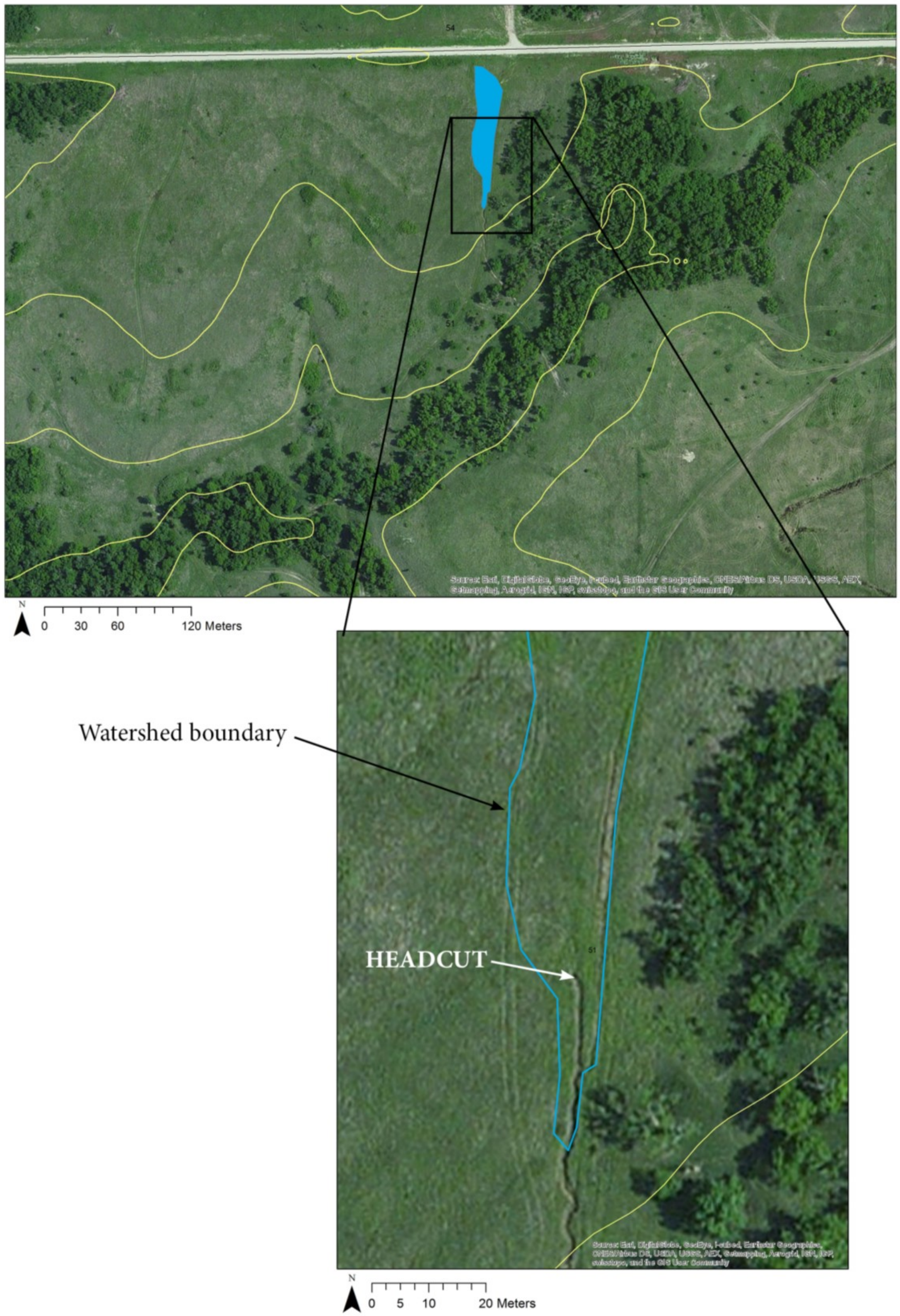


Training Area 51 Gully

Figure 1.18 is an example of Gully 51 conditions, and Figure 1.19 shows Gully 51 (indicated by the arrow), along with the gully's watershed and 3-meter contour lines. Note the old farm field terraces to the west of the gully. A study of Google Earth imagery showed that before it became a gully, the area was a well-used tank trail since 2002 or before. The gully seems to have formed sometime between 2005 and 2006, but imagery is too coarse to be sure. Gully 51 has two channels, both from tank tracks, which converge into one channel. The channel follows the tank track down a steep path into a wooded draw. The gully is 2 meters wide 0.5 meters deep just below the headcut, and becomes larger downslope. Most of the drainage area to the gully is prairie grasses and forbs, with woody species encroaching from the east.

Figure 1.18 Training Area 51 Gully, looking downstream at Cross Section 2. Photo by author.

Figure 1.19 Training Area 51 Gully. ESRI imagery modified by author.

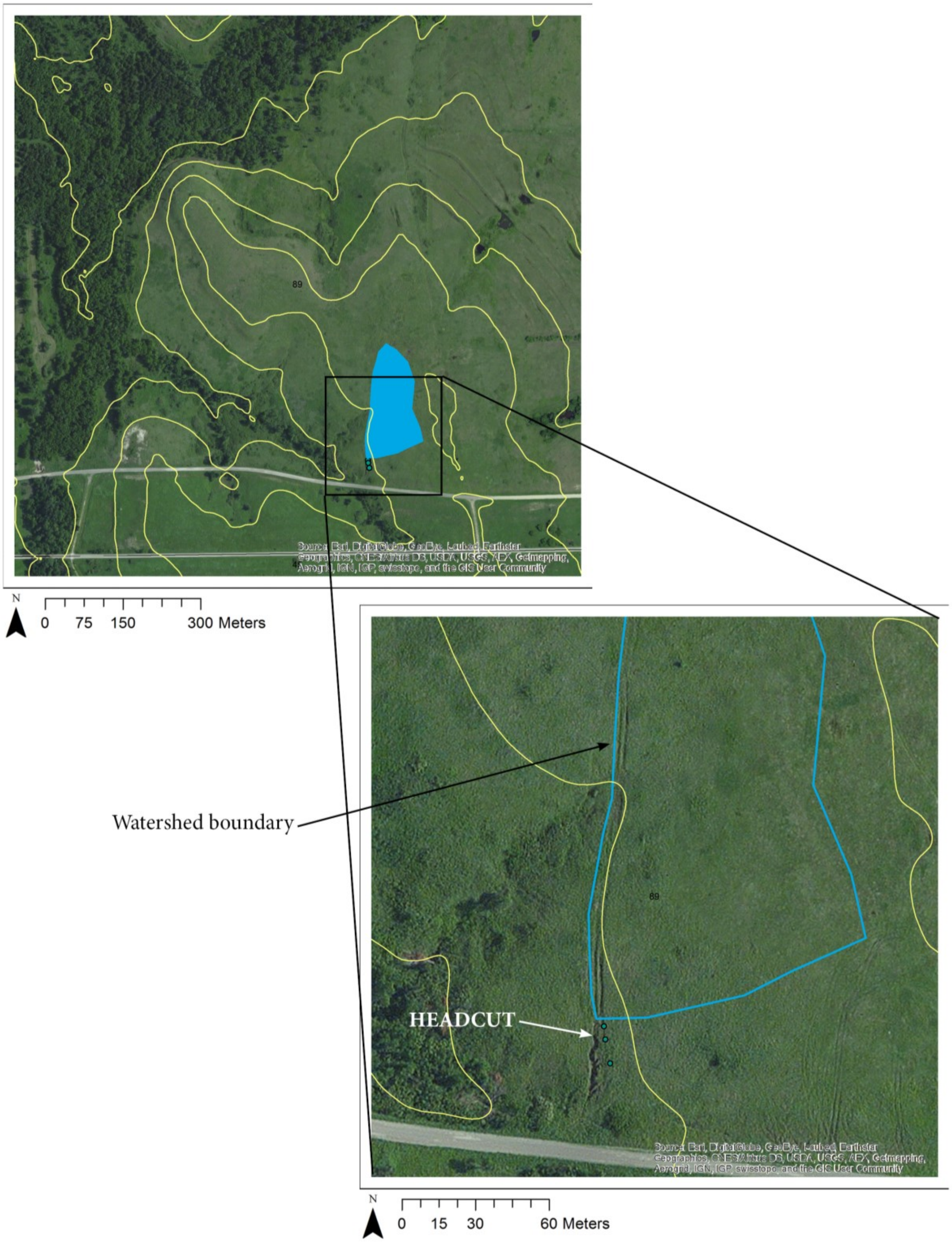


Training Area 89 Gully

Figure 1.20 is an example of Gully 89 conditions, and Figure 1.21 shows Gully 89 (indicated by the arrow), along with the gully's watershed and 3-meter contour lines. A study of Google Earth imagery showed that Gully 89 formed sometime between 2003 and 2006. The gully formed within tank tracks that follow a downhill slope to a road. Right below the headcut, the gully is 2.5 meters wide and 1 meter deep, and the gully becomes deeper downslope. A rock outcrop at the headcut of the gully provides some natural control. Most of the drainage area for the gully consists of prairie grasses and forbs – there are very few woody species in the watershed.

Figure 1.20 Training Area 89 Gully, looking downstream toward the road. Photo by author.

Figure 1.21 Training Area 89 Gully context. ESRI imagery modified by author.

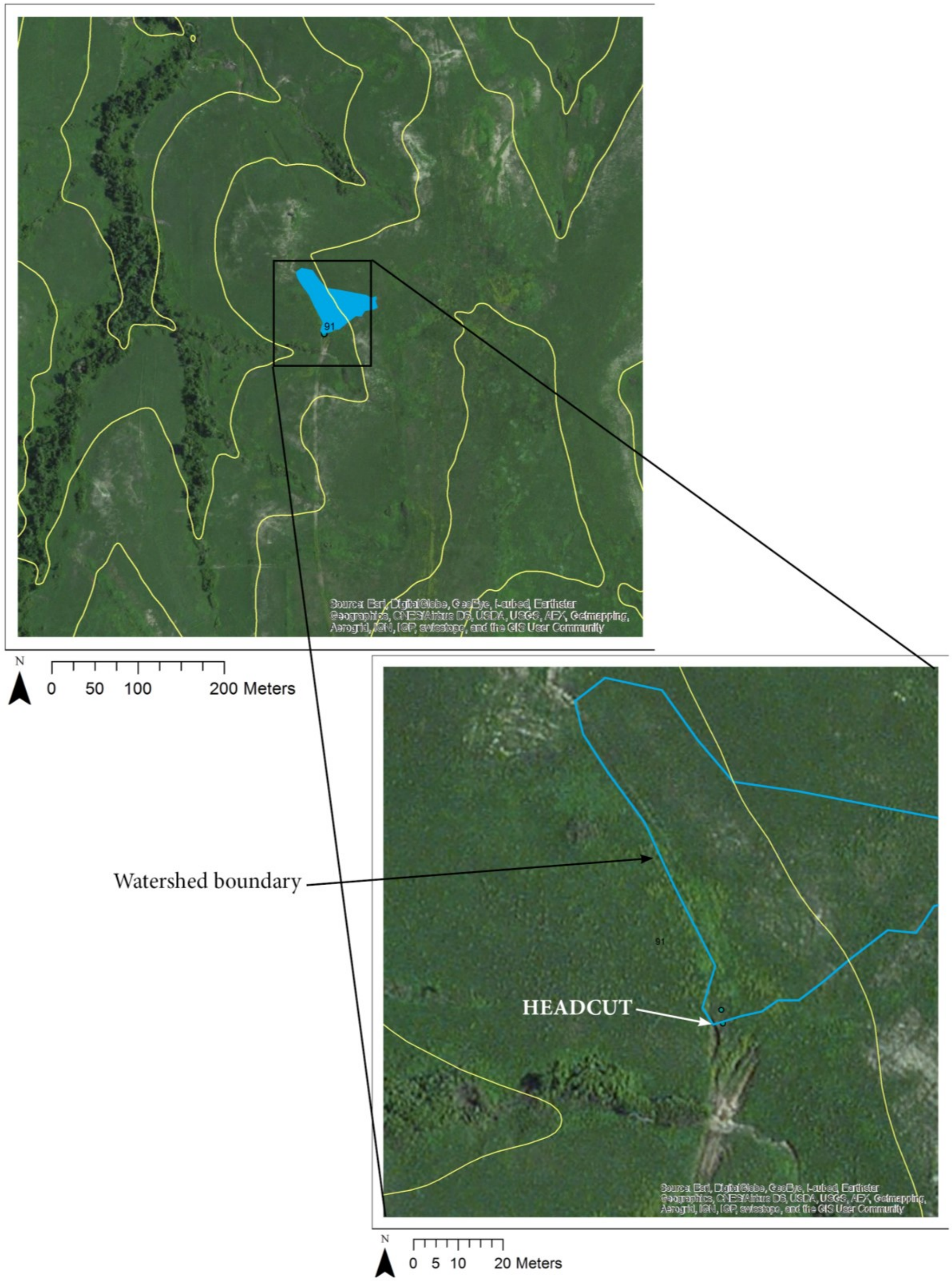


Training Area 91 Gully

Figure 1.22 is an example of Gully 91 conditions, and Figure 1.23 shows Gully 91 (indicated by the arrow), along with the gully's watershed and 3-meter contour lines. A study of Google Earth imagery suggested that since the 1990s or early 2000s, the area was used as a common tank path. Imagery is not detailed enough to be sure, but the gully formed sometime between 2002 and 2010. The tank tracks that the gully formed within travel downslope to a hardened crossing at an ephemeral channel. The gully is one meter wide and 0.6 meters deep just below the headcut and is shorter in length than the others. The gully watershed is nearly all prairie grasses and forbs with very few trees.

Figure 1.22 Training Area 91 Gully, looking downstream, recently driven through. Photo taken by author.

Figure 1.23 Training Area 91 gully context. ESRI imagery modified by author.

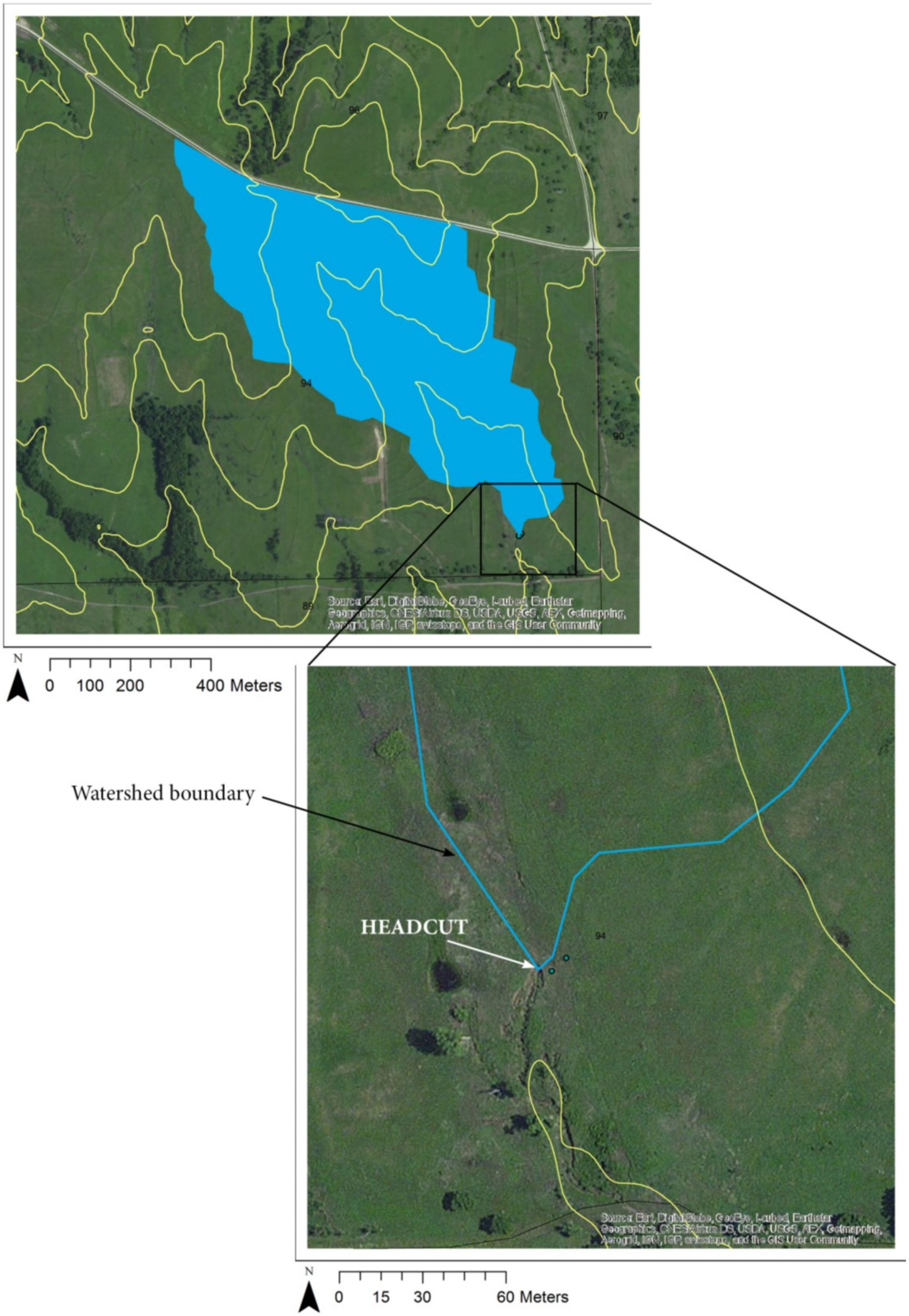


Training Area 94 Gully

Figure 1.24 is an example of Gully 94 conditions, and Figure 1.25 shows Gully 94 (indicated by the arrow), along with the gully's watershed and 3-meter contour lines. It is the largest gully in the Fort Riley study at 4.1 meters wide and 1.5 meters deep just below the headcut; the headcut is a wide arch, as opposed to the other gullies in the study, which have a narrow arch or have v-shaped headcuts. It also has the largest watershed. Gully 94 is potentially the only gully in this study that hasn't noticeably been fed by tank tracks. The bed of the gully has established grass cover due to mass bank failures, unlike the other gullies, making the gully more difficult to identify in aerial photos. However, Gully 94 seems to be an older channel; it is able to be identified in early-1990s Google Earth imagery. The gully connects to a larger, more stable drainage network just downstream of the channel. Surrounding the gully is dense smooth brome, and the larger watershed is mostly prairie forbs and grasses, with some woody species in the swale uphill from the headcut.

Figure 1.24 Training Area 94 Gully, looking downstream from headcut. Photo by author.

Figure 1.25 Training Area 94 gully context. ESRI imagery modified by author.

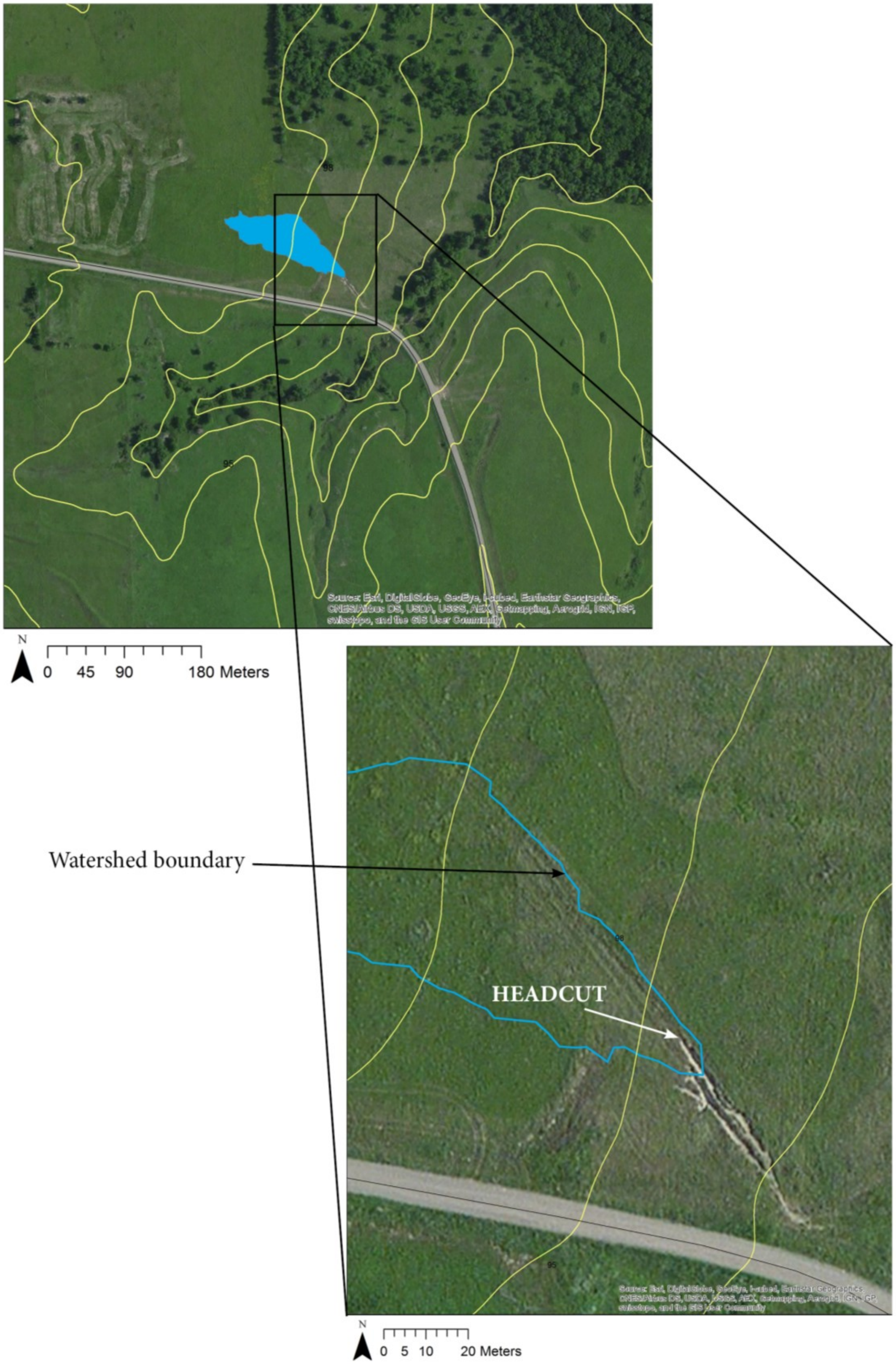


Training Area 98 Gully

Figure 1.26 is an example of Gully 98 conditions, and Figure 1.27 shows Gully 98 (indicated by the arrow), along with the gully's watershed and 3-meter contour lines. Gully 98 was added to the study in 2013 after Gully 36 was filled and "fixed" for safety purposes. Gully 98 is a two-channel tank-track gully that is highly visible from the road. A study of Google Earth imagery suggested that the gully formed in tank tracks sometime between 2002 and 2005. The gully is located in what used to be a farm field in the 1960s. The main channel is 1.4 meters wide and 0.7 meters deep just below the headcut. One of the two track channels has bifurcated, or split, into four total headcuts. The gully channels are noticeably exposed to more wind and southern sun than the other gullies, and have light colored, dense clay soils with sparse, short vegetation surrounding the channels.

Figure 1.26 Training Area 98 Gully, looking downstream at Cross Section 4. Photo by author.

Figure 1.27 Training Area 98 Gully. ESRI imagery modified by author.



Common terminology and concepts (alphabetical)

Alluvial fan – depositional feature as a stream channel meets a plain (flat area) or larger stream (Harpstead, Sauer, & Bennett, 2001). Alluvial fans can form at the outlet of gullies.

Concentrated flow erosion - Concentrated flow erosion begins where runoff concentrates at the junction of several rills that have formed a dendritic (branching) drainage pattern (Spomer & Hjelmfelt Jr., 1986).

Crust formation – The development of a dense, hard, and relatively impermeable layer at the soil surface, due to breakdown of soil aggregates (Hillel, 2004). Soil crusts can prevent gully erosion to some extent, but when a soil crust starts to erode, gullies can form easily due to the softer materials underneath.

Erosion – the process by which soil is washed, blown, or otherwise moved by natural agents from one place on the landscape to another (Harpstead et al., 2001).

Gullies – channels that carry water during and immediately after rains. Gullies are distinguished from rills in that gullies cannot be obliterated by tillage (Huffman, Fangmeier, Elliot, Workman, & Schwab, 2011). All gullies flow ephemerally, but only some gully types are called "ephemeral" (see below).

Bank gullies – Bank gullies form where concentrated flow cuts a channel in an earth bank such as a terrace or stream bank (Poesen et al., 2003).

Classic/Permanent gullies – Gullies that are too large to fill with farm tillage equipment or to drive through (Kirkby & Bracken, 2009; Poesen et al., 2003).

Critical flow shear stress - The threshold force required to move sediment in concentrated flow erosion (Poesen et al., 2003).

Ephemeral gullies – Ephemeral gullies are larger than rills (see below), but small enough to fill in with tillage equipment. Generally associated with agricultural fields, and typically form again in the same spot (Poesen et al., 2003).

Headcut – A vertical or nearly vertical drop in flow elevation (Poesen et al., 2002). Headcuts retreat or migrate uphill, sometimes called headward migration.

LiDAR –Light Detection and Ranging: a short wavelength laser light scan that records the amount of light backscattered from the terrain using light travel time at a very fine resolution. The result is elevation measures of ground terrain and vegetation canopy (Jensen, 2000).

Failure (as in mass failure/mass movement) – The reaction of a body (of soil or other earth materials) to stresses that exceed its strength, generally leading to the loss of cohesion or structural integrity by such modes as fracturing, slumping, plastic yielding or apparent liquefaction (Hillel, 2004). Gully sidewalls and headcuts sometimes fail in the form of slumping.

Plow pan/Hardpan – A soil layer that acts as a barrier to the movement of water and the extension of plant roots (Harpstead et al., 2001).

Plunge pool - Plunge pools, also referred to as scour holes, are formed by falling water at the base of vertical overfalls such as headcuts of gullies (Van der Poel & Schwab, 1988).

Return flow – Infiltrated water that returns to the land surface after flowing for a short time beneath the soil surface (Whipkey and Kirkby, 1978).

Rill erosion – Rills are eroded channels that are small enough to be removed by normal tillage operations. Rill erosion is detachment of soil particles by concentrated flow erosion (Huffman et al., 2011).

Sidewalls – A common term in the gully literature referring to the "banks" or side slopes of a gully.

Subsurface flow/subsurface runoff – The movement of subsurface storm water within the soil layers to stream (or gully) channels at a rate more rapid than the usual groundwater flow (Chorley, 1978).

Threshold- The magnitude or intensity that must be exceeded for a certain reaction, phenomenon, result, or condition to occur or be manifested (Oxford Dictionaries, 2014). In gully erosion, threshold usually refers to a set of conditions that contribute to gully formation once they reach a certain level (e.g. the topographic threshold is a relationship between slope and drainage area that, once both slope and drainage area values are high enough, contribute to gully erosion or soil detachment).

Watershed/drainage area/catchment - The area of land that drains water and sediment to a common waterway, such as a stream, lake, estuary, wetland, aquifer (USEPA, 2013). Every gully has a watershed, or area of land that drains to it.

Chapter 2 - Literature Review

Introduction

The following literature review addresses hillslope processes, gully initiation and growth processes, descriptions of the factors driving gully erosion, examples of naturally-occurring gullies, the timeframe of gully growth, and a selection of gully type classifications. A description of methods in the literature follows, covering methods on collecting gully driver data, erosion rate data, sediment transport data, and a short summary on modeling efforts. Finally, trends in the literature are summarized, and common challenges in gully data collection are presented.

Hillslope Processes: Brief Background

To understand gully erosion, one must first understand hillslope process, the precursor to gully initiation. On soil surfaces, or hillslopes, erosion can occur through sheetflow (uniform erosion over a soil surface, often undetectable by the eye), rill erosion (small channels) or gully erosion (larger channels). Sheet erosion and rills are caused by overland flow, which is "…both unsteady and spatially varied since it is supplied by rain and depleted by infiltration, neither of which is necessarily constant with respect to time and location" (Emmett, 1978, p. 147). For any type of erosion to occur, rainfall must first produce runoff, either by Hortonian overland flow or saturation overland flow:

<u>Hortonian overland flow</u>: rainfall intensity is greater than the soil's ability to infiltrate the rainfall, and water runs over unsaturated soil;

<u>Saturation overland flow</u>: rain falls upon saturated soil with no room for infiltration, and runs over the soil surface. Runoff can be joined by exfiltration of subsurface flow (Bull & Kirkby, 2002).

Soil detachment is most influenced by soil texture, aggregate stability, and soil shear strength (Bull & Kirkby, 2002). When sheetflow, rill flow, or subsurface flow concentrates with enough energy, a gully may form. According to Schumm (1988), there are three zones in the fluvial system: Zone 1 is the sediment-source area that is dominated by sediment detachment processes; in Zone 2 sediment transport is dominant; and in Zone 3 sediment storage is the dominant process. Gully channels participate in all three processes of detaching, transporting, and storing sediment.

Gully Processes

Gullies come in a variety of shapes and sizes, depending upon controlling variables and their influence on the landscape. Gullies generally consist of a headcut, ranging from gently sloping to vertical or undercut; side walls that can also be gently sloping or steep; and a "bed" or gully bottom. See Figures 2.1, 2.2 and 2.3 for examples of gully form variation. The following sections will describe gully formation and growth, factors driving gully erosion, natural examples of gully erosion, and a gully's lifetime or length of time that a gully expands.

Figure 2.1 Gully network in Morocco

Source: http://www.geo.uu.nl/landdegradation/Fieldwork.htm

Figure 2.2 Gully in Kansas. Photo by C. Corkins.

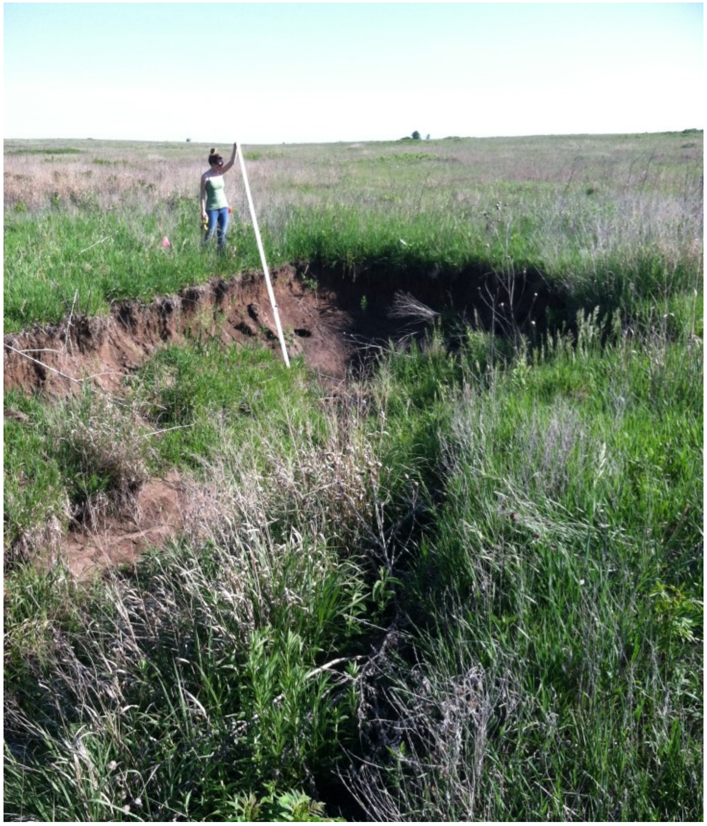


Figure 2.3 Gully network on hillside. Location unknown.

Source: http://www.kwaad.net/tablet/GullyErosion.html

Gully formation and growth

Initiation and growth

Erosion, including gully initiation and growth, occurs due to the relationship between stresses of water and resistance of soil to shear stress. For a gully headcut to form, concentrated surface or subsurface flow energy must be strong enough to detach surface sediments or weaken soil layers and transport them, along with incoming sediments from uphill; the energy must also be great enough to meet gully size criteria. Gully initiation due to mass failure can occur when subsurface flow seepage weakens the soil layers above (Poesen et al., 2002). Once a headcut forms, flow concentrates around the headcut, with enough of a vertical drop that a plunge pool often forms. Plunge pools increase the chance for headcut and side wall failure (Poesen et al., 2002; van der Poel & Schwab, 1988), by undercutting banks. For headcut retreat to occur, also called headcut migration, the bed of the gully must have a lower gradient than the soil surface above the headcut (Kirkby & Bracken, 2009).

For gullies to maintain their size or grow larger, the energy of flow must be able to remove all sediment from upstream, as well as accumulated sediments in the channel and any mass movements from the headcut or side walls (Kirkby & Bracken, 2009). Otherwise, sediments would be deposited into the gully. Gullies grow in size due to many different processes that relate to increased instability of the surrounding soil. Certain gullies only erode at the headcut, expanding uphill solely due to fluvial surface processes. Others are mass-movement dominated, growing laterally and at the headcut due to subsurface flow (Bergonse & Reis, 2011) and weakening of soil layers. Piping, fluting, and formation of tension cracks are all forms of vertical instability in the soil – pipes are voids caused by porosity, dissolved eluviated sediments, or other weaknesses in the soil profile; flutes are vertical grooves, usually formed because of dispersive soils; and tension cracks form along the sides of gullies due to gravitational pull or shrink/swell clay soils (Poesen et al., 2002).

Depth and length of gullies

Deepening or incision of gullies can be limited by a harder subsurface layer such as bedrock or a plow pan (Poesen et al., 2003), but hard subsurface layers can also create a temporary water table, creating saturated conditions more quickly in the soil above (Knapp, 1978) and concentrated subsurface flow, causing instability and sometimes enough flow energy to cut through the harder subsurface layer (Vanwalleghem et al., 2005). The length of a gully ends where surface roughness increases, or where gradient slope decreases (Poesen et al., 2002).

Factors driving gully erosion

Gullies form due to anthropogenic alterations to the land, inherent characteristics of a site, or a combination of both. Rainfall intensity, the amount of runoff, soil characteristics such as porosity and texture, slope gradient, and surface roughness such as vegetation all influence the initiation and growth of gullies at different scales; the literature has shown that in every studied region, different factors are at play. The following is an overview of how different elements control or contribute to gully erosion.

Rainfall:

Water runoff is required for gully erosion, so rainfall is needed to create runoff. Some studies find that rainfall intensity and antecedent moisture are strongly related to gully erosion, while others do not. A 12-year study in Italy found that although several erosive rainfall events occurred each year, they found that a 3-day event threshold of 51 mm is required to erode or create gullies – thus, they used an antecedent rainfall index as a successful "surrogate" for soil water content (Capra et al., 2009). However, gully erosion cannot always be explained by rain events; for example, a study in Belgium found that extreme rain events are not required to form deep gullies (Vanwalleghem et al., 2005).

Slope and slope length:

Steeper slope gradients and longer slopes create high-energy pathways for water runoff. Linear elements in the landscape such as roads, vehicle tracks and tillage lines "feed" gully erosion by increasing slope length, thus runoff energy (Makanzu Imwangana, Dewitte, Ntombi, & Moeyersons, 2014; Poesen et al., 2003; Prasuhn, 2011; Svoray & Markovitch, 2009). Svoray & Markovitch (2009) created a GIS database that included topography, tillage direction, and unpaved roads; mapped gully heads over two seasons; and then examined the three factors' effect on gully initiation. Authors found that topography could explain 78% of gully locations, while linear elements such as tillage lines and unpaved roads helped to predict gully head locations by an additional 15%. Also, a study in the Swiss midlands found that on average, 75% of total soil loss from rills and gullies was linked to linear erosion features (Prasuhn, 2011).

Soils and soil moisture:

Infiltration is determined by the resistance of the least permeable layer in the soil horizon. As soil is compacted, soil layers become less permeable - "Even with a vegetation cover, heavy pressure by humans, animals or machinery can break up the surface structure and close many voids" (Knapp, 1978, p. 56). Infiltration rate is determined by "(i) the amount of water available at the soil surface; (ii) the nature of the soil surface; (iii) the ability of the soil to conduct infiltrated water away from the soil surface" (Knapp, 1978, p. 56). Infiltration depends on soil structure, or the number and size of voids, as well as the presence of shrink swell clay (Knapp, 1978). The least permeable, limiting layer can be a plough pan – but as stated above, although hard sub-layers like plough pans can limit downward gully growth, they can also concentrate subsurface flow causing positive pore water pressure, and decreased erosion resistance, in the layers above (Poesen et al., 2003).

Soil texture and structure govern water flow in many cases. Steep, abrupt headcuts tend to develop in cohesive soils, while gradual headcuts can develop in more coarse, uncohesive sediments (Bull & Kirkby, 2002). Also, coarse-textured soils cause more vertical subsurface flow, and if soil is deep, lateral subsurface flow won't occur as quickly as in shallow soil. Large voids/cracks/fissures can be present in fine textured soils. When large voids connect, they can cause pipe flow, which can deliver rainfall to groundwater quickly (Whipkey and Kirkby, 1978).

Antecedent soil moisture can affect how quickly runoff occurs, and can influence subsurface mass movements. When soil moisture increases to nearly-saturated conditions, soil shear strength decreases, "while drier soils retain more rainfall, reducing the probability of runoff generation" (Gao et al., 2011, p. 358). On the other hand, shrink-swell cracks develop during dry periods, and become larger with increasing time between rain events, increasing the vertical erodibility of the soil when it finally does rain. In addition to soil instability due to wetting and drying, freeze/thaw cycles such as frost heave and needle ice have been examined for their contribution to sediment "preparation" prior to rainfall and fluvial entrainment (Lawler, 1986; Prosser, Hughes and Rutherfurd, 2000). Freeze/thaw of river and gully banks can degrade soil even more than wetting/drying cycles and are most effective at loosening or preparing sediments in silt-clay soils (Couper, 2003).

Vegetation and roots:

Vegetation creates not only surface roughness and flow resistance on a slope, but it also causes more infiltration as opposed to runoff. Land use changes that decrease vegetation biomass (particularly in concentrated flow zones) also decrease the threshold for gully initiation (Poesen et al., 2003). Zucca et al. (2006) found that in a region in Italy, lands recently converted from marginal shrubland to pasture, thus recently stripped of vegetation, and were heavily eroded. A flume experiment in New South Wales showed that light grazing and increases in discharge (below the 100-year storm) were not enough to initiate gullies, but heavy degradation to the natural tussock and sedge vegetation plus increases in discharge (or bare soil surface) could reduce critical shear stress for scour "by three to eleven times compared with at most a fourfold increase in discharge in historical times" (Prosser & Slade, 1994, p. 1130). Also, recent studies attempt to illustrate the importance of root structure in enhancing soil strength (De Baets, Poesen, Meersmans, & Serlet, 2011; Gyssels & Poesen, 2003). Two of the ways roots can mechanically reinforce the soil are: 1) Roots and root remnants can bind soil particles, creating greater cohesion and resisting erosion by overland flow. The extent of binding depends on root diameter, degree of bifurcation, appearance of root hairs, friction between root and soil, and root network distribution; 2) Roots provide a food source for soil microorganisms, which also create better cohesion (through excreted binding agents) and soil aggregation (Gyssels & Poesen, 2003).

Summary – Gully-driving factors

As humans develop more land for agriculture, housing and commerce, we have a great influence on driving factors of gully erosion. Anything affecting water infiltration and storage (such as soil compaction, soil crusting, concrete and other hard surfaces), vegetation biomass, and slope length create ideal conditions for increased erosion energy. "Land use change is expected to have a greater impact on gully erosion than climate change" (Valentin et al., 2005, p. 133); and "…it becomes clear that any land use change implying a vegetation biomass decrease in the landscape, and particularly in concentrated flow zones, will decrease the threshold for incipient gullying. This implies that for a given slope gradient (S), the critical drainage area (A) for gully head development will decrease, and therefore gully density will increase" (Bull & Kirkby, 2002, p. 248).

Natural examples of gully erosion

Gullies do form naturally in certain landscapes. Badlands are natural systems of gullies that form in steep terrain, low vegetative cover, and low soil moisture-holding capacity; perfect conditions for erosion without human influence. Another specific example of natural conditions for gully erosion is following wildfires – removal of vegetation on steep mountain slopes often creates prime conditions for gullying.

Certain natural soil characteristics can also create gullying potential: marl soil layers were a main gully erosion factor in a study in Slovakia (Dlapa, Chrenková, Mataix-Solera, & Šimkovic, 2012). A marl is "a loose or crumbling earthy deposit (as of sand, silt, or clay) that contains a substantial amount of calcium carbonate," (Merriam-Webster, 2015). Pipe flow, occurring when large voids connect, also creates gullying potential, and is a result of natural soil characteristics.

A gully's lifetime

Some researchers have attempted to track gully erosion to determine how gullies sustain themselves. Many conclude that gullies erode quickly in the early stages of development until some level of equilibrium is reached (Wu & Cheng, 2005), then gullies continue to grow slowly. In fluvial process-dominated systems, gully headcuts advance toward the drainage divide; the drainage area and runoff volumes decrease, thus so do the erosive forces, ever-slowing the headward advance. In his paper relating gullies to isotope half-lives, Graf (1977) states, "Just as decaying isotopes approach new stable isotopes at continuously decreasing rates, so gullies erode toward equilibrium lengths at continuously decreasing rates" (p. 183), and gully erosion rates generally decline exponentially.

However, only fluvial-dominated processes have decreasing drainage areas and runoff volumes as they grow. A study in Iowa showed that decreasing surface runoff is not always caused by a shrinking drainage area. In that study, they noted that from 1965-2000, the ratio of runoff to baseflow decreased by 77 percent, but catchment or drainage area remained the same. They concluded that runoff was high in the 1960s due to vegetation removal, then terracing and other conservation measures reduced overland flow and encouraged baseflow, or subsurface flow (Thomas et al., 2004), making fluvial process a much smaller influence on the gully.

Research also shows that long-term studies give a much more accurate view of average erosion rates and distribution than shorter studies, or test plot studies, which could overestimate erosion due to "low-frequency high magnitude effects" (Prasuhn, 2011). In a 10-year study in the Swiss midlands, gullies accounted for 18% of total erosion, and erosion in general only occurred on average once every three years on each of 203 fields that were studied. Twelve percent of the fields showed no erosion at all, while one percent showed erosion every year (Prasuhn, 2011). Gully erosion rates calculated from one year of study differ greatly from a 3-year, or 20-year study. For example, a 1- or 3-year study done during high-rainfall years will likely show high erosion rates, especially when paired with intense land use or an increase in impermeable surfaces. However, a 20-year study would likely incorporate years of both cut (erosion) and fill (aggradation), which would show a lower overall erosion rate. More research is needed to determine the importance of erosion rate change at different time scales (Poesen et al., 2003).

Gully Types

Gully type by size

In the literature, the most general classification of gullies is by size. Ephemeral gullies are larger than rills. Poesen (1993) uses a 929 cm^2 areal dimension (1-square foot) to distinguish between a rill and a gully, and they are small enough to drive over with farm equipment and small enough to fill in with tillage. Ephemeral gullies are associated with cultivated agricultural fields in most cases, and after tillage, they typically form again in the same location (Poesen et al., 2003).

Larger gullies have several different names, and can range in size from just larger than a rill to too large to drive through or too large to fill with tillage equipment: they are called classical (Poesen et al., 2003), deep (Vanwalleghem et al., 2005), or permanent (Vandekerckhove et al., 2000). These larger, permanent gullies tend to form in rangelands or abandoned fields (Poesen et al., 2002). Deep gullies require a larger topographical threshold than do shallow ephemeral gullies (Vanwalleghem et al., 2005), meaning that more energy is required to initially create a deep gully than an ephemeral gully. They most often form on steep side slopes and in some cases "their position is strongly affected by the presence of linear landscape elements" (Vanwalleghem et al., 2005, p. 76).

Deep or classic gullies may require more energy for creation due to the fact that different processes are at play on a steep hillside than in a lower gradient farm field. As stated previously, deep gullies tend to form on rangelands or other surfaces that have continuous cover, which partly explains the requirement of a larger threshold for gullies to form; Vandekerckhove et al. (2000) found that on rangelands in the Mediterranean, vegetation could be more influential than rainfall in the formation of gullies, and that "seepage erosion and landsliding are potentially active processes interfering with the action of Hortonian overland flow" (p. 1218). At one point in time in the literature, there was agreement that "… most gully types expand by headcut migration" (Poesen et al., 2002, p. 241) and fluvial processes, as discussed in the previous section. However, subsurface processes and resulting mass movements are receiving more attention in the literature in relation to classic or deep gullies (Bergonse & Reis, 2011).

Examples of published gully classifications

Several examples of gully classifications are given in this section, though it is not a comprehensive list. One classification that has stood the test of time, though it has also morphed a bit in definition, is the idea of continuous and discontinuous gullies. Bryan (1928) described the headwaters of the Rio Puerco in New Mexico as a *discontinuous* channel. Leopold and Miller (1956) seem to be the first to apply the terms "continuous" and "discontinuous" to gullies (arroyos, specifically). Their definition of a discontinuous gully is one with a steep headcut, whose bed slope is more gentle than the land surface slope above and below it; and an alluvial fan forms where the terminal end of the gully bed and original land slope meet. A continuous ephemeral channel, or gully, would have a bed slope parallel to the land surface slope of its banks (Leopold & Miller, 1956). Currently, continuous gullies are simply considered to be part of the drainage network (forming with relationship to dynamics in the watershed), and discontinuous gullies are separate from the drainage network (forming due to localized soil failures) (Poesen et al., 2002, p. 234).

Other classifications are by shape, materials, and headcut types. Imeson and Kwaad (1980) distinguish between U- and V-shaped gullies as well as their channel materials (as cited in Bull & Kirkby, 2002); Dietrich and Dunne (1993) developed a gully headcut classification that considered the difference in morphology based on Hortonian overland flow and exfiltrating subsurface flow (as cited in Bull & Kirkby, 2002); and Oostwoud Wijdenes et al. (1999) created headcut classifications of gradual, transitional, rilled-abrupt, and abrupt. Oostwoud Wijdenes et al. (1999) found that for abrupt headcuts, gully width and depth had a positive relationship while gradual headcuts had a negative width-depth relationship, and also that abrupt headcuts occur more frequently on higher slopes, suggesting again that mass failure rather than fluvial process plays a factor in classic gullies. Also, "plunge-pools are twice as common at rilled-abrupt as at abrupt or transitional gully heads" (Oostwoud Wijdenes et al., 1999, p. 593), again suggesting that abrupt headcuts are not greatly influenced by fluvial processes.

Measurements and Methods

Introduction

There are several different questions that researchers are trying to answer about gullies:

- Where in the landscape do gullies tend to initiate, and can we predict where new ones will form;
- What are the major drivers, controls and processes of gully growth, and how do we quantify them;
- At what rate are gullies growing in different regions;
- What is the sediment yield from gullies, and what is the yield in comparison to other erosion processes like rills and sheet flow;
- What are the erosion and sediment transport patterns across a catchment;
- And where are the associated nutrients/pollutants being transported from and to.

This section describes field research in each subject area, as well as methods used in the literature.

Measuring gully initiation

A valuable asset for gully prevention is the ability to predict where new gullies are likely to form. A common effort in the gully research community is determining a threshold of slope gradient and drainage area (S/A) that, when exceeded, has a higher probability of gully erosion. Other attempts to find spatial trends in gully formation include GIS mapping (Svoray & Markovitch, 2009).

The Slope/Drainage Area (S/A) relationship: steeper slopes and larger drainage areas have more flow energy, and researchers try to find a tipping point between the two where gullies tend to form. The equation used, $S = aA^{-b}$ (S = local slope and A = drainage area), first developed by Patton and Schumm (1975) in northwestern Colorado, applies to landscapes with similar vegetation, land use, climate, and soils. The method has been tested in northern Israel (Svoray & Markovitch, 2009); the Mediterranean (Gómez Gutiérrez et al., 2009; Vandekerckhove et al., 2000; Zucca et al., 2006); China (Wu & Cheng, 2005), the Democratic Republic of the Congo (Makanzu Imwangana et al., 2014); and others, with varying results. Svoray and Markovitch (2009) found that 78% of gullies in their study area were above their topographic threshold; Zucca et al. (2006) found slope to be significant, along with the geological substratum; Wu and Cheng, (2005)'s equation was similar to the original Patton and Schumm (1975) equation; and Makanzu Imwangana et al. (2014) took the equation one step further and replaced drainage area with slope length, trying to find a threshold between slope gradient and length of roads in a new, hilly development where gullying was a problem along roadsides. Several researchers have employed this equation in their gully research.

Spatial analysis with additional variables has also been used to predict trends in conditions ripe for gully formation. Svoray and Markovitch (2009) studied how lines created due to tillage and unpaved roads affected gully initiation flow. They developed a GIS database that included topography, tillage direction, and paved roads; mapped 19 gully heads over two seasons; and examined effects of the three factors on gully initiation. A study at Camp Williams in Utah used overlays in GIS such as vegetative cover, slope and soils to identify spatial trends for gully risk (Bartsch, Van Miegroet, Boettinger, & Dobrowolski, 2002).

Measuring main drivers of gully initiation and growth

Many variables and the interactions amongst each influence gully erosion either by accelerating stress or providing some sort of soil strength. The following methods have been used to measure gully-driving factors that were described earlier.

Rainfall and moisture

De Santisteban et al. (2006) measured rainfall with a rain gauge in each of their study areas, and erosive "events" were categorized by season, intensity, and land usage (e.g., vineyards eroded at all times of the year because of more bare soil). In a different study, Prasuhn (2011) collected gully data after every erosive rainfall or snowmelt event and depended on a local farmer and soil expert to inform the erosion mapper when an erosive rain event had occurred.

Slope and slope length

Researchers have measured slope with in-field surveying above the gully head and along the gully sides (Zucca et al., 2006); with aerial photos and USGS topo quadrangles (Patton & Schumm, 1975), and with GIS programs (Bartsch et al., 2002).

Soils and soil moisture

Soil texture, erodibility and water permeability can be found for the U.S. through the NRCS's Web Soil Survey program, but they are mapped at a coarse scale. Soil samples can be measured for texture, and levels of soil compaction can be measured in the field (Heuer, Tomanova, Koch, and Marlander, 2008). For antecedent soil moisture, Oostwoud Wijdenes and Bryan (2001) used an equation relating number of dry days, daily precipitation, and gully-head retreat. Capra et al. (2009) also used antecedent rainfall indices as a surrogate for soil moisture.

Vegetation and roots

Vegetation and roots have been studied in various ways to determine their relationship to erosion. Hancock & Evans (2010) collected vegetation data from a comparison of biomass clippings to the Normalized Difference Vegetation Index (NDVI - from Landsat imagery). Heede (1991) compared sediment delivery on bare slopes and slopes with a chaparral border strip using runoff simulation. In a study of how different roots enhance soil strength, Gyssels and Poesen (2003) took different species of root samples in the top 5 cm of soil, then dried and weighed each sample to determine biomass (and thus root density).

One might say that land use change is a controlling variable in gully erosion; for instance, studies have shown that abandoned lands and new, marginal pasture land in some areas experience higher gully erosion rates (De Santisteban et al., 2006; Zucca et al., 2006). However, it is the products of land use change, such as soil compaction (influencing permeability), direct physical disturbance, vegetation removal and increases in runoff intensity that accelerate erosion processes.

Measuring erosion rates

Research studies try to calculate gully erosion rates by taking gully measurements after each erosive rainfall event (De Santisteban et al., 2006; Prasuhn, 2011), but often gully erosion rate measurements are taken on yearly or longer intervals (Capra et al., 2009; Daba et al., 2003;

Gómez Gutiérrez et al., 2009; Hancock & Evans, 2010; Vanwalleghem et al., 2005). Aerial photos are sometimes used to find gullies to study over large landscapes, or are used as the sole method of remotely estimating changes in gully volume (Daba et al., 2003). Surveying with equipment such as laser level, pin frame, or total station is also common practice (Spomer & Hjelmfelt Jr., 1986; Wu & Cheng, 2005; Zucca et al., 2006).

Measuring sediment yield and transport patterns

When taking into account rill, interrill, and gully erosion, data from across the world shows that erosion rates from gullies can range from 10% to 94% of total sediment yield from water erosion within a basin. (Poesen et al., 2003). Spomer & Hjelmfelt Jr. (1986) measured sediment yield by extrapolating average channel erosion rates, multiplying by the number of channels, and dividing by watershed area to equal yield.

Transport patterns can be observed by measuring how much sediment is deposited on the fields, at field borders, and beyond field boundaries (Prasuhn, 2011). Patterns can also be observed by not only studying the fields that are visibly eroding, but also adjacent or nearby fields that do not seem to contribute sediment, to get a more accurate view of percentage of contributing land and redistribution of sediment. For example, a 10-year study in the Swiss Midlands showed that only 1% of 203 arable fields showed erosion every year; on average, erosion occurred on each field about every 3 years; and 12% of all fields showed no erosion at all over the 10 years. Their methods were surveying and continuous mapping of rills, interrill erosion (which is splash and sheet erosion combined) and ephemeral gullies (Prasuhn, 2011).

Tracking nutrient movement

Research in Australia, China, Ethiopia, and the U.S. has shown that a major part of reservoir sedimentation may come from gully erosion: "tracers such as carbon, nitrogen, the nuclear bomb-derived radionuclide 137 Cs, magnetics and the strontium isotopic ratio are increasingly used to fingerprint sediment" (Valentin et al., 2005 p. 132). For example, one study used Cesium-137, a fall-out chemical from nuclear testing beginning in the 1950s, to determine what percentage of deposited sediments in a reservoir were from topsoil (found to be 40%), assuming that all deposited sediments that did not contain CS-137 (60%) had to have come from the subsoil, including stream and gully banks (Plata Bedmar et al., 1997 as cited in Poesen et al., 2002, p. 232).

Modelling gully erosion and process

One of the big questions in gully research is: "What are appropriate models of gully erosion, capable of predicting (a) erosion rates at various temporal and spatial scales and (b) the impact of gully development on hydrology, sediment yield and landscape evolution?" (Poesen et al., 2003, p. 92). For gully erosion, it is difficult to get all of the answers in one model (ie. point sources, sinks, spatial variations, driving factors or detachment, erosion rates, sediment yield), and each model requires some level of inputs (de Vente, Poesen, Verstraeten, Govers, Vanmaercke, Van Rompaey, Arabkhedri, and Boix-Fayos, 2013), making accurate, thorough modelling efforts challenging.

Physical models such as flumes provide insight for gully erosion processes, like how different land cover conditions affect flow (Prosser & Slade, 1994). Mathematical and computerized models such as the Universal Soil Loss Equation (USLE, or RUSLE for the revised version), AnnAGNPS (Agricultural Non-Point Source Pollution Model), SWAT (Soil and Water Assessment Tool), EGEM (Ephemeral Gully Erosion Model), and many others (see de Vente et al. (2013) for a complete review of 14 different gully models) have been applied to gully erosion conditions with varying results.

Brief summary of modelling conclusions

EGEM was found to be an inaccurate model in Mediterranean environments, but because an input for EGEM is gully channel length, studies have found that length itself is a good predictor of gully erosion volumes (Di Stefano & Ferro, 2011; Nachtergaele, Poesen, Vandekerckhove, Oostwoud Wijdenes, & Roxo, 2001). The USLE/RUSLE is not accurate in estimating erosion rates, but can be a good starting point for locating areas of high erosion risk (Bartsch et al., 2002; Gaffer, Flanagan, Denight, & Engel, 2008). de Vente et al. (2013) state that

> "Validation of the spatial patterns of sediment source and deposition areas at the catchment scale is not frequently done, but is crucial to answering other research questions and supporting development of environmental management plans" *and that* "Moreover, catchment sediment yield does not always respond immediately to changes in land use and management. This time aspect and related process interactions are until now poorly represented in most catchment models, which means that understanding and predicting the sediment delivery process at the catchment scale, under present and future land use and climate conditions, is still a major challenge in soil erosion and sediment yield research" (p. 26).

In conclusion, more field observations and re-working of model concepts are necessary for predicting soil erosion rates and sediment yield.

Additionally, de Vente et al. (2013)'s evaluation of soil erosion models was for overall erosion and sediment yield, including gully, rill, and sheet erosion. They state that models based on RUSLE, and even most physics-based models, do not take gully erosion into account (they only evaluate rill and overland erosion), but that gully erosion can have a large contribution to total sediment yield. The first priority they list in further efforts for models is incorporating "point" sediment sources like gullies, channel banks and landslides.

Three-dimensional modelling could have great potential in the near future for estimating erosion rates and volume changes within a gully. Gómez-Gutiérrez et al. (2014) photographed five gully headcuts and used free modelling software to create a 3D model of each gully head. They compared their results to a Terrestrial Laser Scanner (TLS), an expensive but accurate method, and the free software was comparable to the expensive equipment at the centimeter level. With the rise of unmanned aerial vehicles and photogrammetry, 3D modeling through photography may be a large part of the future of gully monitoring and modelling.

Trends and Conclusions in Peer-Reviewed Literature

Below is a brief compilation of conclusions from the gully literature, some of which have already been noted above. Common subjects for conclusions in the literature include the value of long-term studies and studies at the catchment scale, best predictors of erosion and control, and conservation efforts.

The value of long-term studies and studies at the catchment scale

The time scale of data collection can play an important role in measuring gully erosion rates. A 1-year value for gully erosion rates as a percentage of total soil loss can differ greatly from a 3-year, or 20-year study due to changes in land use and climate (Poesen et al., 2003). Without long-term studies, we cannot know if gully erosion rates are constant, or if gullies become stable after reaching a state of semi-equilibrium (Bull & Kirkby, 2002). Prasuhn (2011) states that erosion measurements of 10 years or longer can give a much more accurate view of average erosion rates and distribution than shorter studies, or test plot studies. More research is needed to determine the importance of rate change at different time scales (Poesen et al., 2003). Also, because specific areas of the catchment may be more prone to gully erosion than others, studying gully erosion at the catchment scale will give a better picture of the proportion of gully erosion to other forms of erosion, or areas that do not erode (Prasuhn, 2011).

Documented predictors of gully erosion and control

The list below summarizes conclusions in the literature regarding variables that have the most influence on gully initiation or growth in studied regions. The list is not comprehensive, but is a sampling of the variability in findings:

1. Ephemeral gully length is important in predicting erosion volumes (Di Stefano & Ferro, 2011; Nachtergaele et al., 2001)
2. Vegetation is the main control for gullies in one study (Prosser & Slade, 1994); vegetation is more important than slope in gully prevention, due to increased infiltration and decreased flow energy (Heede, 1991); in rangelands, surface resistance (ie. vegetation) is more influential for gully erosion than rainfall magnitude (Vandekerckhove et al., 2000)
3. Gully initiation is not determined by daily rainfall, but by soil structure and moisture conditions (Vandekerckhove et al., 2000)
4. Deep gullies are generally caused by linear landscape elements (Vanwalleghem et al., 2005)
5. Geologic substratum and slope angle are the biggest controllers of gully erosion (Zucca et al., 2006)
6. Antecedent moisture is an important variable to include in gully erosion studies (Capra et al., 2009)

Conservation successes and suggestions

In the 1960s and 1970s, Forest Service employee Burchard Heede studied gullies in Colorado, and he developed detailed reports on constructing check dams and waterways (Weinhold, 2004). In the published, peer-reviewed literature, few solutions are offered as how to "fix" gullies. However, suggestions and observations have been made. Spomer and Hjelmfelt Jr. (1986) compare ephemeral gullies in conservation tilled fields and conventionally tilled fields, finding ephemeral gully erosion to be much lower in the conservation-tilled fields. Management practices for ephemeral gullies that seem effective in Spain are direct drilling of winter cereal crops, permanent vegetative cover, and tilling immediately before seeding (De Santisteban et al., 2006). One study found that overall, grassed waterways were more effective than no-tillage, and that the effects of no-till on ephemeral gully erosion varied as to where the no-till plot was located in the catchment (Ludwig & Boiffen, 1994 as cited in Poesen et al., 2003).

For deeper, hillside gullies, Bergonse and Reis (2011) state that because subsurface flow plays a large part in many hillside or rangeland gullies, restoration measures need to consider that increasing infiltration may in some cases exacerbate the problem through seepage and mass movements. As for roadside gullies, Valentin et al. (2005) suggest directing road runoff over large areas; in the Democratic Republic of Congo, they are currently diverting runoff from roadside gullies to prevent further growth, and if they had the knowledge of massive gullying potential prior to when the new town was built, they could have designed the road plan in a way that prevented so much concentrated flow down a hill side (Makanzu Imwangana et al., 2014).

Challenges in Gully Studies

Soil erosion is influenced by a number of factors, making studies of erosion in natural conditions challenging (Sadeghi, Moosavi, Karami, & Behnia, 2012) because of complex variables and interactions between variables. After erosion data is collected, researchers may be able to make predictions about dominant process variables, but often are not be able to draw strict cause/effect conclusions (Ott & Longnecker, 2004). Not only is the complexity of variables challenging, but modelling and field work itself can also pose hurdles and provide for setbacks. The following section is a brief overview of challenges in studying gully erosion.

Separating variables

A prime example of how variables in gully erosion are interconnected and complex is the relationship between vegetation growth and moisture. Saturated or near-saturated soils have less shear strength, especially when additional rain falls on top of saturated soils. So in many cases, excess moisture causes gully erosion. But excess moisture also supports more vegetation, and vegetation often helps prevent gully formation and growth. On the flip side, soils are “protected” from erosion when there is no water – but dry conditions damage or prevent the protective cover of vegetation, further exacerbating the risk of erosion when it does rain. In statistical analyses, you cannot use vegetative cover and soil moisture as separate variables in a model – vegetation would represent itself, and soil moisture would also represent vegetation potential, thus doubly accounting for vegetation and skewing statistical results.

Spatial variation within gullies is another complex aspect to consider. For instance, because gully bottoms are wetter and more protected from wind, Melliger and Niemann (2010) suspect that vegetation can protect the gully bottom, but "spatial variations in soil moisture may promote the retreat of gully sidewalls" (p. 299).

Modelling

"Existing gully erosion models do not adequately forecast gully erosion rates at different temporal scales, and this may in part be due to a poor understanding of the subprocesses involved…" (Poesen, 2002, p. 256). As stated previously, no one shoe fits for modelling gully erosion processes, and each model needs some level of inputs (de Vente et al., 2013). Also, changes in land use do not immediately change sediment yield – there is a lag time that is poorly represented in catchment-scale models, "which means that understanding and predicting the sediment delivery process at the catchment scale, under present and future land use and climate conditions, is still a major challenge in soil erosion and sediment yield research" (de Vente et al., 2013, p. 26).

The ability to extrapolate gully erosion data to regional and even local environments is challenging. Each different land use context, or land use change, creates a new set of processes in a different setting, making extrapolation of erosion rates questionable.

Challenges in field research

The data to develop this research study was collected from two relatively intensive land uses – agricultural fields and military trainings areas. Because the land was actively being used by heavy vehicles (military tanks, hum-vees, tractors and farm equipment), data could only be collected when military units were not training, when farmers did not need access to their fields, when crops were not too high for survey equipment to function, and when crops were at a stage where they would not be damaged by survey procedures. Accessibility was also a challenge after rainfall. Even though the goal was to survey after every erosive rain event (described in more detail in the methods chapter), fields and training areas were sometimes too wet to drive to or survey between rain events.

Another challenge was placing survey markers in the field like reference elevations (benchmarks) and pin flags. There was always a chance that farm or military machinery would pull them up or unintentionally move them. Figure 2.4 shows one of the gullies that was studied on Fort Riley – multiple large tanks drove over/through the gully, bending and burying rebar survey end pins which also served as elevation references.

Figure 2.4 Fort Riley gully site location, study disrupted by tank traffic. Photo by author.

Chapter 3 - Data Collection and Analysis Methods

Overview Statement of Methods

Comparable gullies were selected on Fort Riley, and gullies in different types of field management were selected in McPherson County. Sites were also selected based on accessibility in terms of military training schedules and agricultural landowner permission. Two primary data collection methods were used: monitoring gully change through surveying and other in-field measurements, and collecting weather and land condition data such as rain data, drainage area, and vegetation conditions. The survey data was first compiled into tables and entered into RIVERMorph® software to determine rates and patterns of change, and then the survey data was combined with the land characteristic data for statistical analyses with the intention of identifying drivers of erosion.

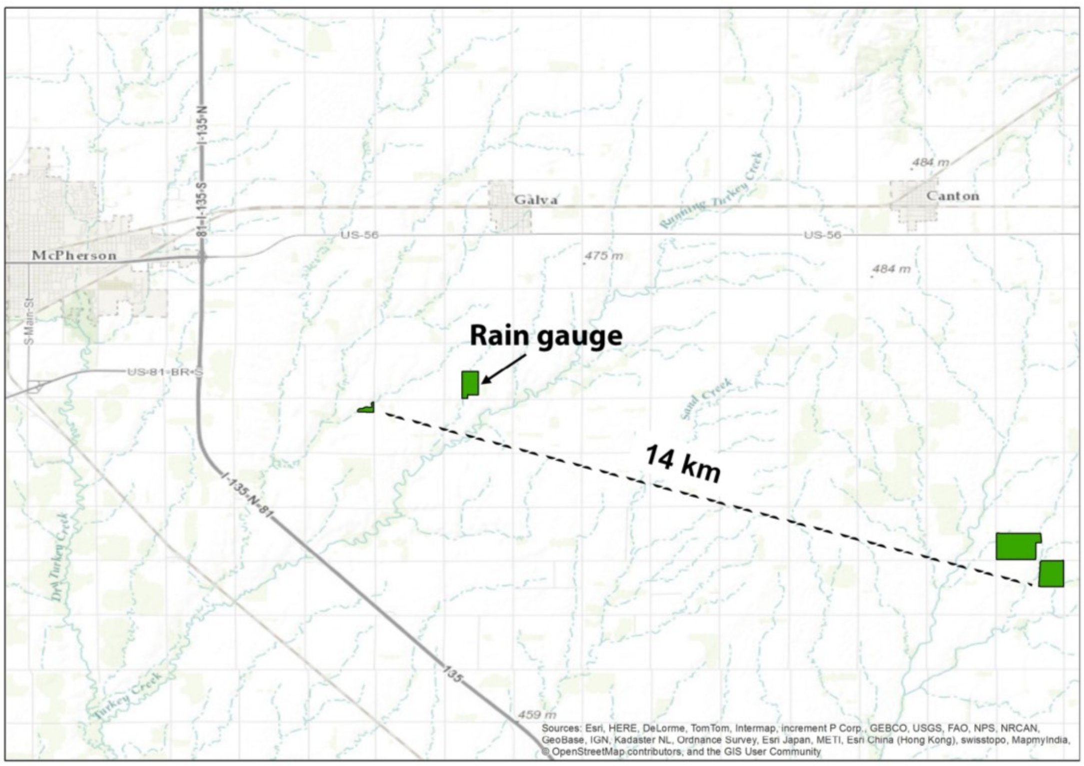
Site Selection

McPherson agricultural fields and Fort Riley training areas were selected as two under-studied areas in Kansas where gullies are forming. Both locations were chosen because the two land uses – agricultural land and military training areas – represent larger land use areas across the Midwest, and related erosion studies had already been done in both the McPherson area and on Fort Riley. Relationships with extension agents, farmers and Fort Riley personnel were already established, providing a solid foundation for studying the land uses and gully erosion more closely.

McPherson site selection

The McPherson gully study is a multi-disciplinary project funded by the U.S. Department of Agriculture and the National Institute of Food and Agriculture. Using Google Earth and ground-truthing, the Principal Investigators of the USDA grant selected four McPherson agricultural fields for study that either had existing gullies or a history of gully formation. The four selected fields are paired in several ways: the two western fields are about 1.5 kilometers apart, and the two eastern fields are less than one kilometer apart. The close proximity decreases variability in rainfall amounts and intensities across all fields, the furthest distance between sites being 14 kilometers (see Figure 3.1). Also, two of the four fields are no-till, and the other two are traditionally tilled. Soils vary across all fields, but dominant soil types are Crete Silt Loam, Farnum Loam and Longford Silty Clay Loam, which are all well-drained or moderately well-drained with no ponding or flooding potential. Textures range from silty clay loam to silt loam to some sandy clay loam in the Schmidt field, attributed to the Schmidt field's alluvium parent material as opposed to the loess parent material of the other fields (Natural Resource Conservation Service (NRCS), 2013).

Figure 3.1 Overview map of four McPherson gully sites



There are a few potential limitations to the selection of field sites. Fields had to be chosen based on access granted by land owners, and the number of field sites to be studied would ideally be higher for statistical purposes. However, it was determined that due to the distance of the McPherson sites from campus, four fields could realistically be resurveyed in a two-day span after every significant rainfall event.

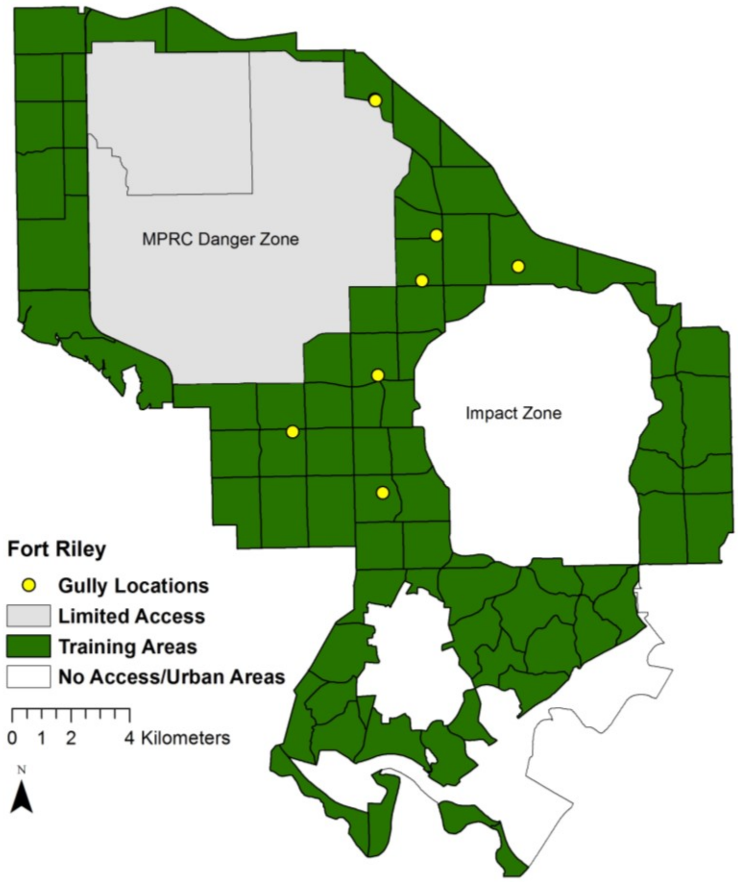
Fort Riley site selection

On Fort Riley, more than 30 gullies have been located and studied for growth in past gully studies. Katie Handley, MS in Biological and Agricultural Engineering, located many gullies in 2010 through LiDAR imagery and ground-truthing. Handley also documented the location of gully headcuts as well as widest and deepest measurements of each gully (Handley, 2011). In 2012, Chelsea Corkins, MS in Biological and Agricultural Engineering, continued Handley's study by re-measuring widest and deepest gully dimensions, along with tracking any headcut growth (Corkins, 2013). Handley's gullies fell into numerous categories: roadside "ditch" gullies, bank gullies that flow directly into streams, and gullies obviously caused by tank tracks (see Figure 3.2), all with differing drainage areas and soil materials. From Handley's gullies, sites for this study were filtered by soils, accessibility, and by how they formed. To reduce variability, the only gullies considered for this study were gullies formed by tank tracks or gullies formed in low-lying areas; gullies that formed due to roadside runoff or unprotected stream banks were excluded. The similar soil types of the Fort Riley gullies helped further reduce variability. There are three major soil types (Irwin silty clay loam, Clime-sogn complex, and Wymore-Kennebec complex) and one soil subgroup (Crete silty clay loam) for all seven gullies, and all soils have silty clay loam or silty clay texture. All soil types are well-drained or moderately well-drained with no risk for flooding or ponding.

Figure 3.2 Two small gully channels that formed in tank tracks. Photo by C. Corkins.

In considering accessibility, there are areas on Fort Riley that have restricted access much of the year, and most of the summer (see Figure 3.3). Gully sites that were chosen could be accessed after rainfall events on short notice with little to no difficulty. Also, each gully is in a different training area so that if, for instance, two of the training areas were being used by the military, we could still survey the other five. Seven gullies were selected because they could realistically be surveyed in two full field days following a rain event.

Figure 3.3 Fort Riley gully accessibility



Data Collection Methods

Surveying and physical measurements

Field data collection was similar in both study locations. To measure changes in gully dimension, cross sections and longitudinal profiles were surveyed using a laser level and survey rod (see Figure 3.4). Longitudinal profiles were resurveyed yearly. Cross section resurveys were completed periodically each year to determine if a threshold rainfall depth or rainfall intensity caused gully growth. Headcuts were also measured to determine if headward expansion occurred since the last survey (see Figure 3.5 for an illustration of headcut growth methods).

Figure 3.4 Survey equipment. Photo by author.

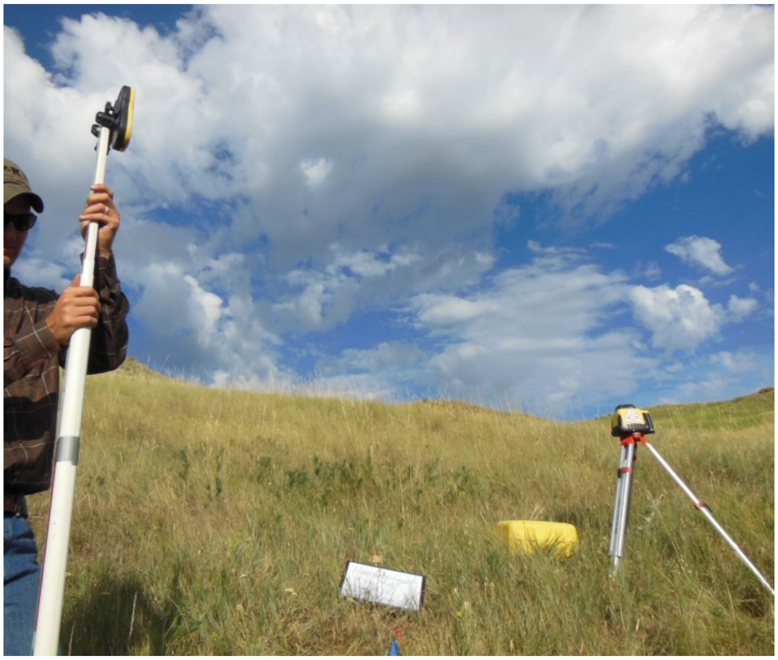
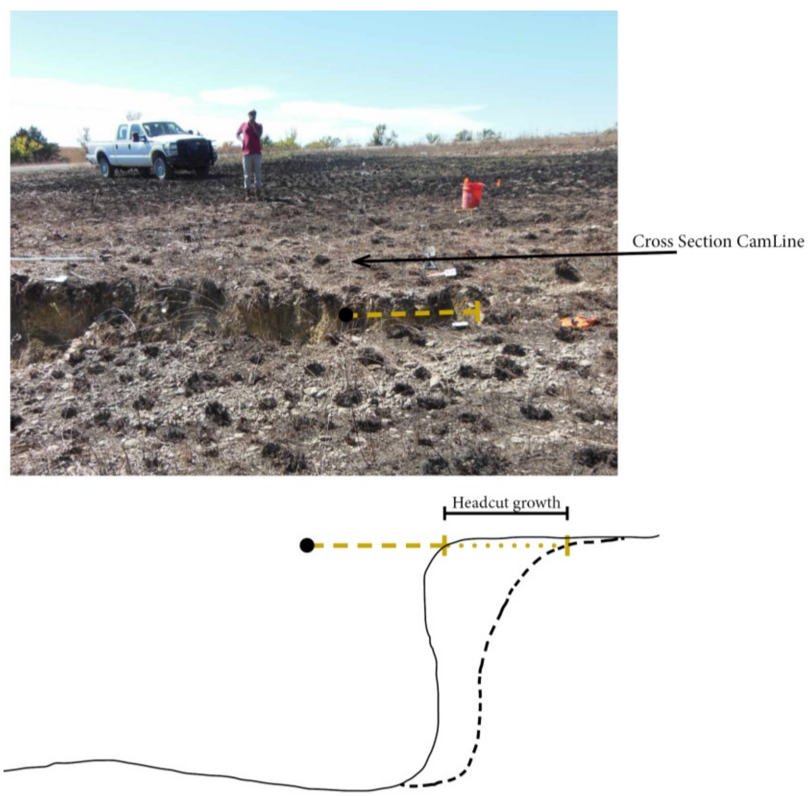


Figure 3.5 Headcut measurement method (both figures below). Photo by author.



The original intent was to resurvey cross sections and re-measure headcut locations after each significant rainfall event in order to correlate rainfall with erosion rates. However, unanticipated difficulties due to either too-dry conditions (no data) or too-wet, muddy conditions (making survey data inaccurate) limited our data collection timing, making it impossible to relate erosion rates to each specific rainfall event throughout the study period. Table 3.1 and Table 3.2 show survey dates for each gully site.

Table 3.1 Fort Riley survey dates for each gully

Date Surveyed	**Gully ID**						
	36	**42**	**51**	**89**	**91**	**94**	**98**
5.23.12	x	x	x	x		x	
6.26.12	x	x	x	x		x	
3.22.13	x						x
4.25.13							x
5.13.13	x	x	x	x	x	x	
6.3.13	x		x	x	x		x
9.6.13		x	x		x		x
10.10.13				x		x	
8.1.14		x	x	x		x	
10.16.14					x		x

Table 3.2 McPherson gully field survey dates

Date Surveyed	Gully Field		
	Wedel	**Schmidt**	**Goerhing**
5.5.12	x		
6.7.12		x	
6.20.12	x	x	x
8.9.12	x	x	x
3.15.13	x	x	x
5.23.13	x		
6.27.13	x	x	x
4.18.14	x	x	x
6.18.14	x		
8.5.14			x
1.9.15	x	x	

Because the gully channel in one McPherson agricultural field appeared to be changing relatively quickly, we installed additional cross sections to developing gullies in that field, and in 2013 we drove erosion nails and washers vertically into the ground at six selected cross sections to monitor variations in cut and fill in the gully channel (see Figure 3.6). The nail head and washer are pounded in flush with the ground surface, and any nail exposure indicates erosion. In cases of filling, nails are found with a metal detector and depth of fill above the nail is documented.

Figure 3.6 Nail and washer in gully bed, McPherson (Wedel) field, indicating erosion. Photo by author.

Handheld GPS and metal detector

An Archer Rugged Handheld PC with Hemisphere GPS was used to locate and map each cross section location or other relevant feature of each gully in order to relocate pin flags and end points. The Archer and a metal detector were used to relocate cross sections, which was helpful on Fort Riley due to dense tallgrasses, and in agricultural fields where we could not leave large markers due to farming operations.

Other collected data

Rainfall amounts and intensity

One goal for this study was to relate gully erosion rates as closely as possible to rainfall/runoff events. A HOBO weather station was installed in the middle of one of the McPherson fields by means of the USDA grant, from which rain data was recorded from May 2013 to September 2014. Because the study period was from May 2012 to January 2015, gaps in rain data were filled by data from the Equus Beds Mesonet station, approximately 29 kilometers away from the furthest field site. Fort Riley operates a weather station that is a maximum of 8 kilometers away from the furthest gully, and rain data for the entire study period was acquired with help from the ITAM (Integrated Training Area Management) office on Fort Riley.

In 2013, significant rainfall events were often closely preceded or followed by other rainfall events, with rain falling on a daily basis for parts of the summer. Muddy conditions and timing made surveying after each rain event impossible, which meant that direct correlations between erosion and one rain event's total depth and intensity was not possible. Trouble accessing gully sites after each rain event is not an uncommon problem (i.e. De Santisteban et al., 2006).

Watershed characteristics

Drainage area, slope and slope length were three watershed characteristics needed for gully evaluation. Drainage area was determined with the most recent available LiDAR data for the area, and was ground-truthed in the field. McPherson County LiDAR was flown in 2011 at a 2-meter resolution, and Fort Riley LiDAR was flown in 2010 at 3-meter resolution. Drainage area was calculated for headcut retreat rate analysis with the outlet set right at the gully headcut, and drainage area was also calculated with the outlet at each cross section to relate runoff to cross-sectional area change (see Figures 3.7 and 3.8 for example drainage areas).

The slope of the hill leading into the gully headcut was measured using contours in ArcGIS and verified with laser level surveying equipment in the field. When tank tracks were the apparent cause of gully initiation or accelerated growth, which was the case in most of the Fort Riley gullies, aerial photos and contour maps were used to measure track length.

Figure 3.7 Example watershed delineation for Fort Riley

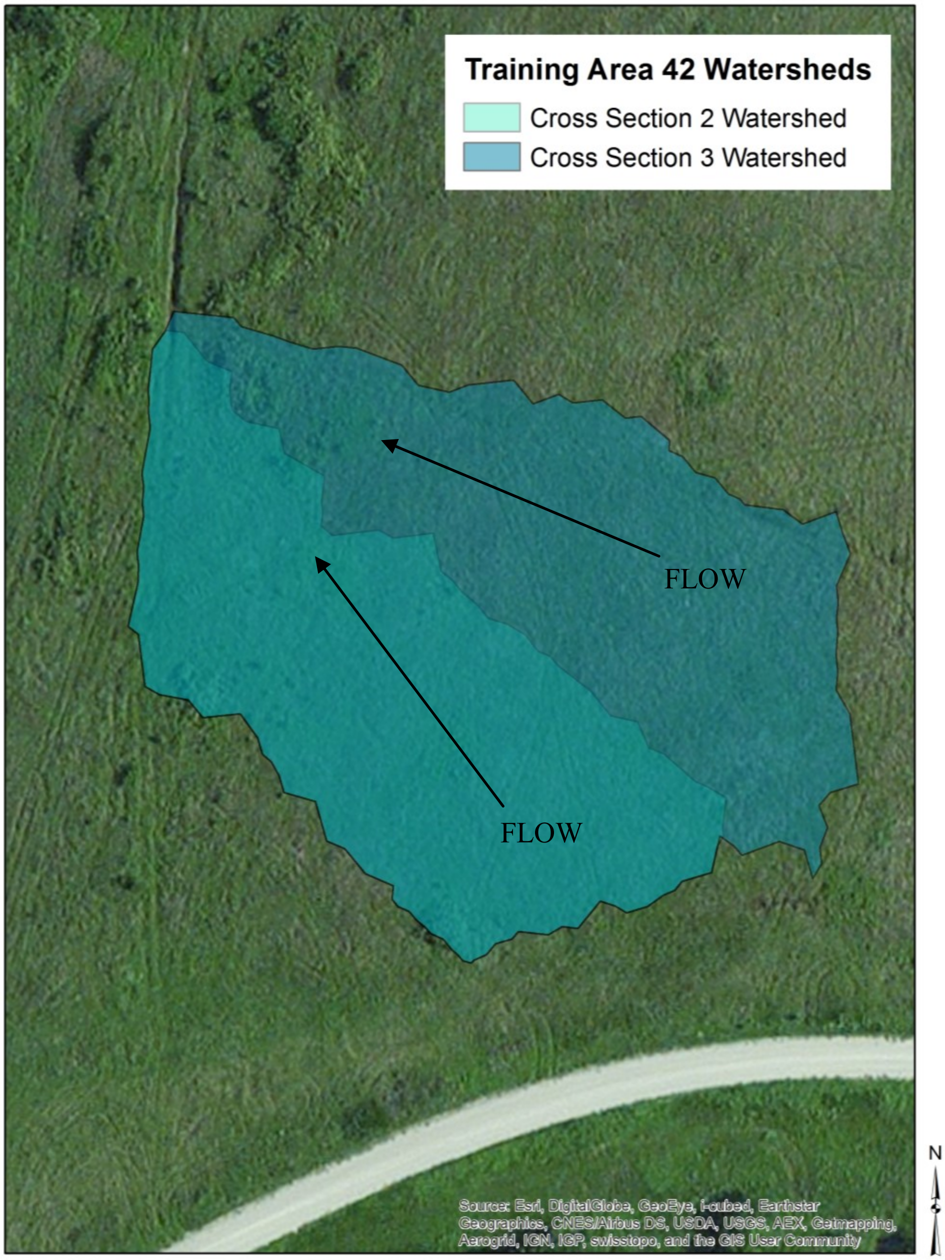
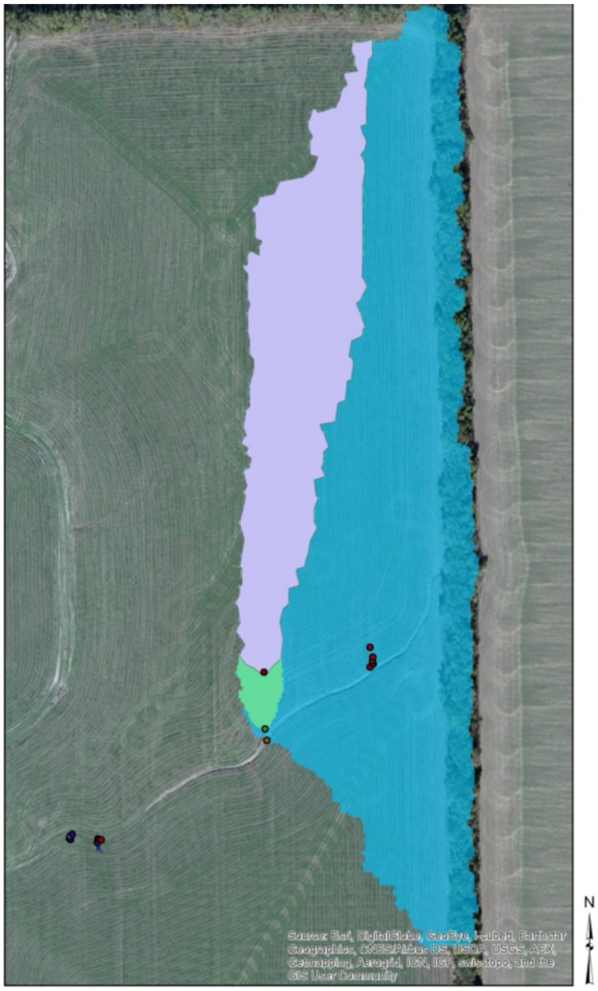


Figure 3.8 Example – Three cross section watersheds in the Wedel field



Vegetation data

NDVI data for Fort Riley was provided by Shawn Hutchinson of Kansas State University's Geography Department. NDVI (Normalized Difference Vegetation Index) is a measure of greenness. It uses light wavelengths to determine how green a patch of land is – the more green leaves there are in the observed pixel of land area, the higher the NDVI value. The NDVI values used for data analysis in this project are in 8-bit format at 250-meter resolution. NDVI was evaluated for each gully's watershed for the timeframe preceding each large storm or peak rainfall intensity event occurring in between each resurvey, so that data would represent vegetation conditions at the time of large or peak rainfall events. Most gully watersheds fit into one pixel of the NDVI data, but when multiple pixels covered a watershed, the average pixel value was calculated. In theory, a higher NDVI value, or a higher value for greenness, would indicate better soil protection from runoff and erosion.

Data collection limitations

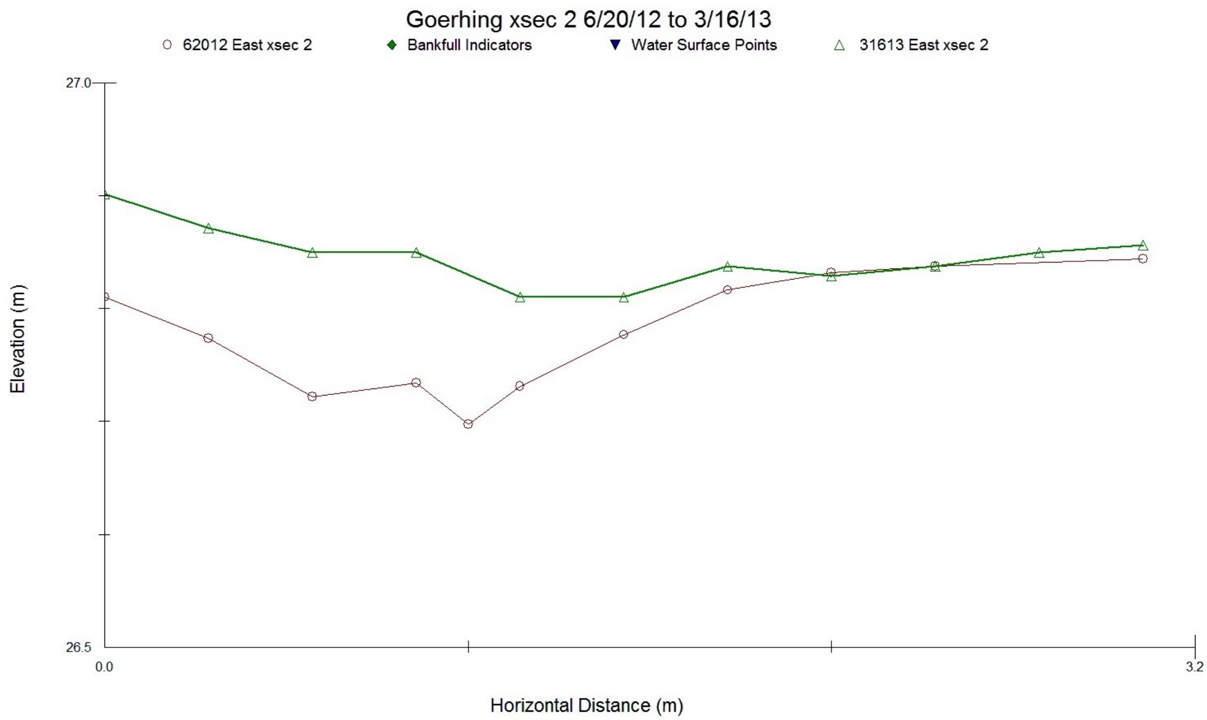
Site disturbances

Both study locations were and continue to be actively used for military training or crop production. On Fort Riley, cross section end pin markers were occasionally run over or hit by tank traffic, which disrupted reference elevation points for survey comparisons. Similarly, in McPherson fields a few cross section end markers (pin flags) were washed out by large rain events or pulled up by farming equipment, leaving us with no accurate reference point for that cross section's starting or ending elevation point. In those cases, we used the Archer handheld GPS to relocate the ground point to within 1 meter and installed a new reference pin or pin flag. Data collected from disturbed cross sections are not included in the data analyses.

Crop production timing

In McPherson agricultural fields, we were unable to survey when there was risk of damage to crops or when crops were above the height of the laser level beam, which ruled out data collection from July to October for corn and milo fields, and mid-spring for wheat. In the fields that were tilled, a new initial survey was started each year due to the ground and flow path being significantly altered by post-harvest tillage. Cross sections and longitudinal profiles were not comparable across all three years for tilled fields due to the rearrangement of large amounts of soil by tillage equipment (see Figure 3.9 for example of "deposition" from tillage on the Goerhing field).

Figure 3.9 Example: Issues comparing cross section surveys after tillage (Green line represents $0.17m^2$ of fill in one year, due to tillage instead of channel processes of deposition)



Data Processing and Analysis Methods

Data analysis overview

Data analysis methods for this gully study –measuring gully erosion rates and drivers through surveying and collection of land characteristic data – are presented in detail below. The data analysis for Fort Riley and McPherson gully erosion rates involved comparing multiple variables and running many statistical regression trials. Assumptions about the datasets and dataset summaries are also described below.

Gully erosion data analysis for Fort Riley and McPherson

Assumptions

To determine rates of gully erosion and main driving factors of gully erosion, surveyed gully cross sections and longitudinal profile data for Fort Riley and McPherson were considered along with rain data, vegetation data, and land characteristics of slope and drainage area. **The following assumptions were made:**

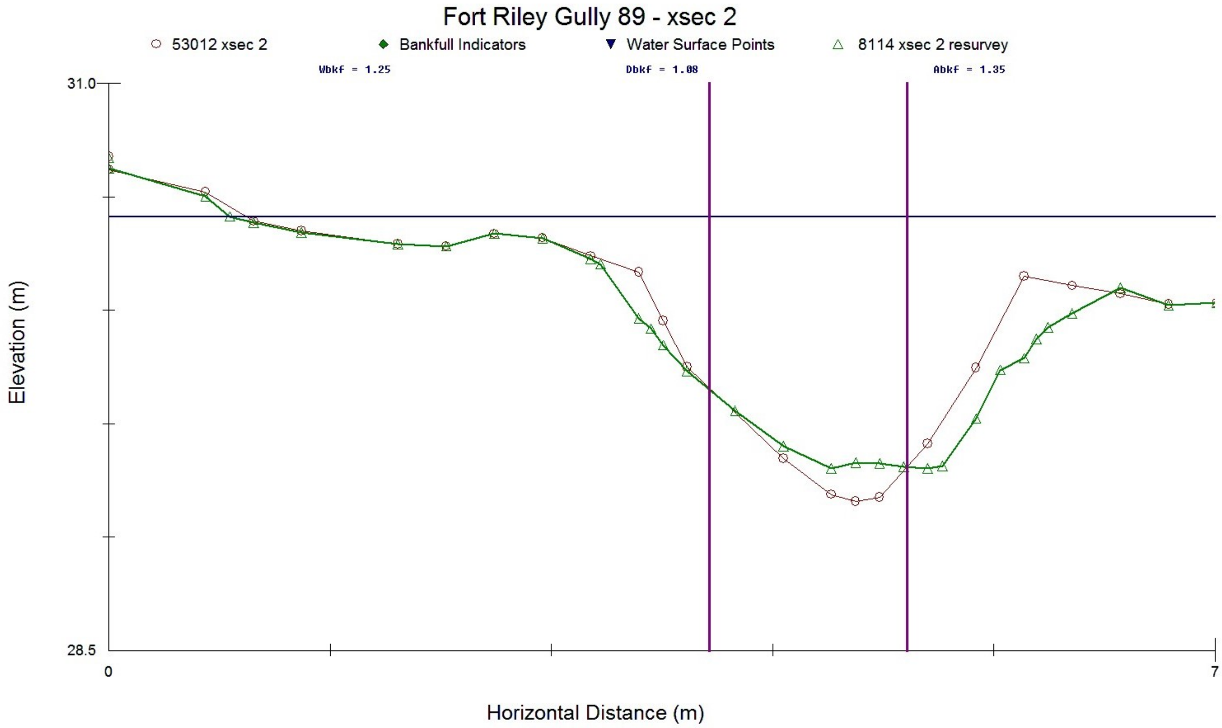
1. The data layer used to determine drainage area of each gully accurately represents the watershed area. Adjustments to watershed area were made when GIS watershed analysis did not reflect observed field conditions (for example, GIS watershed analysis showed no watershed area or accumulated flow for Tributary D in the Wedel field, so an estimated drainage area was created in the field).
2. Flow patterns in each watershed remain constant. Although traffic (tanks, tractors, etc.) may increase or decrease runoff intensity within each watershed, we assume watershed flow properties remain constant because of difficulties and constraints in tracking all vehicle movement (active tracking of military vehicles is not permitted, and aerial imagery to locate tracks is not always available at a high resolution on a frequent, immediate basis).
3. Even if more than one rainfall event occurred between surveys, the largest event, series of events or peak rainfall intensity most likely relates to the observed gully erosion.

Dataset summaries and what the data tells us

The following are descriptions of how each variable is used in analysis.

Cross sections: For McPherson and Fort Riley, surveyed cross sections provide information about widening, filling, cutting, or bank failure at a specific location in the gully. In some cases, cross section overlays show that gully beds are changing differently than gully banks (for example, several Fort Riley cross sections show bed filling and bank widening). When necessary, cross section beds and banks are analyzed separately. Cross sectional area was calculated by setting an arbitrary, static reference elevation for each cross section location, and cross sectional area and area changes below the reference elevation were calculated using RIVERMorph® software (see Figure 3.10).

Figure 3.10 Calculating cross-sectional area below an arbitrary reference elevation, separating bed and banks when necessary. Green line represents most recent survey.



Longitudinal Profiles (Long. Pro.): Surveyed longitudinal profiles give information about bed elevation changes along the length of the gully, including filling, cutting, and resulting bed slope changes. Long. pro. also provides the bed slope variable for statistical analyses of cross section erosion rates and drivers.

Headcut measures: Headcut growth is measured as changes in length from a set location at the cross section below the headcut.

Rainfall: Because more than one rain event occurred between field visits, several scenarios could have caused gully erosion: the largest storm (largest rain depth in one storm series), the largest storm series that had smaller amounts of rainfall in the days preceding the storm, the peak rain intensity (mm/hour), or the total rain (depth in mm) that occurred between survey visits. Each of these scenarios was compared to erosion through statistical regression to determine which has a relationship with erosion rates.

Drainage area: For cross section erosion data, drainage area is calculated for each cross section within each gully. For headcut erosion data, drainage area is calculated for each headcut location that was monitored. See Figure 3.11.

Slope: For headcut erosion data, land slope approaching the gully headcut is used. For cross section erosion data, gully bed slope above the headcut is used.

Landscape position: The combination of drainage area and the average slope of the drainage area were used to approximate the position of the gully in the landscape/greater watershed.

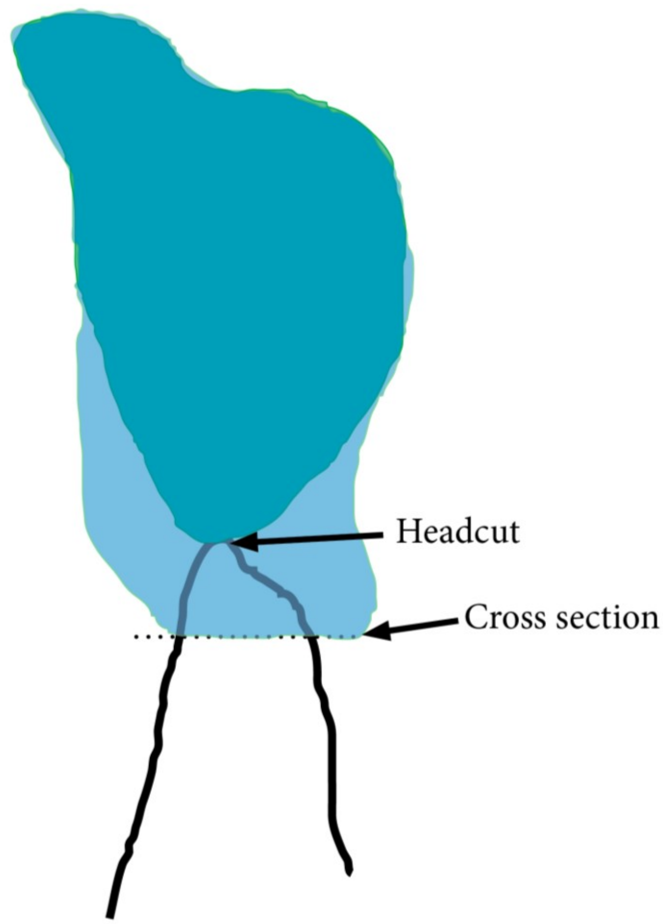
Vegetation: For Fort Riley, MODIS 8-bit NDVI values (unitless) were found for the timeframe that preceded the largest rainfall event, the largest event with antecedent moisture, or the peak intensity rainfall event. NDVI data was not used for analysis of total rain depth in between survey dates. For McPherson, crop type and residue cover throughout the season were documented for each field, used to qualitatively assess crop conditions and cover at the time of rainfall.

Inherent soil erosivity: At Fort Riley, gully soils were visibly different in terms of erodibility. The USDA-NRCS soil erosivity factors t (an estimate of the maximum average annual rate of soil erosion by wind and/or water) and k (the susceptibility of a soil to sheet and rill erosion by water) were both included in statistical analysis.

Tank track length: For Fort Riley gullies, tank track length leading up to the headcut is used as another factor influencing gully erosion, which is related to flow length in other runoff and erosion models such as TR-55 and RUSLE.

Gully width and depth: Because of the range of sizes of Fort Riley gullies, gully topwidth and gully maximum depth were used as scale factors. Topwidth was measured as the width from top of bank to top of bank, and max depth was the depth from the top of bank to the deepest point, both taken from cross section data.

Figure 3.11 Illustration of watershed delineation for a headcut and cross section, by author.



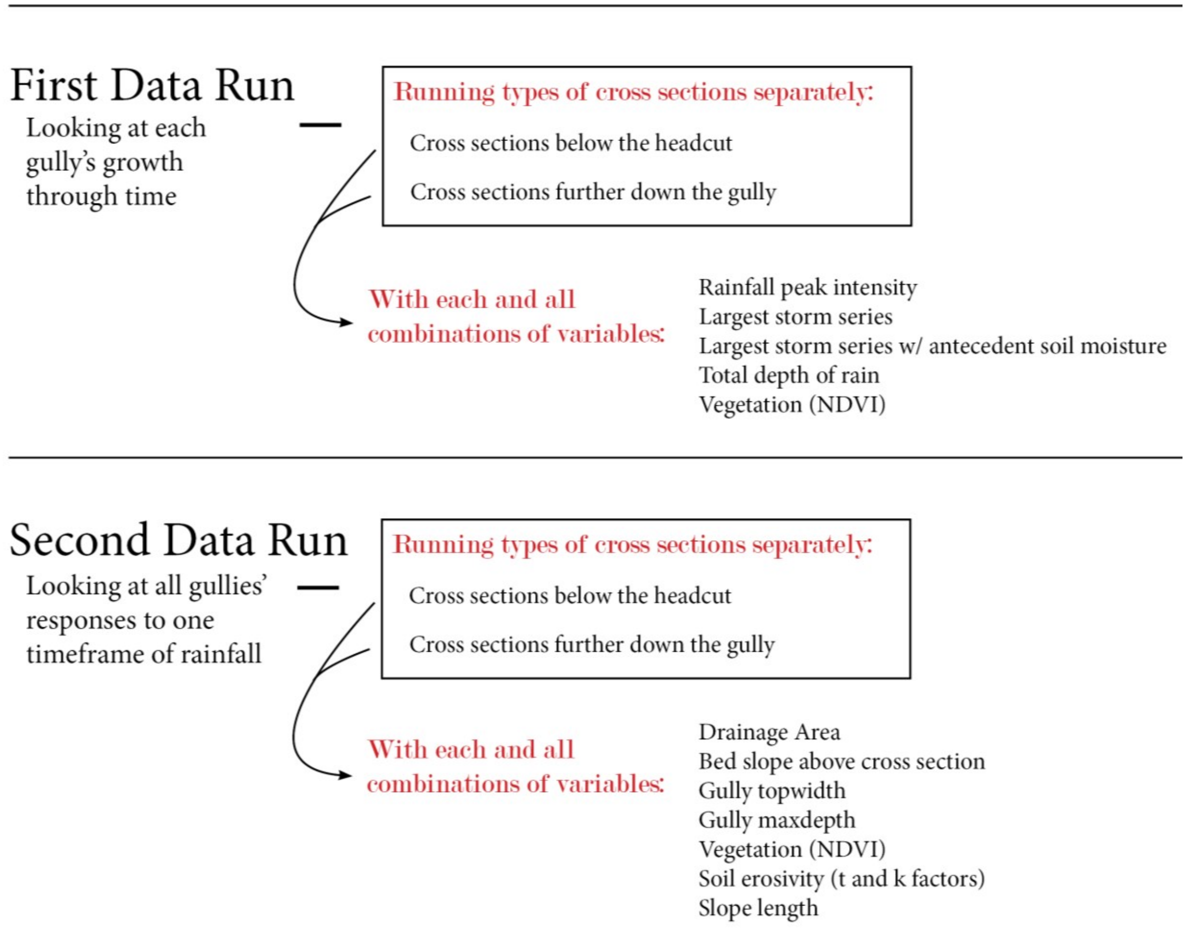
How the data is divided for statistical analyses

The McPherson and Fort Riley gully erosion data is statistically analyzed two different ways, because the requirement for non-independence in regression is not met, and categorizing data is necessary for more accurate analyses.

The first statistical data analysis process looks at individual gullies (more specifically, individual cross section change) through time. In this process, drainage area, slope, gully size and soil conditions remain constant because only one gully is being evaluated through time. This statistical procedure first uses simple linear regression to determine which rainfall scenario (largest storm series, largest storm series with antecedent moisture, peak intensity, or total rainfall) has the largest influence on each gully through time. The vegetation variable NDVI is then compared to the erosion data, and finally NDVI is added to each rainfall scenario to determine which rainfall scenario/vegetation combination is most influential. To ensure data points are independent of each other, cross sections directly below the gully headcut and cross sections further down the gully are analyzed separately.

The second statistical data analysis process compares all gullies during one timeframe, meaning gullies are analyzed together for each separate rainfall period (again, gullies are represented by cross section erosion, and cross section erosion analysis cannot lump more than one cross section per gully into the analysis, so cross sections right below the headcut and cross sections further down the gully are analyzed separately). Comparing all gullies' erosion responses to the same rainfall conditions in between each survey event is necessary since all the gullies have the same rain data from one rain gauge. The second analysis process keeps moisture and rain conditions constant, but evaluates drainage area, slope, gully size, soil erosivity, and vegetation conditions' individual and combined influence on gully erosion in each timeframe between resurveys/field visits. (See Figure 3.12, a diagram of statistical processes).

Figure 3.12 Diagram of steps in statistics methodology, by author.



Methods Conclusion

Gully sites were selected in terms of similar land use, land conditions, and accessibility. Field measurements were taken multiple times per year at each gully site, and rain and land characteristic data were collected for the study period, 2012-2014. Data was put into tables and RIVERMorph® software to be examined for rates and patterns of change, and statistical analyses were used to determine main drivers of gully change.

Chapter 4 - Results

Introduction to Results

This study involved measurement of gully channel change in Kansas agricultural fields and in Fort Riley training areas in order to predict erosion rates and to determine the main drivers in gully morphology in the region. The following sections first describe gully erosion and change on Fort Riley in terms of direct observation and statistical analysis of erosion versus driving forces, and then gully erosion and change on the fields in McPherson is presented. In general, monitoring methods were the same for both sites. The following is a list of slight differences in data collection between Fort Riley and McPherson:

1. Vegetation data: A quantitative vegetation greenness density value was collected from MODIS imagery for Fort Riley, and McPherson vegetation conditions were examined qualitatively by crop type and season.
2. Nails and washers: As an additional way to capture erosion events, nails and washers were placed in various locations along McPherson cross sections (see details of nail and washer method in Chapter 3). This method was not utilized at Fort Riley.
3. Number of cross sections: Because McPherson agricultural gullies were longer and more narrow than many of the gullies at Fort Riley, more cross sections could be monitored per gully in the McPherson fields, whereas Fort Riley gullies had only one or two cross sections monitored per gully. The higher number of cross sections at McPherson sites allowed estimation of soil erosion and deposition for the entire gully channel; but the lower number of cross sections for each Fort Riley gully did not allow total channel volume change estimation.
4. Gully width, gully depth, and soil erosivity: In statistical analyses for Fort Riley, gully topwidth, gully maximum depth, and two soil erosivity factors (t and k) were included, because Fort Riley gullies varied in terms of size and soil type more than McPherson gullies.

Because of differences in land use and location, the results between Fort Riley and McPherson are analyzed separately, then results of the two locations are compared. Overall, the results show that although gully behavior is not easily quantified or predicted using statistics, there do seem to be relationships between rainfall, vegetative cover, watershed size, channel slope, and gully erosion.

Fort Riley Results

Overview of Fort Riley results

Seven Fort Riley gullies were monitored with surveyed cross sections, longitudinal profiles, and headcut retreat measurements. The Fort Riley gullies varied greatly in terms of their rates of erosion or filling; some of the gullies showed significant erosion, while others changed only slightly over the entire study period (May 2012 to October 2014). In some cases, cross sections showed obvious signs that gully banks are widening and creating gentler bank slopes, while the gully beds are filling. Due to the differences in bank and bed changes, each cross section was examined for total area change, and also bank area change and bed area change. The following sections present the data and results for each individual Fort Riley gully, first concentrating on significant erosion or filling; then describing any significant statistical relationships between individual gully erosion, rainfall scenarios as described in Chapter 3, and the leaf greenness density index NDVI, which was also described in Chapter 3. Finally, statistical results that analyzed all gullies' response to the same time period are presented. All cross section and longitudinal profile overlay graphs are in Appendix A. Figure 4.1 illustrates a timeline of daily rainfall, survey dates, and cross section change. Table 4.1 summarizes net change across Fort Riley cross sections by date.

Figure 4.1 Fort Riley gully bank change for each cross section versus rainfall. Compiled by author.

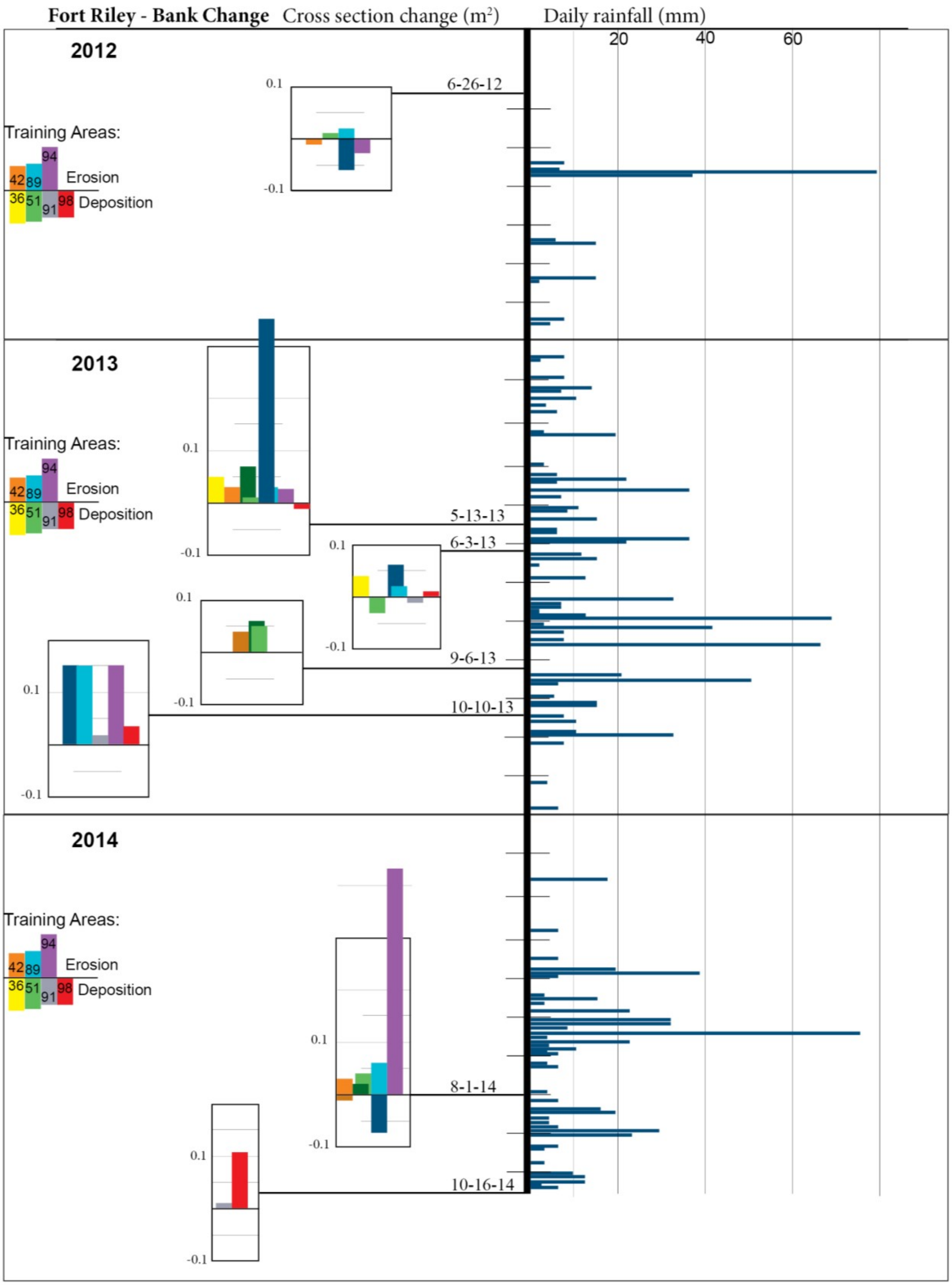


Table 4.1 Net measured change across Fort Riley gully cross sections by survey date (positive numbers indicate erosion)

Survey Date	Net measured change (m^2)
6/26/2012	-0.12
5/13/2013	0.80
6/3/2013	0.08
9/6/2013	0.16
10/10/2013	0.50
8/1/2014	0.50
10/16/2014	0.12

Fort Riley statistical results overview and explanation

Because each individual gully's results include statistical results, an explanation of methods is needed. For the Fort Riley study, each gully had one cross section 1-2 meters below its headcut; most of the gullies had an additional cross section further down the channel, and all of the gullies had a cross section 1-2 meters uphill from the headcut. In running statistical analyses, the cross sections directly below the headcut were used because they were the most consistent comparison from gully to gully, and every one of the cross sections below the headcut showed some change throughout the study period (unlike the cross sections above the headcut). Because data collection was not possible after every rainfall event, estimates were made when analyzing the rainfall data as to what might have caused erosion. The independent rainfall variables that were tested separately are:

1. Total rainfall depth since the last survey using daily rainfall data
2. Largest storm series since the last survey using daily rainfall data: the sum of consecutive days of rain for a total rain "series" depth;
3. Largest event with antecedent moisture, which was similar to #2 but only added large events (14 mm or greater) with rain events that directly preceded the larger event;
4. Peak intensity using hourly data: the greatest amount of rainfall in a one-hour period between survey dates.

Two approaches to statistical analyses were completed: 1) First, each cross section's change through time was used as a dependent variable; and each of the four rainfall scenarios was used separately as an independent variable; then each rain scenario (except for Total rainfall depth) was paired with the NDVI vegetation index. The rainfall and NDVI results are presented in the individual gully results; 2) The second statistical approach was using each cross section below each gully headcut as dependent variables, and examining all gullies' response to the same or similar timeframe of rainfall, with the following independent variables: drainage area, NDVI, gully width and depth, two soil erosivity indexes, and topographic location represented by channel slope above the headcut.

The relationship between peak runoff rate and cross section change was examined through statistics, as well as the relationship between peak runoff rate and long. pro. (bed) change. Finally, long. pro. change was compared to gully drainage area, gully bed slope, and the soil erosivity factors 't' and 'k' to determine if gully bed filling rates could be attributed to local land and soil conditions.

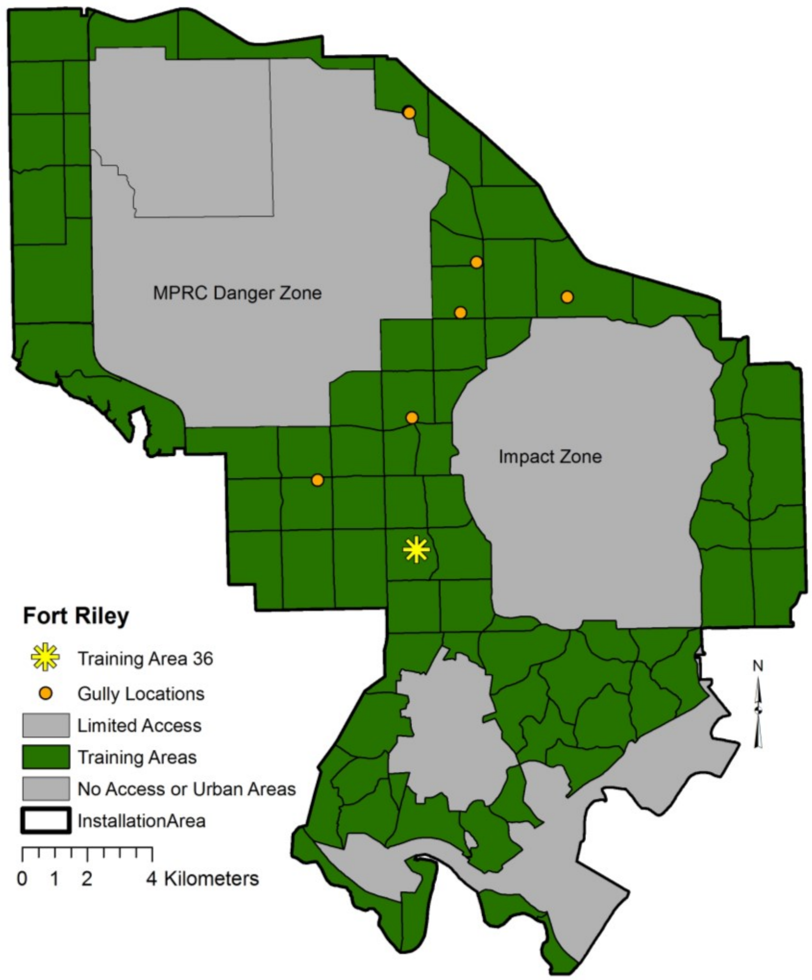
Statistical analysis for Fort Riley gullies showed many weak relationships and a few strong relationships for certain gullies or certain timeframes. Due to the inconsistencies in results across gully location and timeframes, no statistical model is expected to be an accurate prediction for future gully behavior. However, the statistics may provide insight into what drivers are most influential in gully change. Any relationships with an adjusted R^2 of 50% or higher and a p-value of 0.10 or lower was determined significant and examined further.

Gully in Training Area 36

Gully 36 Overview

Figure 4.2 shows the location of the gully in Training Area 36. The gully in Training Area 36 had a large headcut with a 1.2 -meter drop, but was shorter in length (13 meters) than some of the other studied gullies. The gully channel started in a low lying area, and the gully's outlet was another small, natural drainage channel. Three cross sections were monitored. The third cross section was the only one located below the headcut and was the only cross section in Gully 36 that was analyzed for change. In early 2013, a soldier drove a vehicle into the gully and was injured – by late summer 2013, the gully was filled and “fixed” for safety purposes, so no other data could be collected.

Figure 4.2 Location of Training Area 36 Gully



Trends

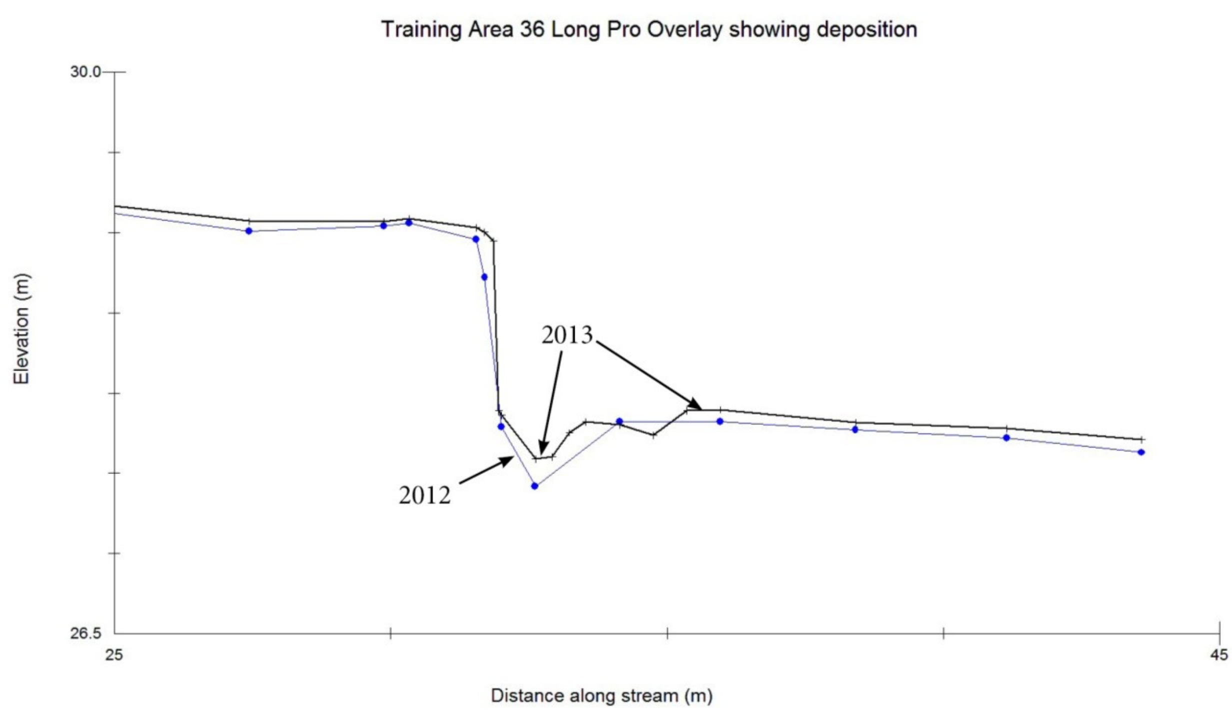
Table 4.2 shows Cross Section 3’s bank change by date of survey. Negative numbers indicate deposition (decrease in cross sectional area), and positive numbers indicate erosion (increase in cross sectional area). The largest amount of erosion occurred between 6-26-12 and 3-22-13, which was erosion of the bed and the left bank. Overall, the gully showed signs of filling on the bed and widening of the left bank. Bed filling was seen not only in the cross section overlays, but in the long. pro. overlay as well. The long. pro. overlay from May 2012 to March

2013 indicated 0.9 m^2 of deposition over 12 meters of gully bed, or an average of 0.075 m^2 of deposition per meter of gully bed. See Figure 4.3, which shows an overlay of the 2012 and 2013 surveys. Methods for headcut change were not developed until this gully was out of commission, so rates of headcut retreat for this gully were not monitored; however, headcut retreat can be seen in Figure 4.3. All other longitudinal profile overlays are in Appendix A.

Table 4.2 Gully 36 Cross Section 3 area change (banks) through time

Survey date	Cross section area bank change (m^2)
5.23.12	Initial survey
6.26.12	-0.058
3.22.13	0.152
5.14.13	0.055
6.3.13	0.035
Net Change	0.185

Figure 4.3 Gully 36 Long. Pro. overlay showing deposition of the bed



Statistically, the Training Area 36 gully showed a weak, positive relationship between Cross Section 3 bank change versus total rainfall depth; bank change versus largest storm series; and bank change versus largest storm with antecedent moisture, but there were no significant or strong relationships.

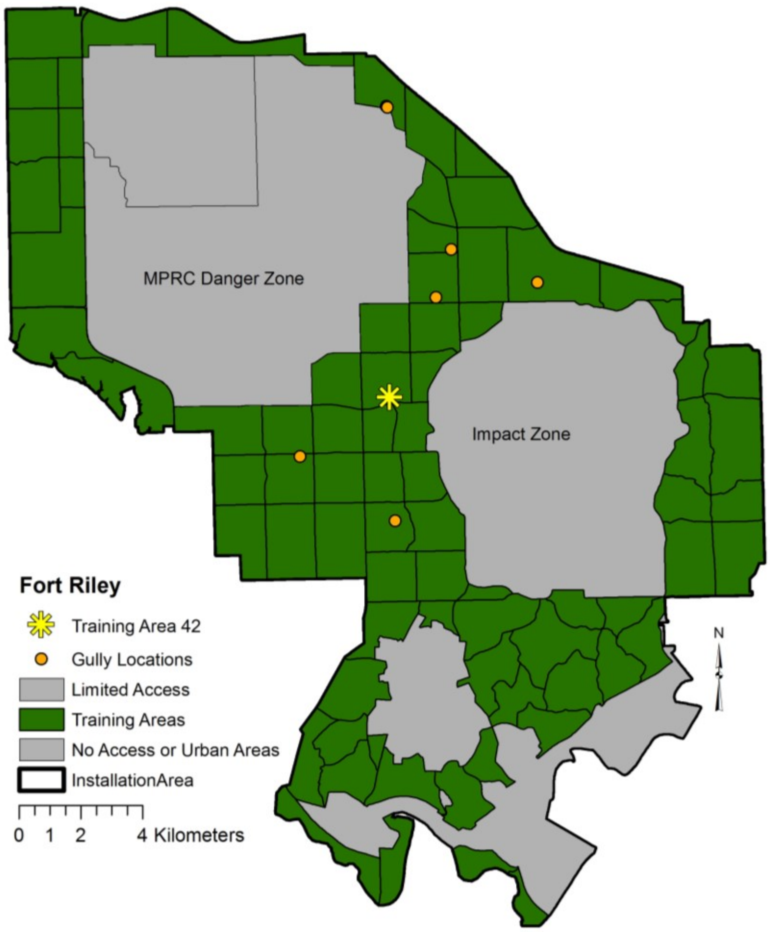
In summary, data collection was interrupted for this gully because Fort Riley filled in the gully for safety purposes. When it was being monitored, Training Area 36 gully was showing signs of decreasing area of the bed (filling) and left bank widening. The long. pro. for the gully from 2012-2013 also shows bed filling. Statistical results examining rainfall or vegetation relationships were inconclusive.

Gully in Training Area 42

Gully 42 Overview

Figure 4.4 shows the location of the gully in Training Area 42. The gully in Training Area 42 had a smaller headcut with a 0.3-meter drop, but was relatively long at 46 meters in length. Gully 42 clearly formed in tank tracks. Three cross sections were monitored, and the only cross sections that showed change were cross sections 2 and 3, both below the headcut. During the May 2013 survey, it was noted that a tank or tanks had driven through the gully, disturbing one end pin for Cross Section 3, which was then reconstructed. From that point forward, a new channel and headcut formed near Cross Section 3.

Figure 4.4 Location of Training Area 42 Gully



Trends

Table 4.3 shows Cross Section 2's total change, bank change, and bed change by date of survey. (Note: bed change plus bank change for a cross section do not necessarily add up to total cross section change due to the way RIVERMorph®, the software used, calculates area.) Overall, Cross Section 2 showed filling of the channel bed and widening of the right bank. After Cross Section 3 was reconstructed, very little change occurred, so results are not shown. The long. pro. overlay from May 2012 to May 2013 indicated 4.7 m^2 of deposition over 46 meters of gully bed, or an average of 0.10 m^2 of deposition per meter of gully bed. Long. pro. data indicated that the Training Area 42 gully had the greatest bed deposition rate. The headcut above Cross Section 2 retreated 0.3 meters in 2013. The headcut near Cross Section 3 retreated relatively quickly: 0.2 meters from May 2013 to September 2013, and another 0.4 meters from September 2013 to August 2014. Cross Section 3's headcut retreat is not surprising since the area was disturbed recently. Though headcuts do continue to retreat over time, periods of the greatest instability may cause the greatest rates of retreat.

Table 4.3 Total change, bank change, and bed change of TA 42 Cross Section 2

Date of survey	Bank area change (m^2)	Bed area change (m^2)	Total area change (m^2)
5.29.12	Initial survey		
6.26.12	-0.010	-0.038	-0.046
5.13.13	0.033	0.001	0.046
9.6.13	0.003	-0.024	-0.019
8.1.14	0.027	-0.009	0.009
Net Change	**0.052**	**-0.071**	**-0.009**

Statistically, the gully in Training Area 42 showed no significant results for Cross Section 2's area change related to rainfall conditions or vegetation conditions. Because Cross Section 3 was reconstructed in 2013, it did not have enough data points to have any statistical results.

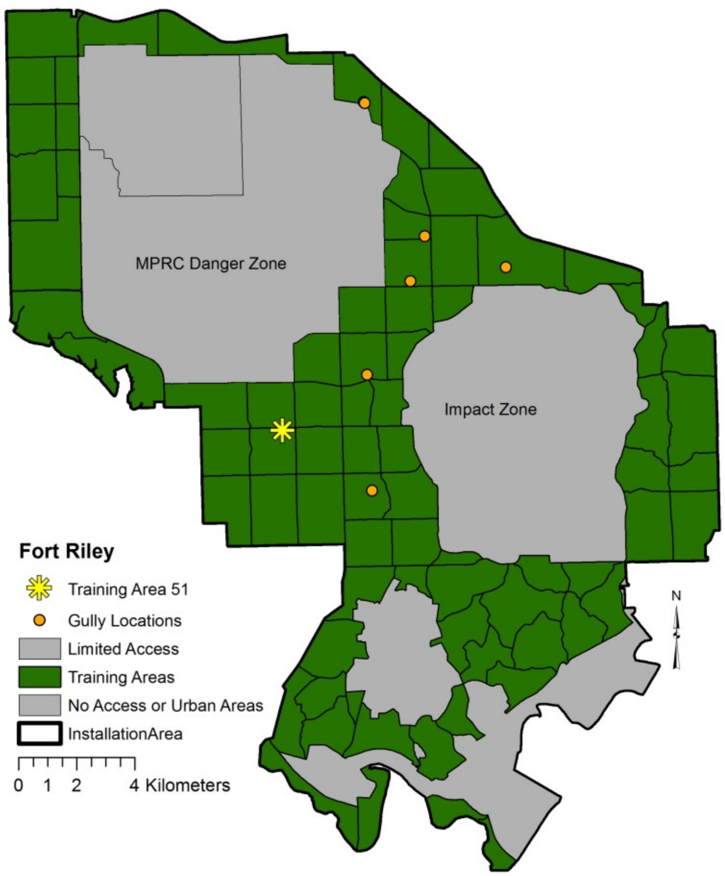
In summary, Cross Section 2 filled and widened. The long. pro. data from 2012 to 2013 also showed that overall, the gully bed filled slightly. The headcut that formed after tank traffic (disturbance) retreated nearly 0.6 meters in 14 months; that rate of headcut growth is quicker than most other gullies in the Fort Riley study. The fast initial retreat of the headcut follows the trend that gullies grow relatively quickly until some equilibrium is reached. Statistically, the gully in Training Area 42 shows no conclusive results.

Gully in Training Area 51

Gully 51 Overview

Figure 4.5 shows the location of the gully in Training Area 51. The gully in Training Area 51 has a small headcut with a 0.6-meter drop and a small initial channel, but becomes deep further down the gully. It is the longest gully channel in the study at 80 meters in length. Clearly formed due to tank tracks, the gully has two channels that converge. Three cross sections were monitored. Cross Section 2, located 1.5 meters below the headcut, and Cross Section 3, located 31 meters down channel from the headcut in the deep section of channel, were the only two cross sections showing change.

Figure 4.5 Location of Training Area 51 Gully



Trends

Tables 4.4 and 4.5 show total, bank and bed change for Cross Section 2 and Cross Section 3 by date of survey. (Note: bed change plus bank change for a cross section do not necessarily add up to total cross section change due to the way RIVERMorph®, the software used, calculates area.) Overall, in Cross Section 2 the bed filled, and both banks eroded making the cross section wider and the bank slopes more gentle. Cross Section 3 also shows bed filling, and one bank eroding. Looking at overlays for Cross Section 2, bed filling clearly began after the 6-26-12 survey, but no other timeframes show significant change of cross sectional area. In looking at overlays for Cross Section 3, the left bank clearly eroded between the 6-26-12 and 5-13-13 surveys; clearly eroded again between 6-3-13 and 9-6-13; and the same bank eroded again between 9-6-13 and 8-1-14 (See Figure 4.6).

When comparing the cross sectional area change for Cross Section 3 to rainfall events, the three time periods when the most erosion occurred (June 2012 to May 2013; June 2013 to September 2013; and September 2013 to August 2014) contain the largest rainfall events of the study period. Table 4.6 shows the left bank area change compared to the largest and peak rain events throughout the study period. The three largest events, highlighted in blue, correspond to the largest amounts of bank erosion, highlighted in yellow.

The long. pro. overlay from May 2012 to May 2013 indicated 4.7 m^2 of deposition over 80 meters of gully bed, or an average of 0.059 m^2 of deposition per meter of gully bed. The gully in Training Area 51 showed no measurable headcut growth.

Table 4.4 Total change, bank change, and bed change of TA 51 Cross Section 2

Date of survey	Bank area change (m^2)	Bed area change (m^2)	Total area change (m^2)
5.23.12	Initial survey		
6.26.12	-0.004	-0.003	-0.009
5.14.13	0.013	-0.037	-0.026
6.3.13	-0.028	-0.007	-0.035
9.6.13	0.054	-0.001	0.052
8.1.14	0.039	-0.013	0.028
Net Change	**0.074**	**-0.061**	**0.009**

Table 4.5 Total change, bank change, and bed change of TA 51 Cross Section 3

Date of survey	Bank area change (m^2)	Bed area change (m^2)	Total area change (m^2)
5.23.12	Initial survey		
6.26.12	0.014	-0.010	0.000
5.14.13	0.072	-0.019	0.037
6.3.13	-0.005	-0.006	-0.009
9.6.13	0.062	0.007	0.102
8.1.14	0.021	-0.005	0.037
Net Change	**0.165**	**-0.033**	**0.167**

Figure 4.6 Training Area 51 Cross Section 3 overlays showing left bank erosion at different time periods

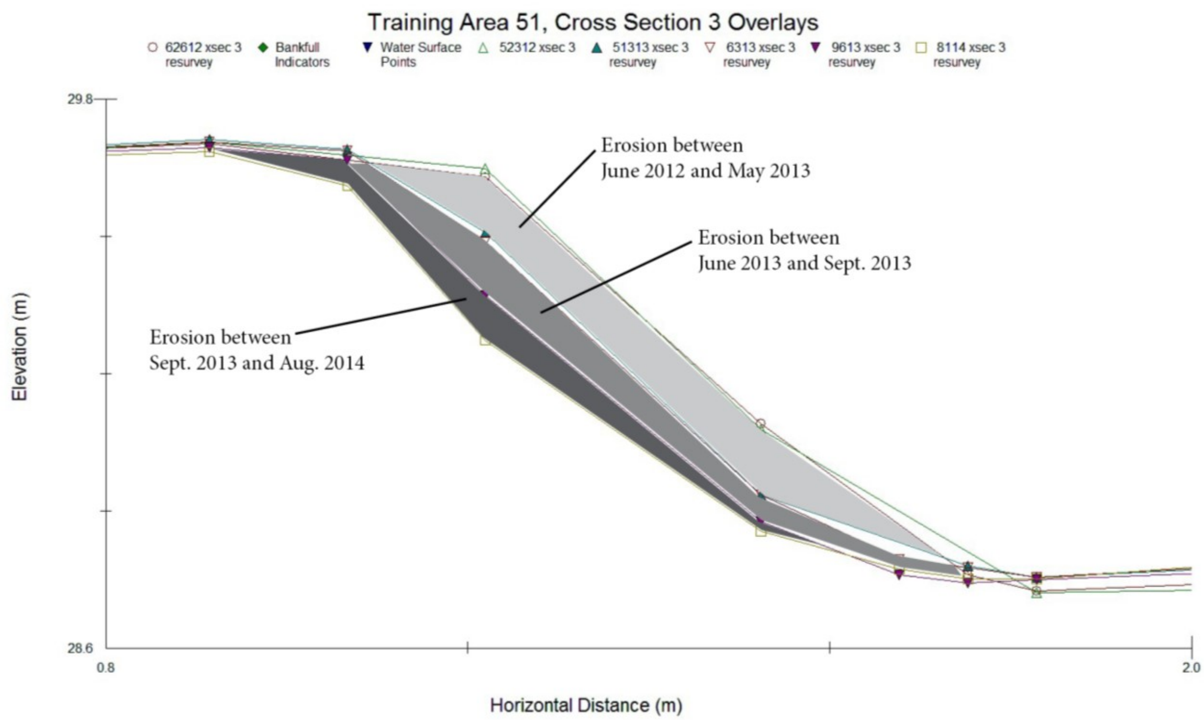


Table 4.6 Training Area 51 Cross Section 3 bank erosion related to rainfall events

	Date of survey	**6/26/2012**	**5/14/2013**	**6/3/2013**	**9/6/2013**	**8/1/2014**
Rainfall since the preceding survey	Total depth (mm)	76	*409	70	410	453
	Largest storm series (mm)	61	122	60	152	119
	Largest event w/antecedent moisture (mm)	61	122	60	140	114
	Highest peak intensity (mm/hr)	23	28	11	34	33
Bank Area Change	Right bank (m2)	0.004	0.012	-0.014	0.010	-0.012
	Left bank (m2)	0.010	**0.060	0.009	0.052	0.033
**Blue highlights mark largest rainfall periods;* ***Yellow highlights mark largest erosion rates in the study period*						

In terms of statistics, the gully in Training Area 51 showed the most numerous statistically significant results out of all individual gullies studied on Fort Riley. Both Cross Section 2 and Cross Section 3 showed significant relationships with rainfall scenarios. Cross section change did not correlate well with total rainfall depth, but the largest storm series, the largest storm with antecedent moisture, and the highest peak intensity rainfall scenarios were all significant for Cross Section 2 or 3 with 90% confidence or better. Table 4.7 breaks down each significant relationship between bank change and rainfall scenarios, the R^2 value and the p-value. Table 4.8 breaks down each significant relationship between total cross sectional area change and rainfall scenarios, the R^2 value and the p-value. Figure 4.7 shows the strongest statistical result for the Training Area 51 gully: peak intensity rainfall versus bank area change. Because of the curve in the graph, different transformations were attempted to improve the data's fit to a line; but overall, the lack of consistency from gully to gully did not warrant further transformations.

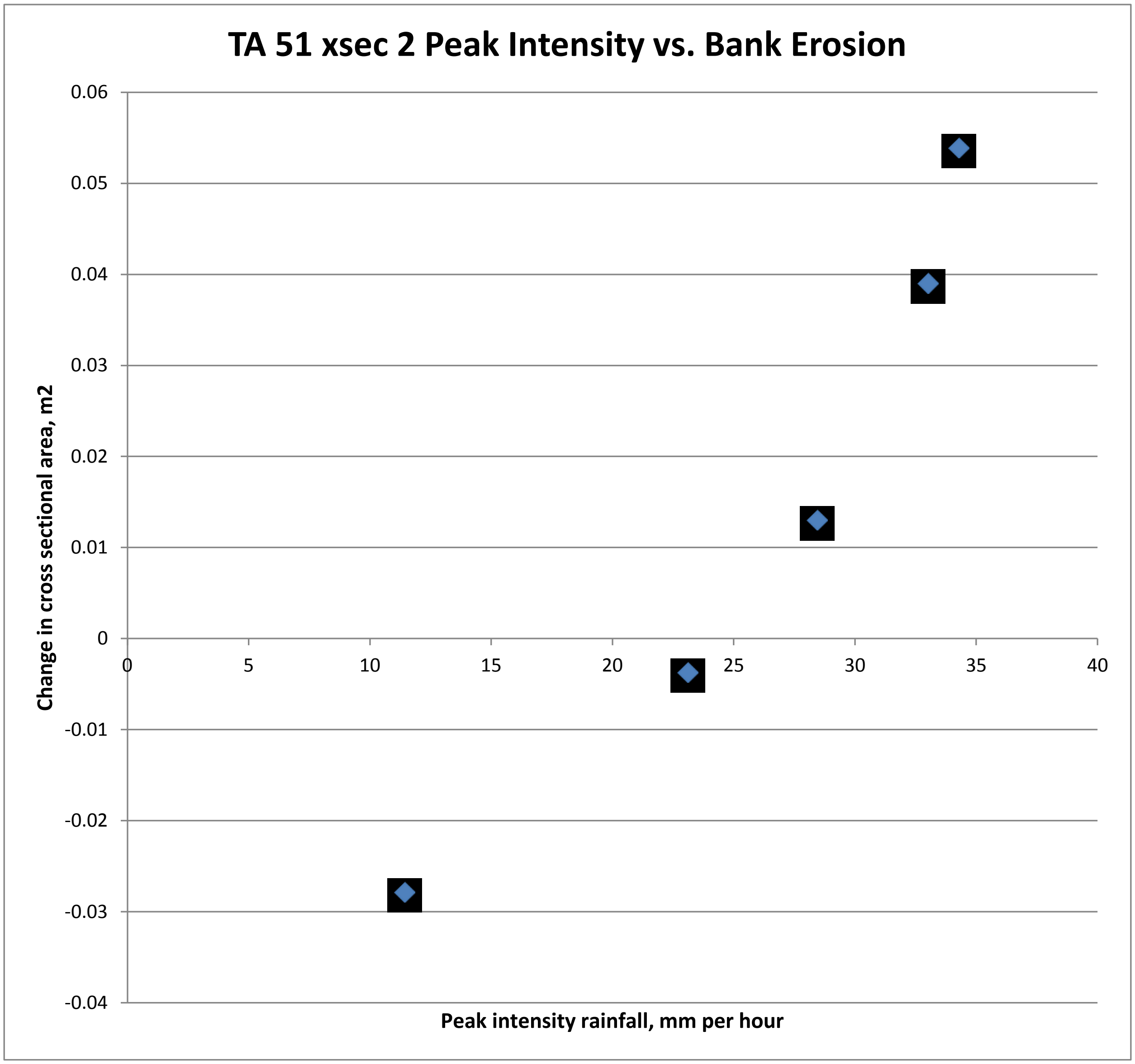
Table 4.7 Bank cross sectional area change versus rainfall scenarios

Gully ID	**XS #**	**Total Rain Depth**		**Largest Storm**		**Antec.Storm**		**Peak Intensity**	
TA		Adj R2	p-value	Adj R2	p-value	Adj R2	p-value	Adj R2	p-value
51	2	0.610	0.121	*0.793	0.027	0.800	0.041	**0.891**	**0.0099**
	3	0.038	0.360	0.567	0.088	0.641	0.065	0.329	0.184
**Yellow highlights mark significant relationships*									

Table 4.8 Total cross sectional area change versus rainfall scenarios

Gully ID	**XS #**	**Total Rain Depth**		**Largest Storm**		**Antec.Storm**		**Peak Intensity**	
TA		Adj R2	p-value	Adj R2	p-value	Adj R2	p-value	Adj R2	p-value
51	2	0.059	0.345	0.391	0.155	0.280	0.208	***0.528**	**0.101**
	3	0.063	0.342	0.856	0.016	0.786	0.029	**0.548**	**0.094**
**Yellow highlights mark significant relationships*									

Figure 4.7 The strongest relationship: peak intensity rainfall versus bank change in TA 51 Cross Section 2



When pairing peak intensity rainfall with NDVI (the leaf greenness density variable) and running multiple variable regression against cross sectional area change, Training Area 51's results are also significant (peak intensity rainfall and NDVI were the only paired rain and vegetation variables that had some successful results). Both cross sections 2 and 3 showed significant results with 90% confidence or better. Table 4.9 shows significant relationships between cross sectional area change, the vegetation index NDVI, and peak intensity rainfall. Results meeting the significance criteria are highlighted.

Table 4.9 Significant relationships: peak intensity rainfall paired with NDVI

Gully ID	XS ID	Bank, Bed or Total area, and type of relationship	Peak Intensity paired with NDVI	
TA			Adj R2	p-value
51	2	*Bank – both positive	0.956	0.022
	2	Total – both positive	0.803	0.098
	3	Bed – both positive	0.693	0.154
	3	Total – both positive	0.816	0.092
Yellow highlights mark significant relationships				

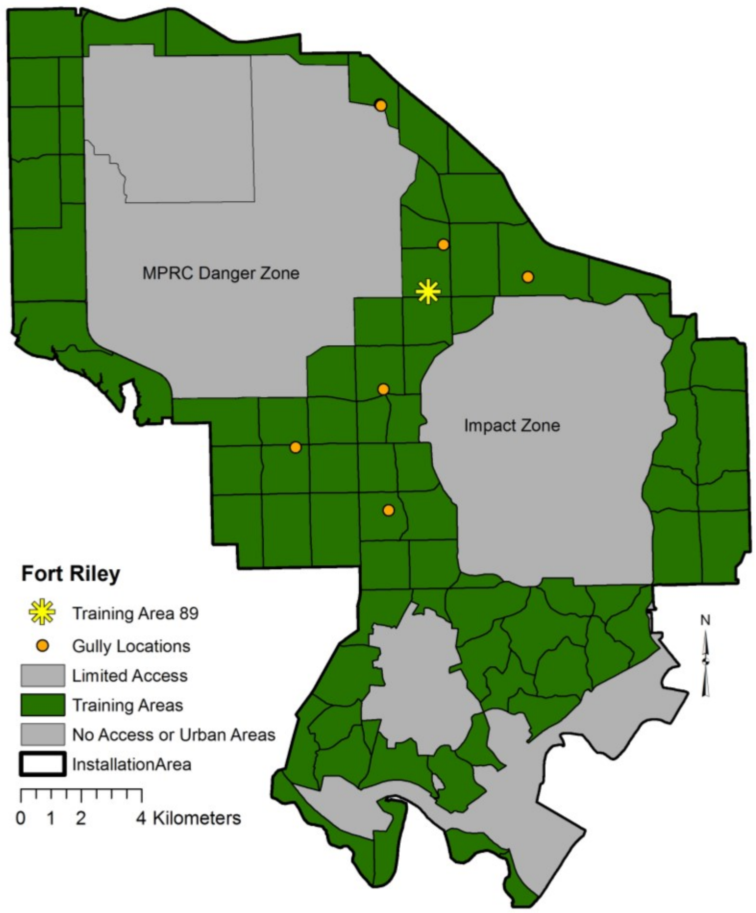
In summary, both cross sections in the Training Area 51 gully show signs of fill and bank erosion/widening. Overall, the long. pro. for this gully also shows bed filling. For Training Area 51, the three largest or most intense rainfall events correspond with the three largest erosion occurrences in Cross Section 3 – bank erosion, specifically. Statistically, this gully shows the most significant relationships between cross sectional area change and rainfall events out of all the studied Fort Riley gullies – as rainfall events got larger or more intense, gully erosion was greater, with a near-linear relationship. When peak intensity rainfall and NDVI were combined and compared to erosion, this gully again showed significant results for both cross sections 2 and 3. However, the rainfall and vegetation variables both showed a positive relationship with erosion when analyzed together: erosion increases when rainfall and greenness density increases. We would expect to see erosion increase when greenness density decreases.

Gully in Training Area 89

Gully 89 Overview

Figure 4.8 shows the location of the gully in Training Area 89. The gully in Training Area 89 is a gully channel within a larger channel. The larger channel approaching the headcut channelizes the flow to the headcut, which is semi-stabilized by natural cobble-sized rock. The headcut drops 0.4 meters, and the channel is closer to 1.2 meters deep further down the slope. Aerial photos show that tank tracks most likely created the gully. Three cross sections were monitored: Cross Section 2 (0.6 meters below the headcut) and Cross Section 3 (10.7 meters below the headcut, in the deeper part of the channel) were the only two cross sections that showed change.

Figure 4.8 Location of Training Area 89 Gully



Trends

Tables 4.10 and 4.11 show Cross Section 2 and Cross Section 3 area change (bank, bed and total change) by date of survey. (Note: bed change plus bank change for a cross section do not necessarily add up to total cross section change due to the way RIVERMorph®, the software used, calculates area.) Cross Section 2's bed filled and both banks widened, while Cross Section 3 showed little bed change, and one bank showed significant erosion. Certain time periods showed more erosion than others, similar to the erosion that occurred in the Training Area 51 gully. For Cross Section 2, the right bank clearly failed/eroded between 6-3-13 and 10-10-13, and banks eroded again between 10-10-13 and 8-1-14. These two time periods match two of the three time periods when Gully 51 saw the most change. For Gully 89 Cross Section 3, the most noticeable erosion occurred between 6-26-12 and 5-14-13. In those three time periods (June 2012 to May 2013; June 2013 to October 2013; and October 2013 to August 2014) the largest storms and the storms with the highest peak rainfall occurred, and the most noticeable erosion occurred, just as was seen in Training Area 51. However, since one rain gauge was used for the whole study area, the rain data may not be completely accurate. Regardless of rain data accuracy, the timeframes that contain the most erosion are the same. Table 4.12 shows area change compared to the largest and peak rain events throughout the study period. The three largest events, highlighted in blue, correspond to the largest amount of bank erosion, highlighted in yellow.

The long. pro. overlay from May 2012 to May 2013 indicated 1 m^2 of deposition over 29 meters of gully bed, or an average of 0.034 m^2 of deposition per meter of gully bed. Although some rock fall occurred at the headcut, Training Area 89's headcut showed no measureable retreat rates.

Table 4.10 Total change, bank change, and bed change of TA 89 Cross Section 2

Date of survey	**Bank area change (m^2)**	**Bed area change (m^2)**	**Total area change (m^2)**
5.30.12	Initial survey		
6.26.12	0.022	-0.028	-0.019
5.14.13	0.034	-0.009	0.046
6.3.13	0.023	0.000	0.028
10.10.13	0.150	-0.009	0.167
8.1.14	0.056	-0.046	-0.009
Net Change	**0.286**	**-0.093**	**0.214**

Table 4.11 Total change, bank change, and bed change of TA 89 Cross Section 3

Date of survey	**Bank area change (m^2)**	**Bed area change (m^2)**	**Total area change (m^2)**
5.30.12	Initial survey		
6.26.12	-0.056	-0.037	-0.111
5.14.13	0.353	0.000	0.362
6.3.13	0.056	0.009	0.065
10.10.13	0.149	0.019	0.204
8.1.14	-0.065	-0.037	-0.111
Net Change	**0.437**	**-0.046**	**0.409**

Table 4.12 TA 89 bank erosion related to rainfall events

Date of survey		6/26/2012	5/14/2013	6/3/2013	10/10/2013	8/1/2014
Rainfall since the preceding survey	Total depth (mm)	76	409	70	456	453
	Largest storm series (mm)	61	122	60	152	119
	Largest event w/antecedent moisture (mm)	61	122	60	140	114
	Highest peak intensity (mm/hr)	23	28	11	34	33
Bank Area Change	Right bank (m^2)	-0.009	0.028	0.009	0.028	-0.009
	Left bank (m^2)	-0.046	0.325	0.046	0.121	-0.056
**Blue highlights mark largest rainfall periods; **Yellow highlights mark largest erosion rates in the study period*						

For statistical analysis of gully change through time, Cross Section 3 had no significant relationships to rainfall scenarios or vegetation conditions. However, Cross Section 2's bank area change had a significant, positive linear relationship to largest storm series, and a curvilinear positive relationship to largest storm with antecedent moisture and peak rainfall intensity scenarios. Table 4.13 shows Cross Section 2's significant relationships to rainfall scenarios along with R^2 and p-value. Results meeting the significance criteria are highlighted. Just like Training Area 51, the curve in the relationship between bank change and peak rainfall intensity would benefit from a transformation (See Figure 4.9). But because of overall inconsistencies from gully to gully, and because these models are intended to communicate trends rather than to predict future amounts of erosion, a take-away message is that erosion rates increase more quickly with increasing peak rain intensity. Another result similar to Training Area 51 is that when pairing peak intensity rainfall with NDVI and running multiple variable regression against cross sectional area change, Training Area 89's Cross Section 2 results are significant (peak intensity rainfall and NDVI were the only paired rain and vegetation variables that had some successful results). Table 4.14 shows the details.

Table 4.13 Bank cross sectional area change versus rainfall scenarios

Gully ID	XS #	Total Rain Depth		Largest Storm		Antec.Storm		Peak Intensity	
TA		Adj R2	p-value	Adj R2	p-value	Adj R2	p-value	Adj R2	p-value
89	2	0.201	0.252	*0.530	0.100	**0.418**	**0.144**	**0.233**	**0.233**
	3	-0.128	0.513	-0.057	0.441	0.018	0.377	-0.303	0.809
**Yellow highlights mark significant relationships*									

Figure 4.9 Training Area 89 Cross section 2 bank showing non-linear pattern, needing potential transformation

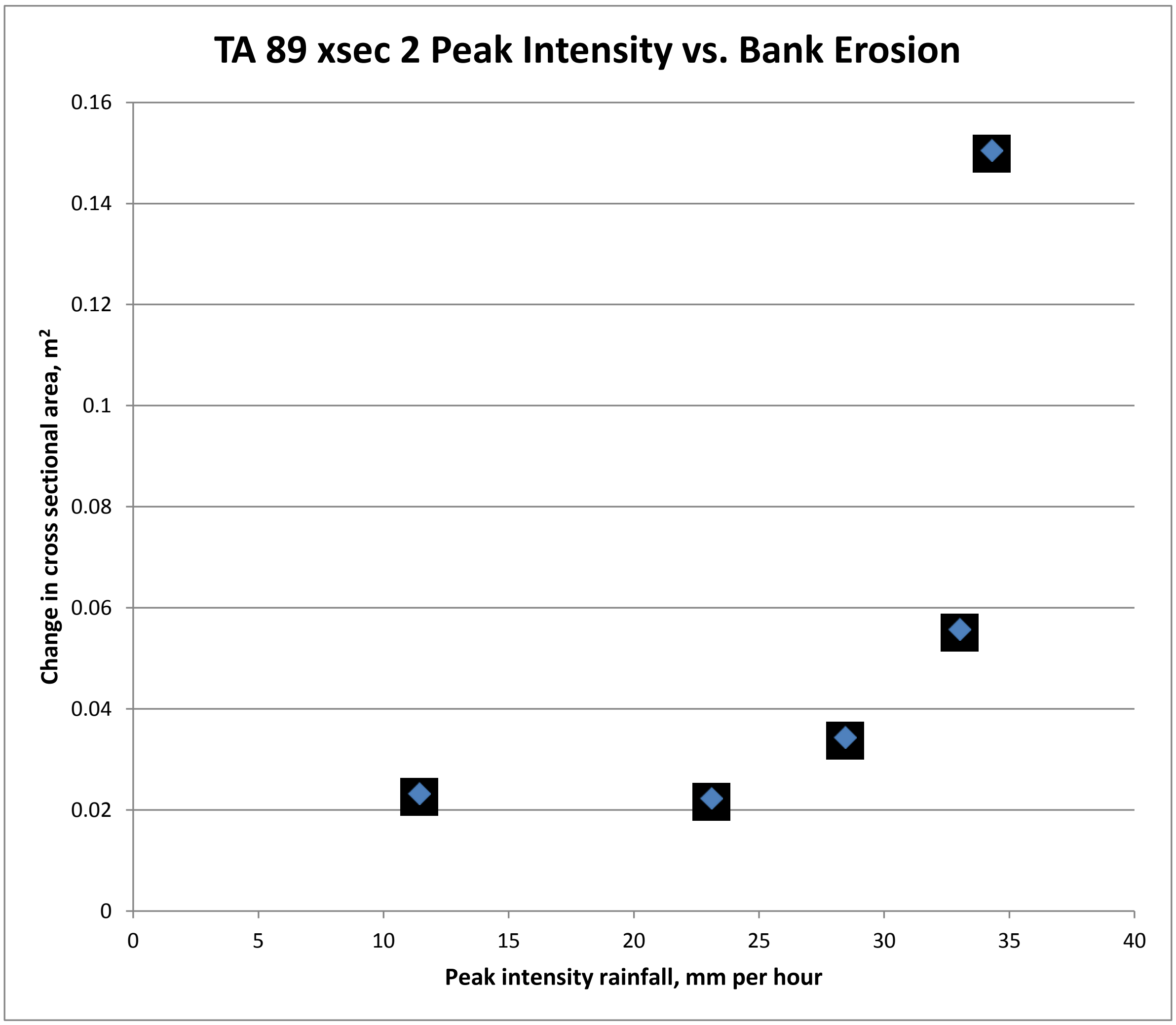


Table 4.14 Significant relationships: peak intensity rainfall paired with NDVI

Gully ID	XS ID	Bank, Bed or Total area, and type of relationship	Peak Intensity paired with NDVI	
TA			Adj R^2	p-value
89	2	*Bank – both positive	0.815	0.093
	2	Total – both positive	0.688	0.156
Yellow highlights mark significant relationships				

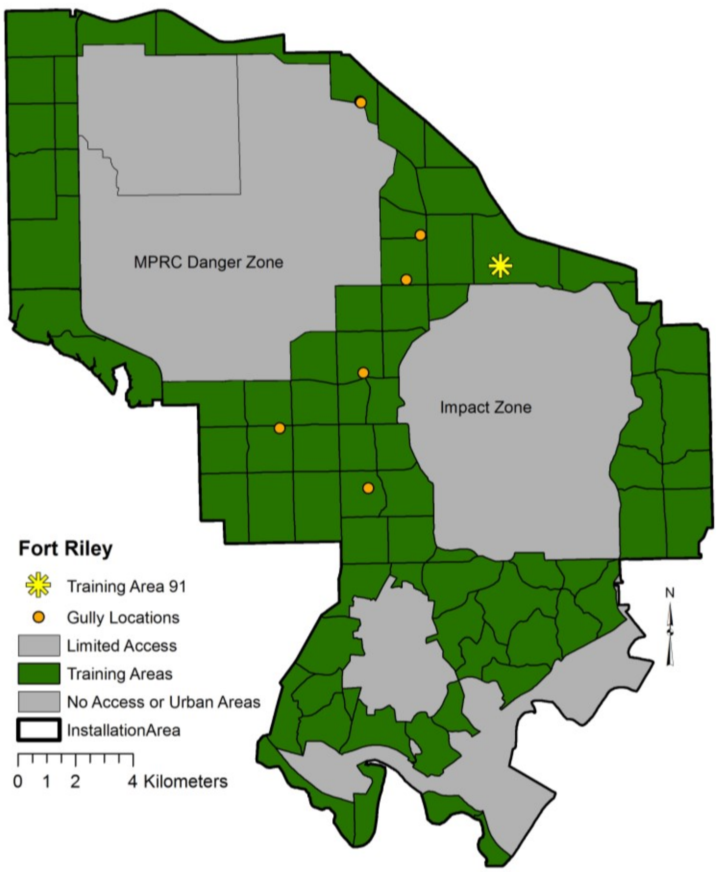
In summary, Training Area 89's Cross Section 2 showed filling and bank widening, while Cross Section 3 just showed bank failure/the left bank slope becoming more gentle. The Training Area 89 long. pro. overlay from 2012 to 2013 showed slight bed filling as well. The two largest storm series and largest peak rainfall event correspond to noticeable erosion in Cross Section 2, and the third largest rainfall events correspond to noticeable bank failure in Cross Section 3. These results are consistent with Training Areas 51 results. Statistically, the Training Area 89 gully results are very similar to Training Area 51 – both have significant relationships of erosion related to largest storms and peak intensity, both have a curvilinear relationship between erosion and peak intensity, and both gullies have a significant relationship when peak rainfall intensity and NDVI are compared to erosion in double-variable analysis.

Gully in Training Area 91

Gully 91 Overview

Figure 4.10 shows the location of the gully in Training Area 91. The gully in Training Area 91 is a smaller gully that drains into a natural draw near an ephemeral channel and vehicle crossing. The headcut drops 0.4 meters, and the gully is 22 meters long. This gully has two cross sections, and Cross Section 2 is the only cross section that showed change. In early 2013, at least two tanks drove through the gully, altering the benchmark pin and Cross Section 2's end pins. A new initial survey had to be reconstructed, and data previous to the disturbance could not be accurately compared to any new data. Because the disturbance greatly reduced the number of comparable data points for erosion, the Training Area 91 gully showed no clear periods of erosion, the longitudinal profile comparison was compromised, and there were no conclusive or significant statistical results.

Figure 4.10 Location of Training Area 91 Gully

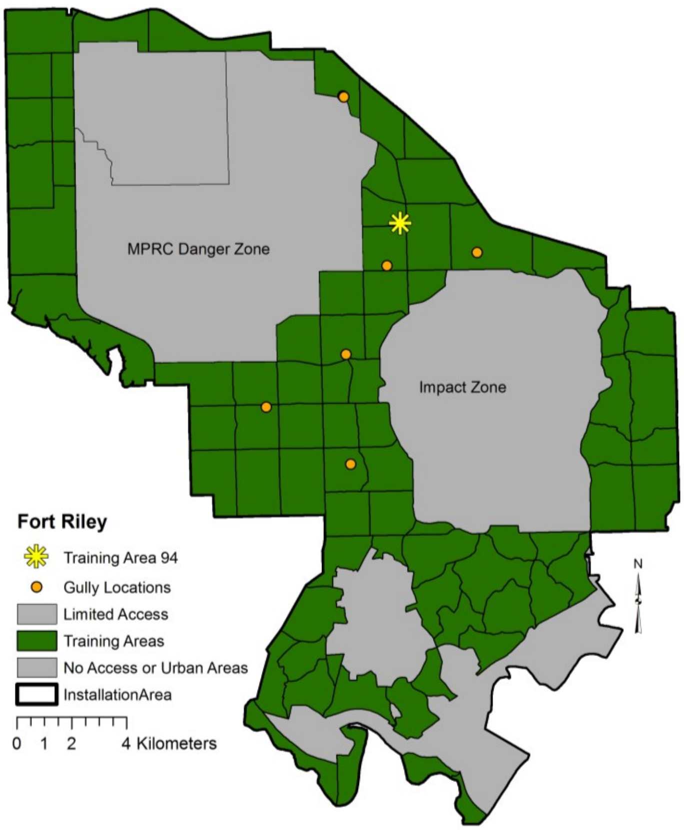


Gully in Training Area 94

Gully 94 Overview

Figure 4.11 shows the location of the gully in Training Area 94. The gully in Training Area 94 is the largest gully in the study with the largest drainage area. There are two cross sections in gully 94. Cross Section 2 is 4.1 meters wide, but the gully is slightly wider further downstream. The depth from top of headcut to bottom of plunge pool is 1.6 meters. The gully seems to be growing by means other than overland flow, because there is no rill or smaller channel flowing toward the gully head; smooth brome surrounds the gully head, with a sudden headcut drop, unlike the others that show erosion above the headcut. Cross Section 2 was the only cross section that showed change.

Figure 4.11 Location of Training Area 94 Gully



Trends

Table 4.15 shows cross sectional area change for Cross Section 2 by survey date. This gully was the only gully in the Fort Riley study that became wider and deeper. Gully 94's bed clearly incised between 6-26-12 and 5-13-13 as seen in the cross section overlays (Figure 4.18). The overlays also show bank widening between 5-13-13 and 10-10-13, and further bed incision between 10-10-13 and 8-1-14. These timeframes also correspond with the greatest amounts of rainfall – see Table 4.16, which compares Cross Section 2's erosion with rainfall scenarios. Another factor that sets this gully apart from the others is that neither of Cross Section 2's bank slopes became gentler – "top of bank" locations remained in relatively the same spot, and the banks actually became more vertical, as seen in Figure 4.12.

The long. pro. overlay from May 2012 to May 2013 indicated 0.45 m^2 of erosion or incision over 18 meters of gully bed, or an average of 0.025 m^2 of erosion per meter of gully bed. The comparison of long. pro. overlays confirms that Gully 94 is the only gully in this Fort Riley study that incised rather than filled. Also, this gully's headcut retreated the most out of all the main headcuts that were monitored. Retreating only 2.5 centimeters in 2013, the headcut retreated 0.45 meters from September 2013 to August 2014.

Table 4.15 Total change, bank change, and bed change of TA 94 Cross Section 2

Date of survey	**Bank area change (m^2)**	**Bed area change (m^2)**	**Total area change (m^2)**
5.30.12	Initial survey		
6.26.12	-0.028	-0.009	-0.065
5.13.13	0.251	0.056	0.316
10.10.13	0.149	0.009	0.177
8.1.14	0.427	0.009	0.465
Net Change	**0.799**	**0.065**	**0.892**

Figure 4.12 Change of bed dimensions after 6-26-12, which occurred in 4 different cross sections (Also showing significant change between 10-10-13 and 8-1-14)

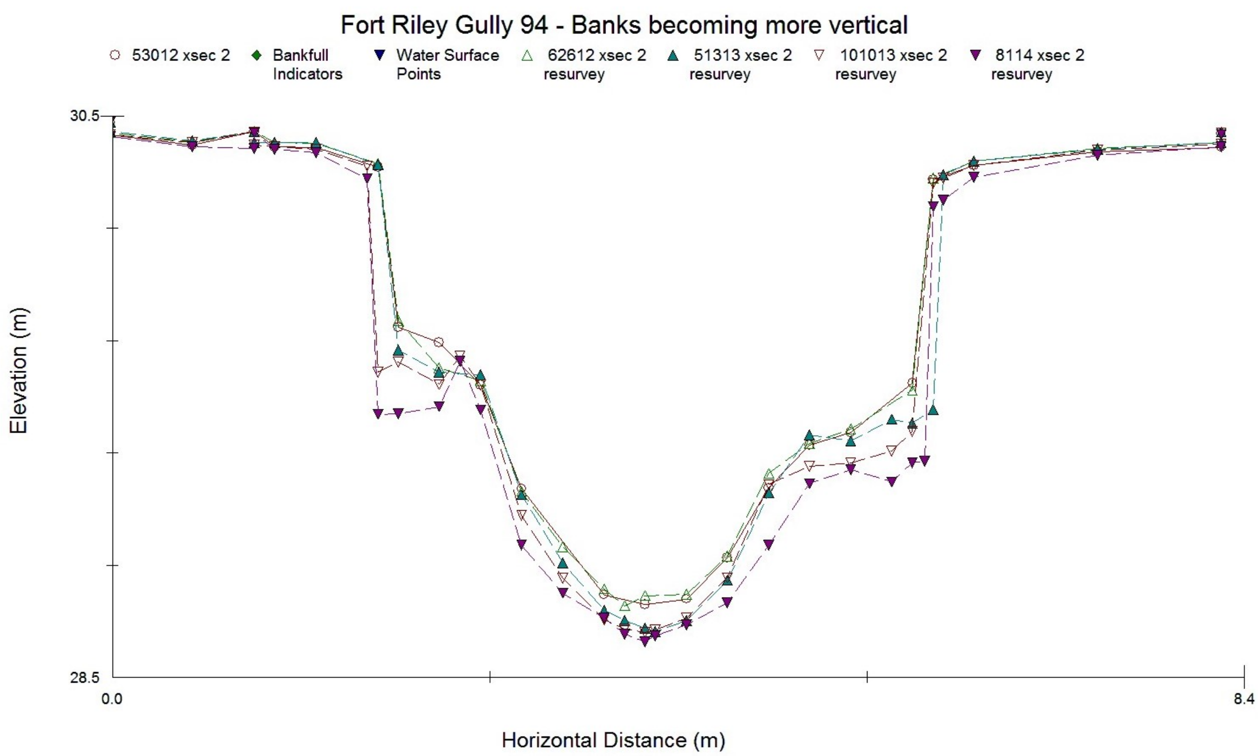


Table 4.16 TA 94 bank erosion related to rainfall events

Date of survey		6/26/2012	5/14/2013	10/10/2013	8/1/2014
Rainfall since the preceding survey	Total depth (mm)	76	*409	456	453
	Largest storm series (mm)	61	122	152	119
	Largest event w/antecedent moisture (mm)	61	122	140	114
	Highest peak intensity (mm/hr)	23	28	34	33
Bank Area Change	Right bank (m^2)	-0.037	**0.195	-0.009	0.260
	Left bank (m^2)	0.009	0.056	0.158	0.167
**Blue highlights mark largest rainfall periods; **Yellow highlights mark largest erosion rates in the study period*					

The gully in Training Area 94 showed no significant or strong statistical results for Cross Section 2's area change versus rainfall scenarios or vegetation conditions.

In summary, Cross Section 2 showed both incision of the bed and widening of both lower banks. The longitudinal profile shows incision at the plunge pool, and varying cut and fill along the rest of the bed. Noticeable erosion occurred between June 2012 and May 2013; May 2013 and October 2013; and October 2013 and August 2014. Statistical comparisons between cross section change, rainfall scenarios, and vegetation condition were not significant.

Gully in Training Area 98

Gully 98 Overview

Figure 4.13 shows the location of the gully in Training Area 98. The gully in Training Area 98 is a 5-channel gully system that was clearly created by tank tracks. Five cross sections were initially surveyed, but only cross sections 2 and 4 were consistently resurveyed. Cross Section 2 spans one channel, and Cross Section 4 spans three channels, named from left to right: 4a, 4b, and 4c. Figure 4.14 illustrates the different channels in Cross Section 4. The Training Area 98 gully channels are medium in size. The soils in the gully are noticeably higher in clay content, less fertile, and more exposed to sun and wind.

Figure 4.13 Location of Training Area 98 Gully

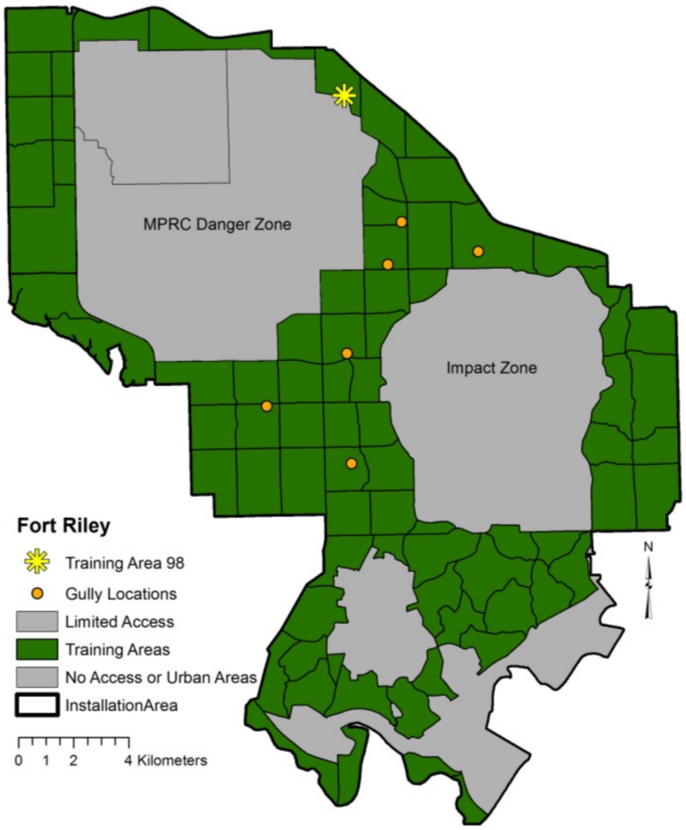
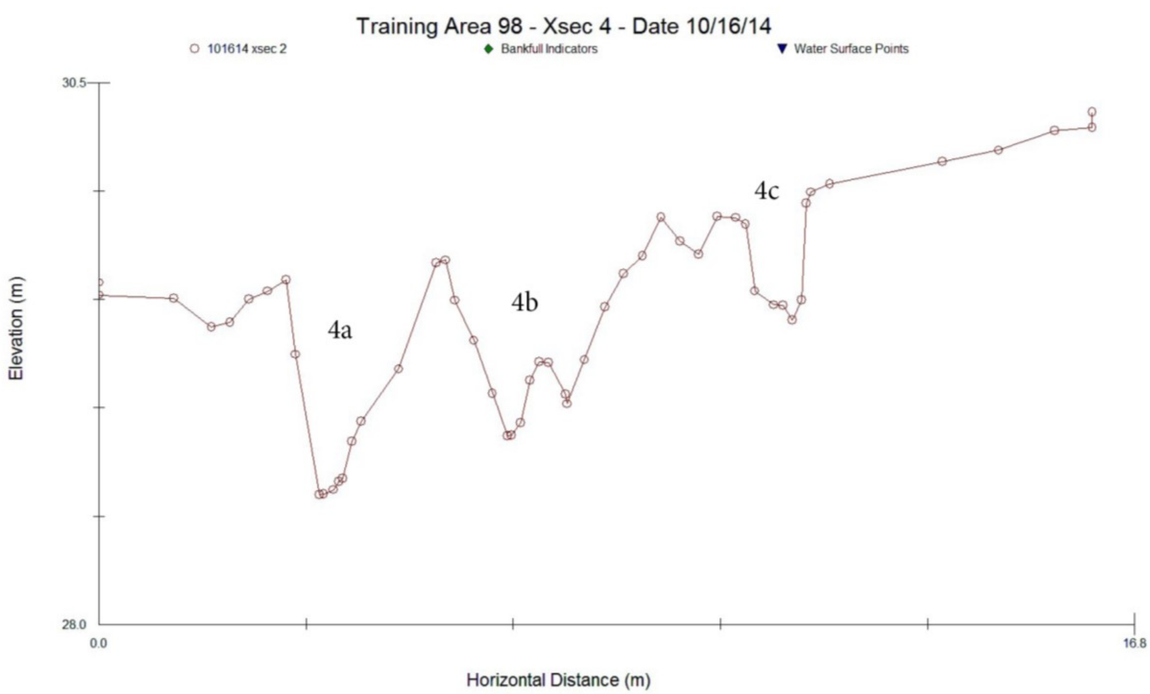


Figure 4.14 Cross Section 4 spanning three channels – named left to right 4a, 4b, and 4c



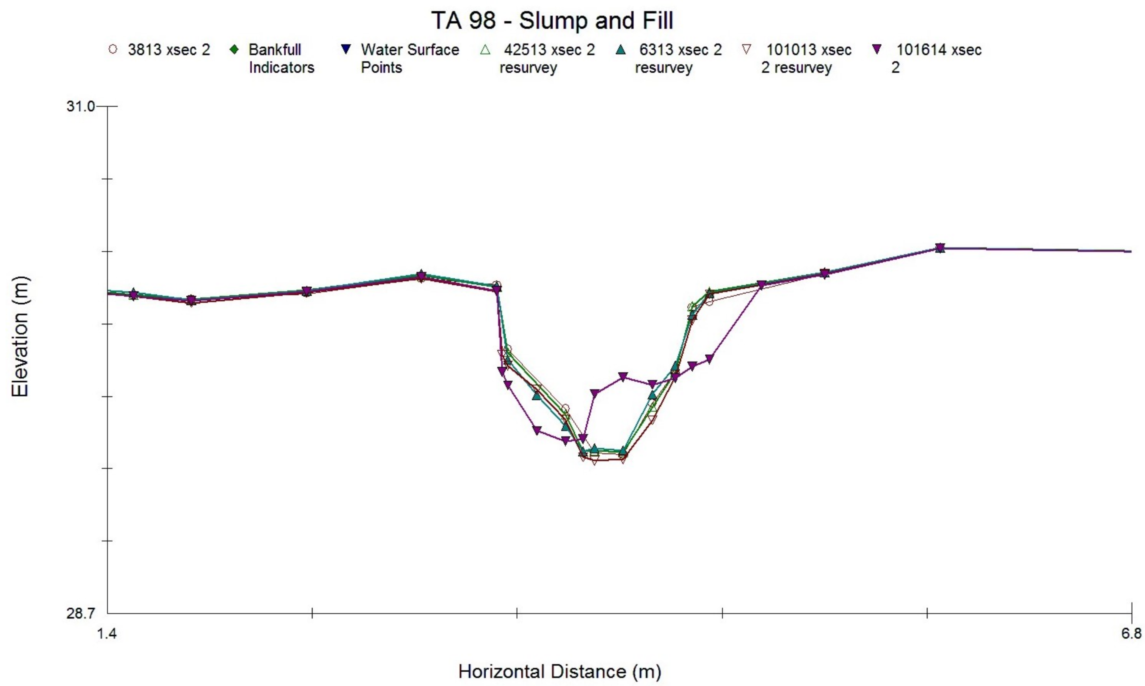
Trends

Table 4.17 shows the changes in cross sectional area for Cross Section 2 by survey date. Overall, one bank slope in Cross Section 2 became more gentle, and one bank in Cross Section 4 eroded, making the channel wider. Only one timeframe showed clear change – between 10-10-13 and 10-16-14, Cross Section 2 experienced bank slump and a shifting of channel position (See Figure 4.15). Cross Section 4 shows cycles of cut and fill, but no obvious drastic change in one time period. There are 5 headcuts in this gully system, but only the headcut just above Cross Section 2 was monitored closely. It grew 7.6 cm from June 2013 to October 2014.

Table 4.17 Total change, bank change, and bed change of TA 98 Cross Section 2

Date of survey	Bank area change (m^2)	Bed area change (m^2)	Total area change (m^2)
3.8.13	Initial survey		
4.25.13	-0.012	0.006	-0.019
6.3.13	0.013	-0.005	0.019
10.10.13	0.030	0.022	0.056
10.16.14	0.111	-0.105	0.028
Net Change	**0.142**	**-0.082**	**0.084**

Figure 4.15 Change in cross sectional dimensions after 10-10-13



Statistically, change for Cross Section 2 in Training Area 98 showed a relationship with peak intensity rainfall, but it is not as strong of a relationship as in Training Areas 51 and 89. Instead, this Cross Section 2 showed a stronger relationship to largest storm series and storms with antecedent moisture. Table 4.18 shows the strength of each rainfall relationship - results meeting the significance criteria are highlighted. Cross Section 4 did not show any significant relationships when compared to single rainfall variables, but when peak intensity is paired with NDVI, there is a very strong relationship to cross sectional area change of channel 4c. However, this is the only relationship of peak intensity and NDVI that we would expect to see: as peak rainfall intensity increases, erosion increases; and as greenness density decreases in terms of vegetation, erosion increases. The gullies in Training Areas 51 and 89 show significant relationships between cross sectional area change, peak rainfall intensity, and NDVI, but in those cases, as greenness density increases, gully erosion also increases. Table 4.19 shows values for the paired relationships for Gully 98.

Table 4.18 Total cross sectional area change versus rainfall scenarios

Gully ID	XS #	Total Rain Depth		Largest Storm		Antec.Storm		Peak Intensity	
TA		Adj R2	p-value	Adj R2	p-value	Adj R2	p-value	Adj R2	p-value
98	2	0.175	0.329	*0.790	0.073	0.849	0.052	0.602	0.143
	4	-0.499	0.980	-0.500	0.990	-0.482	0.889	-0.499	0.972
*Yellow highlights mark significant relationships									

Table 4.19 Significant peak intensity rainfall paired with NDVI

Gully ID	XS ID	Bank, Bed or Total area	Peak Intensity paired with NDVI	
TA			Adj R2	p-value
98	4a	Bed – both negative	0.934	0.148
	4b	Bank – rain negative, NDVI positive	0.926	0.158
	4c	*Bank – rain positive, NDVI negative	0.992	0.053
*Yellow highlights mark significant relationships				

In summary, Cross Section 2 experienced bank slump and a channel shift in the timeframe between the 10-10-13 and 10-16-14 surveys. One bank in Cross Section 4 became wider. None of the monitored headcuts retreated more than 8 centimeters from Spring 2013 to Fall 2014. Statistics again show a strong relationship between peak rainfall intensity, NDVI, and cross section area change of Cross Section 4c, like Training Areas 51 and 89, but the relationships have different signs.

All gullies' response to a similar timeframe of rainfall

In examining all gullies' response to a similar timeframe of rainfall conditions, several individual variables that might contribute to growth were tested, such as drainage area, channel slope, vegetation conditions, gully cross section width or depth, and the inherent erosivity of the soil. Each variable was tested individually, then combined into double and triple variables in every way possible. Total gully change was the dependent variable, and then gully banks and beds were separated. More than 50 double-variable scenarios, more than 40 single-variable scenarios, and more than 30 triple-variable scenarios were run. In the end, 13 scenarios are significant at the 95% confidence interval, but there is no consistency across gullies. For example, the following three scenarios are all significant at the 95% confidence interval:

1. The relationship between drainage area and NDVI is strong, but only for the bed change October 2013 data.
2. NDVI as a single variable has a strong relationship to total cross section change, but only for the 2014 data.
3. The triple scenario of slope, t-factor (an erodibility factor) and topwidth is significant at the 95% confidence interval with an adjusted R^2 of 0.995 – but only for the 2014 bank erosion data. Also, out of all scenarios, this is the only relationship that the t-factor contributes to significant results.

The results were expanded to include anything significant at the 90% confidence interval, which changed the number of significant relationships from 13 to 22; but again there was no consistency across timeframes or cross section area type (total, bed or bank). As a whole, drainage area, cross section depth, and NDVI were the variables that had the most frequent significant relationships, but results were not consistent over different timeframes with different rainfall and seasonal conditions. Some of the single-variable relationships could have been made more strong through transformations, but again, the relationships were not consistent over multiple timeframes, so any improvement of one scenario would still have no improving effect on the dataset as a whole.

Longitudinal profiles were analyzed in a similar way. Five of the seven gullies had accurate long. pro. resurveys, and four of those five resurveys showed deposition. To check to see if deposition on the gully bed could be attributed to drainage area, gully bed slope, or inherent soil erosivity factors (t and k), the filling seen in the four sites' long. pros. was graphed against each variable: bed slope, drainage area, t-factor, and k-factor. Including rainfall and vegetation data would not have been helpful, since conditions fluctuated between survey dates (May 2012 and March or May, 2013). The results were inconclusive, mostly due to the small number of observations; however, the greatest amounts of deposition correspond to gentler slopes and a higher t-factor (see Table 4.20).

Table 4.20 Bed deposition, could be related to bed slope and t-factor

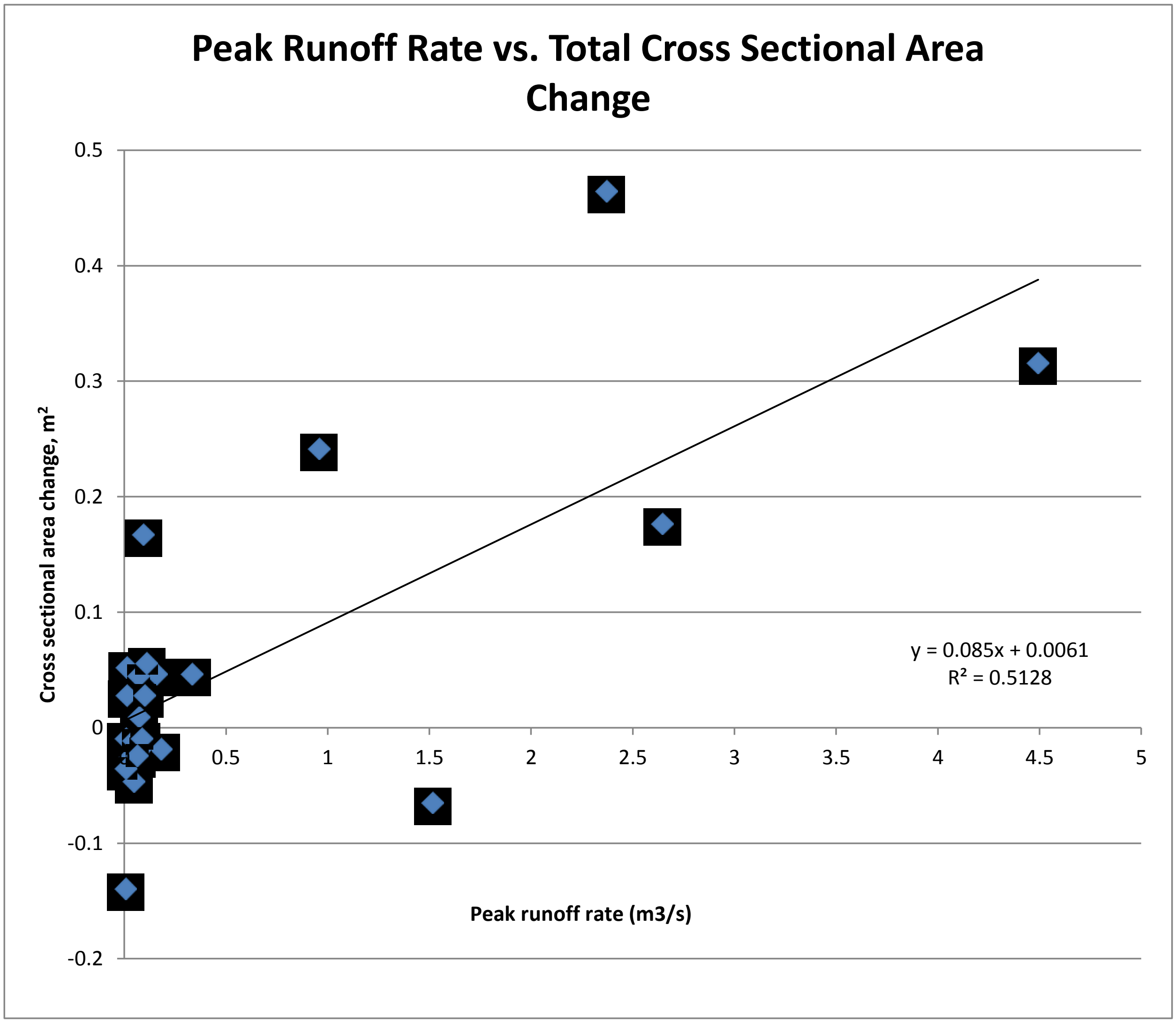
Gully ID	Change m^2	Bed Slope	Drainage Area (hectares)	t-factor	k-factor
36	0.022	0.013	246,106	0.37	4
42	0.031	0.022	24,923	0.37	5
51	0.018	0.031	3,084	0.24	3
89	0.010	0.032	23,669	0.32	5

TR-55

Due to rules of statistics, any attempts described above could not incorporate rainfall and all of the land conditions variables together in one analysis, particularly because all of the gully sites have the same rainfall data. Because it is known that gully erosion is complex, an analysis that incorporated all rain and land variables was needed. As an additional attempt at analyzing the data, the TR-55 peak runoff rate was calculated for each gully, using the largest daily rainfall event in between surveys. Peak runoff rate was then made an independent variable and graphed with cross section bed, bank or total change as the dependent variables. Using TR-55, all gullies could be compared through all timeframes, with drainage area, flow length, slope, soils, and vegetation condition all represented through the calculated peak runoff rate. Results show that the relationship between peak runoff rate and total cross sectional area change is positive but weak, with an adjusted R^2 of 0.51. Figure 4.16 shows the plotted graph.

Peak runoff rate was also compared to the four gullies that experienced bed deposition, as shown through the long. pro. overlays. The comparison showed no relationship between gully bed filling and peak runoff rate.

Figure 4.16 Linear attempt at the TR-55 relationship between peak runoff rate and total cross sectional area change



Fort Riley results summary

Results for Fort Riley can be separated into 5 categories:

1. Gullies that did not provide information. Due to tank disturbance mid-study, the gully in Training Area 91 did not provide helpful erosion data.
2. Gullies that had at least one cross section showing filling and widening trends. The gullies in Training Areas 36, 42, 51 and 89 all showed signs of widening, banks becoming more gentle, and filling of the bed.
3. Gullies showing deepening and widening trends. The Training Area 94 gully was the only one that incised at the plunge pool. Also, this gully's banks did not widen at the top, but steepened as mid-bank soil eroded and slumped into the gully.
4. Gullies that show a relationship to rainfall and vegetation. Gullies in Training Areas 51, 89 and 98 show statistical relationships between rainfall, greenness density, and cross section change. For each of the three gullies, the peak rainfall intensity variable had the most consistent relationship to area change.
5. Filling trends along the length of the bed. Longitudinal profile data shows that four of the seven gully beds filled, at least slightly.

McPherson Results

On all three McPherson fields, deposition occurred more often than did erosion. However, fluctuations of erosion and deposition were detected through cross section surveys. The three fields that were studied – Wedel, Schmidt, and Goerhing – responded differently to similar rainfall conditions, which was expected due to their different land management plans. However, rain data from one rain gauge (on the Wedel field) was used for all three fields, making rain comparisons less than ideal, especially for the Schmidt field, which is the furthest from the rain gauge (about 14 kilometers). The following results are separated by each of the three studied fields, including observations detected through survey data, followed by statistical results. All cross section and longitudinal profile overlay graphs are in Appendix B. Data for extrapolation of cross section change to the length of the gully are in Appendix C, including each survey date and net change.

Introduction to Statistical Results

As with the Fort Riley data, the McPherson data was statistically examined in two different ways: 1) Each cross section's change through time as the dependent variable, and peak rainfall or largest daily event as the independent variable (unlike Fort Riley, NDVI was not used to represent vegetation conditions at this stage, because the data was not as readily-available for McPherson); 2) All cross sections' response to the same rainfall conditions (all cross sections' change as dependent variable) with drainage area and slope as independent variables. Fewer significant relationships were found in McPherson gullies, so the criteria for significance was changed from a p-value of 0.10 or less to a p-value of 0.25 or less. The Fort Riley study included several more variables that weren't included in the McPherson study: gully width, gully depth, and soil erosivity factors. Because McPherson gully cross section sizes were relatively similar in each studied channel or tributary, and the soil properties on each field were similar, those variables were not included.

Examining rainfall and each cross section's change through time

Each cross section in all three McPherson fields was compared to the largest daily rainfall event and the peak hourly rainfall event between resurveys. Graphs were produced that compared each cross section's change through time in relationship to the two rainfall factors. Some conclusions can be made, but the depositional nature of all three fields made it difficult to come to many future predictions about erosion.

Examining all cross sections in one field's response to the same timeframe/rainfall conditions

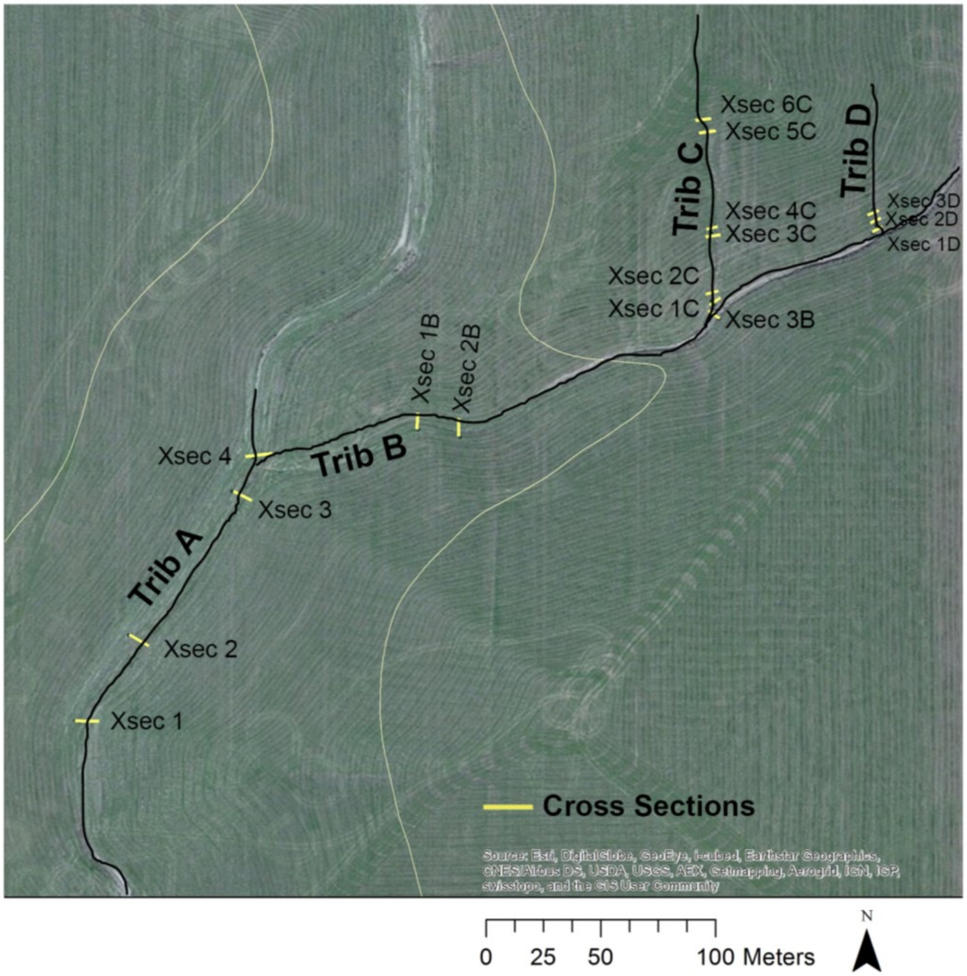
Because all McPherson fields have the same rainfall data, we cannot look at cross section change between different fields in relation to rainfall. However, we can look at all cross sections' change in relationship to slope and drainage area if we separate them by time of survey. For example, we can compare all of Wedel's cross sections' responses to the timeframe between the last survey in 2013 and the first survey in 2014. Comparing different cross sections within the same gully in this manner means our variables are not independent of one another, which violates statistical rules of regression. But by looking at all cross sections' response to the same timeframe of rainfall, we can see how cross sections located in different areas of the field respond differently.

Wedel Field

Overview of cross section change

The Wedel field is a no-till field with a large gully channel running through it – three branches or tributaries of the main gully were studied. Figure 4.17 is a map of the Wedel field tributaries and cross section locations. The cross sections to the Northeast are at higher elevations in the watershed. For much of the study period, the soil surface of the field was not protected by crop residue. The first resurvey of cross sections in June 2012 showed that every cross section eroded, which is interesting since it was a dry summer: from May through September 2012, 152 millimeters of rain depth were recorded, as opposed to 546 millimeters in 2013 and 572 millimeters in 2014 (Kansas Mesonet, 2014a). After the June 2012 survey, cross sections in the lower elevations of the gully channel fluctuated between sediment deposition and erosion, while cross sections in the steeper, higher areas of the field's watershed kept eroding. In summer 2013, two more cross sections in Tributary C were added, as well as a new small Tributary (Trib D), to capture erosion data higher up in the watershed. Sixteen total cross sections were monitored in the Wedel field.

Figure 4.17 Wedel Cross Section placement



A summary of cross section change related to rainfall data through time is shown in Figure 4.18, and Table 4.21 summarizes net change across cross sections by date. Cross section change data through time for the Wedel field is shown in Table 4.22. Negative numbers indicate sediment deposition or fill (cross sectional area shrinking), while positive numbers indicate erosion (cross sectional area increasing). Table 4.23 shows net change for each cross section, indicating at the end of the study whether the cross section is larger due to erosion or smaller due to deposition. Figures 4.19 and 4.20 are cross section overlay examples showing deposition and erosion at different locations along the gully channel.

Figure 4.18 Wedel cross section change: Cross section change and rainfall

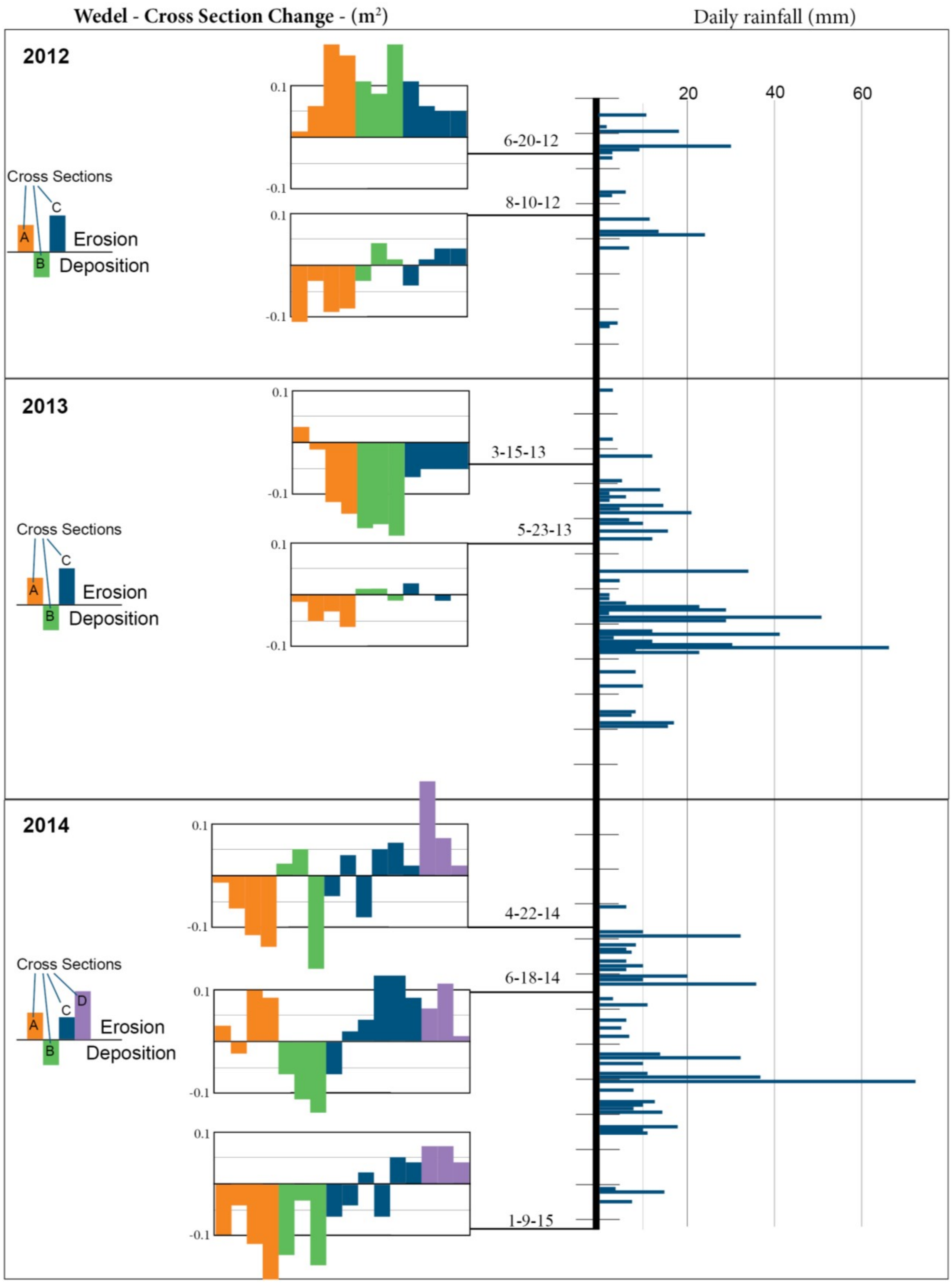


Table 4.21 Net measured change across Wedel cross sections by survey date

Survey Date	Net change across cross sections (m^2)
6/20/12	1.04
8/10/12	-0.28
3/15/13	-1.11
5/23/13	-0.13
4/22/14	0.13
6/18/14	0.39
1/9/15	-0.66

Table 4.22 Wedel field cross section change (m^2) throughout study period

Survey Date	XS 1	XS 2	XS 3	XS 4	XS 1B	XS 2B	XS 3B
5.5.12	Initial survey day						
Field Condition	Heavy wheat stubble						
6.20.12	0.012	0.056	0.177	0.158	0.111	0.084	0.177
Field Condition	Early milo growth						
8.10.12	-0.112	-0.025	-0.093	-0.084	-0.033	0.037	0.009
Field Condition	Heavy milo cover						
3.15.13	0.033	-0.015	-0.121	-0.139	-0.172	-0.158	-0.177
Field Condition	Milo residue						
5.23.13	-0.007	-0.052	-0.033	-0.056	0.008	0.009	-0.009
Field Condition	Fallow: milo residue, very little cover						
4.22.14	-0.010	-0.060	-0.110	-0.145	0.021	0.046	-0.084
Field Condition	Milo residue						
6.18.14	0.032	-0.020	0.099	0.080	-0.064	-0.111	-0.139
Field Condition	Mid-sized soybean crop						
1.9.15	-0.099	-0.036	-0.124	-0.176	-0.144	-0.029	-0.162

Survey Date	XS 1C	XS 2C	XS 3C	XS 4C	XS 5C	XS 6C	XS 1D	XS 2D	XS 3D
5.5.12	Initial survey day								
Field Condition	Heavy wheat stubble								
6.20.12	0.106	0.059	0.048	0.054					
Field Condition	Early milo growth								
8.10.12	-0.040	0.008	0.029	0.026					
Field Condition	Heavy milo cover								
3.15.13	-0.065	-0.103	-0.096	-0.098					
Field Condition	Milo residue								
5.23.13	0.019	0.001	-0.007	N/A	Initial survey for 5C, 6C, 1D, 2D and 3D				
Field Condition	Fallow: milo residue, very little cover								
4.22.14	-0.041	0.042	0.063	0.053	0.059	0.024	0.176	0.074	0.020
Field Condition	Milo residue								
6.18.14	-0.064	0.018	0.037	0.132	0.132	0.080	0.058	0.113	0.010
Field Condition	Mid-sized soybean crop								
1.9.15	-0.059	-0.045	0.018	-0.064	0.048	0.040	0.066	0.066	0.041

Table 4.23 Net change of Wedel cross sections. Note how net erosion only occurred higher in the watershed

	Net Change, 5-5-12 to 1-9-15, (m^2)
XS 1	-0.152
XS 2	-0.152
XS 3	-0.204
XS 4	-0.361
XS 1B	-0.273
XS 2B	-0.122
XS 3B	-0.385
XS 1C	-0.144
XS 2C	-0.020
XS 3C	0.093
XS 4C	0.121
XS 5C	0.240
XS 6C	0.144
XS 1D	0.299
XS 2D	0.254
XS 3D	0.071

Figure 4.19 Large amounts of deposition occurred at Wedel cross section 3, just below the confluence of Trib B. The green line represents 0.12 m^2 of deposition in 6 months.

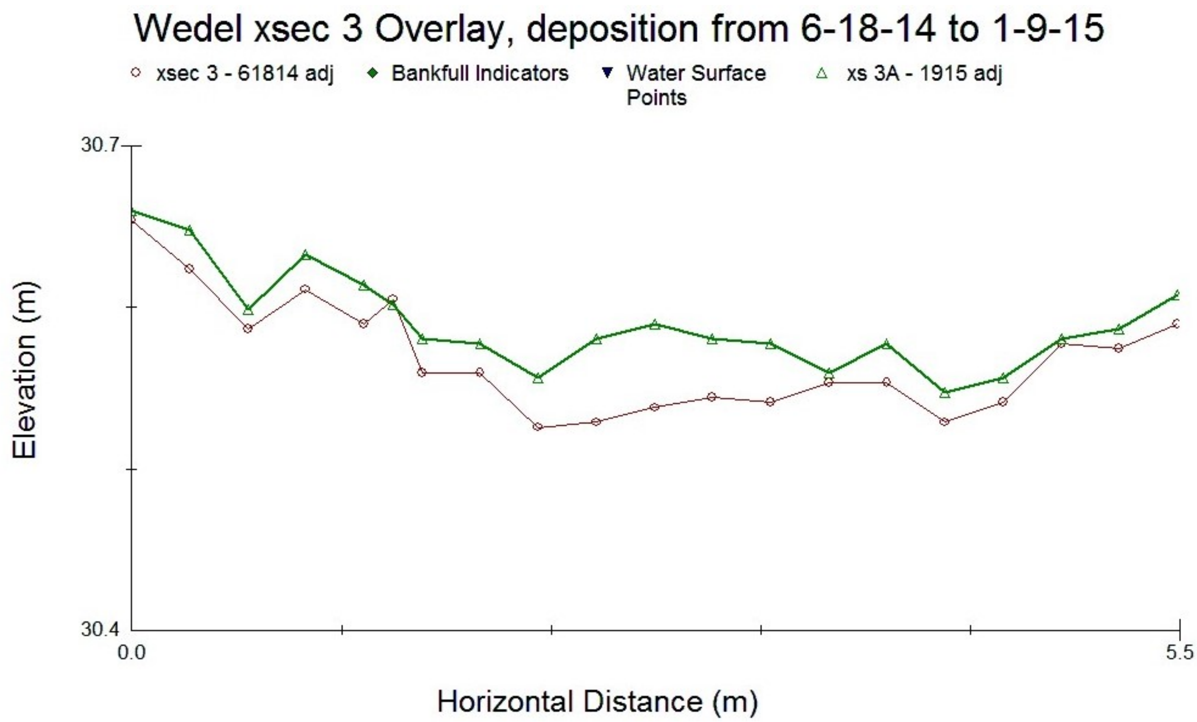
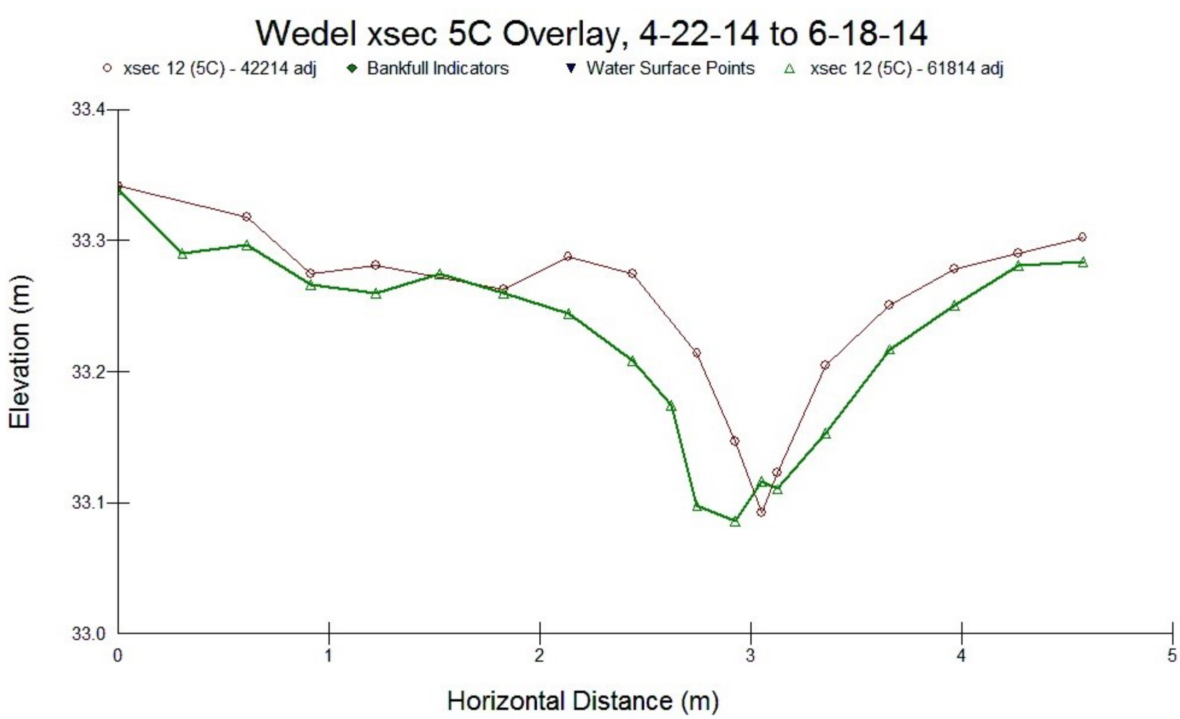
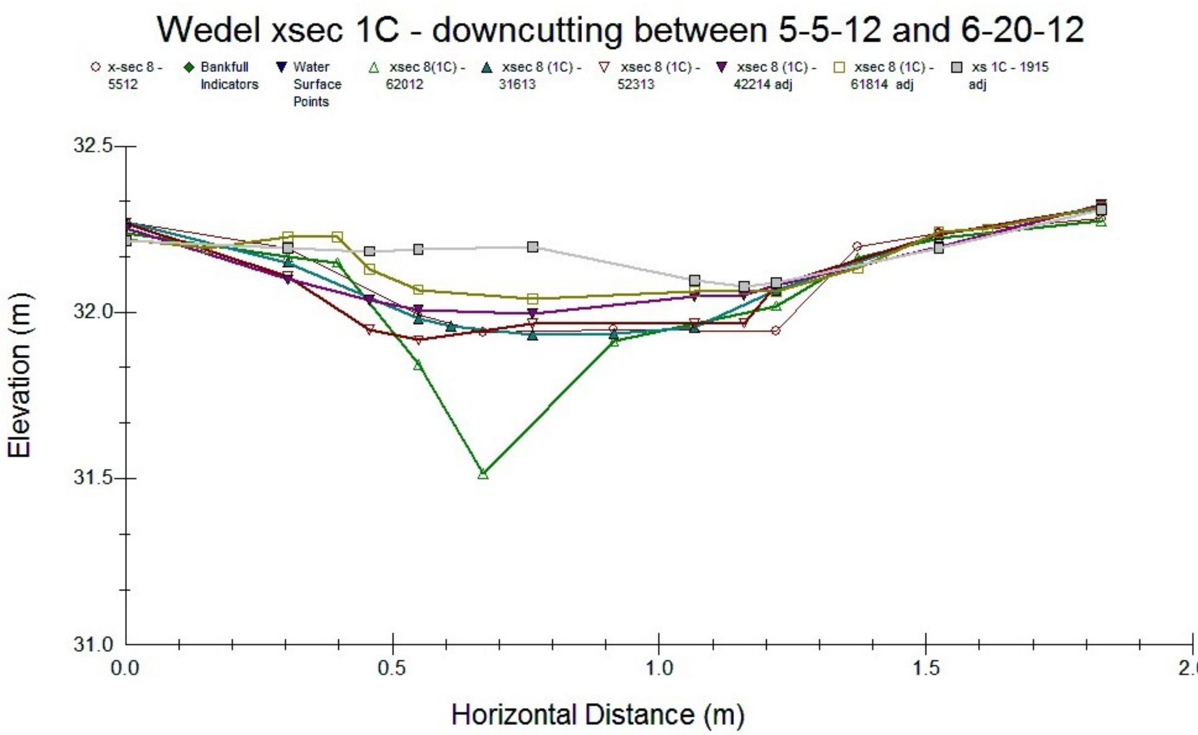


Figure 4.20 Cross sections in the upper reaches of the field showed consistent erosion. Note the channel widening. The green line represents 0.13 m^2 of erosion in two months.



When overlaying all dates for Wedel cross sections, some trends appear. The time period between May 5, 2012 and June 20, 2012 caused clear incision in seven out of the 11 cross sections that were being monitored at that time. But, that time period in 2012 does not represent extreme rainfall: the fourth largest daily rain event fell during that period, as well as the fourth largest hourly peak rainfall, both with no antecedent soil moisture. Figure 4.21 shows an example of downcutting between 5-5-12 and 6-20-12. Six additional cross sections show similar trends.

Figure 4.21 Cross Section 1C downcutting before the 6-20-12 survey (green line), but consistently filling afterwards.

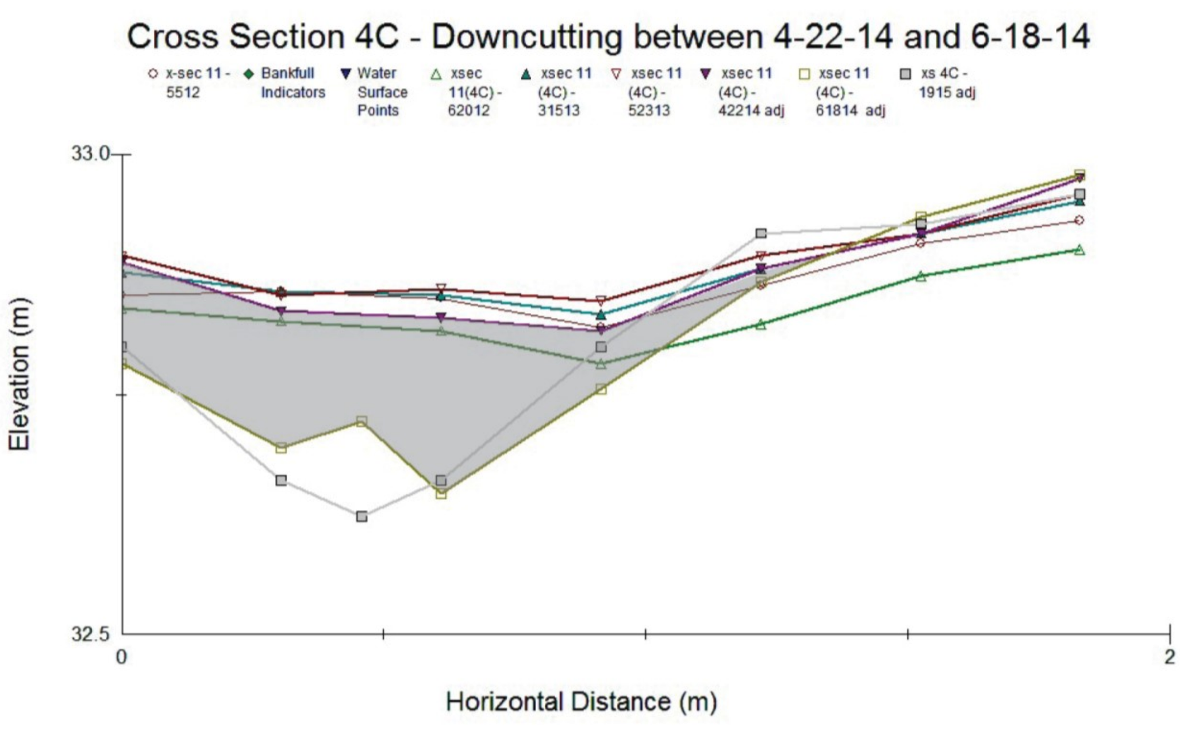


Another trend through time is that noticeable erosion occurred between survey dates 4-22-14 and 6-18-14. Four of the six net-eroding cross sections at higher elevations in the watershed show clear downcutting or widening between these dates (See Figure 4.22 as an example). But again, during the timeframe between 4-22-14 and 6-18-14, the third largest daily rainfall and the third largest peak hourly rainfall occurred, but we might expect to see the largest rainfall events causing the most erosion. A hypothesis was that antecedent soil moisture plays a role – even small rain events can cause the most erosion if the soil is already saturated. However, after the largest daily rainfall of 71 millimeters in September, 2014 and the second largest peak rainfall of 33 millimeters/hour also in September 2014, when there was much antecedent soil moisture prior to these events as noted by rainfall data, only one cross section, 3D, saw its greatest erosion rate. Another answer could be that field cover could be influencing rates of erosion more than rainfall events. There are too few data points to make a conclusion, but the greater erosion rates occurred when there was poor milo residue on the field (late April, 2014), leaving it much less protected than the actively growing soybean crop present during the largest daily event in September 2014.

Another explanation could be that in gully channels, especially below headcuts, there is enough cutting, filling and slumping that a clear relationship between rainfall and cross section change is difficult to determine. Other processes that loosen and prepare sediment, such as freeze/thaw action or rainfall patterns, could be at play, after which virtually any size storm, large or small, could wash the prepared sediment downstream.

In the statistics section below, similar results are shown – as rainfall amount and intensity increase, we see a decrease in erosion in net-eroding cross sections.

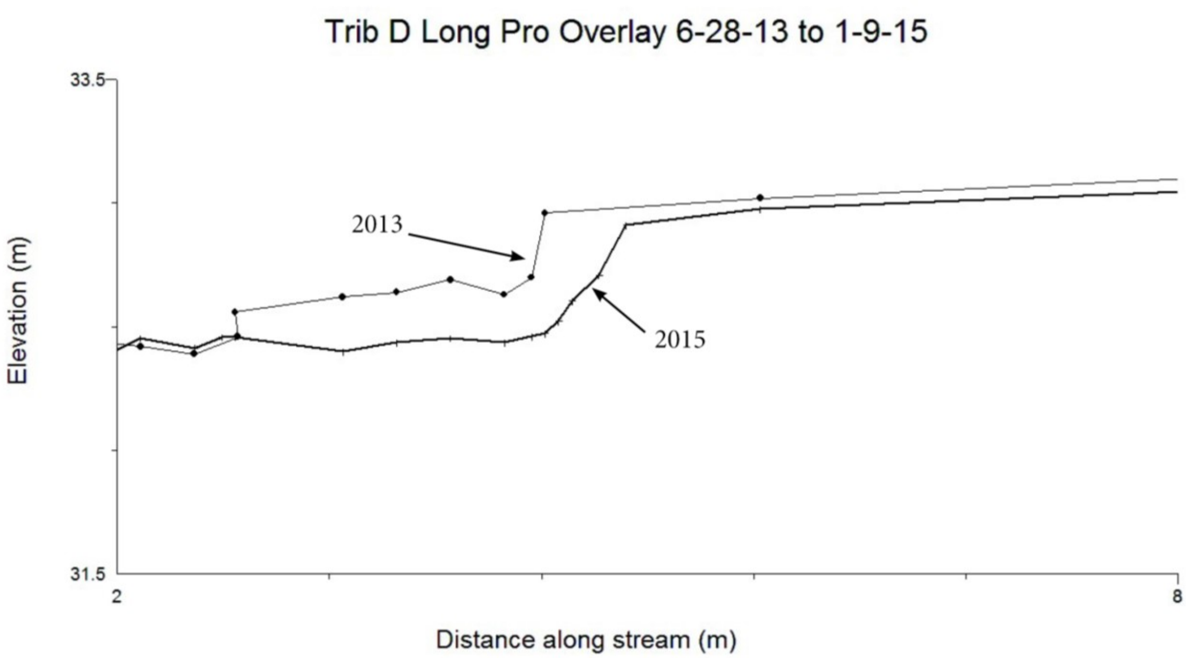
Figure 4.22 Xsec 4C - Clear downcutting between survey dates 4-22-14 and 6-18-14



Headcut growth and longitudinal profile changes

In the Wedel field, Trib C had two distinct headcuts, which by summer 2013/spring 2014 had flattened or turned into knick zones. Because of the headcut flattening, rates of retreat for the Trib C headcuts cannot be determined. When Trib D was initially surveyed in June 2013, one well-defined headcut was observed. That headcut remained well-defined for the rest of the study period. The Trib D headcut retreated a total of 0.66 meters from June 2013 to January 2015 – one and a half years. Just like the cross section data for net-eroding areas of the channel, the headcut in Trib D retreated the most (0.34 meters) during the short time period from April 22, 2014 to June 18, 2014. The headcut retreat during that same time period further confirms that something other than rainfall stimulated erosion during spring 2014. Though the longitudinal profiles were resurveyed less frequently than cross sections, they still show changes in headcut location. Figure 4.23 illustrates Trib D's headcut growth and bed incision.

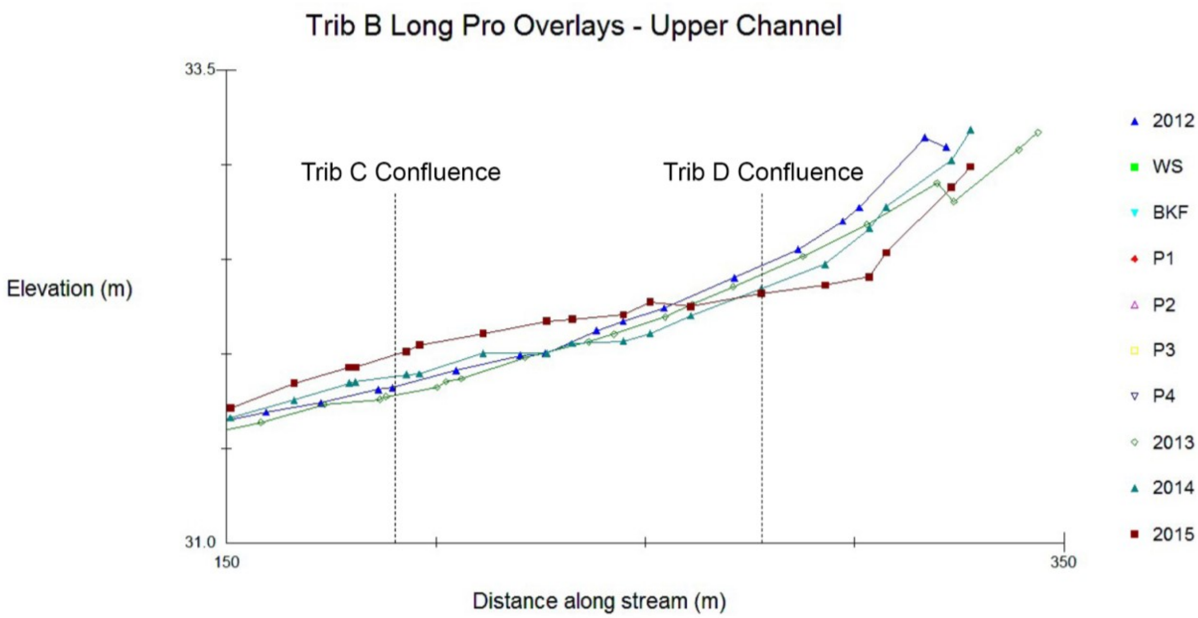
Figure 4.23 Longitudinal profile illustration of headcut retreat on Trib D – uphill retreat of 0.2 meters in 1.5 years



The long. pro. overlays were examined for patterns in erosion and deposition. In Tributary A, the largest main channel running north to south, long. pro. surveys show deposition. The most deposition occurred where Trib B enters the main A channel, which is also observed through the nearby cross sections 3 and 4 data. The latest survey in January 2015 showed slight downcutting at the lower end of Tributary A, signaling that sediment deposited within the field may at some point make it to the field edge, and further down through the larger watershed.

Tributary B also showed deposition, but only in the mid to lower sections of the channel – above Tributary D, the B channel incised. From long. pro. data, it seems that even though incision is occurring in the upper parts of Trib B, the many small side gullies, including Trib D, contribute enough sediment to the B channel that runoff cannot move all of the load, and deposition occurs. See Figure 4.24 for Trib B longitudinal profile overlays showing deposition in the mid and lower sections of the channel.

Figure 4.24 Tributary B Longitudinal Profile showing incision in the upper channel and deposition in the mid and lower channel – Blue line is 2012 survey, red line is 2015.



Tributary C quickly started to fill with sediment just uphill from the B-C confluence, most likely due to filling in channel B. Its two defined headcuts that existed early in the study flattened and filled. So, similar to Tributary B, the C channel incised and widened in the upper sections, but filled in the lower sections. Tributary D actively eroded during the study period, as seen in Figure 4.23.

Influence of gradient on cross section change

Using the long. pro. data, the bed slope of the gully was measured above each cross section to get a sense of the differences in runoff energy approaching each cross section. On the Wedel field, there seems to be a threshold slope for erosion: cross sections whose approaching slope is 1.3% or greater experienced net erosion prior to the last survey on January 9, 2015. The cross sections with slopes of 1.3% or greater (nine total) are all located in Tributaries C and D. At the time of the last survey in January, 2015, the most gentle slopes in Trib C – cross sections 1C and 2C – started to show deposition rather than erosion. Cross sections 1C and 2C are located immediately upstream of Trib B, a larger channel that was also experiencing net fill, suggesting that the lower channel of Trib C is responding to the deposition in the larger Tributary B. Wedel cross sections below Trib C, all of which had approaching slopes of .07% or less, showed net deposition. In the Wedel field, erosion follows typical fluvial processes: erosion in the steeper, higher elevation areas of the watershed, and deposition in the lower watershed elevations/gentle slopes.

Extrapolation of cross section changes to the length of the gully

To estimate sediment changes in the entire gully channel, cross section change was extrapolated to the rest of the channel for each tributary. To get an average total change, a midpoint between each cross section was found using the longitudinal profile stationing along the length of the gully, and data from each cross section was made to represent the channel half-way to the next cross section and half-way to the previous cross section. For example, if cross section 1 is located at station 50, cross section 2 is located at station 100, and cross section 3 is at station 200 in the longitudinal profile, cross section 1 data is extrapolated to the 0-75 unit length of the channel; cross section 2 data is extrapolated from station 75 to 150, and cross section 3 represents stations 150 to the midpoint of the next cross section. The cross section areal change was multiplied by the extrapolated length, and all extrapolated segments were added together for an estimated total channel change for each survey (see diagram in Figure 4.25). All extrapolation data for each survey data are in Appendix C.

Figure 4.25 Diagram of extrapolation methods

Through extrapolation of cross section change, the gully channels that were studied on the Wedel field experienced 113.8 cubic meters of deposition throughout the entire 3 years. The cross sections that show net erosion (in the upper tributaries) experienced a total of 15.2 cubic meters of erosion, while the lower cross sections show 129 cubic meters of deposition. Trib B's three cross sections experienced the greatest rates of deposition between 8-10-12 and 3-15-13 at 52.1 total cubic meters, but showed the greatest rate of erosion between 6-20-12 and 8-10-12 at 38.3 cubic meters. The second largest rate of erosion was in Trib C from 4-22-14 to 6-18-14 with 8.6 cubic meters lost, which is also documented by the statistics. From the extrapolated data, it can be assumed that for most of the field, anything eroding in the upper reaches was stored in the deposition occurring in Tribs B and A during the study period. Table 4.24 shows an example of

Wedel cross section change extrapolation for one timeframe; Table 4.25 shows total gully channel change estimates through extrapolation for the entire study period.

Table 4.24 Example of extrapolated channel change in Wedel gully

Location	xsec	Erosion per foot (ft^2)	# of feet	Erosion by length, ft^3
Wedel 4-22-14 to 6-18-14	1	0.34	71	24.14
	2	-0.21	190	-39.90
	3	1.07	146.5	156.76
	4	-0.86	27.5	-23.65
	1B	-0.69	137	-94.53
	2B	-1.2	191	-229.20
	3B	-1.5	180	-270.00
	1C	-0.69	8.5	-5.87
	2C	0.19	48	9.12
	3C	0.4	50	20.00
	4C	1.42	45.5	64.61
	5C	1.42	43.5	61.77
	6C	0.86	3.5	3.01
	1D	0.62	6.8	4.22
	2D	1.22	6.4	7.81
	3D	0.11	3.4	0.37
Total deposition A-D				-311.34
Total deposition in m^3				**-8.82**

Table 4.25 Total Wedel extrapolated channel change over entire study period

Location	xsec	Erosion per foot (ft^2)	# of feet	Erosion by length (ft^3)
Wedel - Entire study period	1	-1.64	71	-116.44
	2	-1.64	190	-311.60
	3	-2.2	146.5	-322.30
	4	-3.89	27.5	-106.98
	1B	-2.94	137	-402.78
	2B	-1.31	191	-250.21
	3B	-4.14	180	-745.20
	1C	-1.55	8.5	-13.18
	2C	-0.21	48	-10.08
	3C	1	50	50.00
	4C	1.3	45.5	59.15
	5C	2.58	43.5	112.23
	6C	1.55	3.5	5.43
	1D	3.22	6.8	21.90
	2D	2.73	6.4	17.47
	3D	0.76	3.4	2.58
Total deposition A-D				-2010.00
Total deposition in m^3				**-56.92**

Examining rainfall and each cross section's change through time – Wedel Field Statistics

The only significant relationships involving rainfall were in the higher elevation areas of the Wedel watershed: cross sections 5C, 6C and 2D had a significant, negative relationship to the largest rain event, meaning the least amount of erosion occurred after the largest daily rainfall event, and the most erosion occurred related to the smallest daily rain event. Cross Section 4C also exhibited this pattern, but the relationship was not significant. See Table 4.26 for p-value significance, R^2 values, and rainfall and erosion information for the largest daily rainfall relationship to erosion. As a consideration, there are only three data points for these cross sections because they were added later in the study. More data points are needed to confirm the results.

Table 4.26 Significant relationships of Wedel cross sections erosion versus, largest daily rainfall

Cross section	Adjusted R2	P-value	Relationship
4C	.54	.32	negative
5C	.99	.008	negative
6C	.68	.26	negative
2D	.99	.02	negative

Though there are no consistent significant relationships between cross section erosion and peak rainfall events, the peak rainfall graphs also show in cross sections 4C, 5C, 6C, and 2D that the largest amounts of erosion occurred after the relatively smallest peak hourly rainfall event. Upon further investigation, it appeared that in more than half of the net eroding cross sections higher up in the watershed, the timeframe between 4-22-14 and 6-18-14 was the most erosive. A total of 172 millimeters of rain fell during that time period of two months, which could explain the erosion. But, more than 228 millimeters of rain fell within 2.5 months during the time period between 6-18-14 and 1-9-15, which relates to a much smaller amount of cross section erosion. Something besides rainfall during the timeframe between 4-22-14 and 6-18-14 caused the higher rate of erosion. There is a possibility that equal or more erosion occurred after the 6-18-14 survey, but was later covered up with some deposition. Unfortunately, the only nail and washer in the eroding cross sections was hit by farming equipment during that timeframe.

Overall, even though there weren't many significant relationships between rainfall and Wedel cross sections change, there were more negative relationships than positive relationships, suggesting that larger events or more intense events relate to more deposition (or less erosion) in the selected cross sections. See Figures 4.26 and 4.27 for example graphs showing negative relationships between rainfall and erosion.

Figure 4.26 Cross section 6C's relationship to peak hourly rainfall events

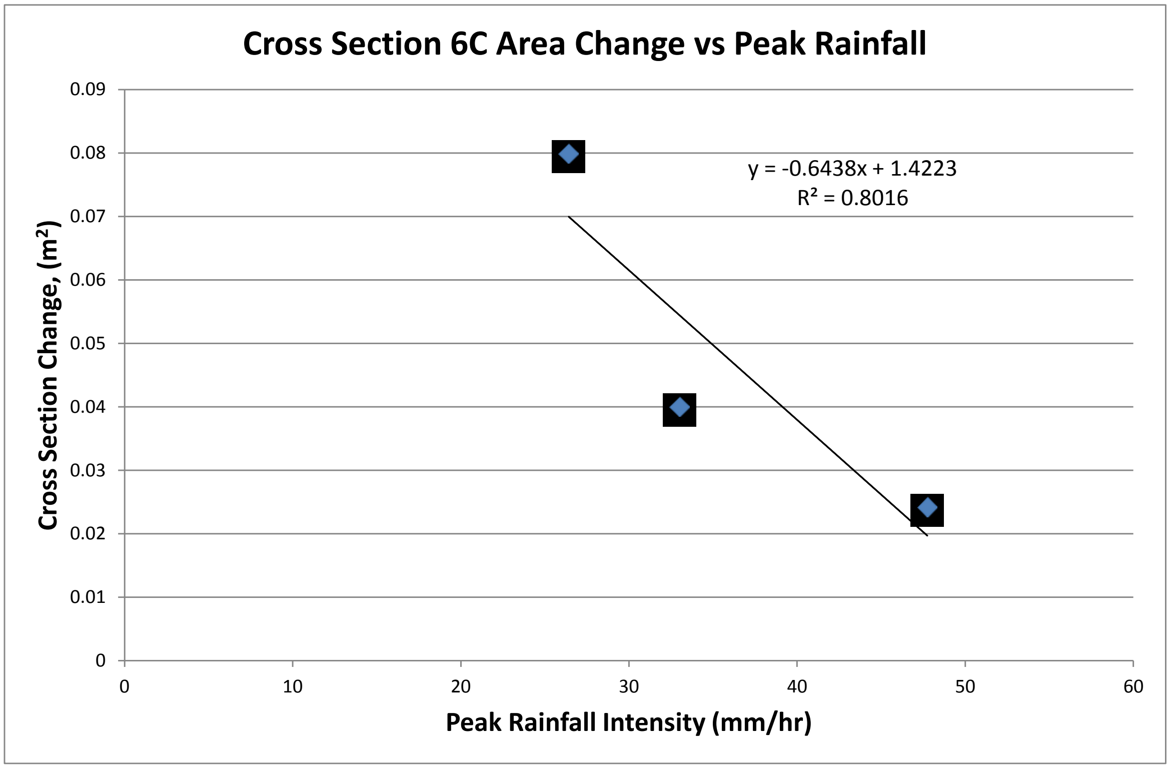
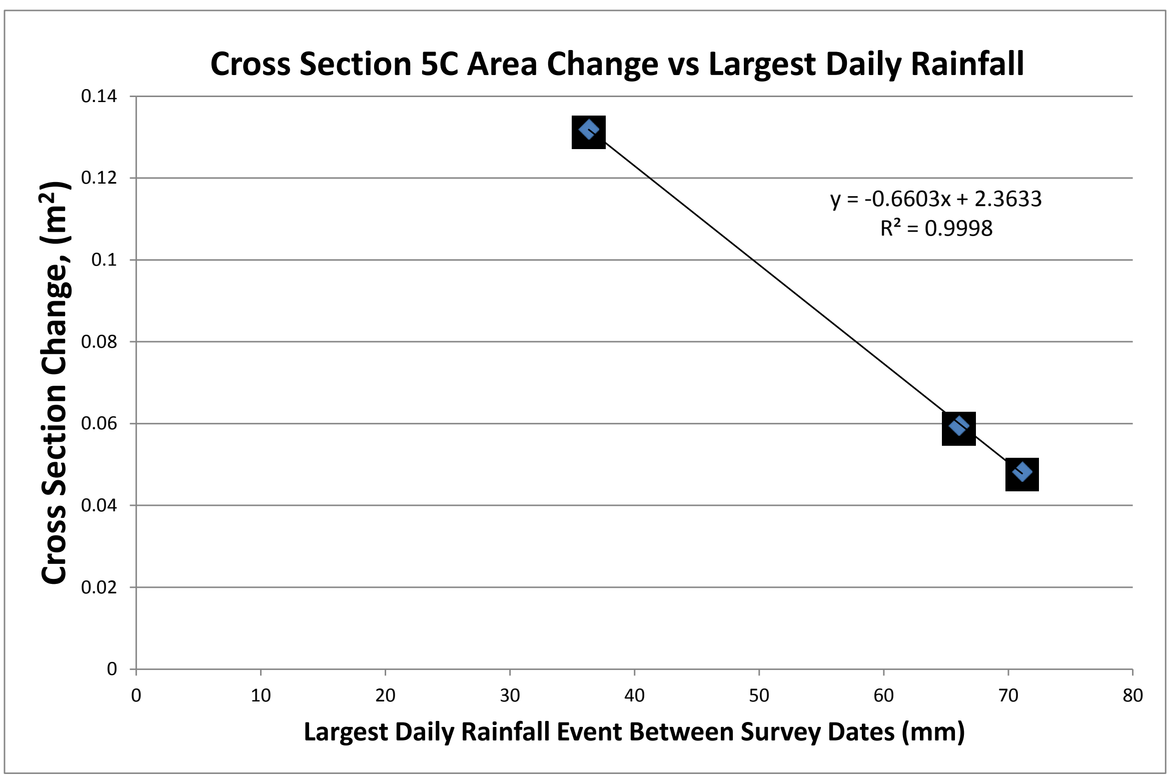


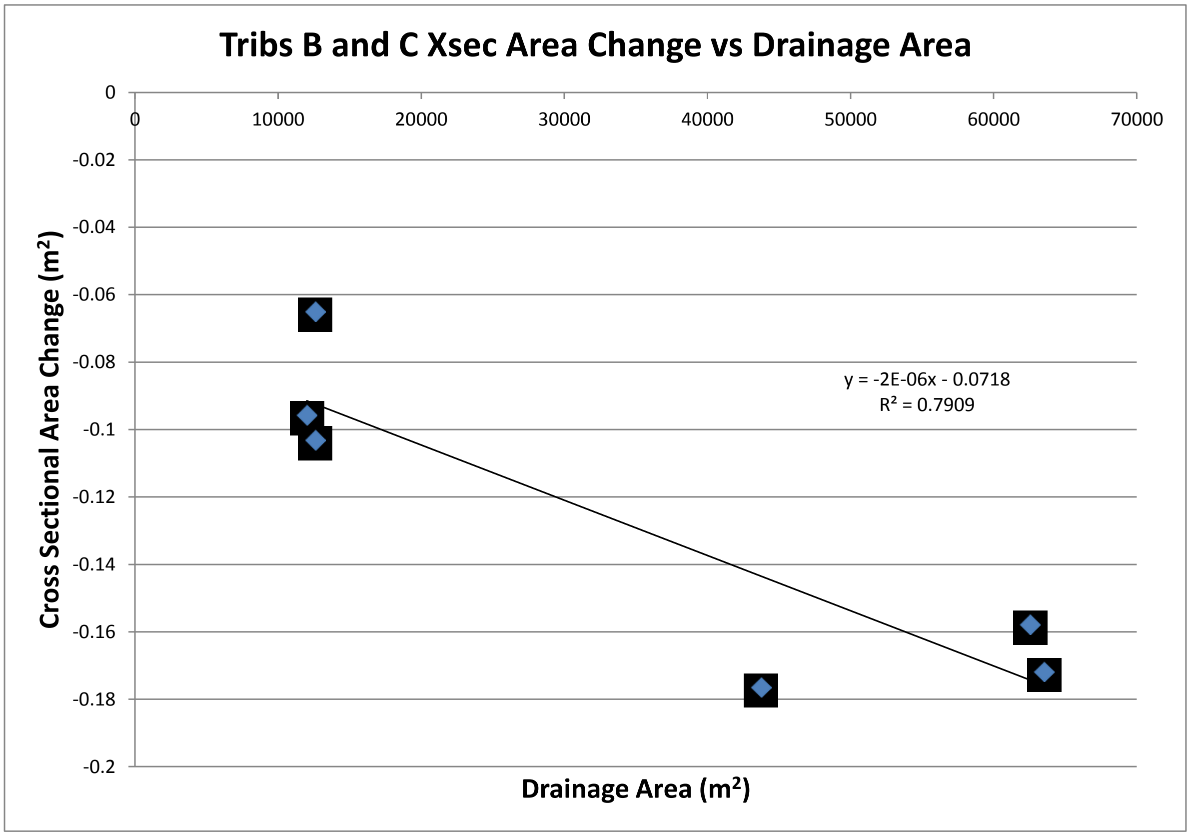
Figure 4.27 Cross section 5C's relationship to largest daily rainfall events



Examining all cross sections' response to the same timeframe/rainfall conditions – Wedel Field Statistics

Differences in drainage area and slope – when graphing all of the Wedel cross section datasets against drainage area and then slope, 3 of the 7 timeframes show a negative relationship between cross section change and drainage area, meaning that the larger the drainage area, the less amount of erosion (and in many cases, the more deposition), which is not surprising given the raw data explained earlier. However, due to the main channel A cross sections having substantially larger drainage areas than the other cross sections, the analysis of drainage area was separated into two groups: the A cross sections (4 total) and the B through D cross sections (12 total). This created more informative outcomes. For the A cross sections, 4 out of 7 timeframes showed that when deposition is occurring, the smaller drainage areas (cross sections 3 and 4) experience more deposition than the largest drainage areas (cross sections 1 and 2). This could be because cross sections 3 and 4 are located near the entry of the large Tributary B, a sediment source. On the other hand, in the B-D analysis (or Tribs B through C when the initial D Tributary was not yet added to the dataset), three of the seven dates showed the opposite: as drainage areas get larger, more deposition occurs. An example of a B-C drainage area relationship is shown in Figure 4.28 – more deposition occurring in the larger watersheds, a significant relationship in this scenario with a p-value of 0.02.

Figure 4.28 Drainage area versus cross section change in Wedel cross sections B-C



As for slope, the majority of the relationships in the Wedel field show a positive relationship between slope and cross section change: either less deposition, or more erosion, occurs at steeper slopes, which is expected. See examples in Figures 4.29 and 4.30. Figure 4.29 shows a strong positive relationship, but only has 3 data points. Figure 4.30 has many data points and also has a positive relationship, but the relationship is not significant.

When drainage area and slope are paired together in regression as independent variables, some relationships can be found at different timeframes, but they are all weak relationships.

Figure 4.29 Wedel Trib A's cross section change versus slope: deposition in the timeframe between March and May, 2013

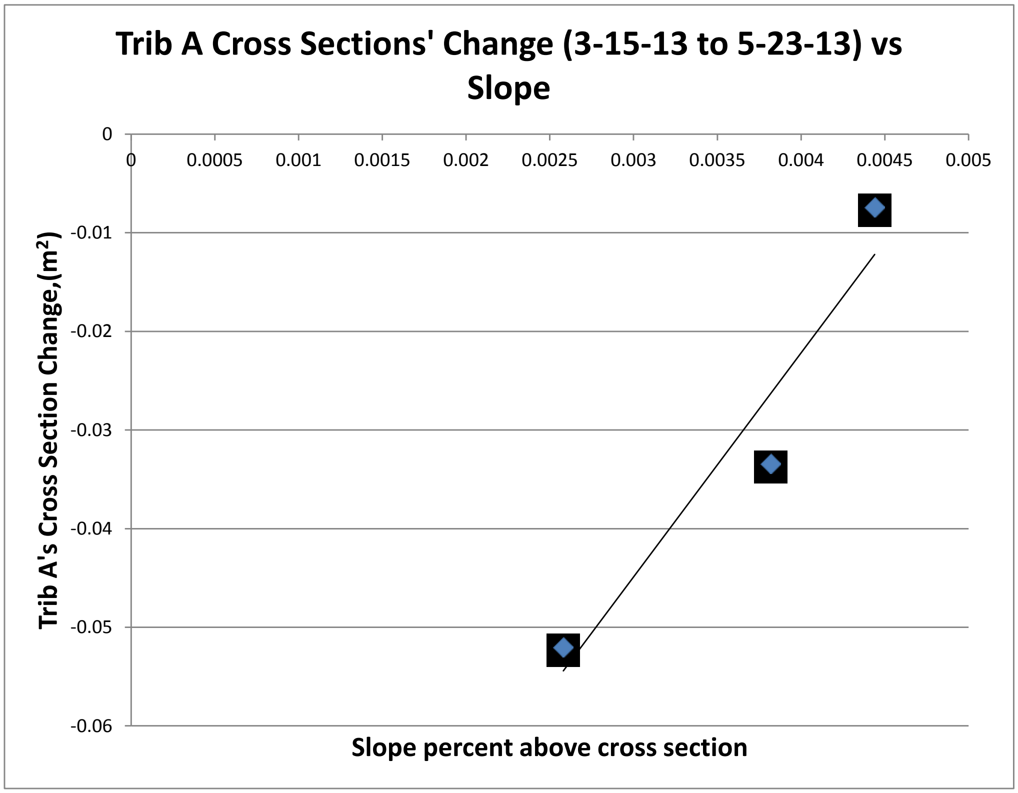
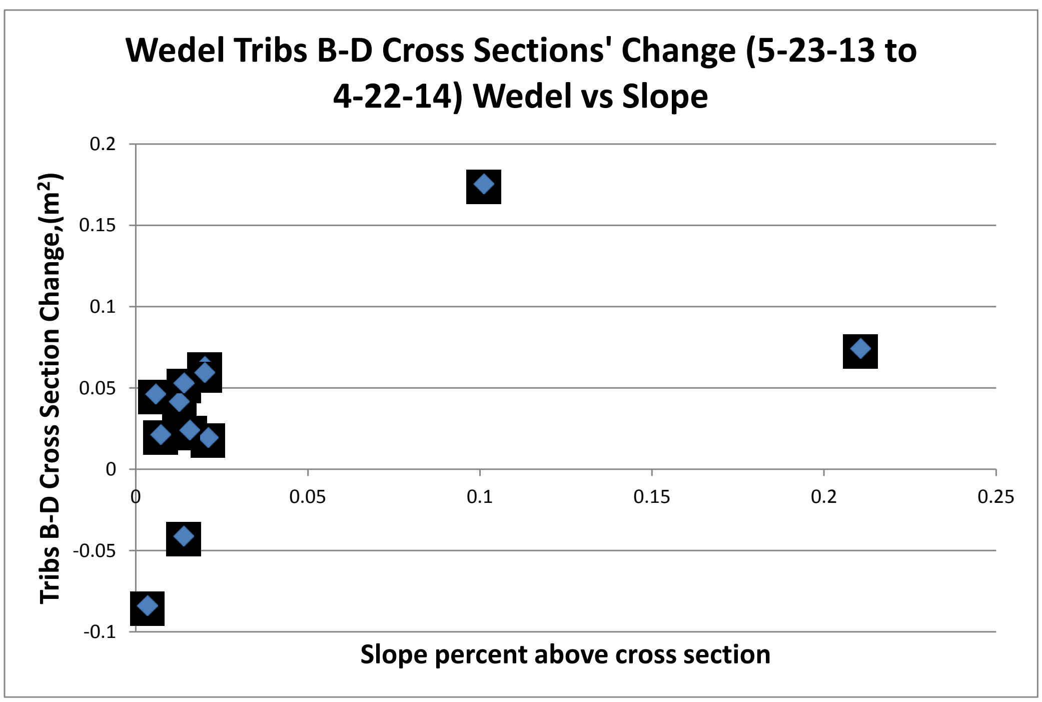


Figure 4.30 Wedel B-D cross sections change versus slope, measured April 22, 2014



Examining inconsistencies in rainfall/erosion relationships

Erosion data for cross sections in the upper reaches of the Wedel watershed show that the largest rainfall events do not correlate with the largest amounts of erosion, and that there are too few data points to relate field condition to erosion rates. Relatively smaller rainfall events seem to have caused some of the greatest amounts of erosion in cross sections, along with the greatest headcut retreat in Tributary D. In an attempt to understand why, two other factors were then examined: was the slope length approaching each cross section influencing erosion quantities? And, are rain or hillslope processes preparing sediment in some way that has not been considered, allowing smaller events to transport the prepared sediment?

The data shows that slope length does not seem to play a role. Two cross sections located within 1.5 meters of each other, and thus only a 1.5-meter difference in slope length, were largely different in terms of cross section change for two of the storm periods. As another example of how slope length does not seem to play a role, Cross Section 4C has about half the slope length as 5C (23.8 meters versus 47.5 meters), but both cross sections experienced nearly the same amount of erosion during two separate timeframes.

Examining prepared sediments led to examining fields photos taken before and after the relatively small rainfall events that caused the most erosion. April 22, 2014 and June 18, 2014 were the survey dates; rainfall occurred April 27th and June 5th during the time period between surveys. Field photos from March 2014 show standing water in the gully, and wet, muddy banks (see Figure 4.31). Field photos from the April survey and the June survey were compared. Figures 4.32 and 4.33 show a similar vantage point for the two different dates.

Figure 4.31 Wet conditions in March, 2014. Photo by author.

Figure 4.32 Loose bank sediments in April, 2014. Photo by author.

Figure 4.33 Hard, dry banks in June, 2014. Photo by author.

In April, even though there were no recorded rainfall events yet that spring, steep gully banks show loose, prepared sediment resting on the banks. The June photos (post-rain) show dry, hard banks. Frost heave, or repeated freezing and thawing of the bank material that loosens bank sediments and prepares them for fluvial entrainment, is suspected to be the cause of accelerated erosion of banks and the Trib D headcut during relatively smaller rainfall events following spring thaw.

Final field visit observations

After the study was completed, multiple large rain storms hit the McPherson area in May, 2015. Researchers visited the Wedel field one last time in June 2015, not to survey, but to observe the gully's response to heavy rainfall. The field was fallow. Herbicide was most likely used in the spring, because very few weeds were growing. It was immediately apparent that much of the sediment that was sitting in the channels in 2014 had been flushed downstream during 2015 rains. Figure 4.34 shows an erosion nail that was exposed 17 cm from January to June. The main channel, A, has obviously grown, has created more-defined cutbanks and looks like a stream channel in terms of dimensions. Trib A also had several new, small tributary branches cutting back into the field, most likely due to the change in base level of Trib A. In many locations along the length of Trib A, all of the loose sediment was flushed downstream, leaving a hard clay bed exposed. During the 3-year study period, some of the clay bed had been exposed in certain locations, but never to this extent.

Figure 4.34 Erosion nail exposed 17 cm after 2015 spring rains

At the confluence of Tribs A and B, sediment from B must have created a small dam, because the upstream portions of Trib A (the main channel) showed signs of water ponding. At the bottom end of Trib B, there was a defined small channel; but near cross sections 1B and 2B, the channel split into multiple channels. Cross section 3B showed some signs of widening, but no obvious cut and fill. Trib C, which eroded in the beginning of the study but had begun to fill in 2014, flushed sediment from its channel. In 2014, the channel looked more like a gentle swale. At the time of the June 2015 visit, it had downcut from the B-C confluence upstream through Cross Section 4. Cross sections 5 and 6 did not look different (6C had a nail that was exposed 6.5 cm), but the length of the headward defined channel may have extended.

Moving up Trib B from the B-C confluence, it appeared that between Tribs C and D, Trib B either stayed the same or experienced slight deposition. Upstream from Trib D, however, obviously downcutting occurred, both in the B channel and in the channel along the east field edge that feeds into the gully. This trend follows what was already seen in longitudinal profile overlays – more cutting in the upstream portions of the B channel, with deposition in lower B.

Trib D also experienced flushing flows. Previously, slumped masses of soil sat in the bed of the channel, but at the time of the June 2015 visit, hard, reddish clay was exposed as the channel's bed material with no slump masses in the bed. The D headcut retreated 0.3 meters since January 2015, and a shallower, second headcut formed 1 meter above the main headcut.

Drainage density observations

Drainage density is a measure of the length of channel in a specified area: total channel length divided by the area of land. Drainage density tends to increase in poorly vegetated areas with high initial relief and increased runoff volumes (Schumm, 1988), which are similar to the conditions seen at the Wedel field. Looking further into drainage density for the Wedel field, historical imagery shows that the gully network expands (and so drainage density increases), and then tillage or other farming activities smooth the land surface again, decreasing the drainage density. See Figure 4.35 for an April 2003 aerial photo that shows high drainage density in the Wedel field, and a photo three months later (August – Figure 4.36) showing smoothing of the field through tillage. When the field was visited after spring rains in June 2015, drainage density had increased again with many new, small tributaries branching from the main channel (see Figure 4.37).

Figure 4.35 Wedel field in April, 2003. Increase in drainage density. Photo courtesy of Google Earth/USGS

Figure 4.36 Wedel field in August, 2003, smoothed out by tillage. Photo courtesy of Google Earth/USGS

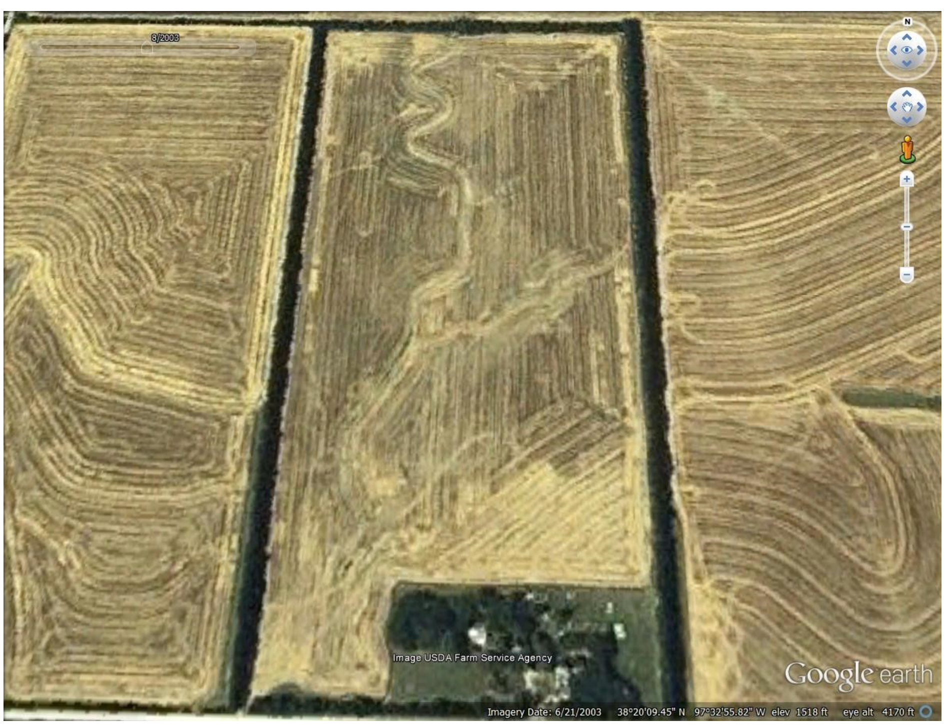


Figure 4.37 June 2015 increase in drainage density through many new, small channels. Example below, branching from Trib A. Photo by author.

The trend at the Wedel field could be that once drainage density increases, the field is smoothed out with farming activities, which creates an increased supply of loosened sediment (made even more ready for transport from the lack of vegetative cover or root binding). The increase in sediment supply is stored in the gully channels temporarily, as seen through this study's data collection. When spring rains are heavy enough, that stored sediment is washed downstream, which lowers the base level of the gully bed, creating a steep initial relief from gully banks to gully bed. The high initial relief, paired with no improvements in soil cover and runoff volumes, causes an increase again in drainage density through the creation of new small channels as seen in Figures 4.35 and 4.37. This potential cycle leads to constant removal of sediment from the field, which can reduce crop yields and impair channels downstream.

Google Earth imagery shows that the Wedel field is not an isolated incident of gully networks expanding and increasing drainage density. Figures 4.38 and 4.39 show a field about 3 kilometers south of Wedel, where similar processes occurred in spring and summer 2003.

Figure 4.38 Example of a field with similar drainage density shifts as Wedel. April 2003. Photo courtesy of Google Earth/USGS

Figure 4.39 Same location as photo above, smoothed with tillage by August 2003. Photo courtesy of Google Earth/USGS

Wedel Field summary

The Wedel field is a no-till field that had very little residue cover in between crop cycles and extended unprotected fallow time periods – the Wedel field practiced no soil conservation measures in addition to no-till. The gully channel experienced fluctuations of erosion and deposition. Overall, the studied gully channel was net depositional during the study period, but several smaller "headwater" cross sections consistently eroded or grew. The erosion at higher field elevations included widening, deepening, and/or extending of the tributary channels, indicating that the gully network is in the process of increasing its drainage density. In the middle and lower elevations of the gully network, sediment deposition occurred more often than erosion. The greatest rates of deposition occurred at or near confluences of two main gully channels and where smaller gullies entered and dumped sediment into the larger B tributary. Also, as watershed size increased in the Wedel field, more deposition occurred.

Statistical analysis was not incredibly useful; however, statistical analysis did confirm that factors other than rainfall must influence rates of erosion in the higher elevations of the gully network. For example, in one cross section a 33-millimeter rainfall event (in one day) was related to nearly three times more erosion than a 71-millimeter rainfall event.

Before the final visit to the field in June 2015, it seemed like the A, B and C channels could have continued to store sediment. However, heavy rains in spring 2015 flushed nearly all the sediment downstream, leaving a hard and resistant clay layer exposed at the bed in many locations.

Schmidt Field

Overview of cross section change

The Schmidt field is a no-till field that has consistently had good to excellent residue cover throughout the study period. A gully exists in the west-central area of the field and is significantly shorter in length than the Wedel gully. The Schmidt gully has a main channel that branches into two tributaries – see Figure 4.40. Overall, the four cross sections that were monitored all showed deposition; Figure 4.41 shows an example. Only one of the six comparable surveys showed significant erosion at all and that was in March 2013 – all four cross sections showed erosion. Prior to the March 2013 survey, farming equipment did alter the gully, but not significantly. A summary of cross section change related to rainfall data through time is shown in Figure 4.42, and Table 4.27 summarizes net change across cross sections by date. See Tables 4.28 and 4.29 for changes in cross sectional area and net change of each Schmidt cross section.

Figure 4.40 Layout of Schmidt cross section locations

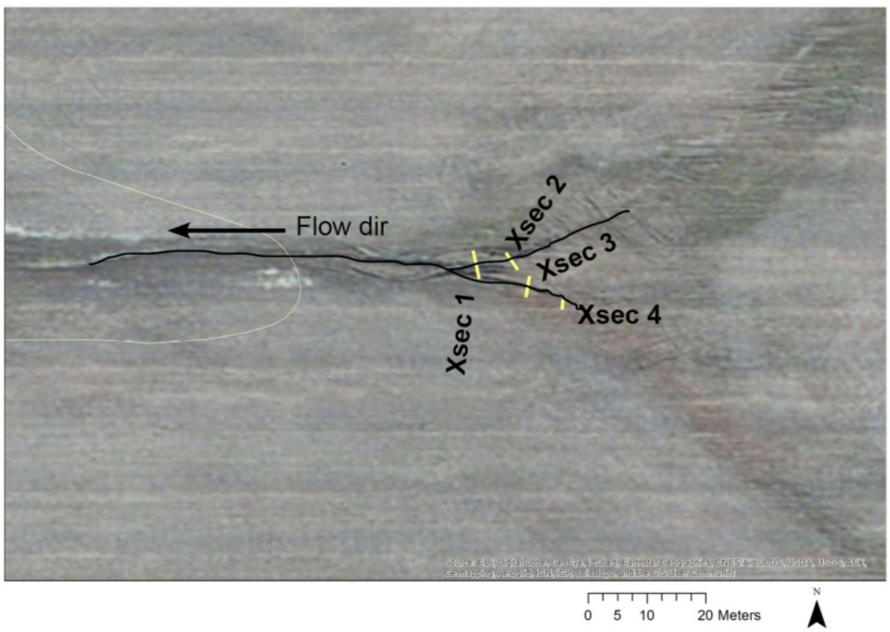


Figure 4.41 Example overlay of Schmidt cross section 1, showing deposition represented by the green line

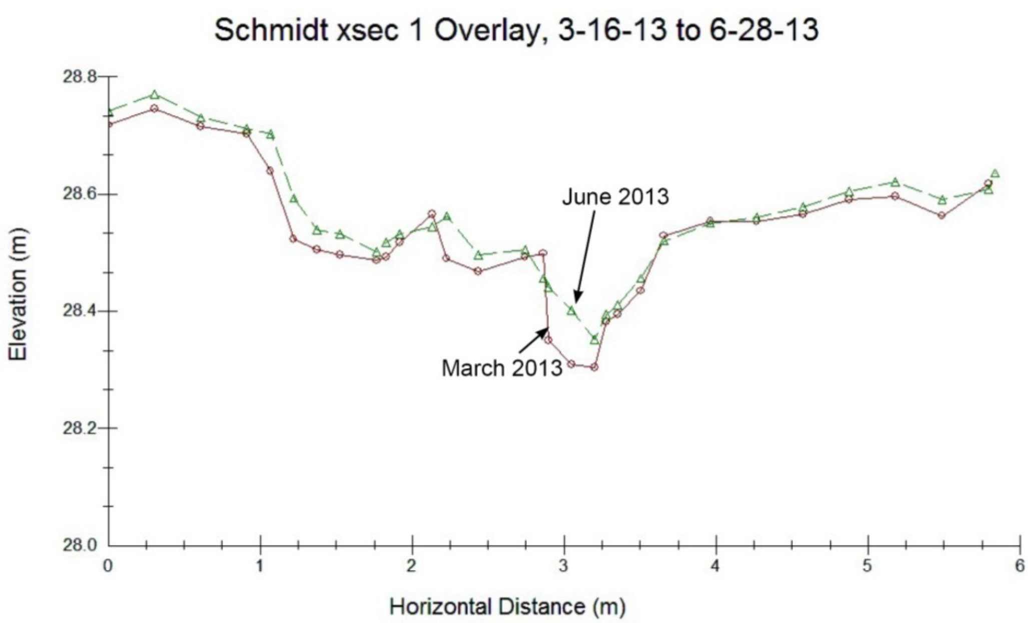


Figure 4.42 Schmidt cross section change versus rainfall

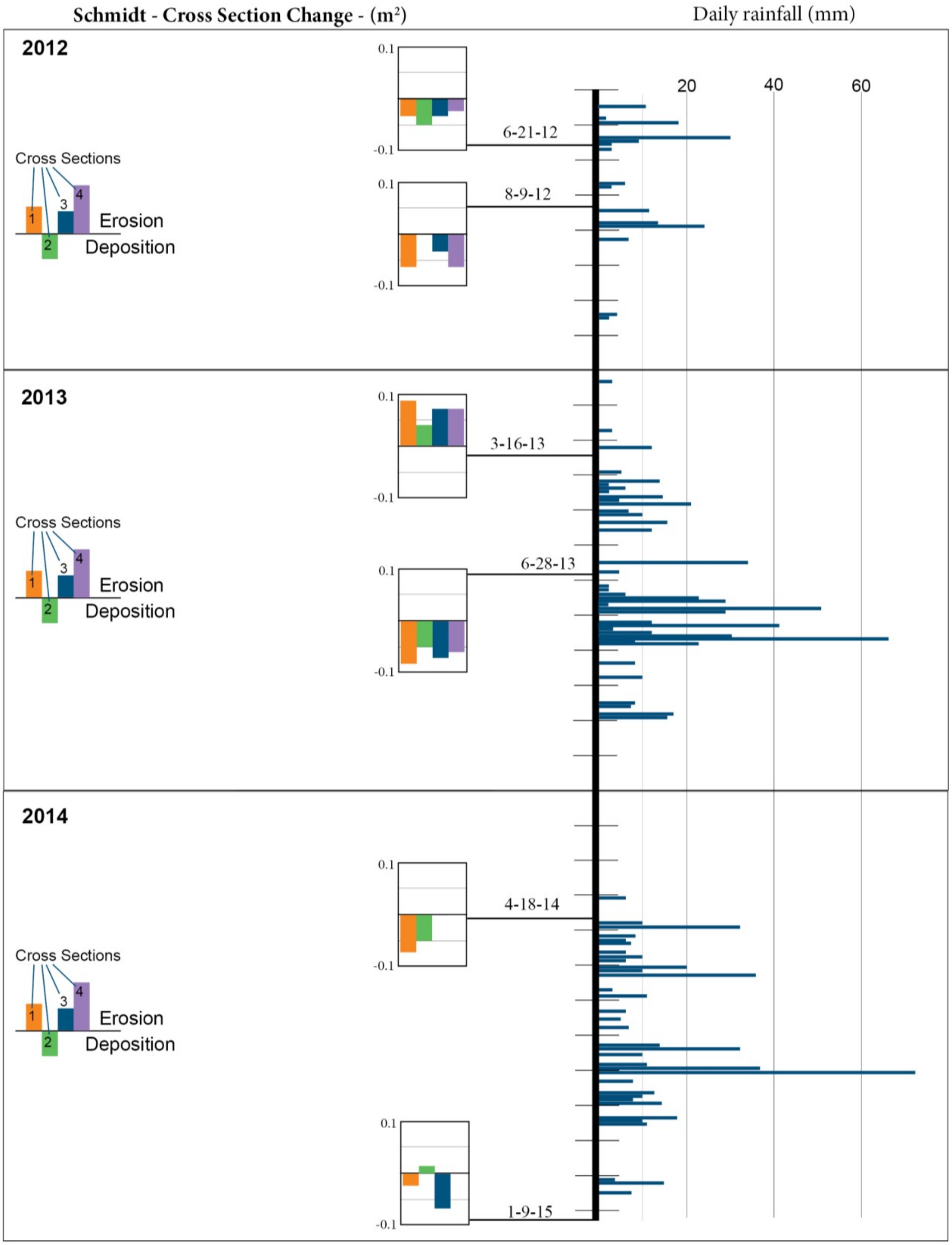


Table 4.27 Net measured change across Schmidt cross sections by survey date

Survey Date	Net change across cross sections (m^2)
6/21/2012	-0.13
8/9/2012	-0.14
3/16/2013	0.27
6/28/2013	-0.27
4/18/2014	-0.11
1/9/2015	-0.08

Table 4.28 Schmidt field cross section change (m^2) throughout study period

Survey Date	XS 1	XS 2	XS 3	XS 4
6.7.12	Initial survey day			
Field condition	Wheat stubble			
6.21.12	-0.028	-0.051	-0.029	-0.020
Field condition	Wheat stubble			
8.9.12	-0.056	0.004	-0.028	-0.058
Field condition	Wheat stubble			
3.16.13	0.093	0.038	0.072	0.067
Field condition	Wheat stubble. Beans drilled.			
6.28.13	-0.084	-0.053	-0.068	-0.062
Field condition	Wheat stubble			
4.18.14	-0.065	-0.051	0.002	0.005
Field condition	Either corn crop, or fallow with corn residue			
1.9.15	-0.019	0.009	-0.073	-0.001

Table 4.29 Net change of Schmidt cross sections

	Net change from 6-7-12 to 1-9-15 (m^2)
XS 1	-0.158
XS 2	-0.104
XS 3	-0.124
XS 4	-0.069

Headcut growth and longitudinal profile changes

The Schmidt gully had one headcut that remained intact and in the same position throughout the study period. Headcut measurements showed little to no retreat. The longitudinal profile overlays show that the gully filled overall, and the most deposition occurred below the confluence of the two tributaries.

Influence of gradient on cross section change

The slope results from Wedel do not carry over to the Schmidt gully. Almost every survey at the Schmidt field showed deposition at all four cross sections, even though three of the four cross sections have a slope greater than 1.3% (1.6%, 2.6% and 3.9%). The exception is that the survey on 3-15-13 showed erosion for all cross sections. The Schmidt field could be depositing more sediment at higher slopes due to its thick residue cover (whereas the Wedel field had very little cover). Overall, the Schmidt field does not show any relationship between channel slope and erosion or deposition.

Extrapolation of cross section erosion to the length of the gully

Each of the four cross sections in the Schmidt gully was net-depositional. The least amount of deposition was detected in the 1-9-15 survey (1.7 cubic meters of fill) and the greatest amount of deposition was detected in the 6-28-13 survey (7.9 cubic meters of fill). When the Schmidt field was experiencing its greatest amount of deposition, the Goerhing field was experiencing its only occurrence of erosion. Conversely, the only erosion on the Schmidt field was detected on 3-15-13 (8.6 cubic meters), which is the timeframe that both Wedel and Goerhing saw the most deposition. See Table 4.30 for an example of extrapolated Schmidt data for one timeframe, and see Table 4.31 for total channel change estimates.

Table 4.30 Example of extrapolated channel change in Schmidt gully for one timeframe

Location	**xsec**	**Erosion per foot (ft^2)**	**# of feet**	**Erosion by length (ft^3)**
Schmidt 6-28-13 to 4-18-14	1	-0.8	59.5	-47.6
	2	-0.64	27.5	-17.6
	3	-0.15	24.5	-3.675
	4	0.05	20	1
Total deposition (ft^3)				-67.875
Total deposition in m^3				**-1.92**

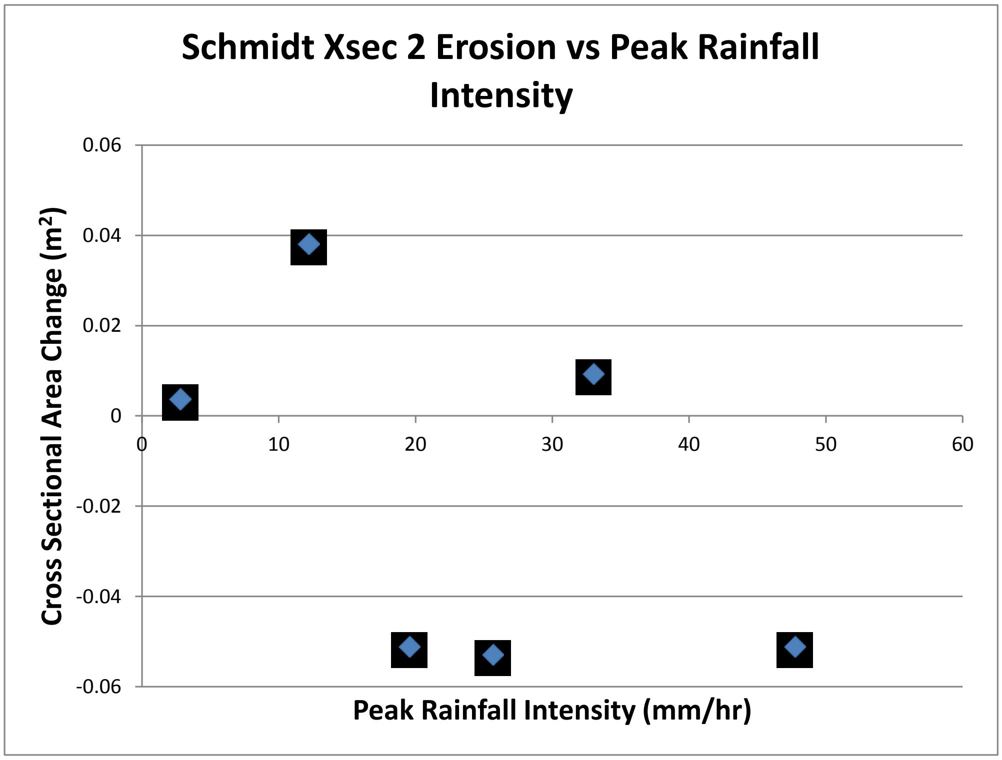
Table 4.31 Total Schmidt extrapolated channel change over the entire study period

Location	xsec	Erosion per foot (ft^2)	# of feet	Erosion by length (ft^3)
Schmidt Entire study	1	-1.7	59.5	-101.15
	2	-1.12	27.5	-30.8
	3	-1.33	24.5	-32.585
	4	-0.74	20	-14.8
Total deposition (ft3)				-179.335
Total deposition in m^3				**-5.08**

Examining rainfall and each cross section's change through time - Schmidt Field Statistics

For rain comparison by date, Schmidt had 6 data points (resurvey dates) to compare. Any relationships found between Schmidt cross section deposition and rainfall were positive, but none were strong relationships. Schmidt cross sections 1 and 2 showed a weak relationship between cross section change and peak rainfall events: the higher the peak rainfall, the more deposition occurred, (while a few data points showed some erosion after a smaller peak rainfall event.) Schmidt cross section 3 showed a weak relationship between cross section change and the largest rainfall event: larger events related to more deposition, and erosion occurred once after a relatively smaller event. Figure 4.43 shows an example of a weak relationship between Schmidt's Cross Section 2 area change and peak rainfall events. Note how the most deposition occurs relative to the largest peak events, while some erosion occurs relative to the smaller peak events.

Figure 4.43 Schmidt Cross Section 2 – weak negative relationship to peak rainfall events

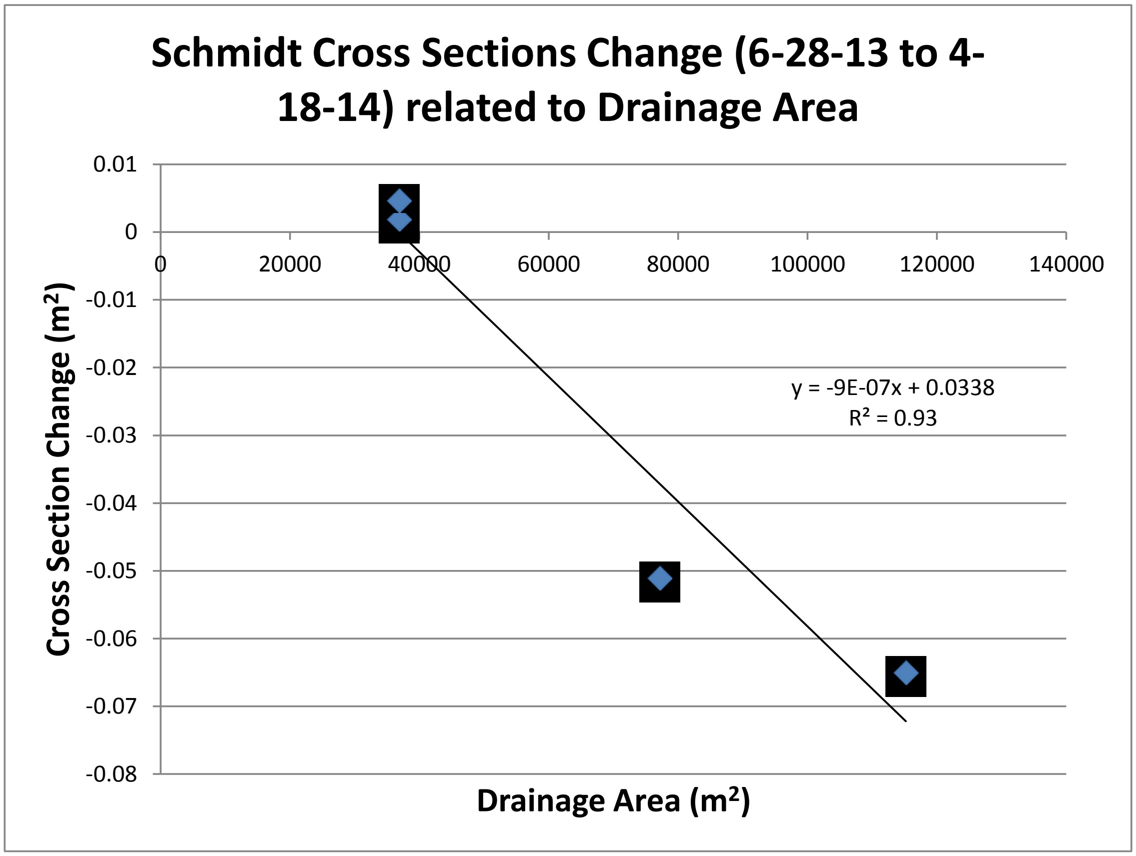


Examining all cross sections in one field response to the same timeframe/rainfall conditions - Schmidt Field Statistics

In the Schmidt field, two time periods show a positive relationship between drainage area and cross section deposition; the larger the drainage area, the more deposition (cross section 1, with the largest drainage area, had more deposition than the other cross sections). The 4-18-14 survey date's drainage area comparison is significant, with a near linear relationship between drainage area and change (See Figure 4.44).

In examining the slope approaching the cross section, one time period shows a positive relationship; more erosion occurred on higher slopes. On two other occasions, no erosion occurred, and more deposition occurred on the higher slopes than the gentle slopes. Cross sections 1 and 3 have the greater slopes out of the 4 cross sections: cross section 3 is located in/near a plunge pool, and cross section 1 was altered by vehicle traffic more than once in the study period, which could explain the odd results.

Figure 4.44 Change of Schmidt's four cross sections prior to the April 2014 survey, related to Drainage Area. R^2 is 0.930, with a p-value of 0.036



Schmidt Field summary

The Schmidt field is a no-till field that had heavy wheat residue cover in between crops during much of the study period. The one headcut within the gully showed no measureable change. Cross sectional area change versus rainfall events shows that many times, increases in deposition relate to time periods with higher peak rainfall. Though the gully channel was depositional overall, erosion occurred in all four cross sections only once, between August 2012 and March 2013. Not much rain fell during that time period, but the rain gauge on the Wedel field was not up and running yet until spring 2013. The rain data used was from the Equus Beds weather station, which is approximately 29 kilometers away from the Schmidt field. Assuming the Equus Beds rain data represents rain conditions for the Schmidt field, 13 millimeters fell March 9, 2013, right before the March resurvey. Freeze/thaw processes might have been at play prior to the March 9 rainfall, loosening bank and surface material in the channel. If so, the 13 millimeters of rain could have washed the loosened material away, explaining the only documentation of erosion in the Schmidt gully. However, there is no data to confirm that freeze/thaw action influences erosion processes on the Schmidt field.

Like the Wedel field, the Schmidt field was visited one last time in June 2015 after heavy spring rains. However, the gully was not accessible because the field was planted to wheat, which was nearing maturity.

Goerhing Field

Overview of cross section change

Figure 4.45 shows the layout of Goerhing cross sections. During the study period, the producer managing the Goerhing field tilled the field multiple times per season. In order to capture purely natural cross sectional area change due to runoff processes, cross sectional area could only be compared in between tillage events: when tillage occurred, a new initial survey was measured for the next season. Consequently, only three survey dates had comparable information. Two of the three survey dates showed deposition – March 2013 and August 2014. The only time erosion was detected was late June 2013, which would have been after wheat harvest and before the next tillage cycle. A summary of cross section change related to rainfall data through time is shown in Figure 4.46, and Table 4.32 summarizes net change across cross sections by date.

Schmidt and Goerhing seem to show opposite results – overall they each experience more deposition than erosion, but when Schmidt cross sections eroded, Goerhing's filled; and when Goerhing cross sections eroded, Schmidt's filled. See Tables 4.33 and 4.34 for changes in cross sectional area and net change of each Goerhing cross section. The net change numbers are from the initial survey date to the last survey date, showing that even when considering tillage, the cross sections appear to have filled, which could be attributed to rearrangement of soil during tillage. Figure 4.47 shows an example of slight deposition in Cross Section 1.

Figure 4.45 Goerhing Field cross section layout

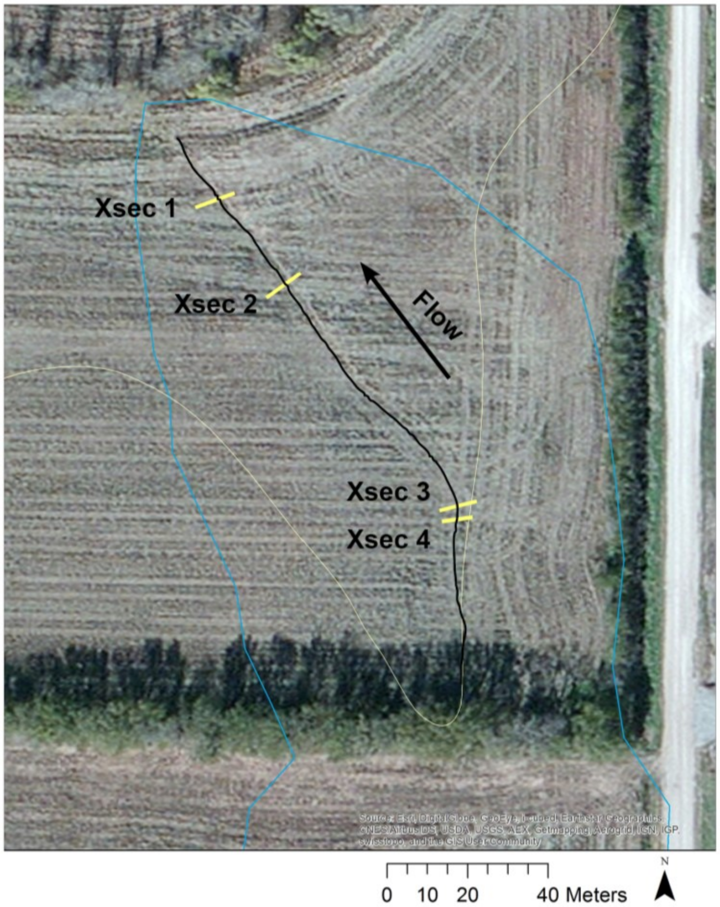


Figure 4.46 Goerhing cross section change versus rainfall

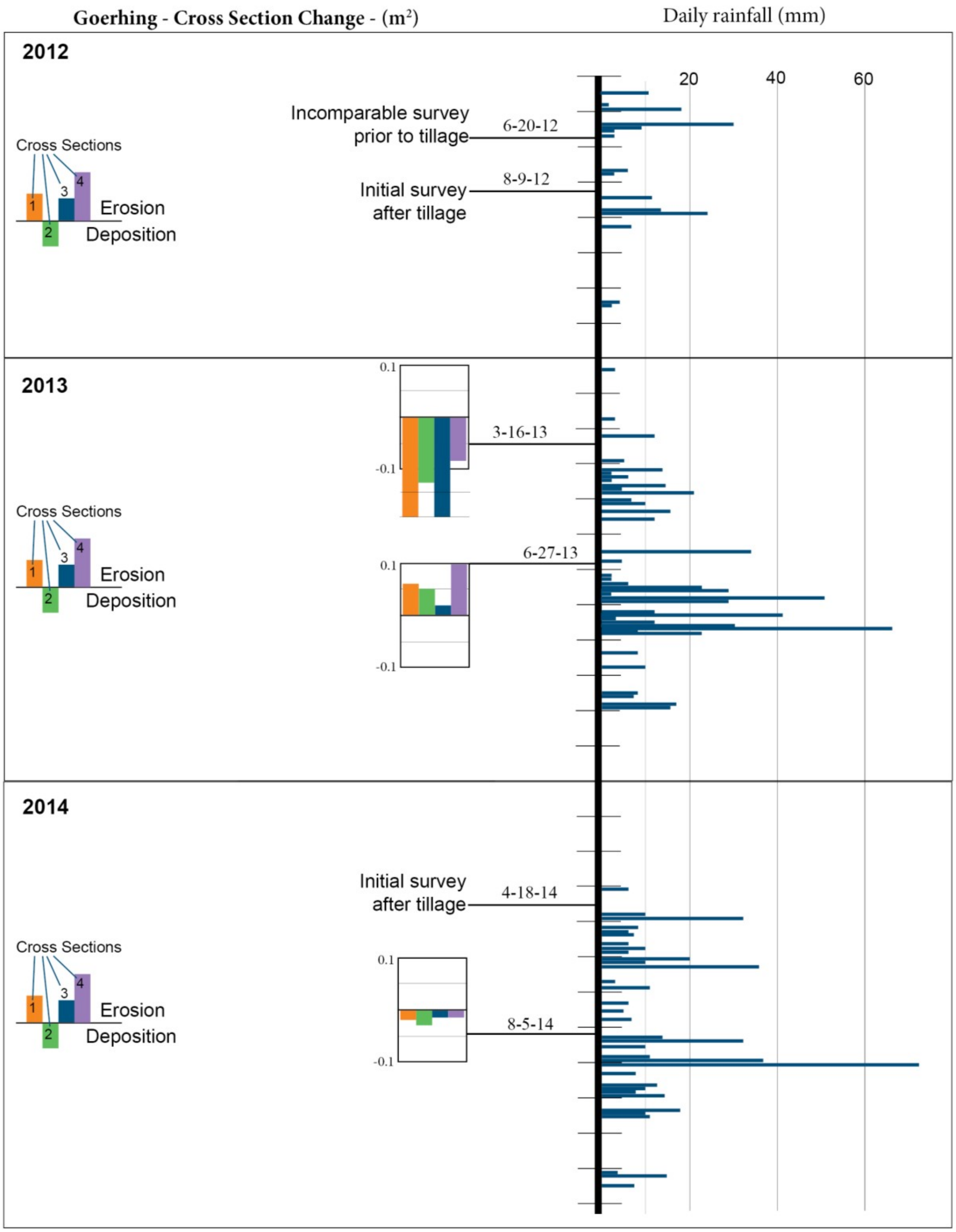


Table 4.32 Net measured change across Goerhing cross sections by survey date

Survey Date	Net change across cross sections (m^2)
3/16/2013	-0.64
6/27/2013	0.24
8/5/2014	-0.28

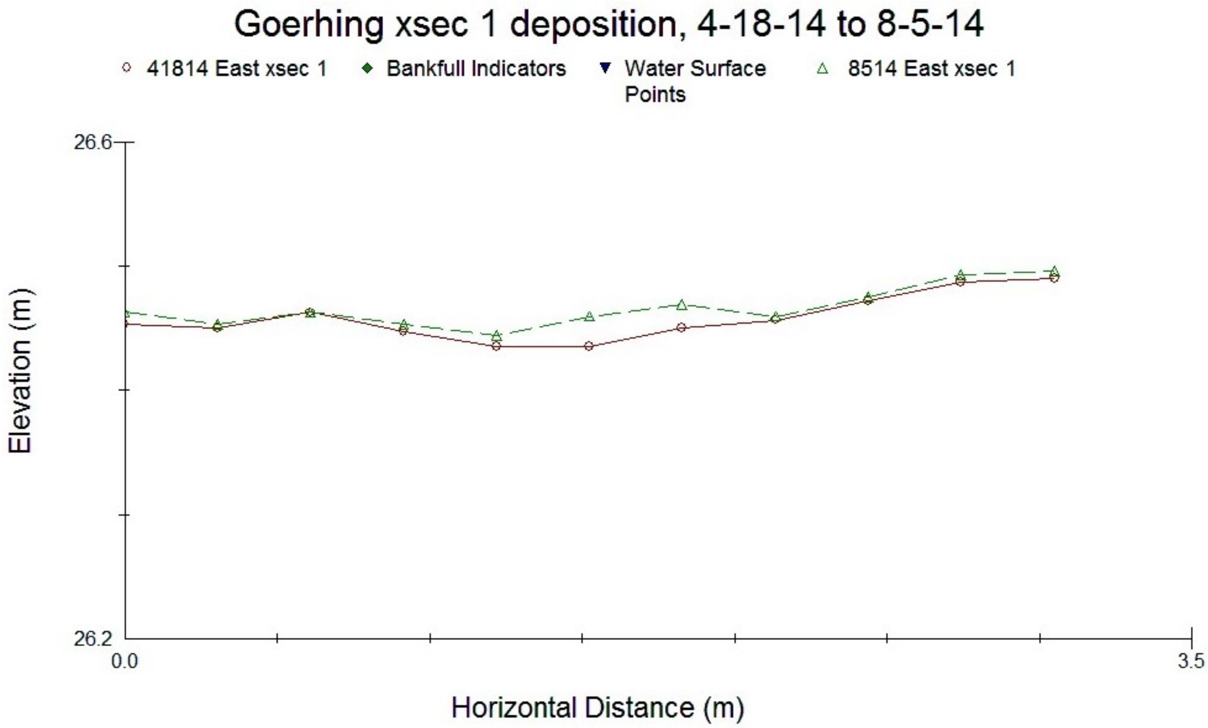
Table 4.33 Goerhing field cross section change (m^2) throughout the study period

Date	XS 1	XS 2	XS 3	XS 4
8.9.12	Initial survey date after tillage			
Field condition	Post-tillage, no cover			
3.16.13	-0.206	-0.136	-0.209	-0.085
Field condition	Either mature wheat or 5-inch residue			
6.27.13	0.060	0.054	0.017	0.105
4.18.14	Initial survey date after tillage			
Field condition	Tall, nearly mature wheat			
8.5.14	-0.024	-0.026	-0.124	-0.106

Table 4.34 Net change of Goerhing cross sections

	Net change from 6-20-12 to 8-5-14 (m^2)
XS 1	-0.333
XS 2	-0.254
XS 3	-0.353
XS 4	-0.238

Figure 4.47 Example overlay of Goerhing cross section 1, showing slight deposition represented by the green line



Headcut growth

Likely due to tillage, there were no defined headcuts on the Goerhing field, so no headcut measurements were taken.

Influence of gradient on cross section change

The slopes approaching the Goerhing cross sections ranged from 1.4% to 2.3%, and three out of the four comparable surveys show deposition at every cross section. Only the 6-28-13 survey shows erosion at all cross sections. The 6-28-13 survey was after wheat harvest and before tillage. Regardless of erosion rates, Goerhing's cross sections 3 and 4 are higher up in the watershed, and are both steeper than the lower cross sections 1 and 2. There seems to be no pattern, though, in rates of erosion compared to slope, or in rates of deposition compared to slope. The cross sections with greater slope sometimes deposited more sediment than the gentle slopes, and when a cross section did erode, the gentle slopes eroded more than one of the steeper slopes. All in all, channel slope shows no relationship to erosion or deposition.

Extrapolation of cross section erosion to the length of the gully

When applying the extrapolation methods to the Goerhing field, the data shows that Goerhing and Wedel experienced their greatest deposition during the same time period – late 2012 to March 2013. The only time Goerhing experienced erosion on all 4 cross sections (measured 6-28-13), the gully totaled 15.5 cubic meters of erosion. See Table 4.35 for an example of extrapolated data for one date, and see Table 4.36 for total channel change estimates for the Goerhing gully.

Table 4.35 Example of extrapolated channel change in Goerhing gully

Location	**xsec**	**Erosion per foot (ft^2)**	**# of feet**	**Erosion by length (ft^3)**
Goerhing 8-9-12 to 3-16-13	1	-2.22	109.5	-243.09
	2	-1.46	150.5	-219.73
	3	-2.25	165.5	-372.38
	4	-0.91	76.5	-69.62
Total deposition (ft3)				-904.81
Total deposition in m^3				**-25.62**

Table 4.36 Total Goerhing extrapolated channel change over study period

Location	**xsec**	**Erosion per foot (ft^2)**	**# of feet**	**Erosion by length (ft^3)**
Goerhing Total change	1	-3.58	109.5	-392.01
	2	-2.73	150.5	-410.865
	3	-3.8	165.5	-628.9
	4	-2.56	76.5	-195.84
Total deposition (ft^3)				-1627.615
Total deposition in m^3				**-46.09**

Examining rainfall and each cross section's change through time - Goerhing Field Statistics

For rain comparison by date, Goerhing had only 3 data points to compare. Cross sections 1, 2 and 3 had negative relationships for both largest rainfall and peak rainfall compared to deposition – the smaller events showed more deposition, and the larger events showed less deposition or slight erosion.

Examining all cross sections in one field response to the same timeframe/rainfall conditions - Goerhing Field Statistics

Through statistics, the Goerhing field showed no conclusive relationship between drainage area, slope, and erosion/deposition rates. On one date, there was a negative relationship between deposition and drainage area, and another date showed a positive relationship between deposition and drainage area, but neither was significant. No relationships between deposition and slope were found.

Final field visit observations

After the study was completed, multiple large rain storms hit the McPherson area in May, 2015. Researchers visited the Goerhing field one last time in June 2015, not to survey, but to observe the gully's response to heavy rainfall. The field was planted to corn. For the first time since the beginning of the study period, the producer did not plant through the Goerhing gully channel, leaving a fallow buffer along each side of the gully channel.

For most of the study period, the Goerhing gully looked more like a swale than a gully channel. Rarely, erosion occurred in places along the swale. However, likely due to the lack of cover paired with 2015 spring rains, the gully channel was defined for almost the whole length of the swale. Figure 4.48 illustrates. At the bottom of the channel there was deposition – it did not drain directly into the larger channel bordering the field at the north.

More erosion activity was seen in the west portion of the field – another gully channel was studied there in 2013, but was abandoned for the rest of the study because the channel, or even a swale, could not be found due to tillage. But in June 2015, there was a definite gully network forming between the corn rows. The main channel flows north, and is fed by many rows of erosion in between corn rows. There were at least two well-defined, small headcuts, and the corn rows, planted perpendicular to the gully channel, were feeding water and sediment to the main channel (See Figure 4.49).

Figure 4.48 Defined gully channel at Goerhing field, looking downhill. Photo by author.

Figure 4.49 Corn rows as linear erosional feature, feeding the main channel (A second Goerhing gully that was not studied). Photo by author.

Goerhing Field summary

The Goerhing field was planted to wheat each season of the study period and was also tilled each season. Because of tillage, few of the cross section resurveys were comparable. The gully channel was depositional overall, but erosion did occur before the June 2013 survey date, which was after wheat harvest and before the next tillage cycle. Out of all three fields, the Goerhing gully was the only gully that showed more deposition related to smaller rainfall events, and erosion or less deposition related to larger rainfall events. Otherwise, no discoveries were found related to Goerhing cross section change related to drainage area, slope, or vegetation conditions. The last observational visit in June 2015 showed that heavy spring rains cut channels both on the east and west sides of the field.

McPherson results summary

All three gully channels on the three fields that were studied showed net deposition over the study period. Two events seemed to cause clear erosion in the Wedel field (31 millimeters in June, 2012 and 36 millimeters in June, 2014), but statistics show that the largest rain events did not cause the largest amounts of erosion. The only time erosion was measured on the Schmidt gully was March 2013, and the only time erosion was measured on the Goerhing gully was June 2013.

In the Wedel field, cross sections with larger watersheds tended to store more sediment. The Wedel field clearly showed that the upper parts of the field are consistently eroding, while the middle and bottom parts of the field filled over time. There is even a possible threshold slope on the Wedel field for erosion: all cross sections with an approaching slope of 1.3% or greater have eroded, while all cross sections less than 1.3% show net deposition. However, after data collection was complete, 2015 spring rains flushed sediment from the channels at both steep and gentle slopes.

In terms of rainfall statistics, results are opposite than what was expected. The largest daily and peak rain events that occurred in September, 2014, which also had antecedent soil moisture, relate to the least amount of erosion in four of the six eroding Wedel cross sections. The data may suggest that something other than rainfall quantity or intensity is driving gully growth.

Chapter 5 - Conclusions and Discussion

Introduction to Conclusions and Discussion

Several results in this study match what has been found in the literature: steeper slopes, longer slope lengths, and linear landscape features all increase the risk for gully erosion. Also, newly-formed gullies develop quickly at first, and then erosion rates decrease as the channel grows toward equilibrium. This study shows that vegetative cover may have a strong influence in preventing gully growth in agricultural fields in terms of thick crop residues, but a better quantitative variable for vegetation conditions is needed for small-scale prairie studies. No clear relationship was found between antecedent soil moisture conditions and erosion rates; however, freeze/thaw action, a different soil process, seems to have a significant influence on erosion rates in McPherson fields.

The following sections describe in more detail 1) the similar and different results for Fort Riley gullies and McPherson gullies; 2) specific conclusions for Fort Riley and McPherson gullies, including implications for land management and the potential for future studies; 3) and lessons learned in collecting gully field data.

Similarities and Differences between Fort Riley and McPherson Sites

McPherson and Fort Riley show similar and different trends in gully process over the 3-year study period. Similarities include deposition at the gully bed; of the five gullies at Fort Riley that had comparable longitudinal profile surveys, four of them show deposition along the length of the bed. In McPherson, the Schmidt and Goerhing gullies were also net-depositional along the length of their beds, and the Wedel channels were also depositional (except for the tributaries higher up in the gully network).

Gully channels that were similar in shape at Fort Riley and McPherson show a widening trend. One of the Wedel gully channels, named Tributary B, is similar in shape to the Fort Riley gullies in the fact that it a classic gully – too large to be driven through. Wedel Tributary B, along with the eroding portions of Trib C, showed widening of the gully channel, and four of the Fort Riley gullies also became wider.

In both land uses, Fort Riley and agricultural fields seem to be greatly influenced by the presence of man-made linear elements in the landscape. At Fort Riley, training maneuvers cause vehicle traffic to create wheel ruts that concentrate runoff; in agricultural fields, planting lines and wheel ruts also cause flow to concentrate toward the gully channel in both traditional tillage and no-till fields. Figures 5.1 and 5.2 show linear elements on Fort Riley and the Wedel field.

Figure 5.1 Linear elements: Fort Riley rill caused by tank tracks, which flows into the Training Area 51 gully downslope. Photo by author.

Figure 5.2 Linear elements: Goerhing field where crop rows influence flow concentration and direction. Photo by author.

One big difference between McPherson and Fort Riley gullies is their lifespan. On Fort Riley, tank tracks are creating gullies and causing gully growth, whereas linear elements in agricultural fields are supplying water and sediment to a pre-existing, permanent channel in the drainage network. Aerial photos from the 1950s show that the gullies in McPherson existed as part of the drainage network 60 years ago, and likely before that – see Figure 5.3. Agricultural practices since the early and mid-1900s have smoothed the land surface, and the "formation" and growth of gullies is supporting evidence that ephemeral channels have existed in those locations for a long time. On Fort Riley, however, aerial photos show that all of the studied gullies formed as new channels between 1990 and 2007.

Figure 5.3 The Wedel field (circled) in a USGS aerial photo from 1954, showing the same channel network studied in this project

Two other differences between Fort Riley gullies and McPherson agricultural gullies are specific land use and land cover, both of which effect runoff patterns. Fort Riley is still considered a prairie – it was farmland before being converted to training land in the mid-1900s but is currently supporting native tallgrass and forb species, meaning that, despite compaction from military training, prairie vegetation provides more soil protection compared to farmland. In terms of land use, tanks and other military vehicle traffic do not affect the land surface consistently, but affect certain corridors (towards stream crossings, normal pathways, towards objectives, etc.) or they disrupt the ground in random patterns (many times, multiple new tracks are seen entering a training field from the road, instead of from a well-used two-track, pathway, or corridor).

Agricultural gullies like those in McPherson have different land cover conditions than the disturbed prairie at Fort Riley. Agricultural crops provide less surface protection (shoots and residue) and subsurface (roots) protection than native prairie grasses, which influences runoff, infiltration, and the ability to detach and transport sediments. In terms of land use, agricultural fields can have predictable patterns of compaction, linear elements, and soil surface disturbance. So even though Fort Riley seems less disturbed due to the existence of native vegetation, land management strategies may be quite different than agricultural fields, because the disturbance from traffic is not as manageable as the uniform and predictable disturbance in agricultural fields.

Fort Riley – Specific Conclusions

Rates and patterns of change and driving factors of change – Fort Riley

Patterns of gully growth can be seen at Fort Riley. As stated, four of the seven gullies experienced filling of the gully bed from 2012-2013 (with up to 18 centimeters of fill in some locations along one gully bed). However, a longer study is needed to determine if filling of the bed is a long-term trend, or if the fill will be flushed out during certain rainfall/runoff conditions. A second trend is widening; four of the gully's top banks are widening, as determined from cross section overlays. The gully in Training Area 89 showed the greatest widening with a top width change of 0.85 meters from 2012-2014.

To analyze driving factors of gully growth, drainage area; slope above the headcut; vegetation conditions; rainfall scenarios including peak rainfall intensity and antecedent moisture conditions; and inherent soil erosivity factors were all taken into account in the study. Different gullies and even different cross sections within the same gully, showed different potential driving factors: for example, in the Training Area 98 gully, Cross Section 2 showed a positive relationship between erosion and larger storms; but Cross Section 4 in the same gully showed a strong relationship between erosion, peak intensity rainfall, and NDVI. Overall, comparison of gully change to different rainfall scenarios show that larger storms, storms with antecedent soil moisture, and especially high peak rainfall events have more influence on gully erosion than a simple total depth of rainfall over time. Through cross section overlays, visible erosion can be seen in three of the Fort Riley gullies, and the visible erosion corresponds to time periods when a large, multi-day rain event was 114 millimeters of depth or greater. However, we cannot conclude that rainfall was the only process at play in those erosion events, and more data points are needed to determine if there is a threshold of rainfall that causes erosion.

Even though vegetation was not determined as a driving factor of erosion through this study (oftentimes, greater density of greenness correlated to more erosion, which is contrary to what was expected), it is still suspected that compaction and subsequent damage to vegetation – including processes of decreased infiltration and limited root growth, and increased runoff – play a role in driving gully erosion. The conclusion is that NDVI (Normalized Difference Vegetation Index) from MODIS satellite imagery is not a good measure for small-scale erosion studies such as this, due to the fact that pixels are too coarse. Also, NDVI purely measures greenness as an indication of green leaf density; dense vegetation in the fall and winter is represented as poor leaf density due to color changes. (Figure 5.4 shows seemingly healthy October vegetation that would receive a poor score according to NDVI). Additionally, at least one previous study has shown an increase C3 forbs and grasses at Fort Riley following tank track disturbance/compaction (Shaw-Althoff, 2001). Shallow/sparse-rooted disturbance species could be showing a false sense of healthy vegetation community. A separate vegetation and/or compaction measure is needed to take into account root type, root density and root depth as well as soil conditions, all of which can influence runoff and infiltration relationships.

Figure 5.4 Training Area 91 gully in October, showing good vegetative cover, but poor greenness for NDVI values. Photo by author.

As a final conclusion about Fort Riley drivers, further disruption of gully areas temporarily causes increased instability and erosion of the channel. For example, a new headcut and tributary formed in the Training Area 42 gully after it was driven through during wet conditions. It is known that gullies usually grow quickly at first, then the rate of growth decreases as the channel begins to reach equilibrium (Graf, 1977; Wu & Cheng, 2005). Disturbance of a pre-existing gully, and the quick erosion that follows, can be a window into what processes take place during the initial formation of a gully after initial disturbance: the theory that a tank drives through an area, runoff is affected, a headcut forms, which then quickly grows into a gully.

Implications for land management – Fort Riley

Results from this study and others (Shaw-Althoff, 2001; Handley, 2013) suggest that land management on Fort Riley needs to address the timing and location of training maneuvers in order to decrease risk for gully development. Training on wet ground causes soil damage, and consequent shifts in vegetation composition as noted in Shaw-Althoff (2013): "…species composition and ground cover were more strongly affected by soil moisture conditions at the time of disturbance, with greatest damage severity observed for repeated traffic under wet soil conditions" (p. 15). This gully study helps confirm that the most instability and growth in gully development occurs immediately after disturbance, followed by gullies growing more slowly toward a state of semi-equilibrium. If disturbance can be minimized by timing and placement of maneuver activity, ideally soil will not be compacted so severely, and vegetation composition would be less affected. Managing training schedules would not only help prevent new gullies from forming, but would help prevent new disequilibrium in existing, semi-stable gullies.

Best management practices for Fort Riley can be related to studies about pastureland BMPs, because similar processes are at play in both scenarios. Cattle compact the soil and decrease vegetative cover, as does military training; also, cattle create regular "cow paths" or compacted linear pathways that can concentrate water runoff, which are small-scale versions of compacted pathways caused by military traffic. In an evaluation of different BMP implementations for stream bank erosion related to rangeland management, Agouridis, Workman, Warner, and Jennings (2005) state:

> "For reducing the impacts of cattle grazing on the health of a stream, both structural control BMPs and cultural control BMPs are ideal. Structural control BMPs (i.e., riparian buffers and vegetative filter strips) modify the transport of the pollutants to waterways while cultural control BMPs (i.e., managed grazing) are designed to minimize pollutant inputs to waterways through land management practices" (p. 592).

Tank traffic magnifies the effects of compaction compared to cattle, because tanks are heavier, and they are not in single file when moving across the landscape. The consequence is greater damage to larger areas. However, the idea of both structural and cultural control BMPs could be effective in military land management. Structural controls could interrupt flow on a recently driven-through area when track length is long and slopes are steep or watershed area is large. An ideal management situation that can pin point gully potential after a training activity would require tracking all vehicles and using topographic and aerial maps to determine hotspots for gully potential. Tracking vehicles would be a challenge due to security concerns, but would not be impossible (Denker, 2013).

Cultural controls could be avoiding heavy training on wet ground. Dr. Stacy Hutchinson and Dr. Shawn Hutchinson, who have studied vegetation and erosion processes at Fort Riley, state that best management practices must fit into the Army's training framework to be effective. Training schedules are set weeks in advance, so any last minute alteration of schedule to avoid wet or overused areas must be part of a training exercise. For example, areas sensitive to erosion after rainfall could be listed last minute as chemically contaminated or land mine areas (Hutchinson and Hutchinson, personal communication, 2015). Educating trainees about the potential for damage after driving straight down a steep slope is also an option.

Additional questions and future studies – Fort Riley

This study raises several questions about Fort Riley gullies:

1. Have many of the Fort Riley gullies reached a semi-equilibrium state, and would they continue to grow toward equilibrium (getting wider and shallower) if left alone?
2. If gullies tend to form in tank tracks, how can we predict and prevent more from forming?
3. Is it possible to quickly measure gully dimensions directly following a rain event, even in muddy conditions, to pin point causal relationship between rainfall intensity, runoff and gully change?
4. What vegetation variable can be used to account for small-scale conditions in the gully watershed that includes a measure for root depth and density? Can a species composition study tell us what we need to know about soil conditions in terms of runoff energy?

One suggestion for increasing the amount of data points in a study like this is looking into unmanned aerial vehicles for rapid, remote, high-resolution data collection through photography or photographic 3-D models. This study also encourages looking at different in-field mitigation strategies: identifying locations where gullies have the potential to grow (in tank tracks at certain watershed sizes, slopes, and with a certain track length, for instance), implementing several different mitigation measures that interrupt flow velocities in some of the locations, then waiting to see where gullies form.

Training maneuvers compact the soil, creating habitat for cool season grasses and forbs that do not have as deep and dense of a root structure as warm season grasses. One study could address loosening previously compacted soil, through subsoil ripping or plants like tillage radishes that break up compacted soil, and monitor the recovery of C4 vegetation.

McPherson – Specific Conclusions

Rates, patterns, and driving factors of change - McPherson

In the three studied fields – Wedel, Schmidt, and Goerhing – net deposition occurred in each of the gully channels over the 3-year study period, as shown by both cross section and longitudinal profile overlays. However, the tributary channels in the upper watershed areas of the Wedel field experienced net erosion. In both no-till fields – Wedel and Schmidt – sediments are being delivered to the larger gully channels and stored there, at least temporarily. In the Wedel field, the sediment supply from the many small tributaries along Trib B is so high that runoff flows do not have enough energy to transport the sediments downstream, causing the high rates of deposition and the trend toward a gentler slope of the main tributaries A and B. Though the upper-most gully channel beds on the Wedel field are downcutting, enough sediment is deposited at mid-to lower elevations of Tributary B that the smaller channels feeding Trib B, such as Trib C, are backing up with sediments as well.

The increases in erosion at the Wedel field after heavy rain in 2015 shows us that the sediment won't remain in the channel unless secured with plants and potentially grade control. The clay layer exposed at the bed of the channel after sediment was flushed downstream is providing some protection from future downcutting, and should not be disrupted.

The Wedel gully system is an efficient transporter of sediment; in times when the channels are emptied of sediment, the base level of the channel is lowered creating taller banks and greater initial relief, causing more small tributaries to form and drainage density to increase. In a typical fluvial system, drainage density increases when runoff volumes and initial relief, or gradient, are high. As drainage density increases and more channels are created, discharge (flow) increases along with sediment supply. In the Wedel field, drainage density seems to be increasing in the upper areas of the watershed where the higher erosion rates are; but through time, historical photos show a fluctuation between high drainage density in the lower portions of the field (Trib A), and smooth, planted row crops. For this McPherson region under crop production, or in any region, there could be an optimum drainage density for certain systems with a low quality of vegetative cover – and another optimum drainage density for systems with higher vegetative cover.

On the only traditionally-tilled field, Goerhing, the producer was able to manipulate the landscape enough that most of the time, there was no defined gully channel. Though the surveys show that the channel was depositional, soil was rearranged by tillage, and cross section change solely due to runoff was only able to be detected for short periods of time. In spring 2015, the Goerhing gully area was left fallow, and spring rains caused erosion of the studied channel along with erosion of the channel in the west portion of the field that was not part of the study. In studying recently abandoned and marginal lands in Spain, De Santisteban et al. (2006) conclude that a lack of erosion management in these areas can result in great erosion volumes, which could be a similar conclusion for "waterways" that are abandoned in actively-farmed fields.

In studying potential driving factors of change, including quantitative variables of rainfall (largest storms and peak intensity rainfall), drainage area, and bed slope; and qualitative variables of crop type, residue cover, and antecedent soil moisture represented by number of consecutive days with rainfall, connections can be made about variables:

1. The Schmidt gully, which is in a no-till field with good residue cover, rarely showed signs of erosion, and more often showed signs of deposition, suggesting that residue cover slows runoff velocities, preventing erosion;
2. In the Wedel field, cross sections that experienced net-erosion show a negative relationship to rainfall: as rain events got larger and more intense, less erosion occurred in four out of six upper-elevation cross sections. Even when examining consecutive days of rainfall before a larger event to estimate soil antecedent moisture, cross sections experienced the lowest erosion rates after large summer rains on top of moist soil. However, the last visit to the field to observe changes after heavy rainfall showed that there may still be a threshold of rainfall depth or intensity that causes increases in erosion, and the 3-year study period simply did not catch a threshold event.
3. In the Wedel field, there may be a relationship between bed slope and vegetative cover that contributes to increased soil erosion. The Wedel field had poor surface protection in general, and every cross section that had an approaching slope of 1.3 percent or greater

experienced net erosion. However, both the Schmidt and Goerhing fields had cross sections whose slopes were greater than 1.3 percent, and those cross sections experienced deposition. Channel roughness in the Goerhing and Schmidt fields, either from tillage or vegetative surface cover, could be an explanation for deposition at steeper slopes.

One variable that could explain unexpected patterns of erosion on the Wedel field is a variable that was not considered at the beginning of this study: freeze/thaw action. Wedel data indicated that low peak rainfall events and events with relatively small rain depths in the spring related to the highest rates of erosion, and the highest rates of erosion for four of the six net-eroding cross sections all occurred during the same timeframe: April to June, 2014. Field photos from March 2014 show standing water in the gully channel and wet bank conditions, likely from snowmelt. April field photos show large quantities of loosened sediments laying on the gully banks. Freeze/thaw, also called frost heave and sometimes referred to as "needle ice" processes, causes the breakdown of soil aggregates at the soil surface, and is most common in high silt-clay soils (Couper, 2003). In the case of the Wedel field, the freezing front is the exposed gully banks. Studies have examined the processes of "needle ice" and freeze thaw action on exposed river banks, and their conclusions seem similar to the processes going on at the Wedel field: "Flows [within the channel] are unable to erode firm cohesive clays from the banks, and erosion is generally limited by the availability of loosened material" (Prosser et al., 2000, p. 1085). In summer conditions, large rain events at the Wedel field did not detach the largest quantities of sediment when the gully channel surface was hard and crusted over from previous flows. Instead, it is the sediment preparation processes before a rain event that seem to drive the highest erosion rates. The discovery of freeze-thaw processes loosening the soil in the McPherson area magnifies the need for soil conservation strategies, particularly those that stress vegetative cover and bank slope stabilization, discussed below.

Implications for land management – McPherson

The conclusions from this study can inform land management, particularly for gullies in no-till fields. This study does not provide specific management suggestions for gullies in traditionally tilled fields. Because only one traditionally tilled field was studied, and because the data from that tilled field shows that deposition occurred even in between tillage cycles, improvements for land management practices in similar tilled fields cannot be provided from this study.

Improvements can be suggested, however, for the management of no-till or conservation-tilled fields. Though studies show that erosion has been reduced through practices such as conservation tillage (Garbrecht & Starks, 2009), no-till fields that are home to gully channels need to have extra soil conservation practices to prevent gully channel enlargement, since the producers do not re-work and smooth out the channel each year. Where freeze/thaw action is a main driver in channel enlargement when the gully banks are not completely inundated during high flow, producers can expect their gully channel to continually get wider. Prosser et al. (2000) explains how peak erosion elevations at the mid-bank encourages upper bank failure and continued steepening and widening. Figure 5.5 shows the formation of a notch on the bank of Wedel field Trib B. In order to curb channel widening and extension, design objectives for BMPs are suggested below.

Figure 5.5 Notch created on banks after fluvial entrainment of the bank material. Photo by author.

Recommended BMP design objectives for McPherson-area agricultural gullies

The Wedel field results show that steeper gully bed slopes, lack of channel roughness, and freeze/thaw loosening of the gully banks are potentially the most significant contributors to high erosion rates and channel extension, especially in times of average rainfall conditions. As a response, BMPs should address gully bed slopes, vegetation as roughness in the channel and throughout the field, and gully bank stabilization. Using the Wedel field as a model, two locations in gullied agricultural fields can be targeted for best management practices: the soil surfaces outside of the gully channels, and the gully channels themselves. Overall BMP objectives from the results of this study suggest similar goals to typical soil conservation practices: increase infiltration, catch and store detached sediment, decrease runoff velocities, and in turn, store more water on the field for crop use. Common conservation practices that address improving runoff relationships include leaving residue on the field; planting cover crops in the off-season; creating vegetated waterways in the field; and decreasing overland flow length though terracing, contour cropping, and strip cropping. As a note, many producers in the McPherson area already use vegetated waterways, terracing, and residue cover practices.

To specifically focus on gully channel best management practices, two objectives should be addressed: 1) increasing bank stability, and 2) designing a channel that allows the gully to be a part of the drainage network. As stated, many of the gullies in the McPherson area are on the aerial map from the 1950s – they are not going to disappear after the land is reshaped for agriculture. Contributions of sediment from stream and gully banks is a well-known issue, and bank height, bank angle, and soil shear strength – influenced by surface roughness and soil moisture – are common factors in bank erosion (Rosgen, 2006; Shields et al., 2009). Objectives to increase bank stability include decreasing the gully bank angle and height, and protecting the banks with vegetation. Healthy bank vegetation will utilize excess soil moisture, also helping to stabilize gully banks. BMPs can include vegetated banks that provide protection from freeze/thaw: "Grass cover can provide three forms of protection: improved soil cohesion, protection against fluvial scour and insulation against the formation of needle-ice and desiccation… grass is a particularly effective insulator against freeze/thaw activity with soil temperatures nearly twice as likely to fall below 0°C on bare banks than on banks with a grass cover" (Prosser et al., 2000, p. 1097).

Care should be taken when trying to curb high sediment yields. If you decrease sediment loads to the main channels by stabilizing bank material, runoff shear stress would potentially increase. As a solution, securing sediments will help prevent new mobilization of sediments:

> "Conservation practices on cropland will reduce lateral sediment supply to channels, yet the watershed runoff system will usually respond by seeking a new regime equilibrium, remobilizing previously deposited sediments, or by eroding channel boundaries, thereby concealing beneficial conservation impacts at the watershed scale by shifting sources of sediment (Meade, 1988; Allen and Naney, 1991; Trimble, 1999; Walling, 1999). It may take some time to flush accumulated and stored sediments before the full effect of upstream soil conservation practices can be seen at the watershed outlet" (Garbrecht & Starks, 2009, p. 314).
> *Also:*
> "The inherent lag times within the social and physical system can disguise the actual effectiveness of a BMP or watershed scale suite of BMPs. Hydrologic land types can shift in space and time, and modifications from BMPs can alter the dominant flow path, triggering a new transport path for pollutants" (Rittenburg, Squires, Boll, Brooks, Easton, & Steenhuis, 2015, p. 20).

Another objective of BMPs is designing a gully channel, and channel features, that are a stable part of the drainage network. In fields like the Wedel field, which has a high sediment supply from steep gully banks and poor vegetative cover, catching and securing detached sediments is one objective in the channel design. Dave Rosgen, an expert in river science and restoration, has constructed alluvial fans to catch increased sediment loads following forest fires (Rosgen, personal communication, 2014). The Wedel field is experiencing a similar process – removal of vegetation is creating increased sediment production and movement, which needs to be captured and secured. On fields with high sediment supply, sediment can be caught and stored in the channel with bio-materials, or with land alteration that creates mini-alluvial fans. The area catching sediments must be planted to a cover crop or in permanent grass to hold the sediment in place as the channel continues to participate in draining the field. At the end of the study, the gully channel at the Wedel field was storing large amounts of sediment, but nothing is in place to secure those sediments from the next large, flushing flow event, as was seen during the last visit to the field in June 2015.

In working with the gully channel rather than against it, one option would be to design a channel that can handle what in river science is called the bankfull flow – or the channel discharge that does the most geomorphic work over time. Stream bankfull discharge occurs on average every 1.5 years, and can be determined by stable physical stream features and stream gage data. Because gullies do not have gage data, and because they are all unstable incised channels with no physical bankfull features, a gully channel design would need to incorporate site-scale runoff curves from plot studies, which could be informed by an extrapolation of regional curves, or the SWAT model. In the gully channel design, a floodplain feature could be constructed to ease stress within the bankfull channel, while slowing runoff volumes and allowing deeper infiltration. The floodplain features could be permanently planted to grass, or planted to a cover crop.

Additional questions and future studies - McPherson

This study raises several questions for gullies in McPherson agricultural fields, which can inform future studies:

1. Can the contribution and pattern of runoff volumes and velocities from linear elements such as planted rows and tire tracks be quantified?
2. What specific factors drive freeze/thaw actions on gully banks, and can those processes be modeled?
3. In examining the two no-till fields, did the Schmidt gully show less signs of erosion than Wedel due to the good residue cover?
4. In traditionally-tilled fields like Goerhing, what role does soil surface roughness (post-tillage) play in preventing erosion?
5. How much sediment is actually leaving gully fields and impairing downstream water bodies?

The results of this gully study can spur future studies related to gully erosion. One study could closely examine linear landscape elements in the field, using mapping programs to track both man-made linear elements and rills and gullies, similar to a study done by Svoray and Markovitch (2009). Also, a future study for Kansas agriculture is furthering the understanding of freeze thaw action in crop fields in terms of how much sediment freeze/thaw prepares, and what factors in the landscape are related to the process.

Moving forward from this study, a field test of multiple BMPs could be done on multiple no-till fields where gully problems exist. Measurements of the existing conditions would be taken, including sediment loads and patterns in the fields; then, various BMPs that address the objectives above, including bank stabilization measures and constructed channel/floodplain projects, would be implemented and monitored. The BMP study would need to be monitored long enough to give permanent vegetation a chance to reach its full potential, and long enough to monitor drought and wet years (ideally several wet years and several drought years). The BMP study would, in the end, give producers direction in choosing management practices that fit their needs for soil conservation and gully channel management.

Lessons Learned in Collecting Gully Field Data

There were several learning experiences in this study when it came to monitoring working landscapes. Both at Fort Riley and in agricultural fields, minimal rebar markers could be left in the open fields as elevation and reference pins. As an alternative, pin flags were used as cross section end point markers. They were rarely disturbed by farm equipment in no-till fields, and even if the flag came off, the thin metal pin could be found relatively easily with a GPS locator and a metal detector. Pin flags were often pulled out by equipment in the traditionally tilled field. As a solution for cross section end points, 0.6-meter lengths of rebar were driven vertically into the ground, then driven approximately 0.6 meters deep with a driving pin, so that tillage operations did not move the pin, yet the surface location of the rebar could be found with a metal detector.

Pin flags do not provide stable elevation reference points, so in fields where benchmarks cannot be left in the open, three rebar benchmarks must be placed along the field edge in different locations. If only two benchmarks are installed and one gets hit with tillage equipment, there is no way of knowing for sure that the other benchmark elevation is still accurate.

Muddy conditions made it difficult to access certain locations after rainfall, and even if a site was accessible, accurate surveys cannot be done in mud. Even if it is too wet to survey, photographing conditions after rainfall, or in large time gaps between surveys, provides helpful information in terms of gully process. Additionally, walking on fields to take photos can be done more frequently than a complete resurvey. Using photography to create 3-D models has great potential in erosion research; if a 3-D model from photography is accurate, models from different timeframes can be overlaid and volumes compared for erosion and deposition. More observations, and more detailed observations, could be gathered for the expense of a camera, 3-D modeling software, and the time it takes to photograph the site. However, 3-D gully modeling requires bare or nearly-bare soil – the photographs model the imagery surface, including any vegetation.

Conclusion Summary

Several patterns of gully growth were discovered through this study. On Fort Riley, most of the gullies are widening and filling, and significant erosion only occurred after rain events of 114 millimeters or greater. Though the drivers of gully growth on Fort Riley seem to vary from location to location, compaction and its influence on species composition is suspected to play a significant role in gully formation and growth. Best management practices that include avoiding certain training areas as part of training exercises could keep heavy traffic off of sensitive land areas after rain events. BMPs that also interrupt tank track flow length are suggested.

In McPherson agricultural fields, most of the gully channels stored sediment throughout the study period. After data collection was completed, heavy rainfall in spring 2015 moved much of the sediment downslope and out of the channels. Prior to sediment transport, vegetation as surface roughness can help prevent the high quantities of sediment being delivered to the channels. Best management practices involving catching and storing sediment, as well as designing “stable” gully channels, should be tested and demonstrated. At Fort Riley, gullies can potentially be prevented from forming, but in McPherson, producers must work with the gully networks rather than trying to eliminate them.

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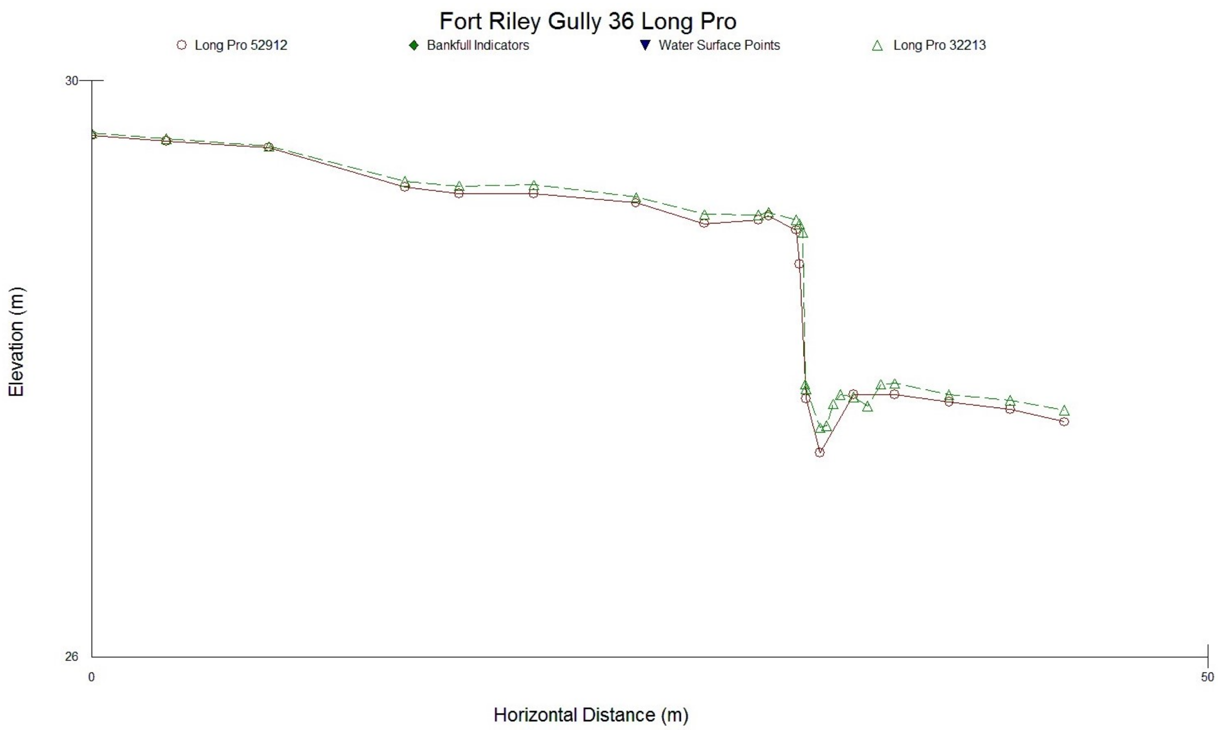
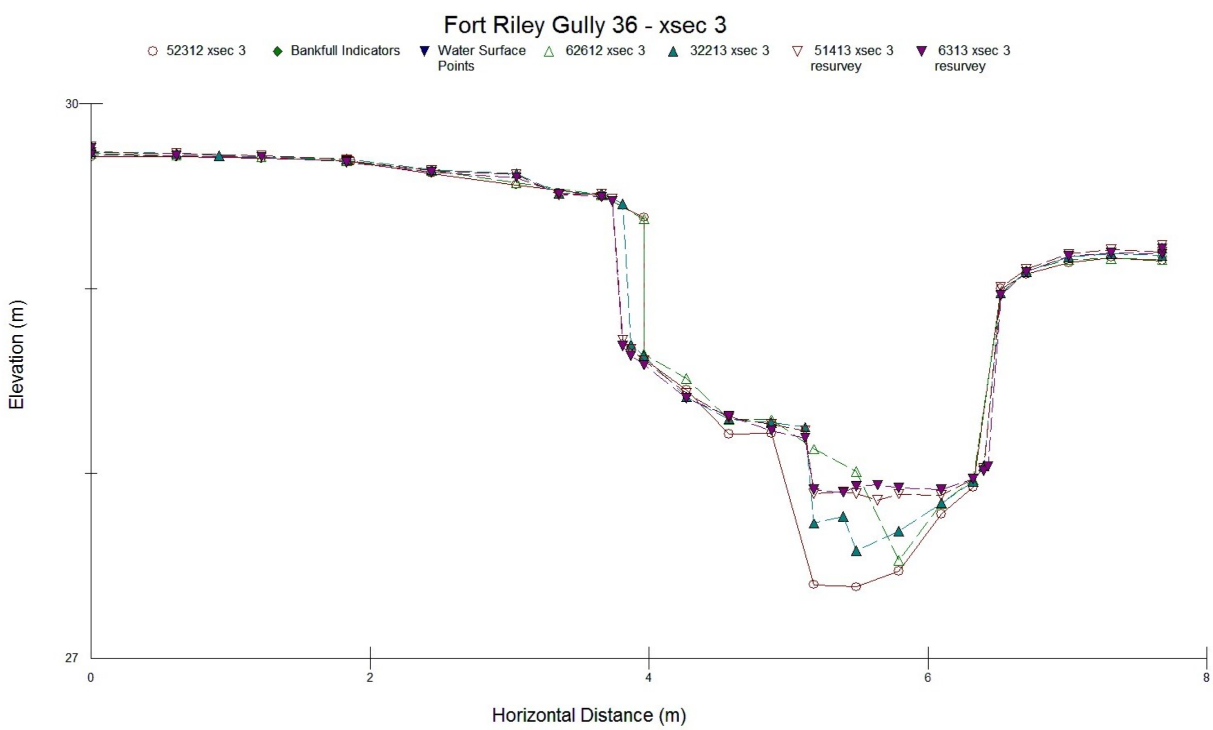
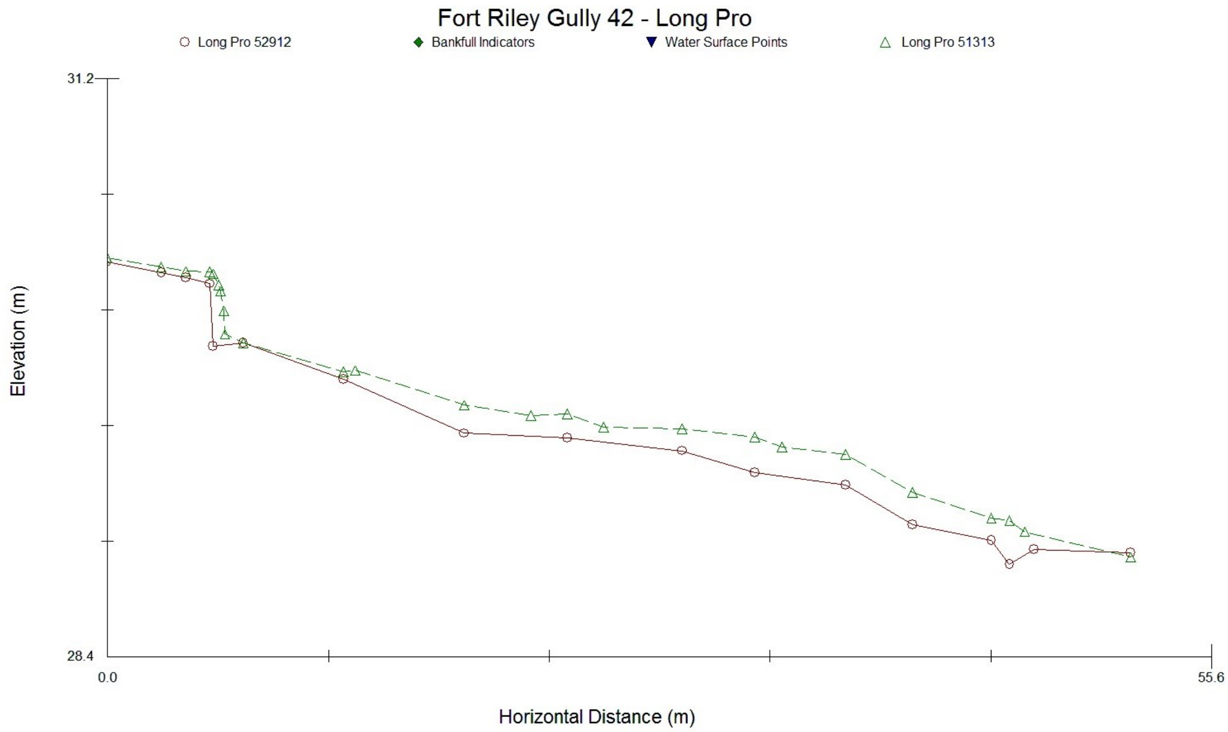
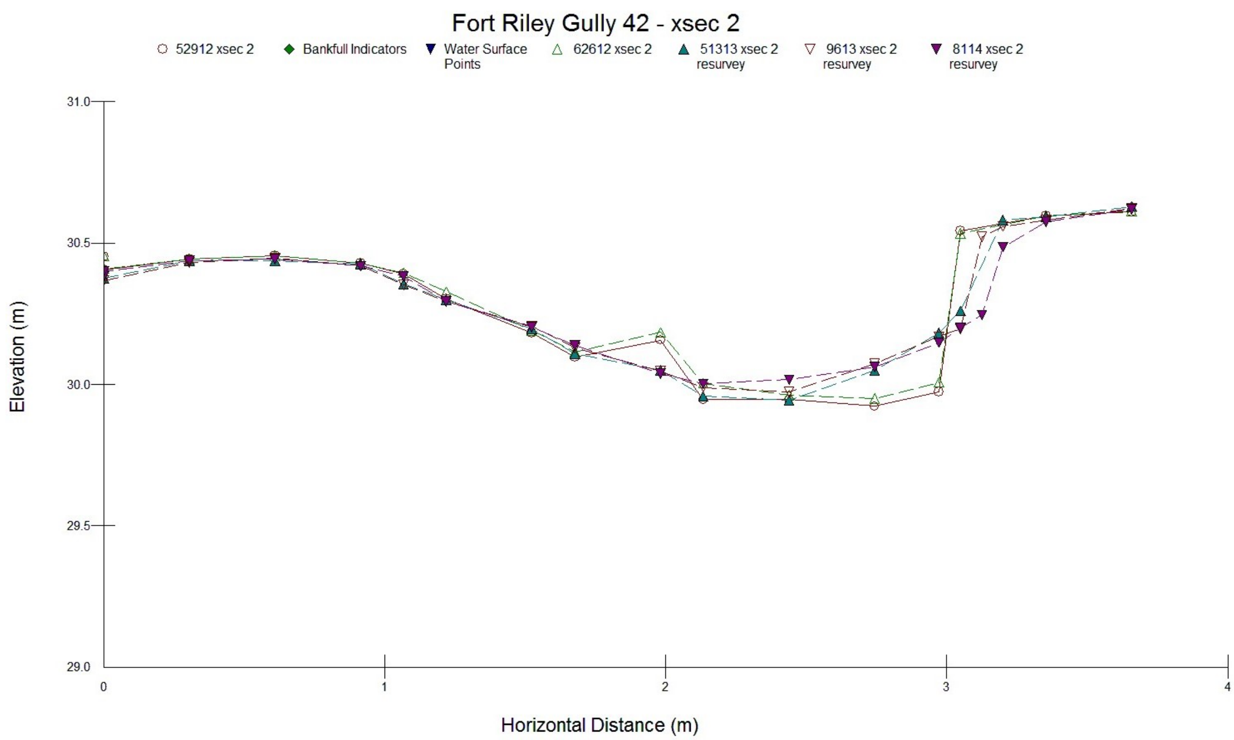
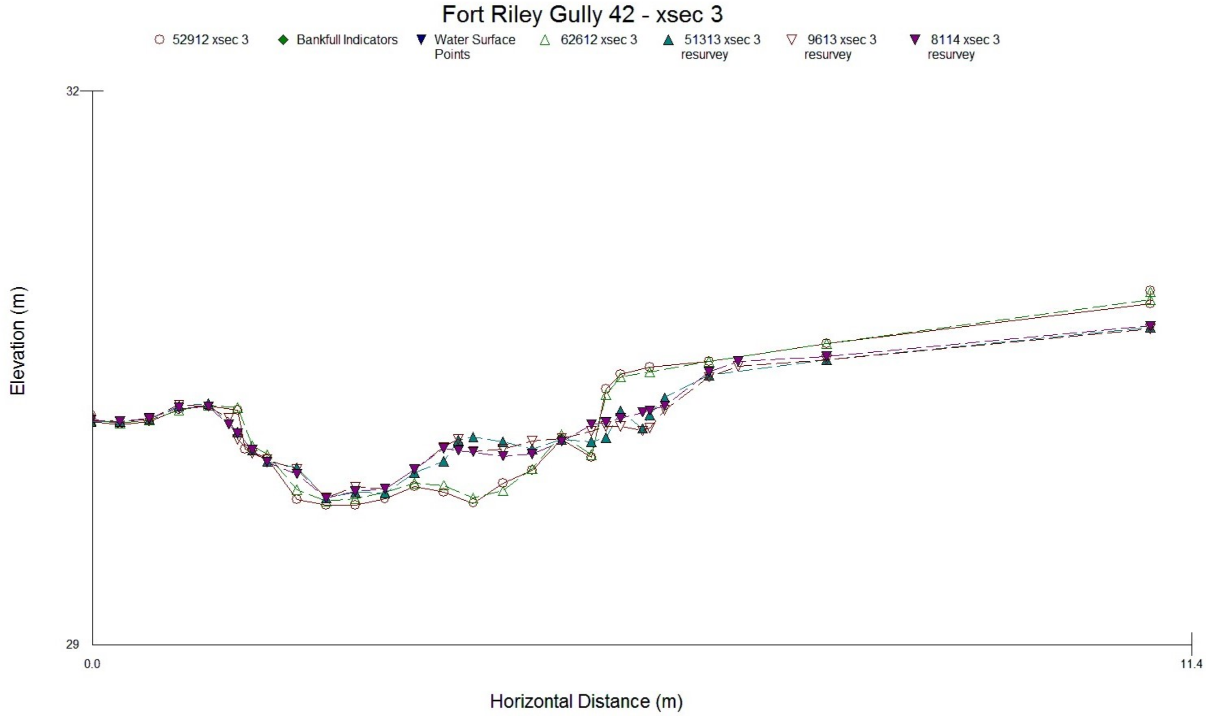
Appendix A - Fort Riley Cross Section and Long Pro overlays



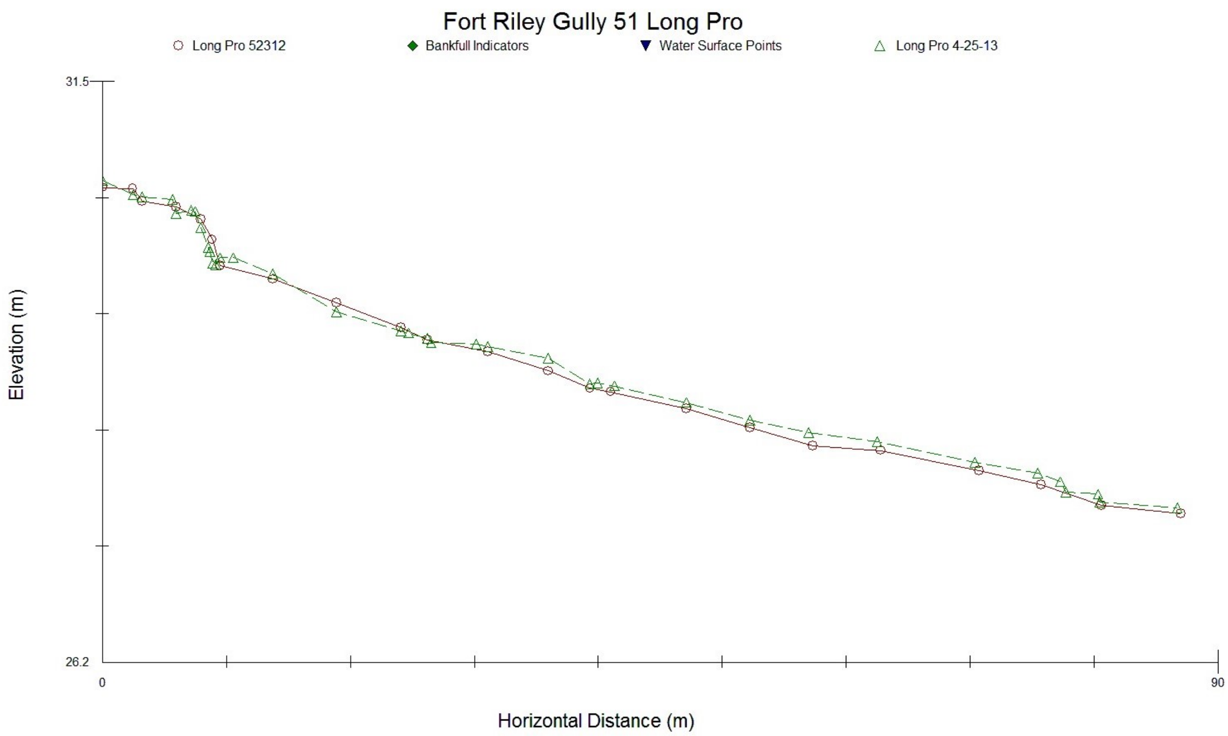



Fort Riley Gully 42 - Long Pro
Long Pro 52912
Bankfull Indicators
Water Surface Points
Long Pro 51313
31.2
28.4
Elevation (m)
0.0
55.6
Horizontal Distance (m)

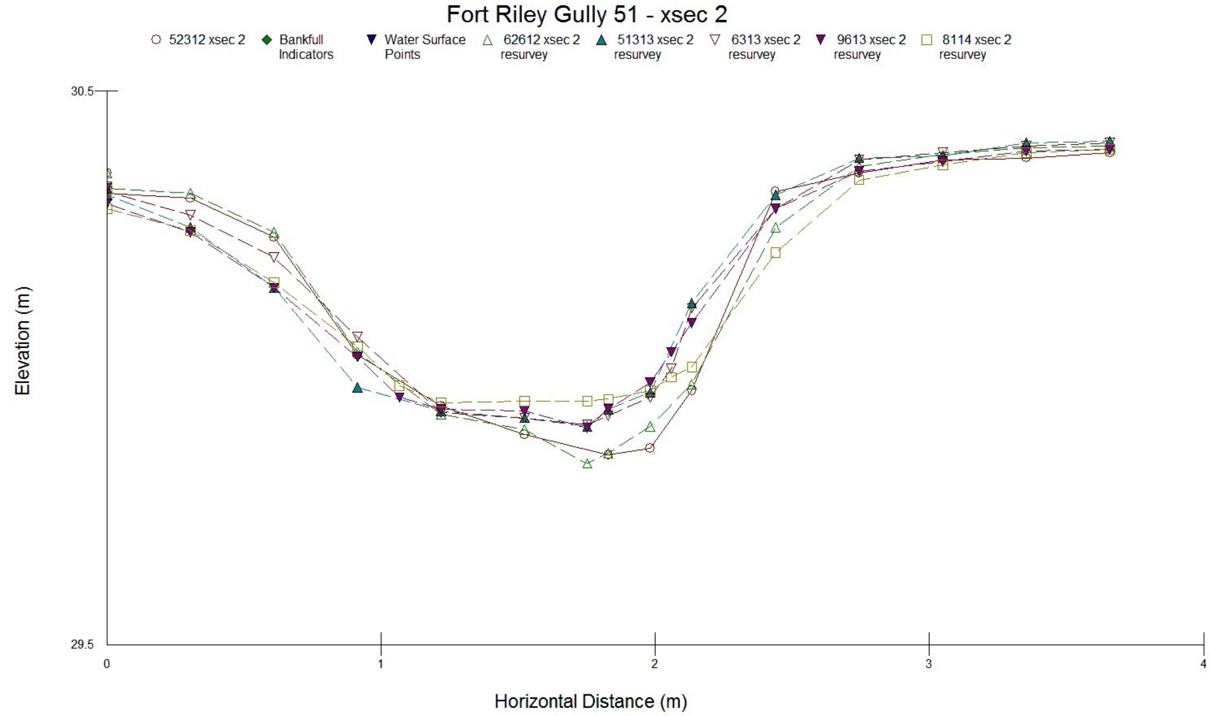

Fort Riley Gully 42 - xsec 2
52912 xsec 2
Bankfull Indicators
Water Surface Points
62612 xsec 2
51313 xsec 2 resurvey
9613 xsec 2 resurvey
8114 xsec 2 resurvey
31.0
30.5
30.0
29.5
29.0
Elevation (m)
0
1
2
3
4
Horizontal Distance (m)

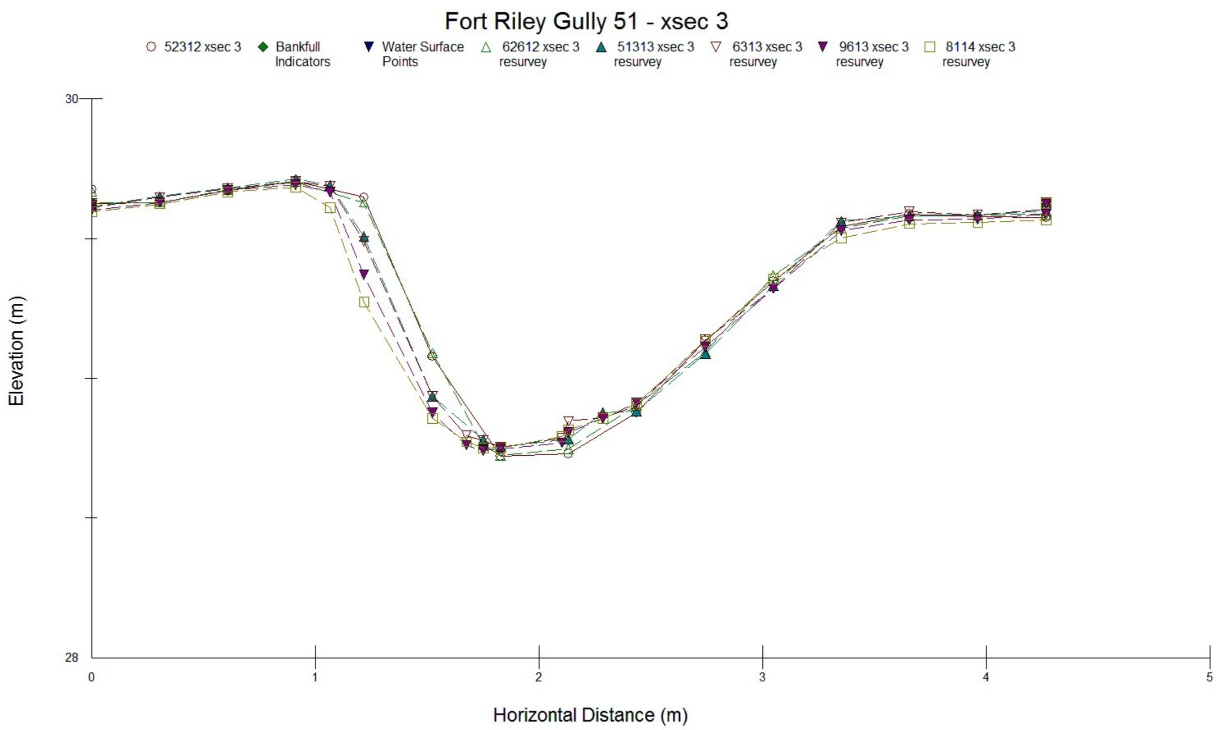


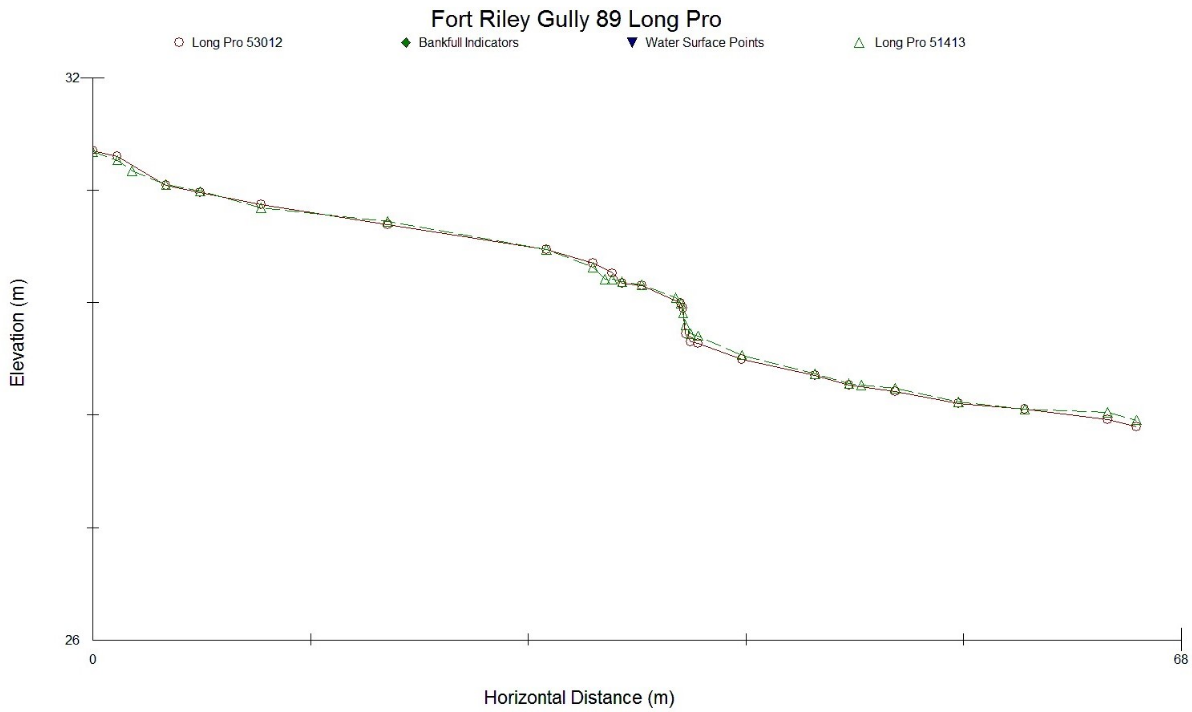
Fort Riley Gully 42 - xsec 3
52912 xsec 3
Bankfull Indicators
Water Surface Points
62612 xsec 3
51313 xsec 3 resurvey
9613 xsec 3 resurvey
8114 xsec 3 resurvey
32
29
0.0
11.4
Elevation (m)
Horizontal Distance (m)

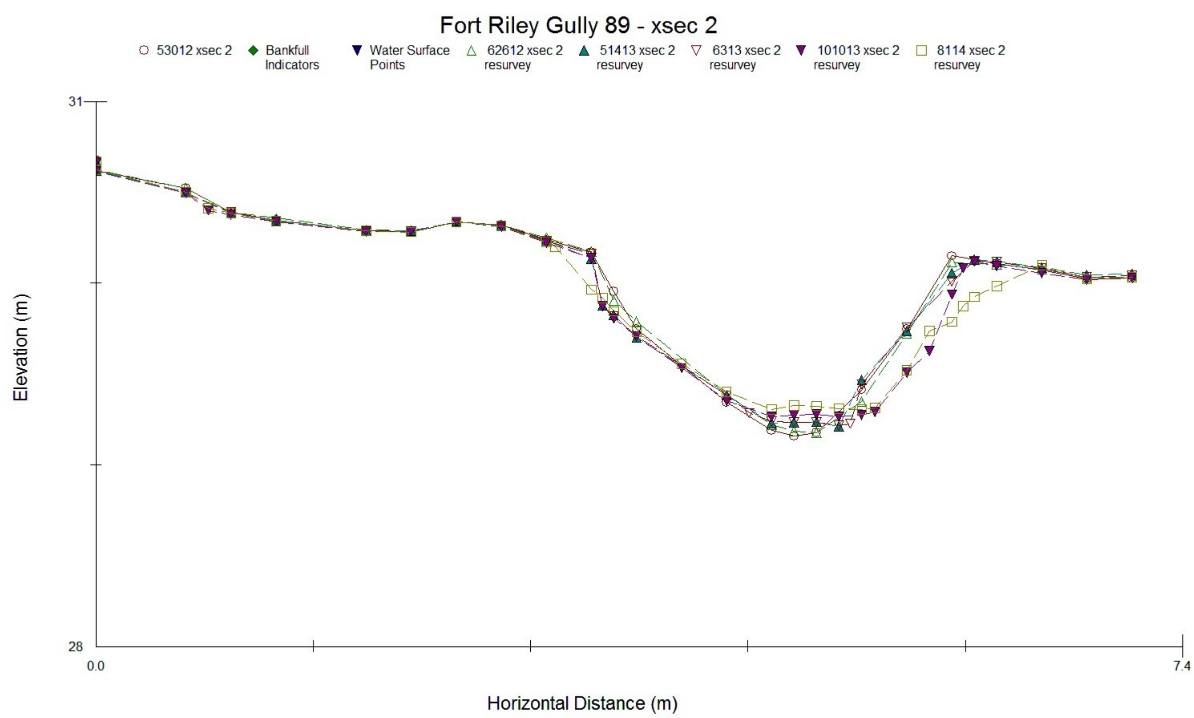


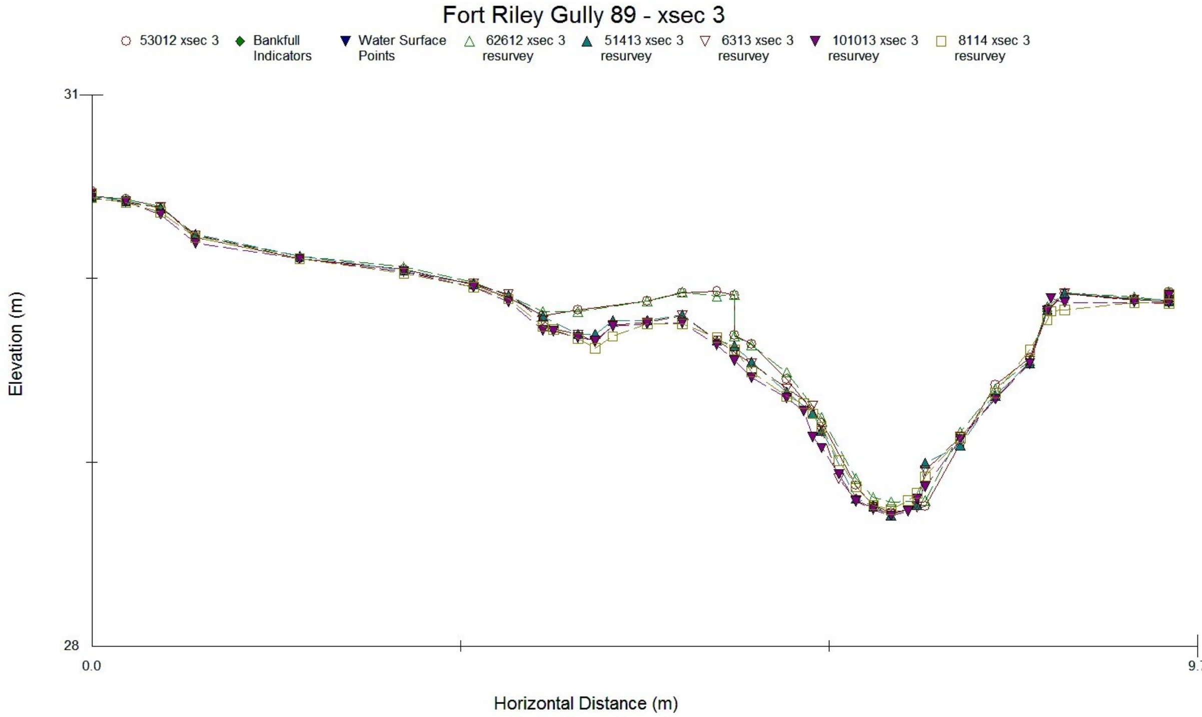
Fort Riley Gully 51 Long Pro
Long Pro 52312
Bankfull Indicators
Water Surface Points
Long Pro 4-25-13
31.5
26.2
0
90
Elevation (m)
Horizontal Distance (m)


Fort Riley Gully 51 - xsec 2
52312 xsec 2
Bankfull Indicators
Water Surface Points
62612 xsec 2 resurvey
51313 xsec 2 resurvey
6313 xsec 2 resurvey
9613 xsec 2 resurvey
8114 xsec 2 resurvey
30.5
29.5
Elevation (m)
0
1
2
3
4
Horizontal Distance (m)

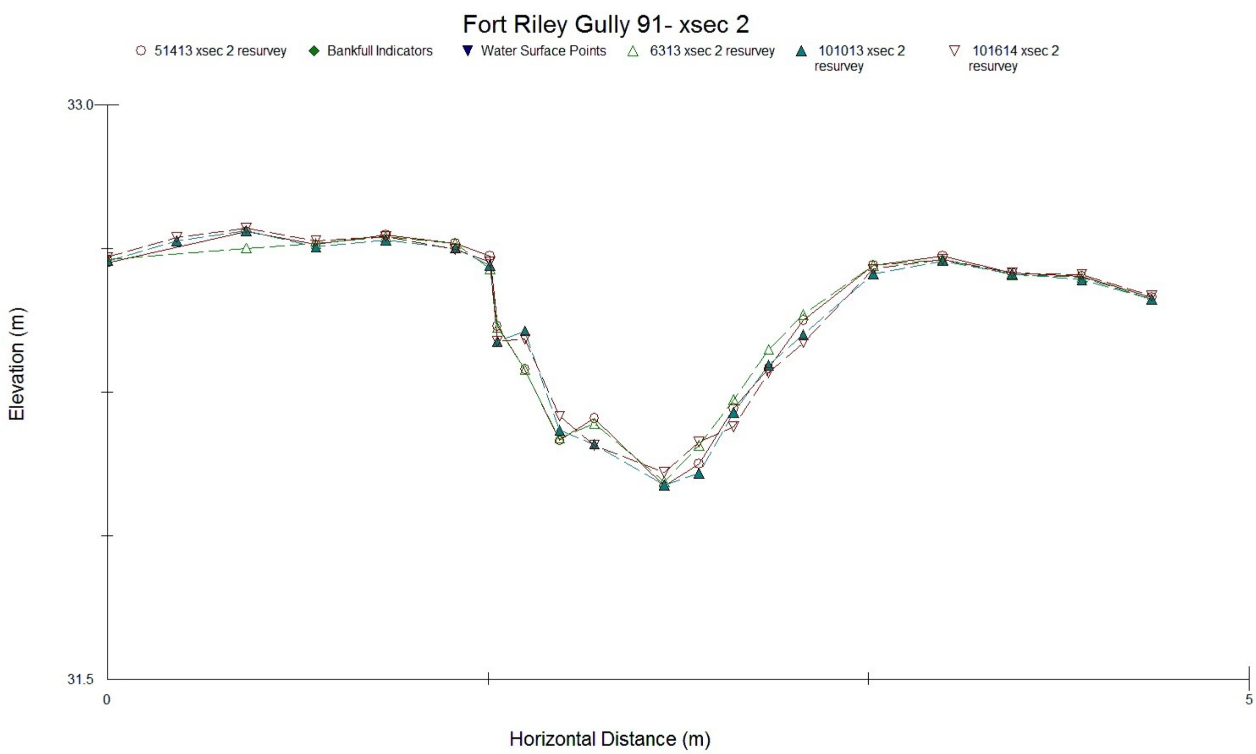

Fort Riley Gully 51 - xsec 3
52312 xsec 3
Bankfull Indicators
Water Surface Points
62612 xsec 3 resurvey
51313 xsec 3 resurvey
6313 xsec 3 resurvey
9613 xsec 3 resurvey
8114 xsec 3 resurvey
30
28
Elevation (m)
0
1
2
3
4
5
Horizontal Distance (m)


Fort Riley Gully 89 Long Pro
Long Pro 53012
Bankfull Indicators
Water Surface Points
Long Pro 51413
Elevation (m)
32
26
0
68
Horizontal Distance (m)

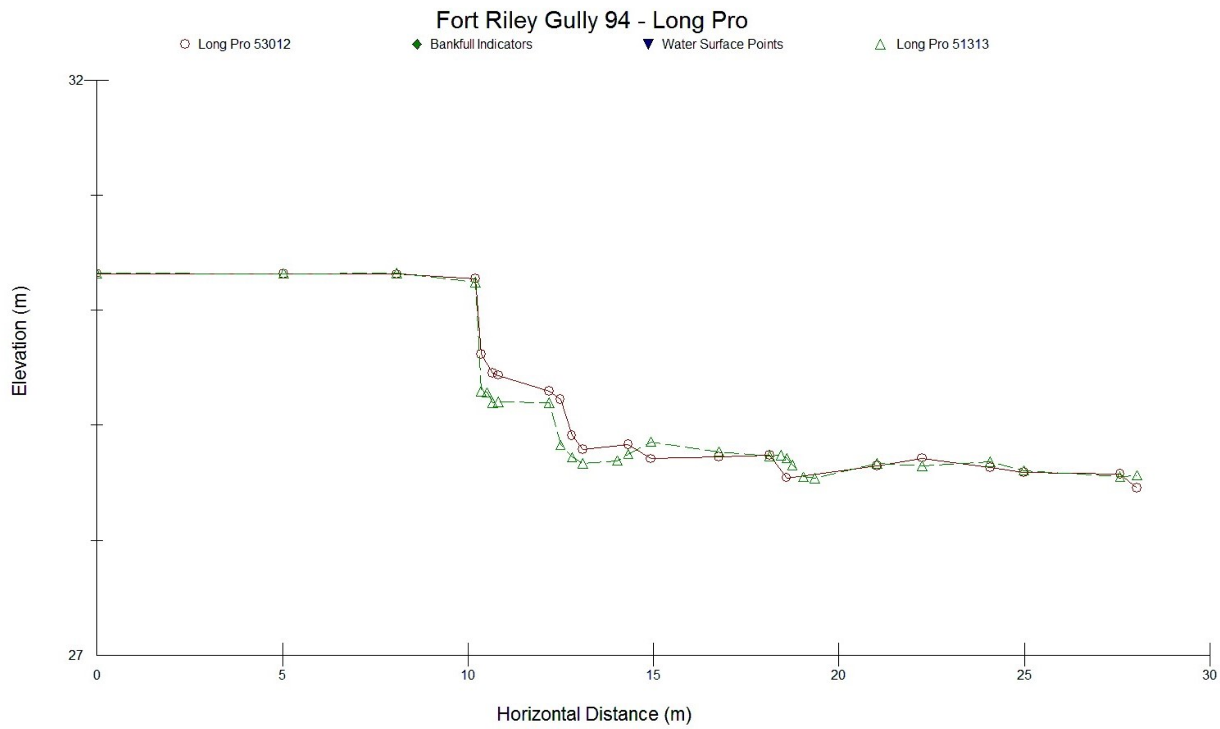

Fort Riley Gully 89 - xsec 2
53012 xsec 2
Bankfull Indicators
Water Surface Points
62612 xsec 2 resurvey
51413 xsec 2 resurvey
6313 xsec 2 resurvey
101013 xsec 2 resurvey
8114 xsec 2 resurvey
Elevation (m)
31
28
0.0
7.4
Horizontal Distance (m)

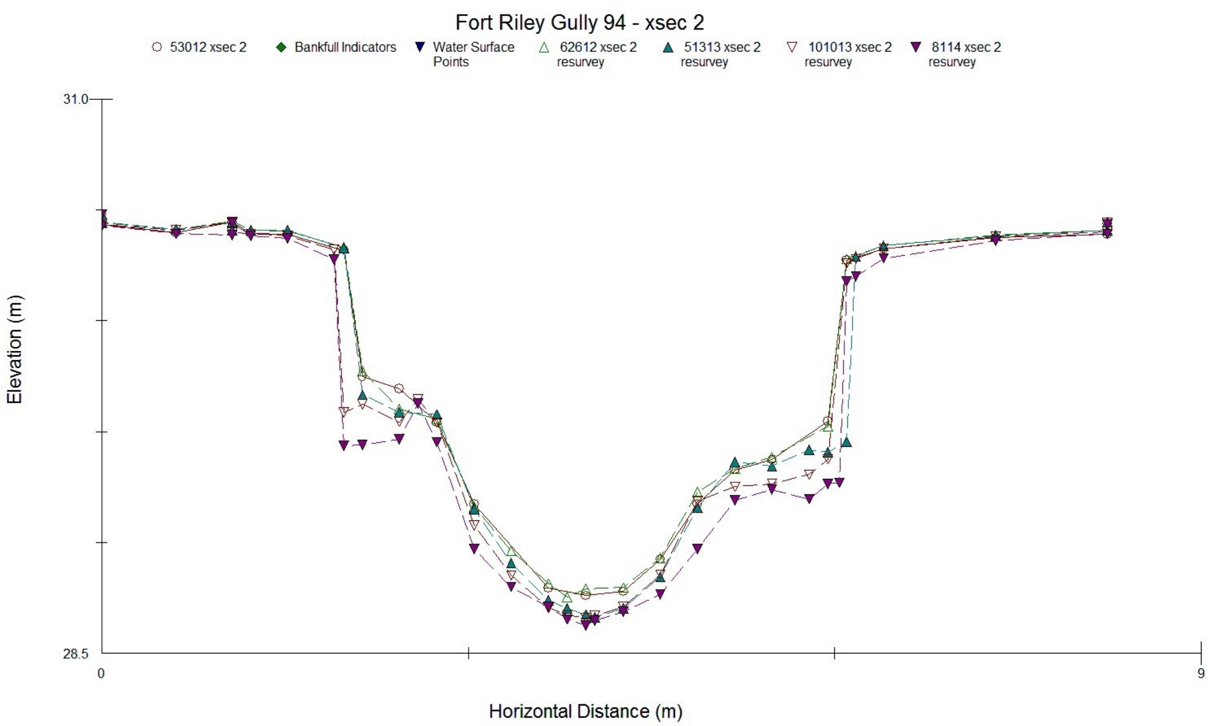


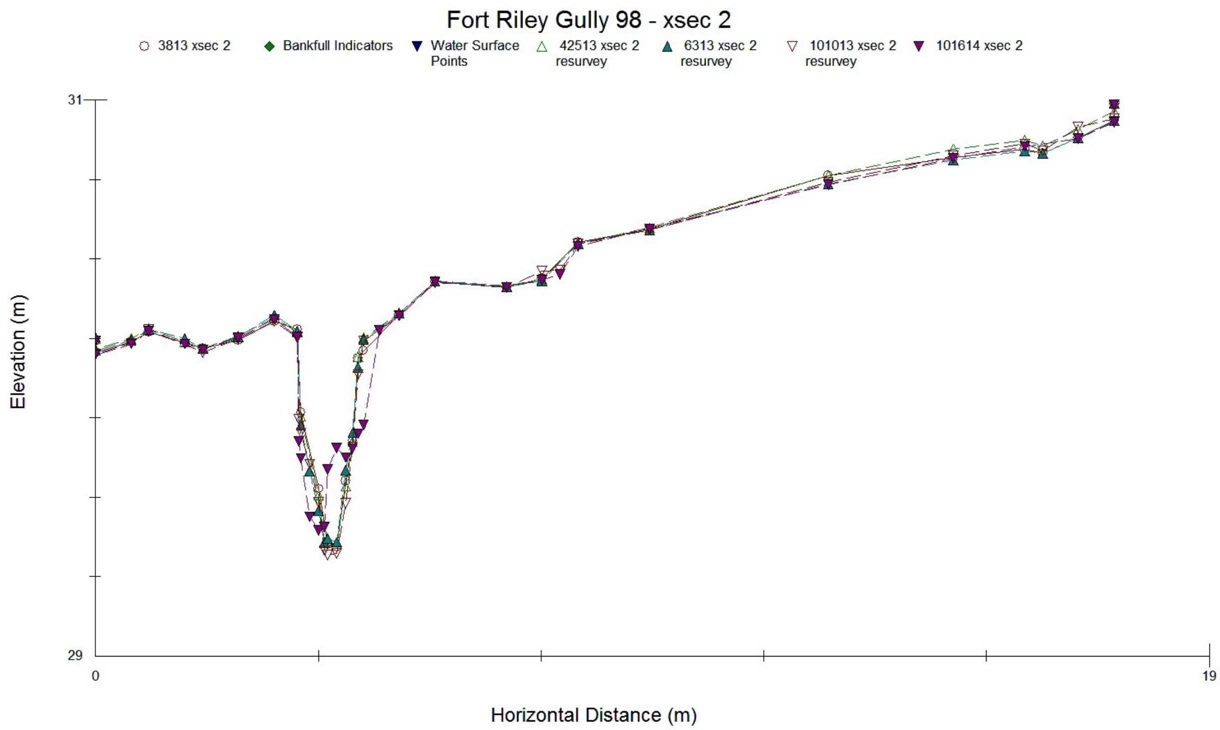
Fort Riley Gully 89 - xsec 3
53012 xsec 3
Bankfull Indicators
Water Surface Points
62612 xsec 3 resurvey
51413 xsec 3 resurvey
6313 xsec 3 resurvey
101013 xsec 3 resurvey
8114 xsec 3 resurvey
31
28
Elevation (m)
0.0
9.7
Horizontal Distance (m)



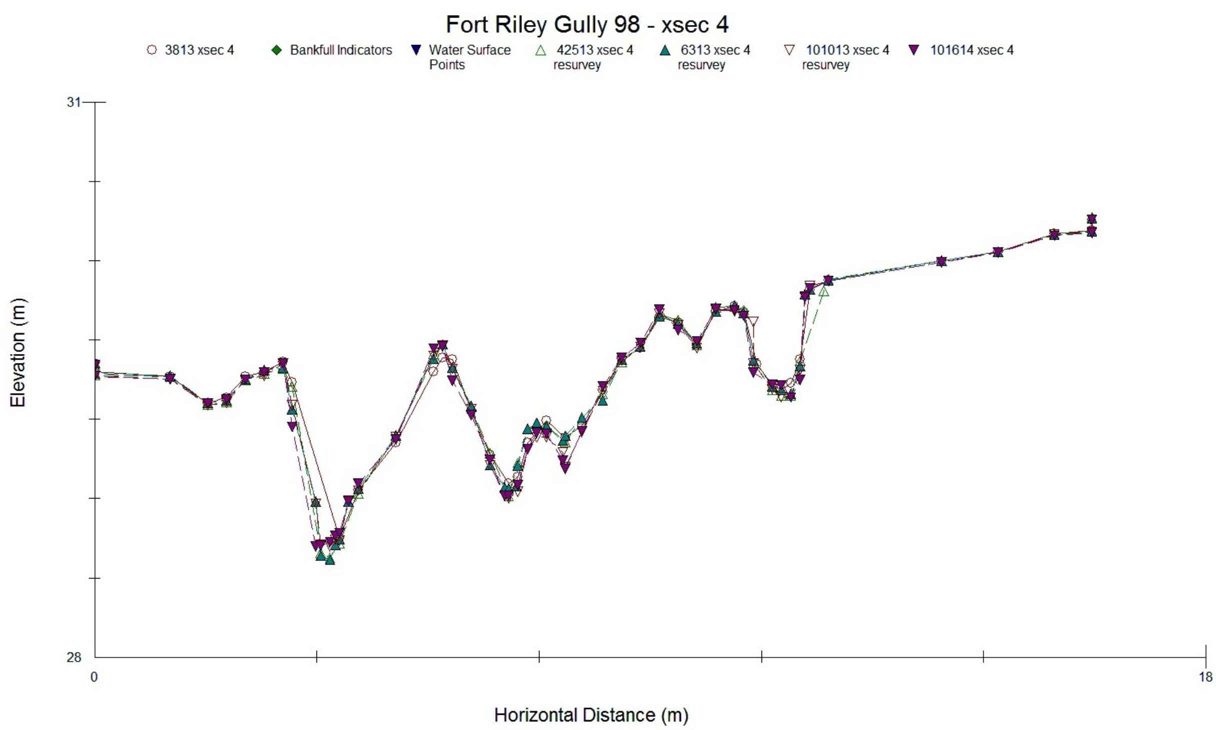
Fort Riley Gully 91- xsec 2
51413 xsec 2 resurvey
Bankfull Indicators
Water Surface Points
6313 xsec 2 resurvey
101013 xsec 2 resurvey
101614 xsec 2 resurvey
33.0
31.5
Elevation (m)
0
5
Horizontal Distance (m)


Fort Riley Gully 94 - Long Pro
Long Pro 53012
Bankfull Indicators
Water Surface Points
Long Pro 51313
Elevation (m)
Horizontal Distance (m)
32
27
0
5
10
15
20
25
30


Fort Riley Gully 94 - xsec 2
53012 xsec 2
Bankfull Indicators
Water Surface Points
62612 xsec 2 resurvey
51313 xsec 2 resurvey
101013 xsec 2 resurvey
8114 xsec 2 resurvey
Elevation (m)
Horizontal Distance (m)
31.0
28.5
0
9

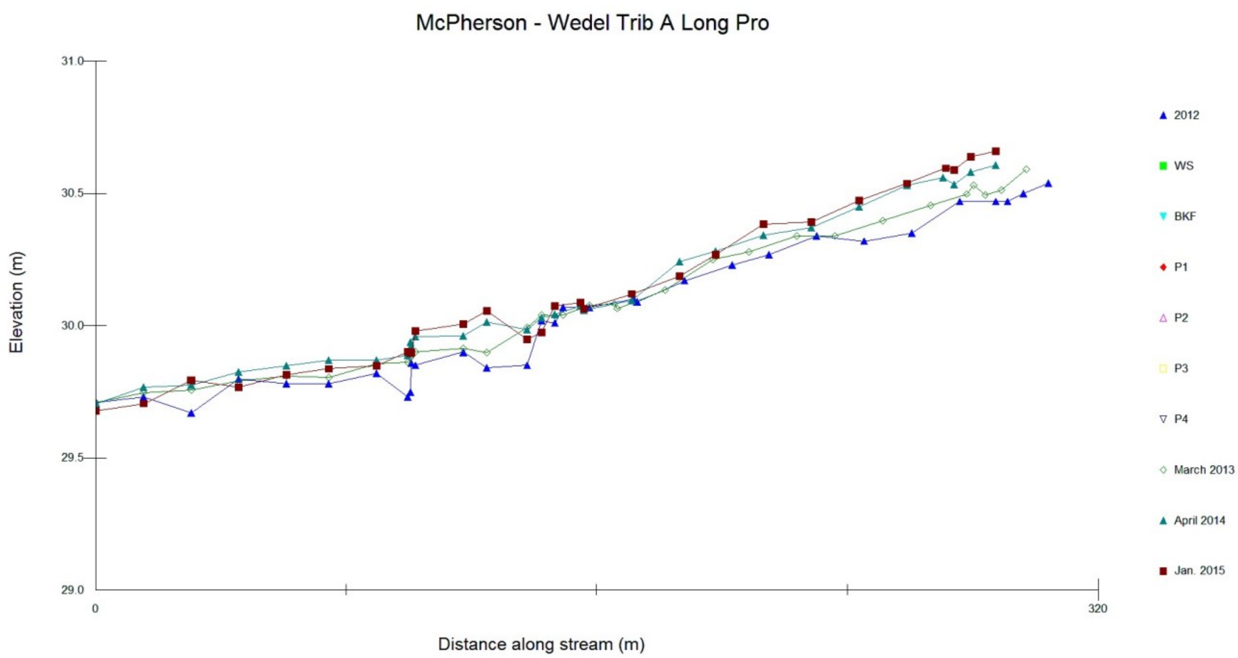


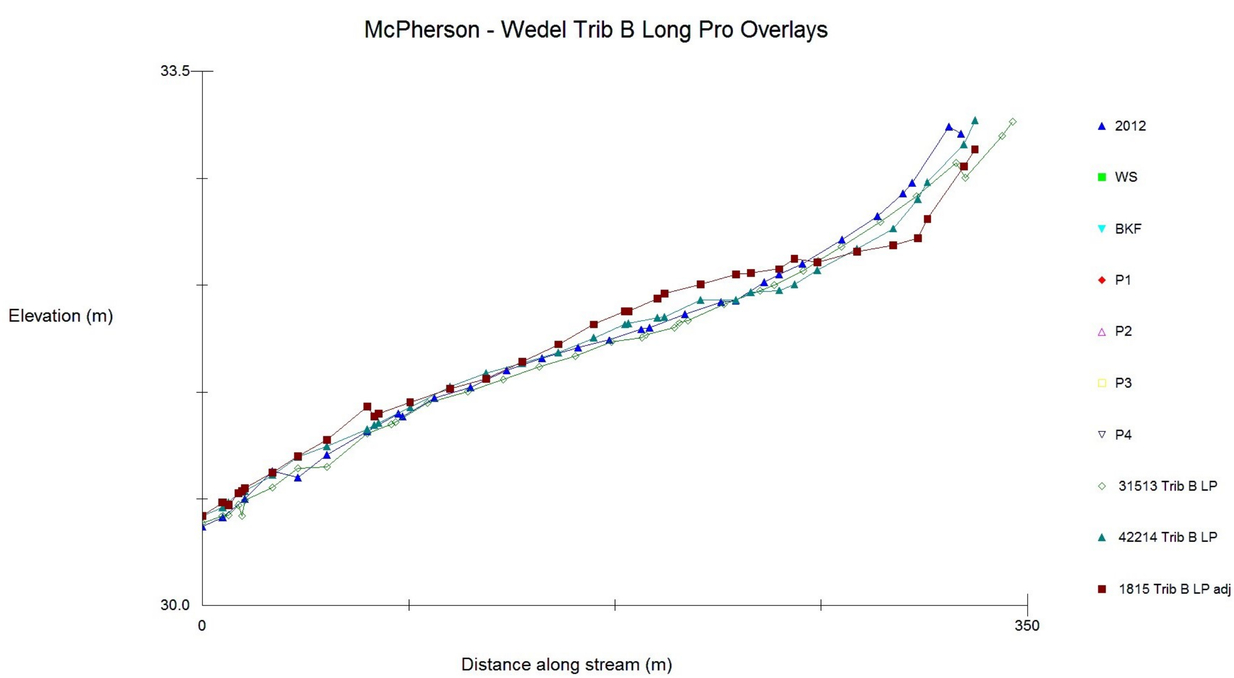
Fort Riley Gully 98 - xsec 2
3813 xsec 2
Bankfull Indicators
Water Surface Points
42513 xsec 2 resurvey
6313 xsec 2 resurvey
101013 xsec 2 resurvey
101614 xsec 2
31
29
Elevation (m)
0
19
Horizontal Distance (m)

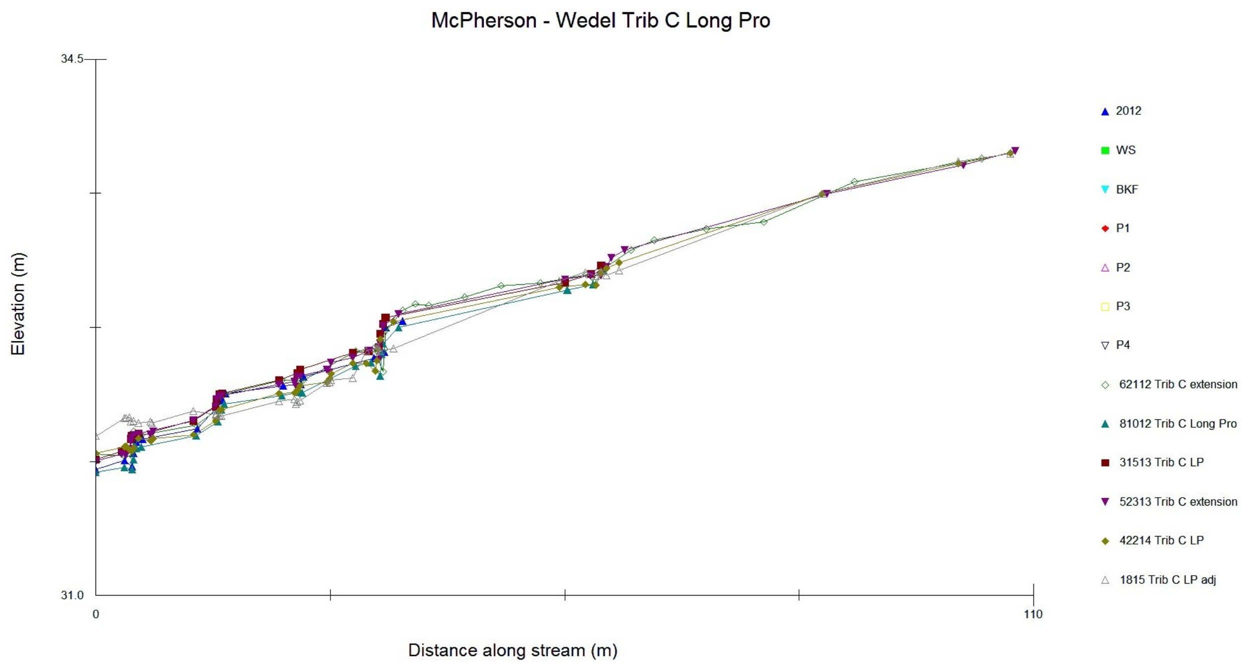


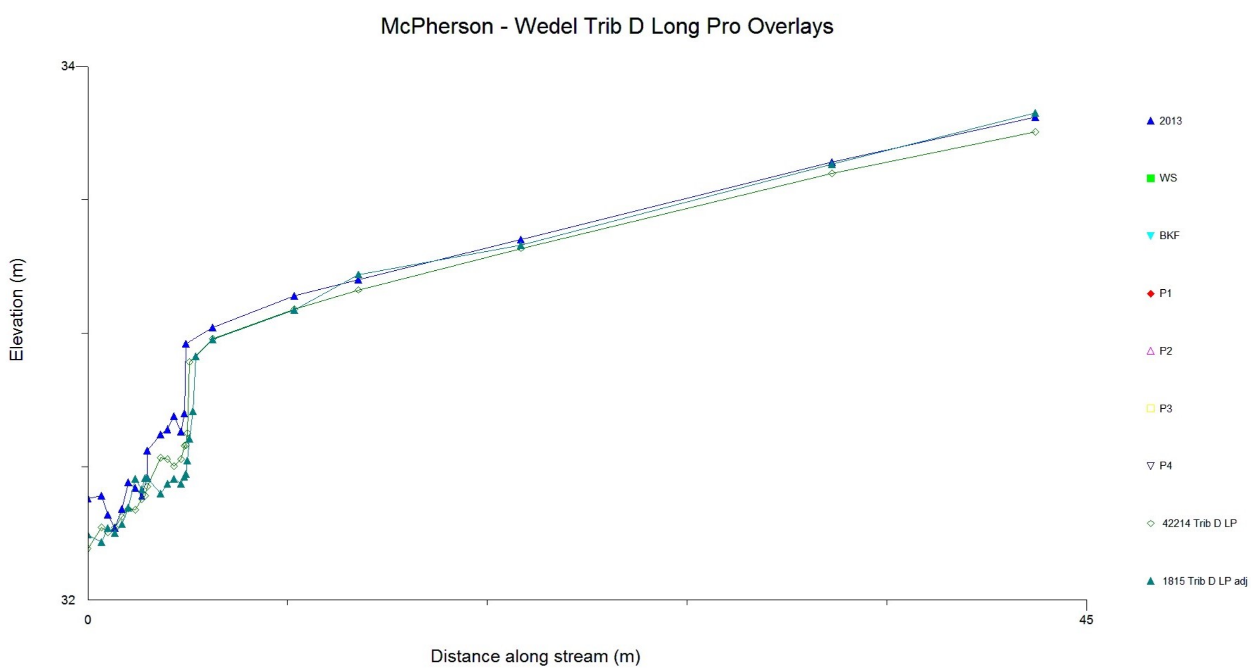
Fort Riley Gully 98 - xsec 4
3813 xsec 4
Bankfull Indicators
Water Surface Points
42513 xsec 4 resurvey
6313 xsec 4 resurvey
101013 xsec 4 resurvey
101614 xsec 4
31
28
Elevation (m)
0
18
Horizontal Distance (m)

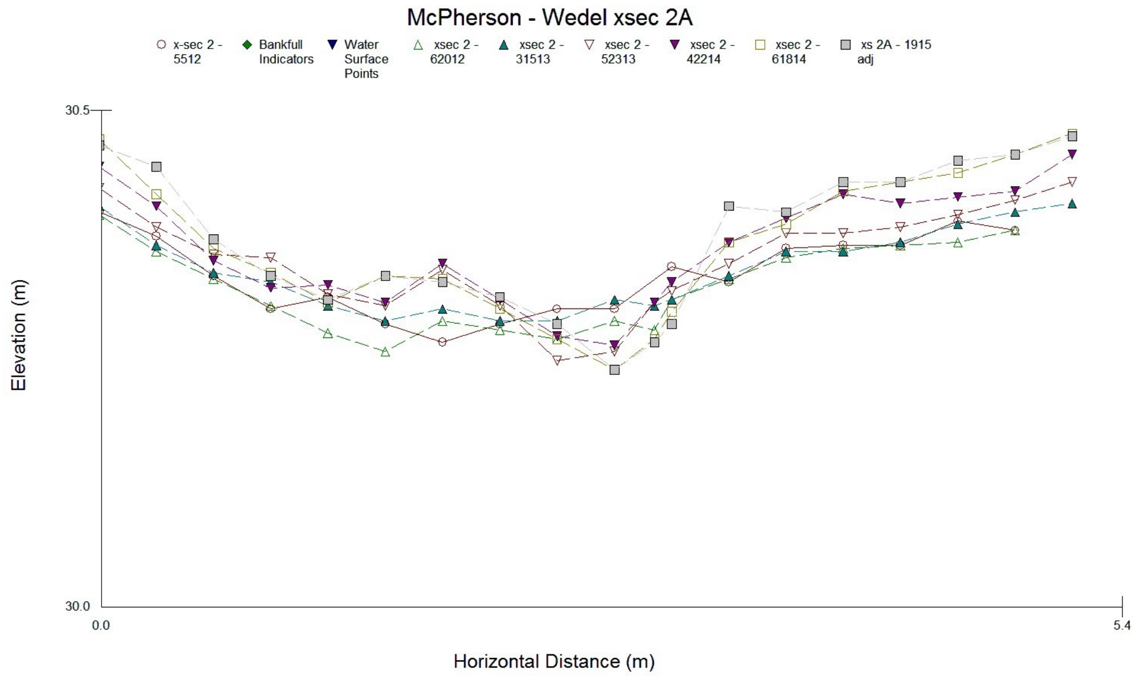
Appendix B - McPherson Cross Section and Long Pro overlays



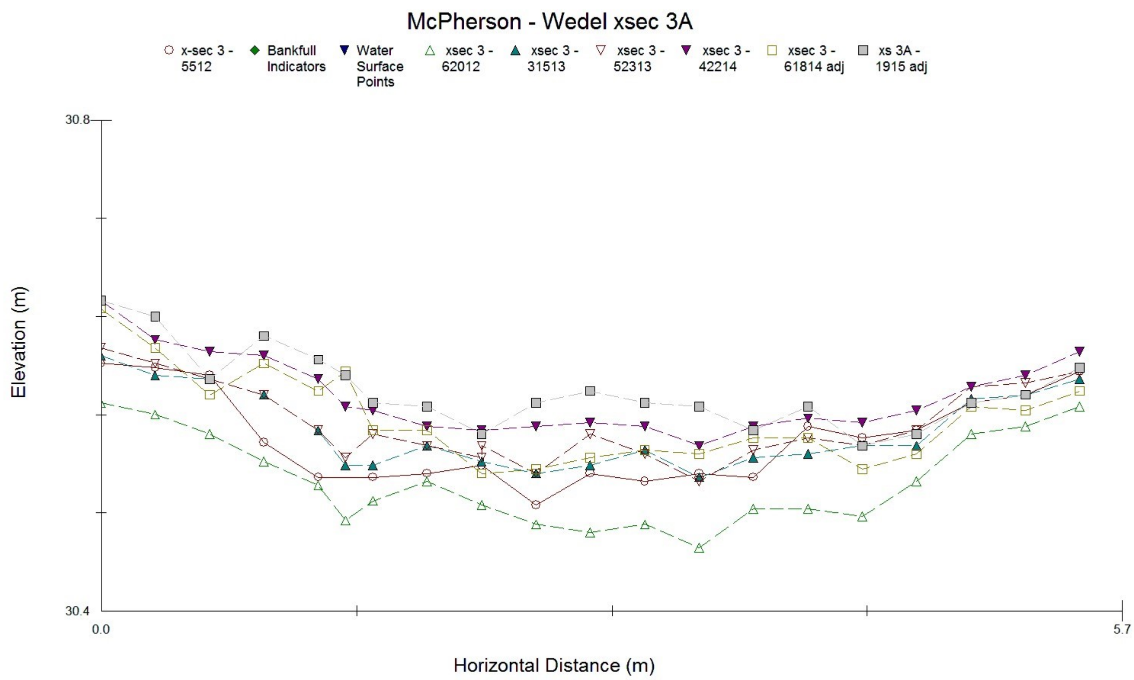



McPherson - Wedel Trib C Long Pro
34.5
31.0
0
110
Elevation (m)
Distance along stream (m)
2012
WS
BKF
P1
P2
P3
P4
62112 Trib C extension
81012 Trib C Long Pro
31513 Trib C LP
52313 Trib C extension
42214 Trib C LP
1815 Trib C LP adj

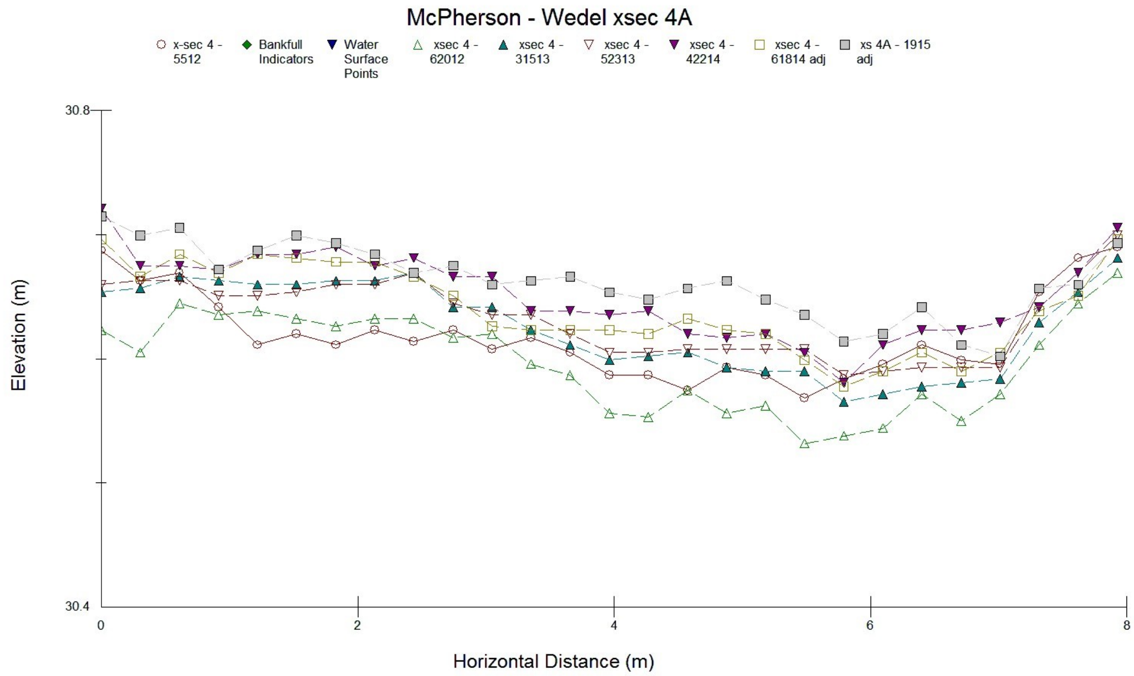

McPherson - Wedel Trib D Long Pro Overlays
34
32
0
45
Elevation (m)
Distance along stream (m)
2013
WS
BKF
P1
P2
P3
P4
42214 Trib D LP
1815 Trib D LP adj

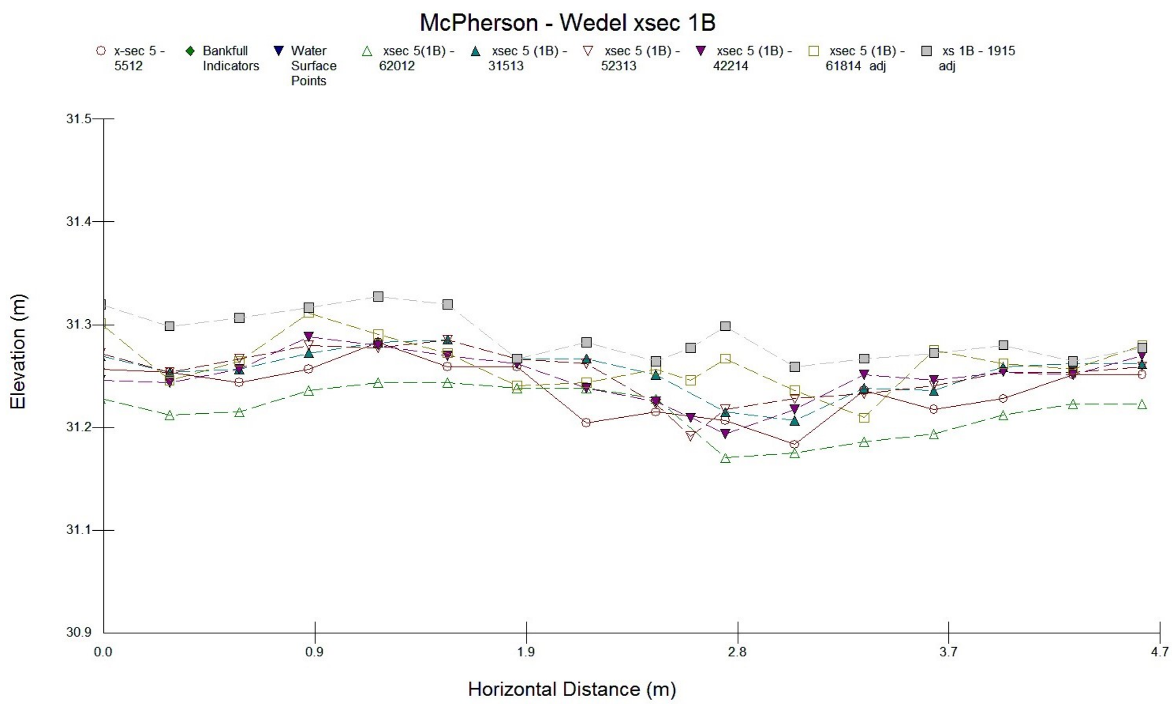


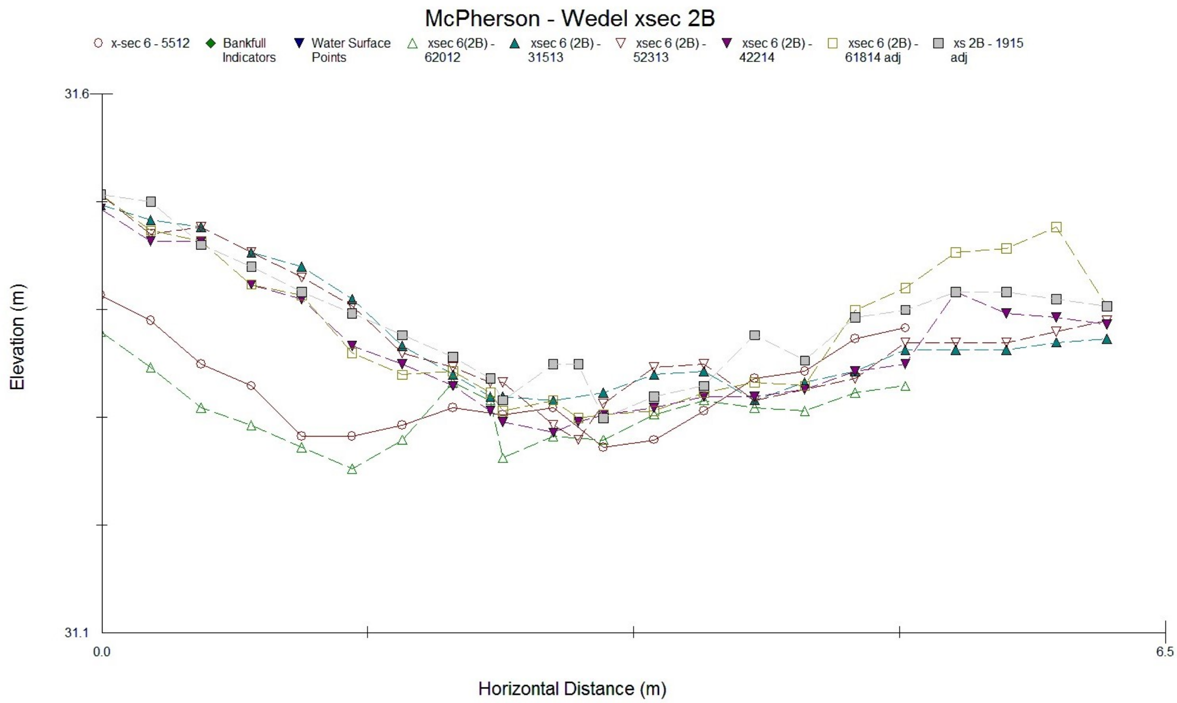
McPherson - Wedel xsec 2A
x-sec 2 - 5512
Bankfull Indicators
Water Surface Points
xsec 2 - 62012
xsec 2 - 31513
xsec 2 - 52313
xsec 2 - 42214
xsec 2 - 61814
xs 2A - 1915 adj
30.5
30.0
Elevation (m)
0.0
5.4
Horizontal Distance (m)

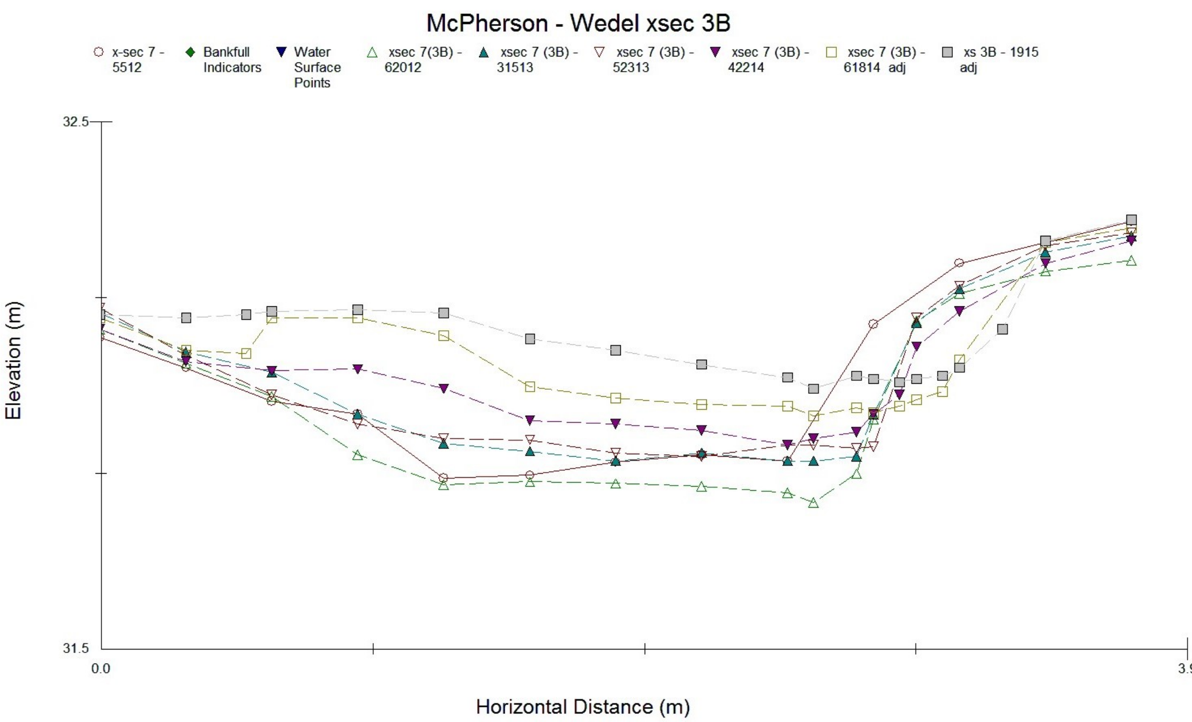


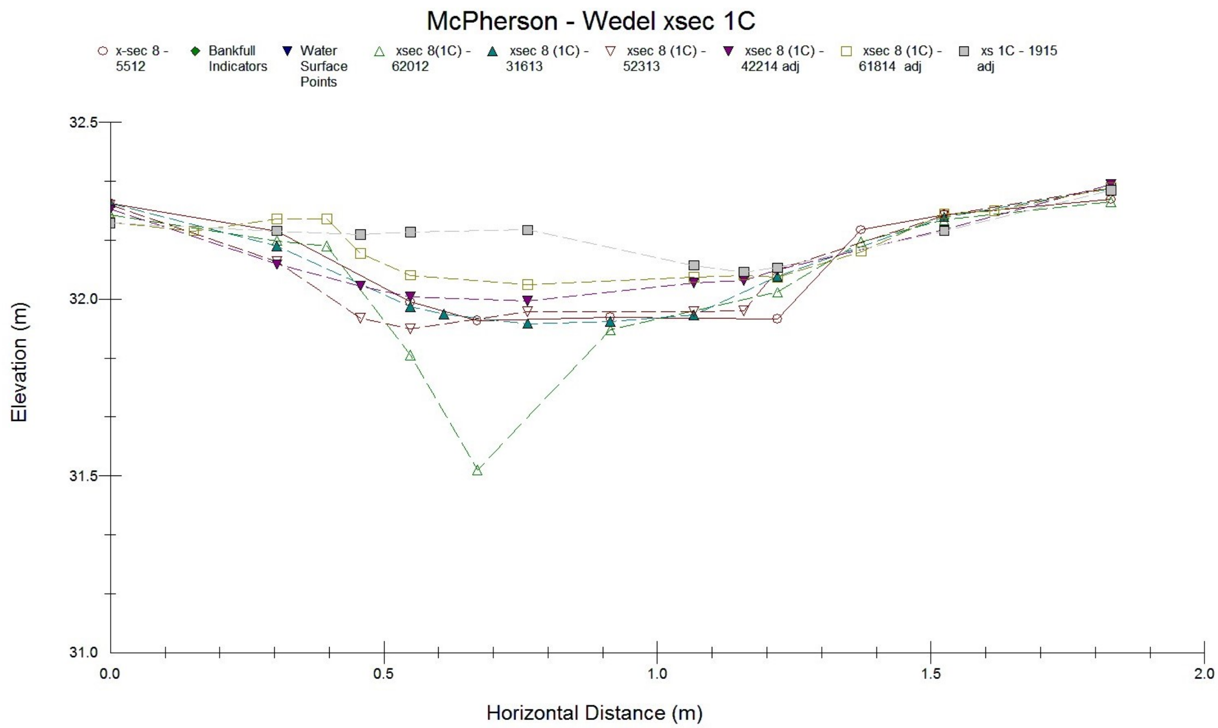
McPherson - Wedel xsec 3A
x-sec 3 - 5512
Bankfull Indicators
Water Surface Points
xsec 3 - 62012
xsec 3 - 31513
xsec 3 - 52313
xsec 3 - 42214
xsec 3 - 61814 adj
xs 3A - 1915 adj
30.8
30.4
Elevation (m)
0.0
5.7
Horizontal Distance (m)

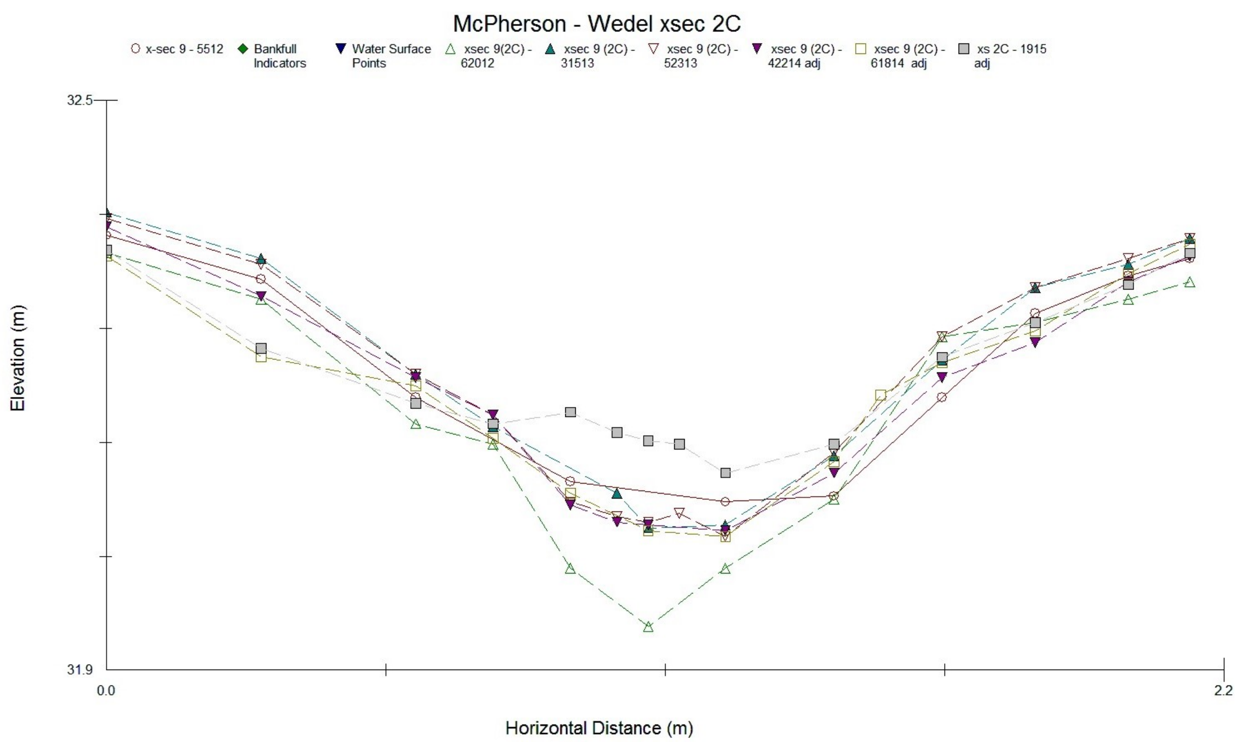

McPherson - Wedel xsec 4A
x-sec 4 - 5512
Bankfull Indicators
Water Surface Points
xsec 4 - 62012
xsec 4 - 31513
xsec 4 - 52313
xsec 4 - 42214
xsec 4 - 61814 adj
xs 4A - 1915 adj
30.8
30.4
0
2
4
6
8
Elevation (m)
Horizontal Distance (m)

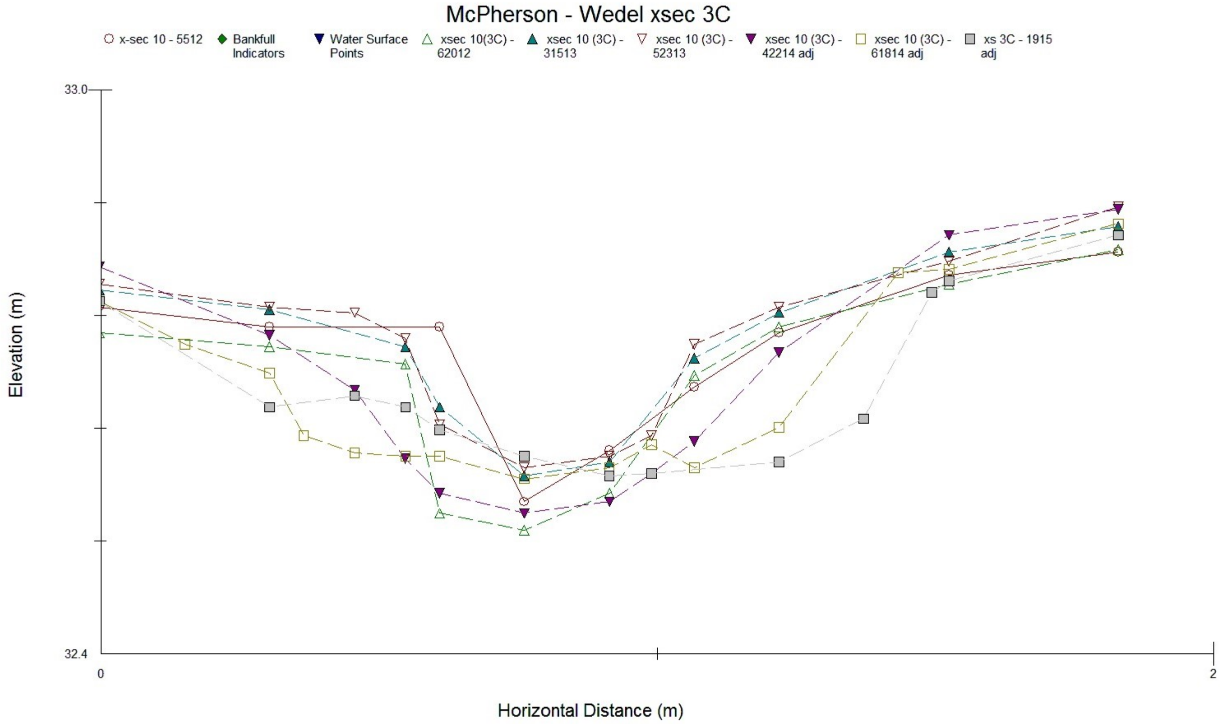

McPherson - Wedel xsec 1B
x-sec 5 - 5512
Bankfull Indicators
Water Surface Points
xsec 5(1B) - 62012
xsec 5 (1B) - 31513
xsec 5 (1B) - 52313
xsec 5 (1B) - 42214
xsec 5 (1B) - 61814 adj
xs 1B - 1915 adj
31.5
31.4
31.3
31.2
31.1
30.9
0.0
0.9
1.9
2.8
3.7
4.7
Elevation (m)
Horizontal Distance (m)

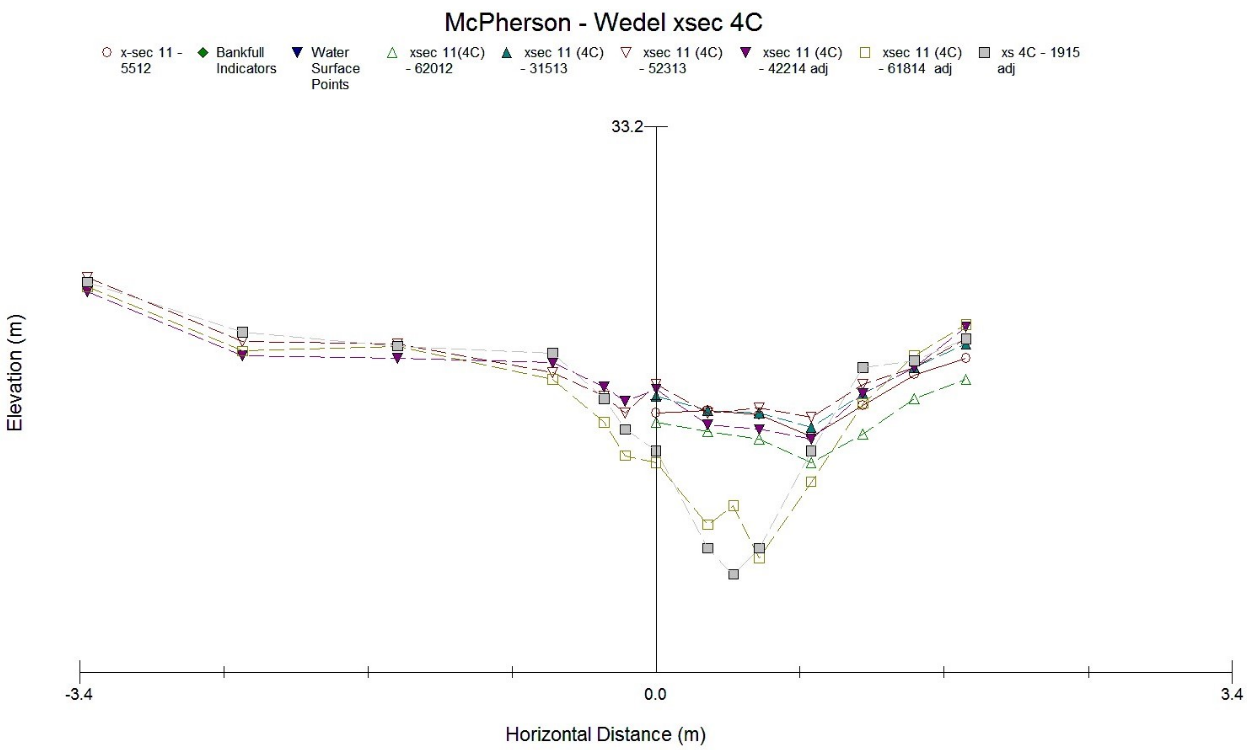

McPherson - Wedel xsec 2B
x-sec 6 - 5512
Bankfull Indicators
Water Surface Points
xsec 6(2B) - 62012
xsec 6 (2B) - 31513
xsec 6 (2B) - 52313
xsec 6 (2B) - 42214
xsec 6 (2B) - 61814 adj
xs 2B - 1915 adj
31.6
31.1
0.0
6.5
Elevation (m)
Horizontal Distance (m)

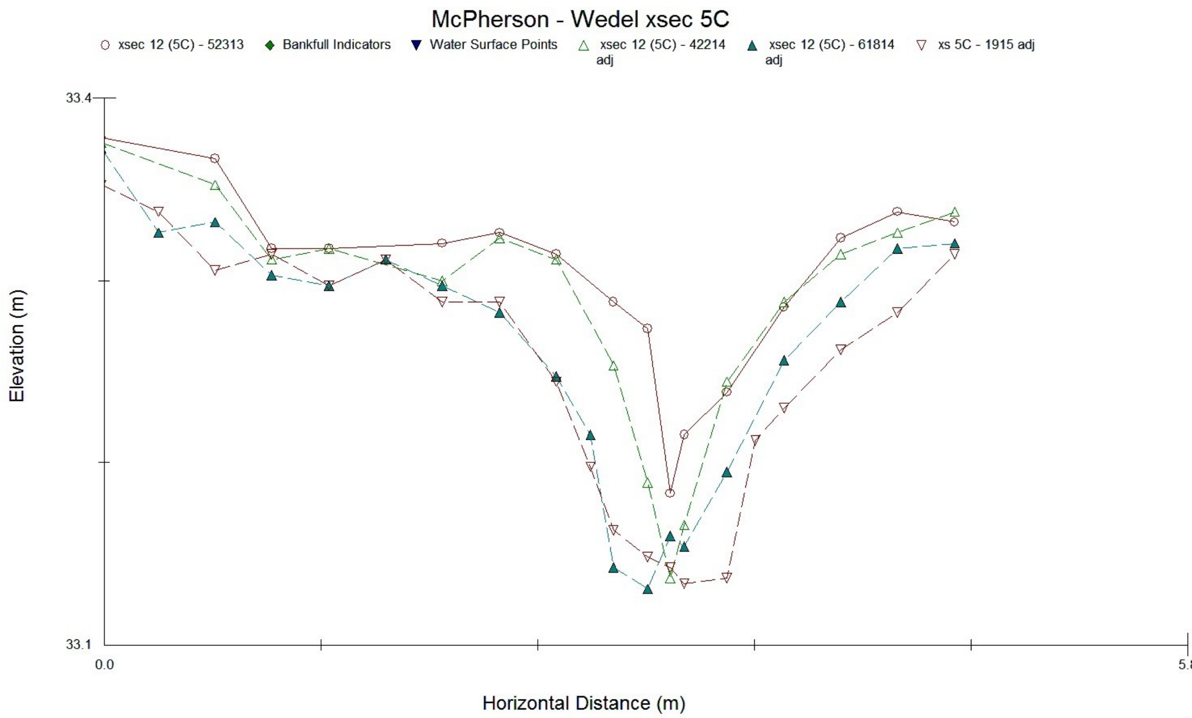

McPherson - Wedel xsec 3B
x-sec 7 - 5512
Bankfull Indicators
Water Surface Points
xsec 7(3B) - 62012
xsec 7 (3B) - 31513
xsec 7 (3B) - 52313
xsec 7 (3B) - 42214
xsec 7 (3B) - 61814 adj
xs 3B - 1915 adj
32.5
31.5
0.0
3.9
Elevation (m)
Horizontal Distance (m)

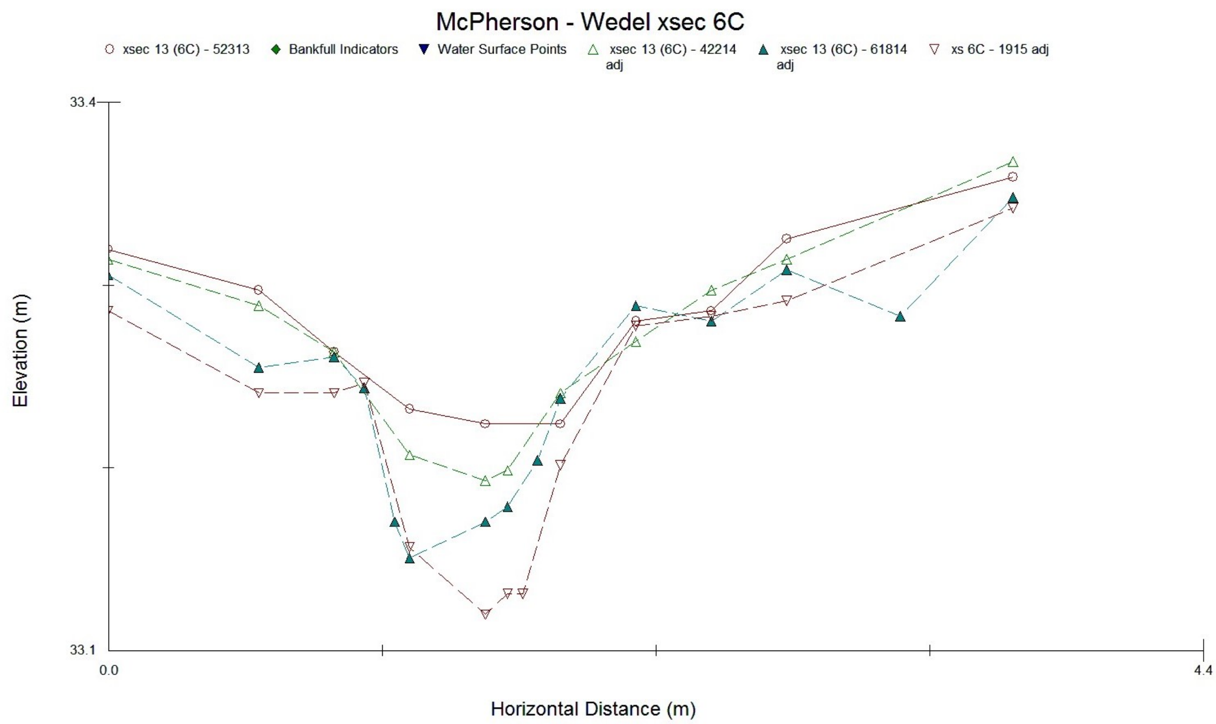

McPherson - Wedel xsec 1C
x-sec 8 - 5512
Bankfull Indicators
Water Surface Points
xsec 8(1C) - 62012
xsec 8 (1C) - 31613
xsec 8 (1C) - 52313
xsec 8 (1C) - 42214 adj
xsec 8 (1C) - 61814 adj
xs 1C - 1915 adj
Elevation (m)
32.5
32.0
31.5
31.0
0.0
0.5
1.0
1.5
2.0
Horizontal Distance (m)

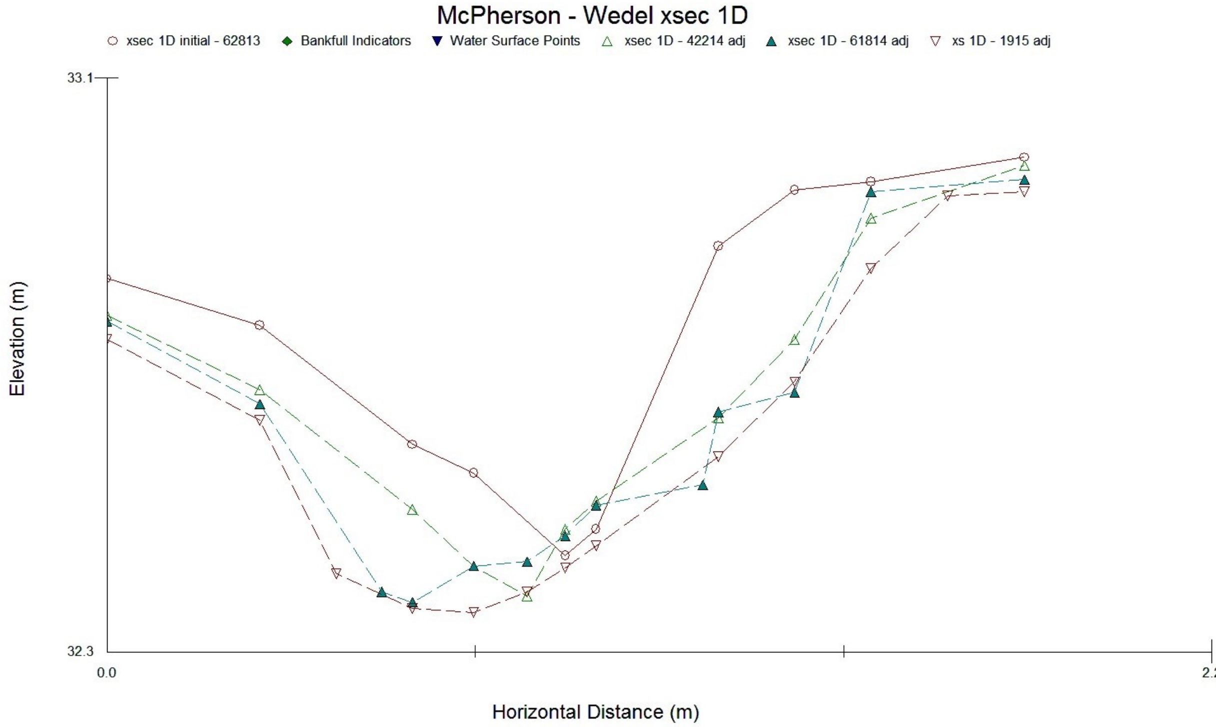

McPherson - Wedel xsec 2C
x-sec 9 - 5512
Bankfull Indicators
Water Surface Points
xsec 9(2C) - 62012
xsec 9 (2C) - 31513
xsec 9 (2C) - 52313
xsec 9 (2C) - 42214 adj
xsec 9 (2C) - 61814 adj
xs 2C - 1915 adj
Elevation (m)
32.5
31.9
0.0
2.2
Horizontal Distance (m)

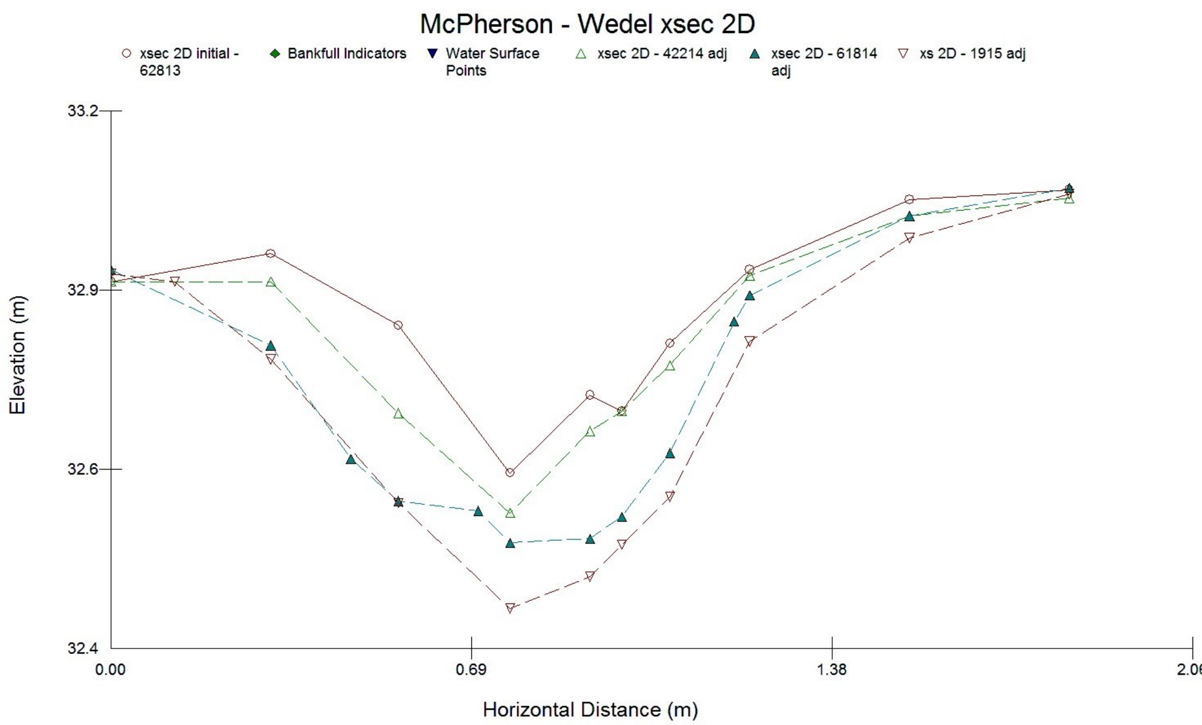

McPherson - Wedel xsec 3C
x-sec 10 - 5512
Bankfull Indicators
Water Surface Points
xsec 10(3C) - 62012
xsec 10 (3C) - 31513
xsec 10 (3C) - 52313
xsec 10 (3C) - 42214 adj
xsec 10 (3C) - 61814 adj
xs 3C - 1915 adj
33.0
32.4
0
2
Elevation (m)
Horizontal Distance (m)

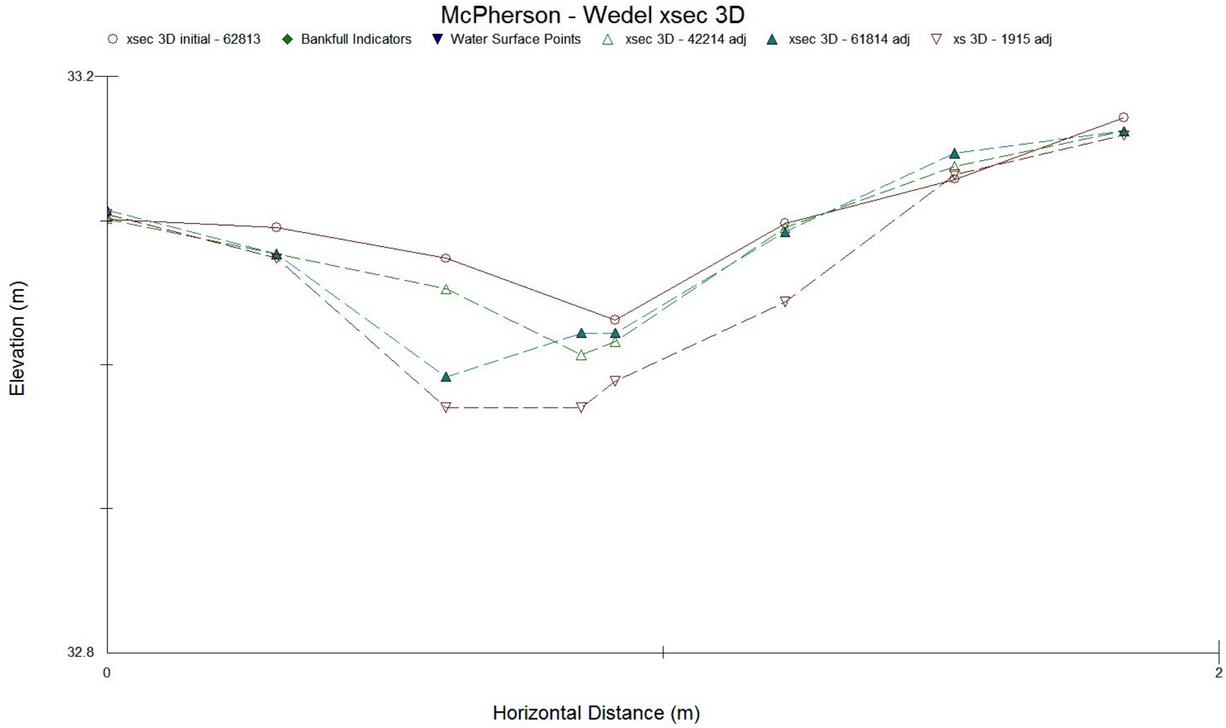

McPherson - Wedel xsec 4C
x-sec 11 - 5512
Bankfull Indicators
Water Surface Points
xsec 11(4C) - 62012
xsec 11 (4C) - 31513
xsec 11 (4C) - 52313
xsec 11 (4C) - 42214 adj
xsec 11 (4C) - 61814 adj
xs 4C - 1915 adj
33.2
-3.4
0.0
3.4
Elevation (m)
Horizontal Distance (m)

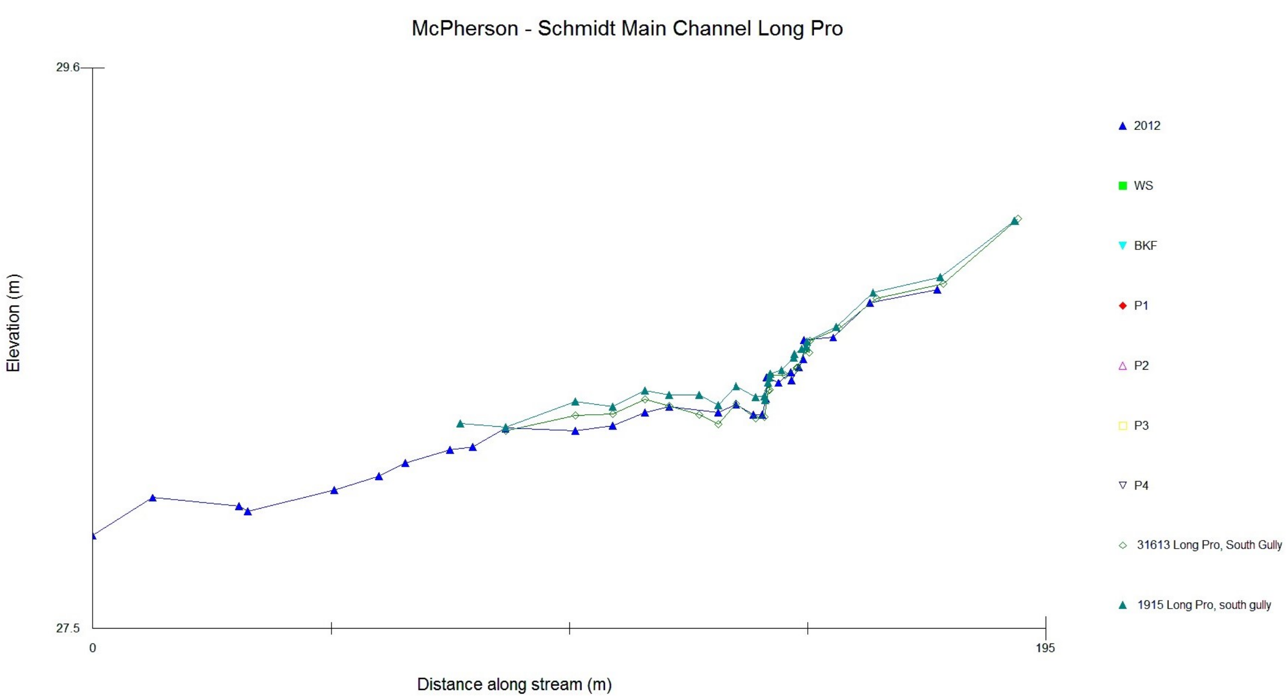

McPherson - Wedel xsec 5C
xsec 12 (5C) - 52313
Bankfull Indicators
Water Surface Points
xsec 12 (5C) - 42214 adj
xsec 12 (5C) - 61814 adj
xs 5C - 1915 adj
33.4
33.1
Elevation (m)
0.0
5.8
Horizontal Distance (m)

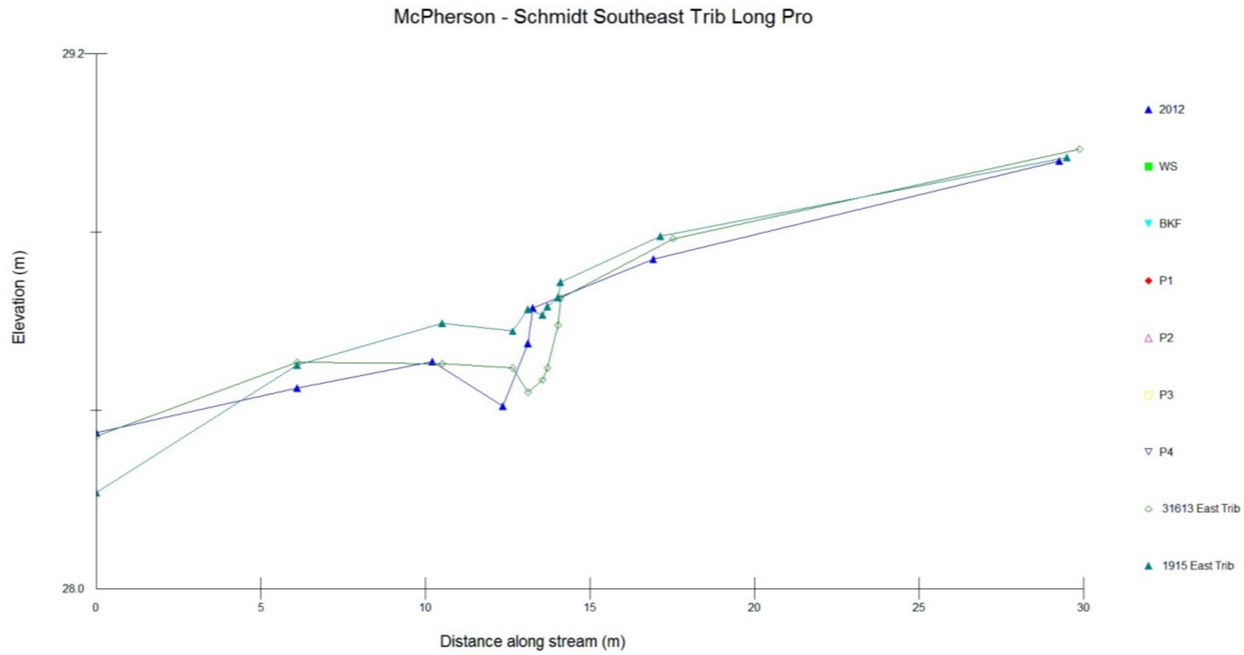

McPherson - Wedel xsec 6C
xsec 13 (6C) - 52313
Bankfull Indicators
Water Surface Points
xsec 13 (6C) - 42214 adj
xsec 13 (6C) - 61814 adj
xs 6C - 1915 adj
33.4
33.1
Elevation (m)
0.0
4.4
Horizontal Distance (m)

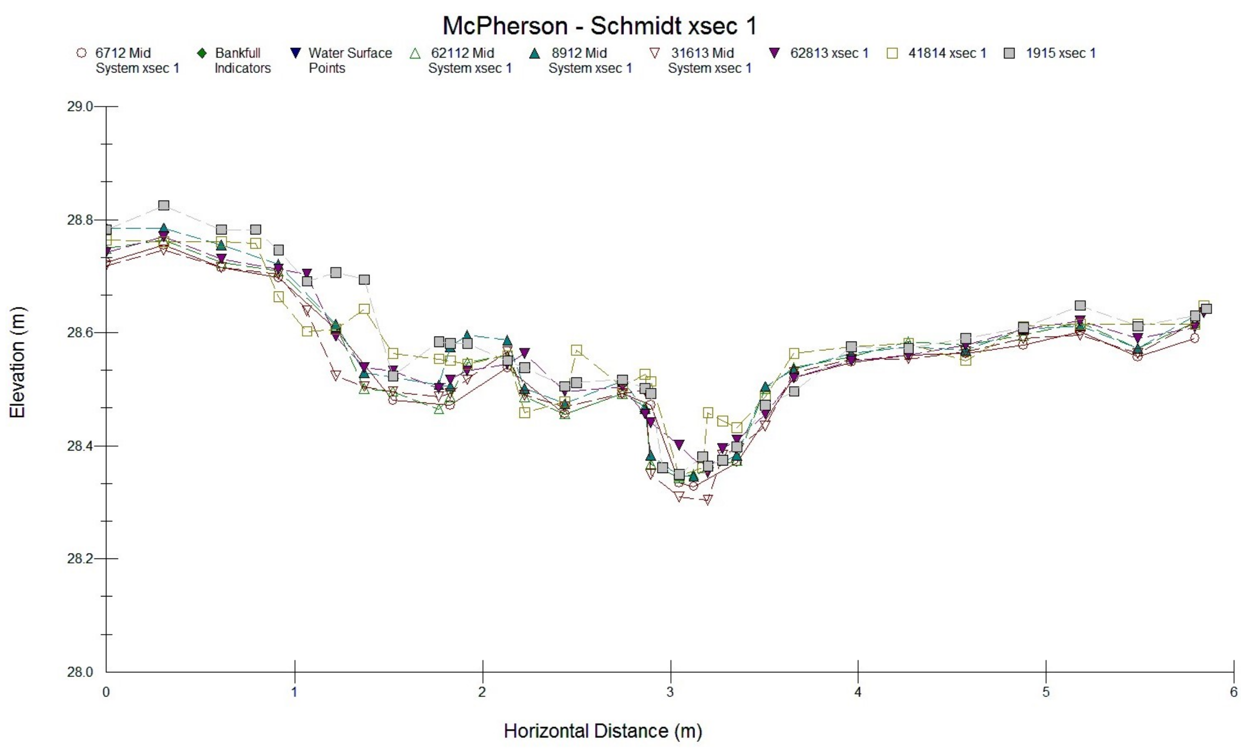

McPherson - Wedel xsec 1D
xsec 1D initial - 62813
Bankfull Indicators
Water Surface Points
xsec 1D - 42214 adj
xsec 1D - 61814 adj
xs 1D - 1915 adj
33.1
32.3
0.0
2.2
Elevation (m)
Horizontal Distance (m)

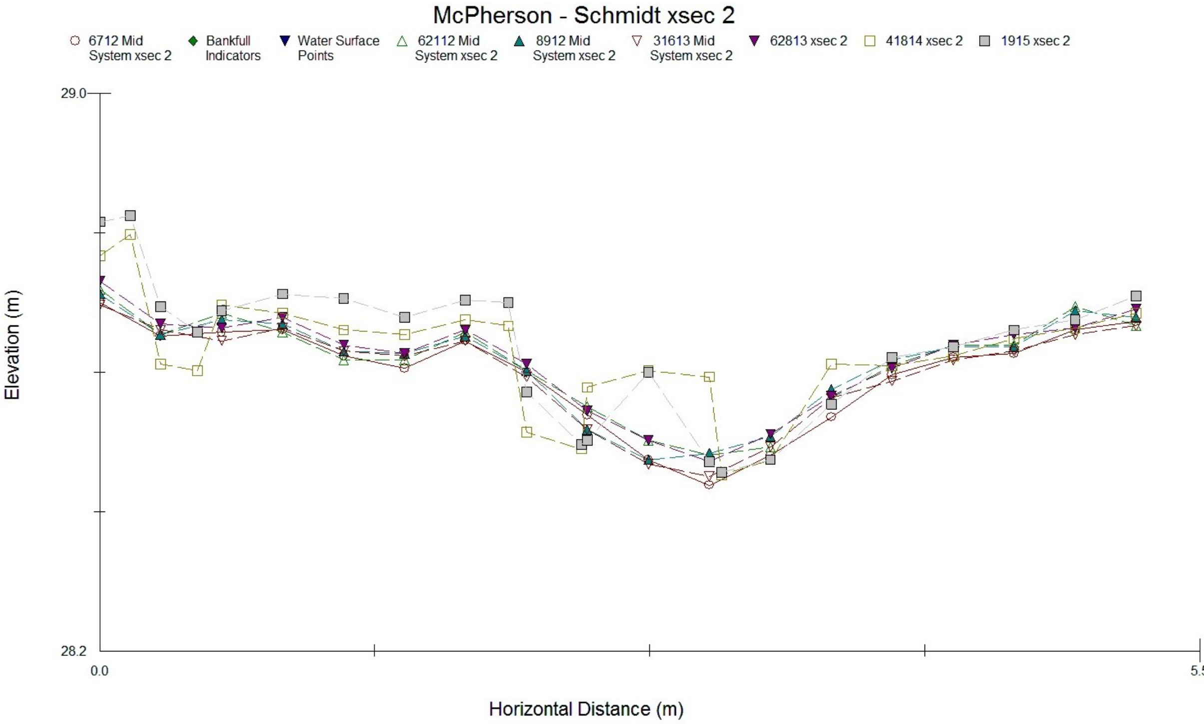

McPherson - Wedel xsec 2D
xsec 2D initial - 62813
Bankfull Indicators
Water Surface Points
xsec 2D - 42214 adj
xsec 2D - 61814 adj
xs 2D - 1915 adj
33.2
32.9
32.6
32.4
0.00
0.69
1.38
2.06
Elevation (m)
Horizontal Distance (m)

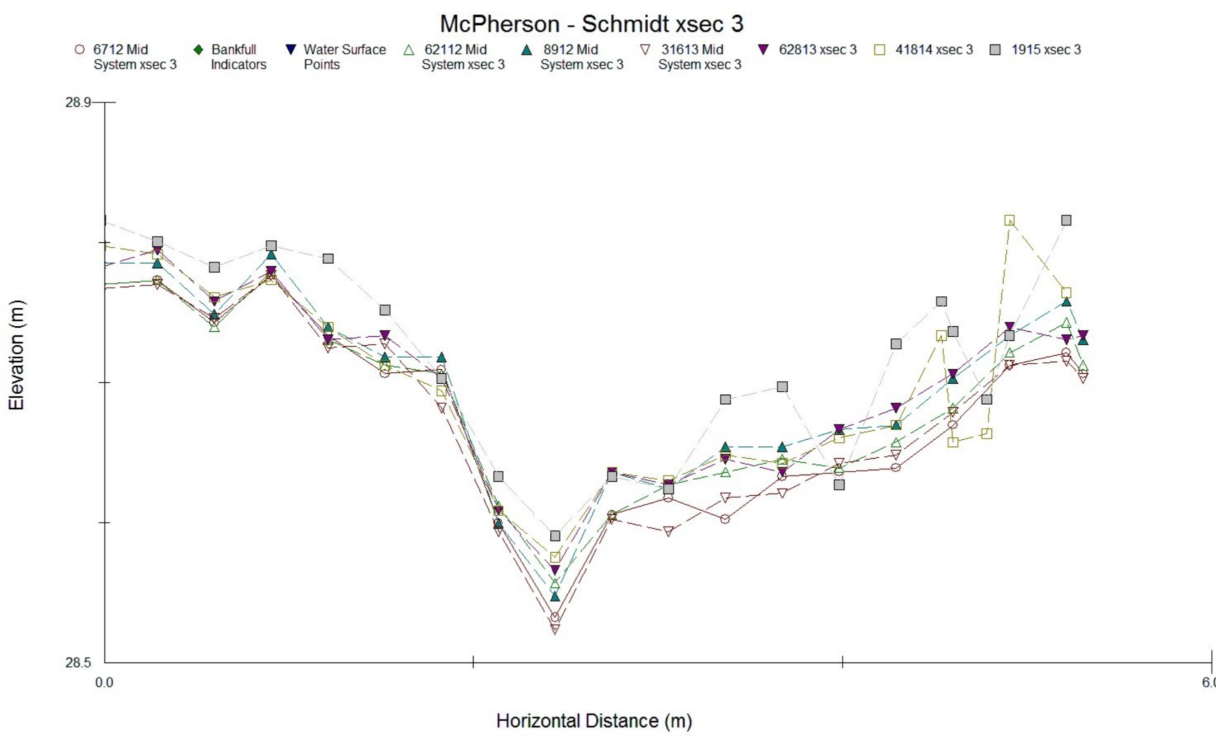

McPherson - Wedel xsec 3D
xsec 3D initial - 62813
Bankfull Indicators
Water Surface Points
xsec 3D - 42214 adj
xsec 3D - 61814 adj
xs 3D - 1915 adj
33.2
32.8
Elevation (m)
0
2
Horizontal Distance (m)

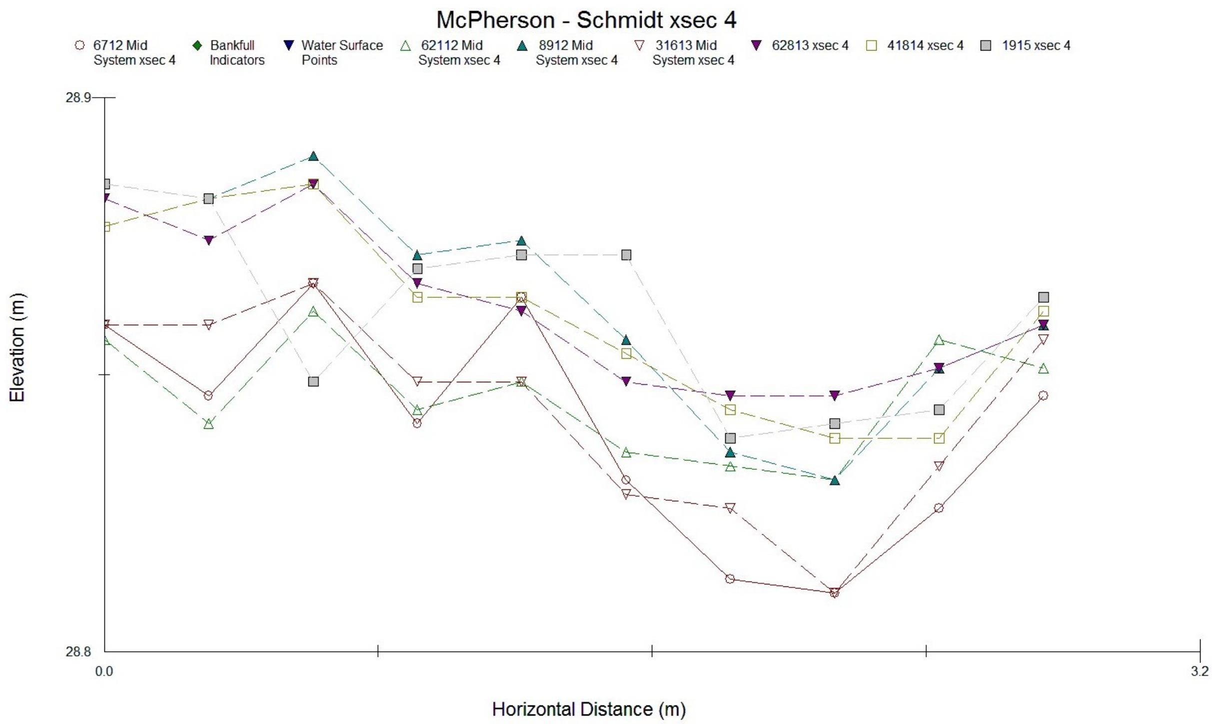

McPherson - Schmidt Main Channel Long Pro
29.6
27.5
Elevation (m)
0
195
Distance along stream (m)
2012
WS
BKF
P1
P2
P3
P4
31613 Long Pro, South Gully
1915 Long Pro, south gully


McPherson - Schmidt Southeast Trib Long Pro
29.2
28.0
Elevation (m)
0
5
10
15
20
25
30
Distance along stream (m)
2012
WS
BKF
P1
P2
P3
P4
31613 East Trib
1915 East Trib

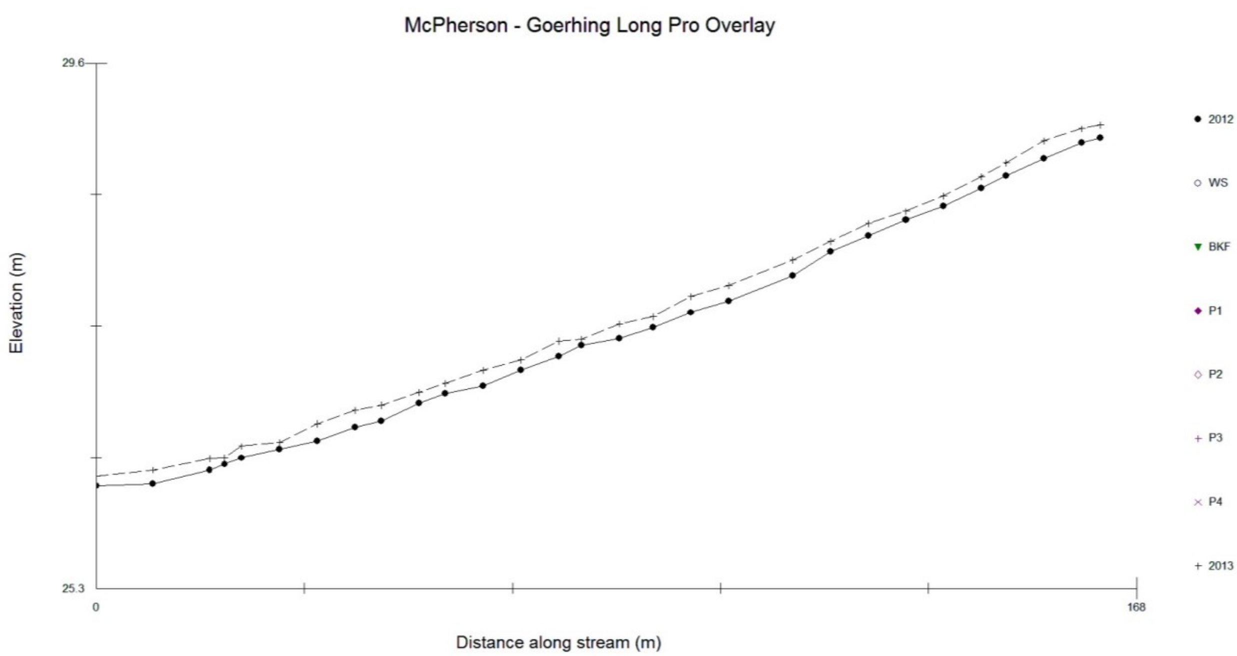

McPherson - Schmidt xsec 1
6712 Mid System xsec 1
Bankfull Indicators
Water Surface Points
62112 Mid System xsec 1
8912 Mid System xsec 1
31613 Mid System xsec 1
62813 xsec 1
41814 xsec 1
1915 xsec 1
29.0
28.8
28.6
28.4
28.2
28.0
Elevation (m)
0
1
2
3
4
5
6
Horizontal Distance (m)


McPherson - Schmidt xsec 2
6712 Mid System xsec 2
Bankfull Indicators
Water Surface Points
62112 Mid System xsec 2
8912 Mid System xsec 2
31613 Mid System xsec 2
62813 xsec 2
41814 xsec 2
1915 xsec 2
29.0
28.2
Elevation (m)
0.0
5.5
Horizontal Distance (m)

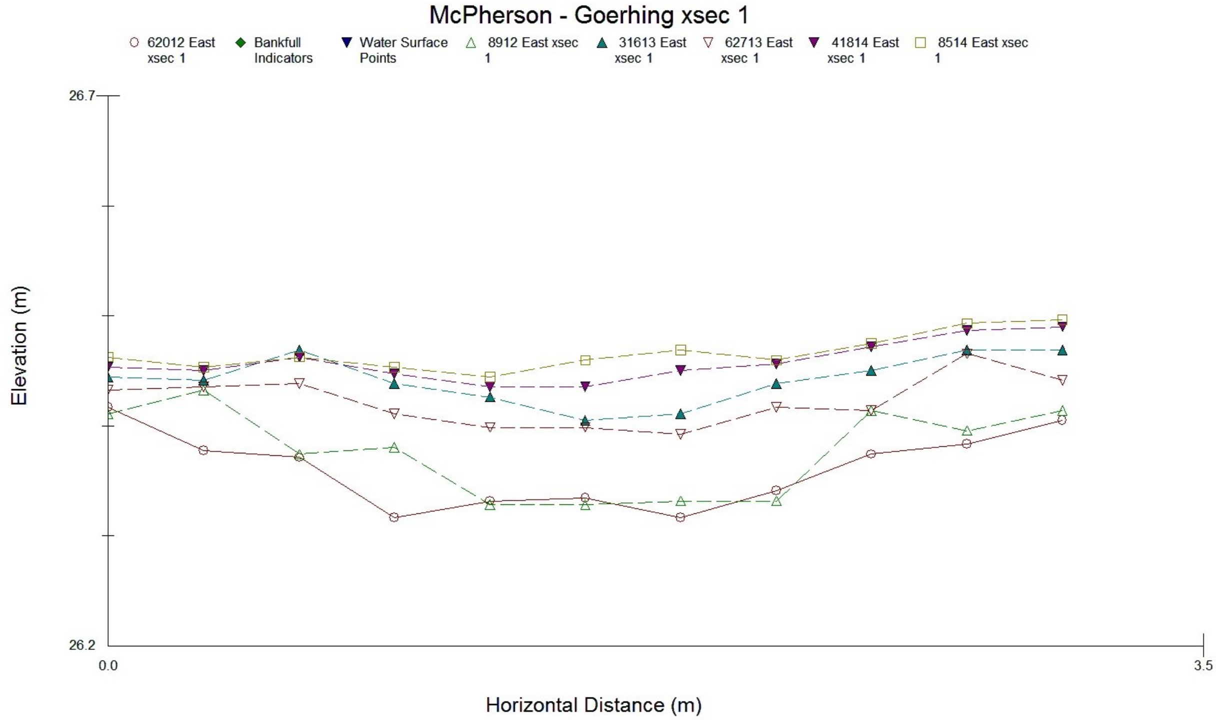

McPherson - Schmidt xsec 3
6712 Mid System xsec 3
Bankfull Indicators
Water Surface Points
62112 Mid System xsec 3
8912 Mid System xsec 3
31613 Mid System xsec 3
62813 xsec 3
41814 xsec 3
1915 xsec 3
28.9
28.5
Elevation (m)
0.0
6.0
Horizontal Distance (m)

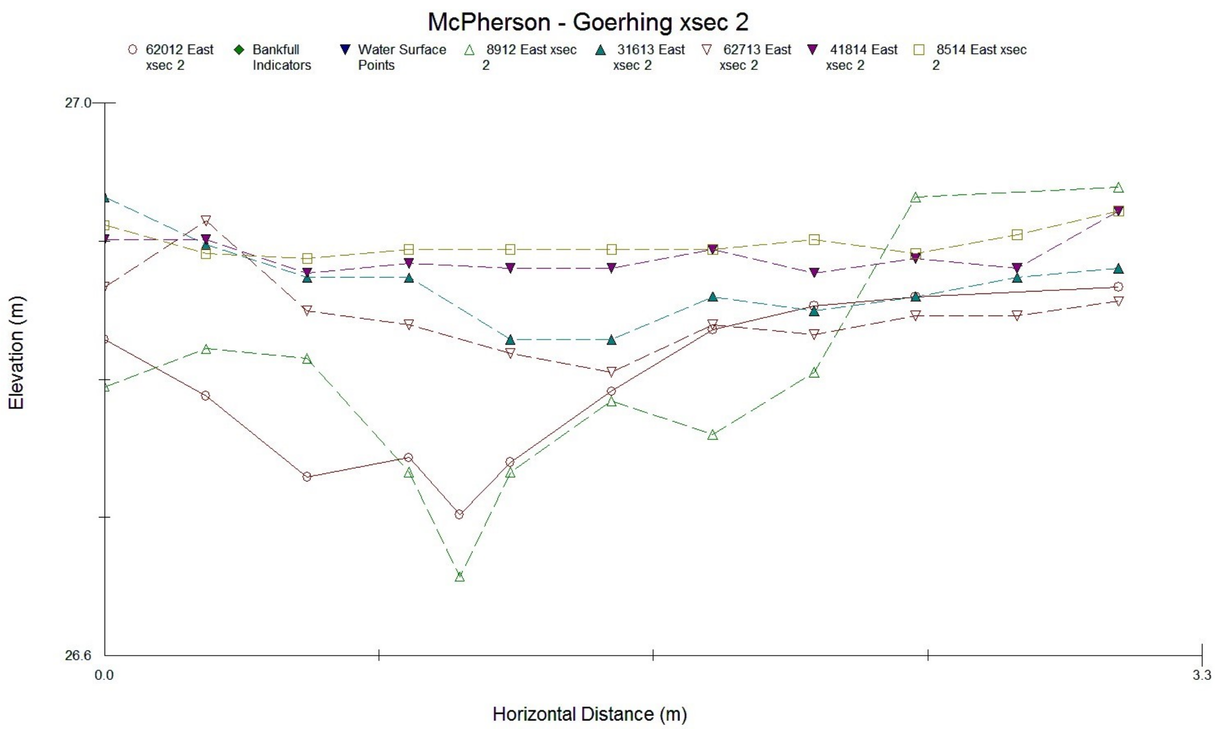


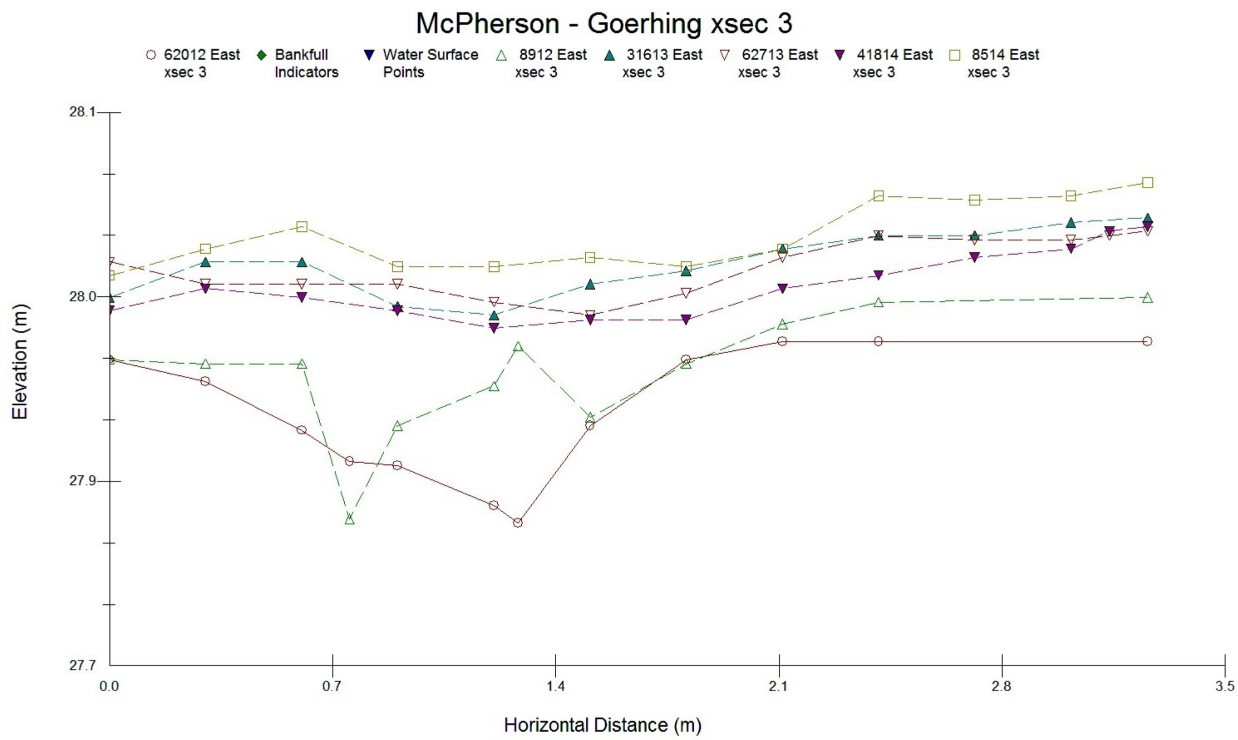
McPherson - Schmidt xsec 4
6712 Mid System xsec 4
Bankfull Indicators
Water Surface Points
62112 Mid System xsec 4
8912 Mid System xsec 4
31613 Mid System xsec 4
62813 xsec 4
41814 xsec 4
1915 xsec 4
28.9
28.8
Elevation (m)
0.0
3.2
Horizontal Distance (m)

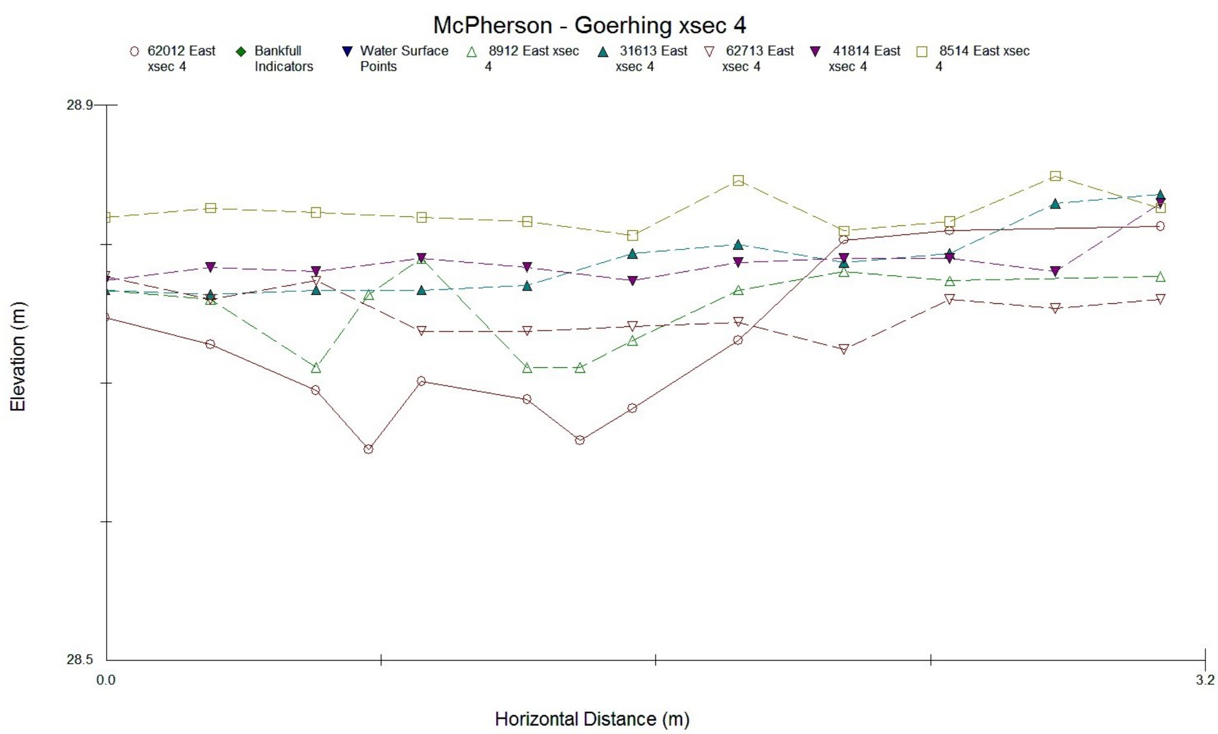


McPherson - Goerhing Long Pro Overlay
29.6
25.3
Elevation (m)
0
168
Distance along stream (m)
2012
WS
BKF
P1
P2
P3
P4
2013


McPherson - Goerhing xsec 1
62012 East xsec 1
Bankfull Indicators
Water Surface Points
8912 East xsec 1
31613 East xsec 1
62713 East xsec 1
41814 East xsec 1
8514 East xsec 1
26.7
26.2
Elevation (m)
0.0
3.5
Horizontal Distance (m)


McPherson - Goerhing xsec 2
62012 East xsec 2
Bankfull Indicators
Water Surface Points
8912 East xsec 2
31613 East xsec 2
62713 East xsec 2
41814 East xsec 2
8514 East xsec 2
27.0
26.6
Elevation (m)
0.0
3.3
Horizontal Distance (m)


McPherson - Goerhing xsec 3
62012 East xsec 3
Bankfull Indicators
Water Surface Points
8912 East xsec 3
31613 East xsec 3
62713 East xsec 3
41814 East xsec 3
8514 East xsec 3
28.1
28.0
27.9
27.7
0.0
0.7
1.4
2.1
2.8
3.5
Elevation (m)
Horizontal Distance (m)


McPherson - Goerhing xsec 4
62012 East xsec 4
Bankfull Indicators
Water Surface Points
8912 East xsec 4
31613 East xsec 4
62713 East xsec 4
41814 East xsec 4
8514 East xsec 4
28.9
28.5
0.0
3.2
Elevation (m)
Horizontal Distance (m)

Appendix C - Extrapolation tables for McPherson gully channels – for each survey date, and net change

Wedel data extrapolations

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Wedel	1	0.13	71	9.23
6.20.12	2	0.6	190	114
	3	1.9	146.5	278.35
	4	1.7	27.5	46.75
	1B	1.19	137	163.03
	2B	0.9	191	171.9
	3B	1.9	180	342
	1C	1.14	8.5	9.69
	2C	0.64	48	30.72
	3C	0.52	50	26
	4C	0.58	5.5	3.19
	5C			
	6C			
	1D			
	2D			
	3D			
Total change A-C				1194.86
Total change, m^3				**33.8**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Wedel	1	-1.21	71	-85.91
8.10.12	2	-0.27	190	-51.3
	3	-1	146.5	-146.5
	4	-0.9	27.5	-24.75
	1B	-0.36	137	-49.32
	2B	0.4	191	76.4
	3B	0.1	180	18
	1C	-0.43	8.5	-3.655
	2C	0.09	48	4.32
	3C	0.31	50	15.5
	4C	0.28	5.5	1.54
	5C			
	6C			
	1D			
	2D			
	3D			
Total change A-C				-245.675
Total change, m^3				7

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Wedel	1	0.36	71	25.56
3.15.13	2	-0.16	190	-30.4
	3	-1.3	146.5	-190.45
	4	-1.5	27.5	-41.25
	1B	-1.85	137	-253.45
	2B	-1.7	191	-324.7
	3B	-1.9	180	-342
	1C	-0.7	8.5	-5.95
	2C	-1.11	48	-53.28
	3C	-1.03	50	-51.5
	4C	-1.06	5.5	-5.83
	5C			
	6C			
	1D			
	2D			
	3D			
Total change A-C				-1273.25
Total change, m^3				**-36.1**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Wedel	1	-0.08	71	-5.68
5.23.13	2	-0.56	190	-106.4
	3	-0.36	146.5	-52.74
	4	-0.6	27.5	-16.5
	1B	0.09	137	12.33
	2B	0.1	191	19.1
	3B	-0.1	180	-18
	1C	0.2	8.5	1.7
	2C	0.01	48	0.48
	3C	-0.07	50	-3.5
	4C		5.5	0
	5C			
	6C			
	1D			
	2D			
	3D			
Total change A-C				-169.21
Total change, m^3				**-4.8**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Wedel	1	-0.11	71	-7.81
4.22.14	2	-0.65	190	-123.5
	3	-1.18	146.5	-172.87
	4	-1.56	27.5	-42.9
	1B	0.23	137	31.51
	2B	0.5	191	95.5
	3B	-0.9	180	-162
	1C	-0.44	8.5	-3.74
	2C	0.45	48	21.6
	3C	0.68	50	34
	4C	0.57	45.5	25.935
	5C	0.64	43.5	27.84
	6C	0.26	3.5	0.91
	1D	1.89	6.8	12.852
	2D	0.8	6.4	5.12
	3D	0.21	3.4	0.714
Total change A-D				-256.839
Total change, m^3				**-7.3**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Wedel	1	0.34	71	24.14
6.18.14	2	-0.21	190	-39.9
	3	1.07	146.5	156.755
	4	-0.86	27.5	-23.65
	1B	-0.69	137	-94.53
	2B	-1.2	191	-229.2
	3B	-1.5	180	-270
	1C	-0.69	8.5	-5.865
	2C	0.19	48	9.12
	3C	0.4	50	20
	4C	1.42	45.5	64.61
	5C	1.42	43.5	61.77
	6C	0.86	3.5	3.01
	1D	0.62	6.8	4.216
	2D	1.22	6.4	7.808
	3D	0.11	3.4	0.374
Total change A-D				-311.342
Total change, m^3				**-8.8**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Wedel	1	-1.07	71	-75.97
1.9.15	2	-0.39	190	-74.1
	3	-1.33	146.5	-194.845
	4	-1.89	27.5	-51.975
	1B	-1.55	137	-212.35
	2B	-0.31	191	-59.21
	3B	-1.74	180	-313.2
	1C	-0.63	8.5	-5.355
	2C	-0.48	48	-23.04
	3C	0.19	50	9.5
	4C	-0.69	45.5	-31.395
	5C	0.52	43.5	22.62
	6C	0.43	3.5	1.505
	1D	0.71	6.8	4.828
	2D	0.71	6.4	4.544
	3D	0.44	3.4	1.496
Total change A-D				-996.947
Total change, m^3				**-28.2**

Wedel Totals by Trib, in cubic meters					
Date	Trib A	Trib B	Trib C	Trib D	Total
6/20/2012	25.37548	38.31424	3.93936		67.62908
8/10/2012	-17.4588	2.551528	1.002103		-13.9052
3/15/2013	-13.3882	-52.0805	-6.5973		-72.066
5/23/2013	-10.2627	0.760138	-0.07471		-9.57729
4/22/2014	-19.6447	-1.98043	6.030447	1.057628	-14.5371
6/18/2014	6.641727	-33.6051	8.639707	0.701727	-17.622
1/9/2015	-22.464	-33.0974	-1.48094	0.615129	-56.4272

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Wedel - Entire study period	1	-1.64	71	-116.44
	2	-1.64	190	-311.6
	3	-2.2	146.5	-322.3
	4	-3.89	27.5	-106.975
	1B	-2.94	137	-402.78
	2B	-1.31	191	-250.21
	3B	-4.14	180	-745.2
	1C	-1.55	8.5	-13.175
	2C	-0.21	48	-10.08
	3C	1	50	50
	4C	1.3	45.5	59.15
	5C	2.58	43.5	112.23
	6C	1.55	3.5	5.425
	1D	3.22	6.8	21.896
	2D	2.73	6.4	17.472
	3D	0.76	3.4	2.584
Total change A-D				-2010.003
Total change, m^3				**-56.9**

Schmidt data extrapolations

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Schmidt	1	-0.6	59.5	-35.7
6.21.12	2	-0.8	27.5	-22
	3	-0.49	24.5	-12.005
	4	-0.21	20	-4.2
Total change in distinguishable Channel				-73.905
Total change, m^3				**-2.1**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Schmidt	1	-0.8	59.5	-47.6
8.9.12	2	0	27.5	0
	3	-0.61	24.5	-14.945
	4	-0.62	20	-12.4
Total change in dist. Channel				-74.945
Total change, m^3				**-2.1**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Schmidt	1	1.5	59.5	89.25
3.16.13	2	0.7	27.5	19.25
	3	1.22	24.5	29.89
	4	0.72	20	14.4
Total change in dist. Channel				152.79
Total change, m^3				**4.3**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Schmidt	1	-1.2	59.5	-71.4
6.28.13	2	-0.9	27.5	-24.75
	3	-1.23	24.5	-30.135
	4	-0.67	20	-13.4
Total change in dist. Channel				-139.685
Total change, m^3				**-4**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Schmidt	1	-0.8	59.5	-47.6
4.18.14	2	-0.64	27.5	-17.6
	3	-0.15	24.5	-3.675
	4	0.05	20	1
Total change in dist. Channel				-67.875
Total change, m^3				**-1.9**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Schmidt	1	-0.2	59.5	-11.9
1.9.15	2	0.1	27.5	2.75
	3	-0.79	24.5	-19.355
	4	-0.01	20	-0.2
Total change in dist. Channel				-28.705
Total change, m^3				**-0.8**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Schmidt	1	-1.7	59.5	-101.15
Entire study	2	-1.12	27.5	-30.8
	3	-1.33	24.5	-32.585
	4	-0.74	20	-14.8
Total change in dist. Channel				-179.335
Total change, m^3				**-5.1**

Goerhing data extrapolations

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Goerhing	1	-0.56	109.5	-61.32
8.10.12	2	-0.34	150.5	-51.17
	3	-0.89	165.5	-147.295
	4	-0.55	76.5	-42.075
Total change in dist. Channel				-301.86
Total change, m^3				**-8.5**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Goerhing	1	-2.22	109.5	-243.09
3.16.13	2	-1.46	150.5	-219.73
	3	-2.25	165.5	-372.375
	4	-0.91	76.5	-69.615
Total change in dist. Channel				-904.81
Total change, m^3				**-25.6**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Goerhing	1	0.65	109.5	71.175
6.27.13	2	0.58	150.5	87.29
	3	0.18	165.5	29.79
	4	1.13	76.5	86.445
Total change in dist. Channel				274.7
Total change, m^3				**7.8**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Goerhing	1	-1.19	109.5	-130.305
4.18.14	2	-1.23	150.5	-185.115
	3	0.49	165.5	81.095
	4	-1.09	76.5	-83.385
Total change in dist. Channel				-317.71
Total change, m^3				**-9**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Goerhing	1	-0.26	109.5	-28.47
8.5.14	2	-0.28	150.5	-42.14
	3	-1.33	165.5	-220.115
	4	-1.14	76.5	-87.21
Total change in dist. Channel				-377.935
Total change, m^3				**-10.7**

Location	xsec	Erosion per foot, ft^2	# of feet	Erosion by length, cubic ft
Goerhing	1	-3.58	109.5	-392.01
Entire Study	2	-2.73	150.5	-410.865
	3	-3.8	165.5	-628.9
	4	-2.56	76.5	-195.84
Total erosion in dist. Channel				-1627.615
Total change, m^3				**-46.1**

Fort Riley Bed Change statistics

Table 4.7 Bed change versus rainfall relationships – no significant relationships

Gully ID	**XS ID**	**Total Rain Depth**		**Largest Storm**		**Antec.Storm**		**Peak Intensity**	
TA		Adj R2	p-value	Adj R2	p-value	Adj R2	p-value	Adj R2	p-value
36	3	-0.167	0.529	0.048	0.396	-0.023	0.436	-0.486	0.902
42	2	0.380	0.234	-0.091	0.478	0.053	0.393	-0.234	0.579
	3	Not enough observations							
51	2	-0.087	0.470	-0.270	0.724	-0.207	0.615	-0.311	0.837
	3	-0.333	0.984	-0.144	0.532	-0.221	0.636	-0.242	0.671
89	2	-0.239	0.665	-0.325	0.899	-0.327	0.909	-0.010	0.399
	3	-0.305	0.816	-0.181	0.578	-0.189	0.589	-0.309	0.828
91	2	0.617	0.289	-0.632	0.718	-0.584	0.699	-0.067	0.521
94	2	-0.495	0.942	-0.482	0.891	-0.500	0.995	-0.325	0.659
98	2	0.138	0.348	-0.450	0.817	-0.424	0.775	-0.268	0.607
	4c	-0.287	0.623	-0.461	0.839	-0.402	0.744	-0.390	0.729