GULLY EROSION ASSESSMENT AND GROWTH PREDICTION ON MILITARY TRAINING LANDS

by

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Abstract

Military maneuvers result in significant physical and environmental impacts to the landscape. These impacts generally result in a loss of vegetative cover and increased watershed runoff and rate depending on vehicle speed, turning radius, and soil moisture content. Unless adequately monitored or mitigated, this increased runoff can lead to excessive soil erosion and gully formation. Past studies have revealed that these gullies can impact water quality from excessive erosion and create concerns regarding soldier safety. In order to better understand how gullies form and evolve overtime on military installations, a study is being conducted at Fort Riley, KS.

In 2010, approximately forty gullies were identified, assessed, and measured using common erosion monitoring and surveying techniques. These gully locations, and any newly formed gullies, were remeasured using these same methods in 2012 to determine the rate of growth for each site with respect to width, depth, and headcut. Of fifty-nine gullies total, twenty one were initially included in this study. Upon further analysis including the utilization of watershed characteristics and land management techniques, eleven of the 21 utilized gullies were deemed appropriate to include in predictive assessment, as these eleven systems exhibited singular headcut migration.

Multiple Regression Analysis was utilized to produce predictive equations for Headcut Growth. This equation [Headcut Growth = 0.666 + 0.137(Watershed Slope) – 0.478(Training Intensity) + 0.757(log[Watershed Area]) – 0.278(Drainage Density) – 0.0138(Above Ground Biomass Change) + 0.187(Burning Frequency] resulted in a model relationship of approximately 90%, with Watershed Slope being the most significant variable when an output Headcut Growth was reached.

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Dedication

I would like to dedicate my thesis work to my family. While they may not always understand what my research entails or even what I am talking about a majority of the time when I visit, their support and encouragement has been insurmountable. For that, I am forever grateful.

Chapter 1 - Introduction

Gully erosion, while lacking a universally accepted definition, typically involves reoccurring soil movement through a small channel via concentrated overland flow. While the less significant downcuts or networks can be refilled or tilled under, gullies are the result of unique soil erosion processes in the fact that they will reappear from year-to-year near the same location because of the underlying topographic properties.

Gully progression occurs due to multiple environmentally related factors. These range from topographic properties such as slope and aspect, but also include factors such as vegetative cover. As land management practices are altered and result in higher levels of anthropogenic influence, gully erosion has been accelerated – particularly in agricultural settings.

Accurate gully erosion prediction has been limited due to a variety of research factors. Currently, few studies have compiled extensive research with respect to temporal and topographic variations, resulting in a need for more long-term field testing. Precise rainfall data regarding intensity and amount is also required to more accurately analyze the input variables causing differences in gully erosion over time. Additional factors also require more extensive research and data collection to aid in the accurate prediction of gully erosion. Soil compaction, for example, has been identified as a possible important environmental alteration that could greatly impact gullies on locations such as military bases.

Compared to general gully erosion, even fewer studies have been conducted to determine the effects of military maneuvers on gully formation and growth. Military training installations experience a significant amount of soil erosion caused by the land degradation initiated through vehicle passes. The degree to which these maneuvers impact the landscape have been proven to depend on vehicle variables such as weight, turning radius as well as environmental conditions such as soil moisture (Buck et al, 2011; Anderson et al., 2006; Althoff et al., 2006; Milchunas et al., 1999).

Gully erosion prediction has unfortunately been difficult due to the intricate relationships within the environmental factors and human interactions. Studying situations in which multiple of these influences are combined can lead to a more sufficient modeling process for gully development.

This study strives to continue the research efforts started in the summer of 2010 at Fort Riley located in Geary and Riley Counties, Kansas. By resurveying the gully systems after two years, gully progression on a military base can begin to be predicted over time. Influential factors will be identified as potential influences to gully erosion with regards to headcut growth, channel depth, and channel width change. From these factors, relationships and levels of importance can be produced that can lead to a decrease in the overall environmental degradation witnessed at each gully site.

Chapter 2 - Literature Review

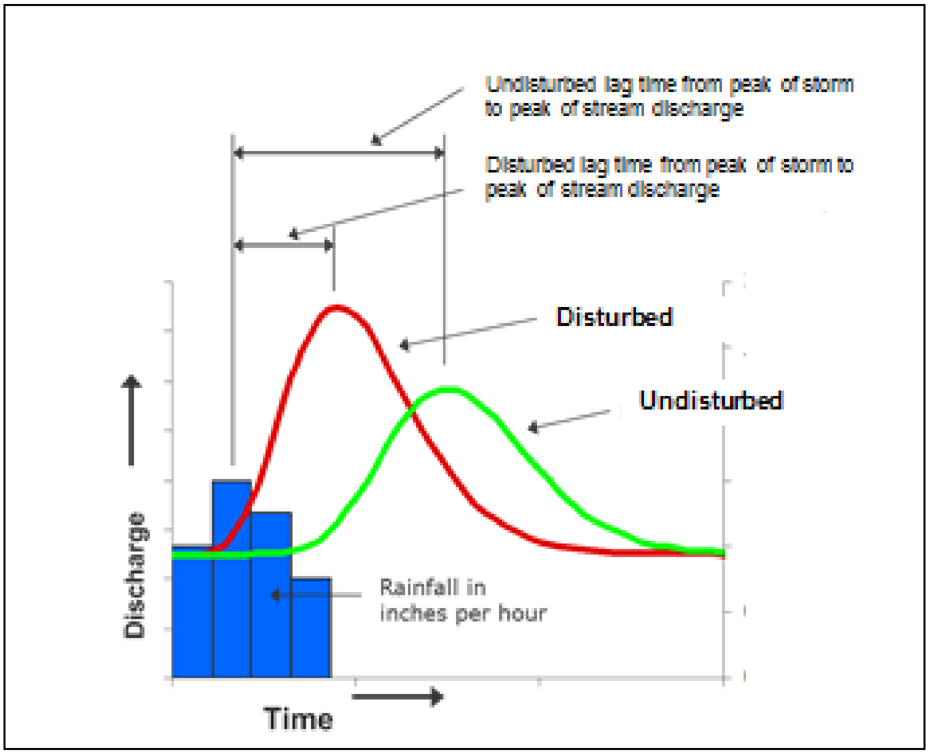
According to the United States Census Bureau, as of September 2012 over 7 billion people inhabit the globe with nearly 315 million in the United States alone. With an increase of approximately 27 million people in the United States since the 2000 Census was conducted (U.S. Department of Commerce, 2012), there is no sign that the population will plateau within the near future. As the human population continues to increase, the need for a growth in resources – both natural and manmade – is also required, which alters land use. Some of these changes in land use include conversions of previously undisturbed landscapes such as forests and grasslands to urban entities such as factories, housing, and industries. Each of these adjustments results in different environmental properties, and when multiplied by the rapid increase in the human population, could significantly change global cycles and processes.

Among the most significant results of this increase in population with regards to land use and environmental alterations are activities such as deforestation, mining, infrastructure development, military activities, tourism, and agriculture (Waele, 2009). To varying degrees, each of these actions significantly affects the hydrologic cycle by altering the ecosystem in which it resides (Zimmermann & Elsenbeer, 2009). For example, Bradshaw et al. (2007) deduced that deforestation significantly increased the average flow and intensities of flood events. This same conclusion was made in Canada where both peak and mean flows surged during flood occurrences due to the regional deforestation (Lin and Wei, 2008). Therefore, empirical evidence seems to support that any change in land use practices will likely modify the flow of water throughout the system.

When discussed in a broader view utilizing a hydrograph, the concept of increased disturbance can begin to be applied to land use change (Figure 2.1). Represented in this figure are the two extreme limitations of this disturbance spectrum. As a landscape is converted from an undisturbed to a disturbed setting, its peak discharge rate not only increases in volume, but also occurs closer to the beginning of the rain event. Likewise, as a pervious surface is converted to a less porous material or the region's soil is compacted into an impermeable pan, the water will have less of an ability to infiltrate into the ground, again resulting in an increased peak runoff.

Therefore, it can be argued that comparatively less natural changes in landscape disturbance will to some degree move the watershed's hydrograph towards the red curve seen below.

Figure 2.1 Hydrograph of Disturbed and Undisturbed settings (adapted from Hutchinson, 2011).



Once this change to the environmental surface occurs – through compaction of the soil due to increased activity in the previous examples – it is considered omnidirectional and therefore cannot easily be reversed, if overturned at all (Schneider et al., 2012). Some common changes such as conversion of lands to less permeable surfaces (i.e. concrete pathways, paved parking lots, building rooftops) also alter the environmental surfaces and are likely not considered reversible. Due to the dramatic results that can be caused by land use modifications, evaluation of certain signals are frequently used to determine the level of disruption to the environmental setting (Waele, 2009). Measuring water runoff, for example, has become a common indicator of significant land use change because of the large variations of runoff amount depending on the type of land cover alteration (Sriwongsitanon & Taesombat, 2011).

While most people will agree that this change to the hydrologic cycle is occurring in today's world, finding a balance between the foreseeable increase in resource needs and conservation of environmental properties creates a challenge. Being able to accomplish this task, particularly with regards to ecosystem benefits such as flood control and soil protection against physical needs, has not been easy for any involved parties (Viglizzo et al., 2012). This tradeoff between progress and environmental protection is likely to continue, with environmental degradation becoming more common and accepted.

Some environmental researchers, however, are not as convinced that land use conversion is the major factor contributing to changes in water infiltration levels. In fact, studies in Canada, Northeastern Thailand and Central Thailand concluded that with a land cover change involving compaction amounts of roughly 5-27% (nearly 50% in Central Thailand), no apparent trends in the hydraulic flow of local river basins could be seen (Sriwongsitanon & Taesombat, 2011). Had there been a conclusive connection directly between land cover conversion and water runoff, the regions with increased human activity should have witnessed increased flow over the landscape. Additionally, there are also some groups who support a relationship between land use change and runoff in only certain settings. Some parties have argued that in general, the correlation between land cover alterations and increased runoff seen in areas with excessive deforestation are indeed directly linked, but only for smaller scale storms in which the threshold of irreversible erosion has not occurred (Cosandey et al., 2005). As a result, an overall relationship including all precipitation intensities cannot be necessarily supported empirically. This inconsistent trend can possibly be explained by the idea that during significant rainfall relative to the sediment profile, soils reach their maximum water capacity before the conclusion of the storm; therefore, the land cover type is irrelevant past that peak time (Lull & Reinhart, 1972). Each variable, therefore, may play a more or less significant influence on the overall water runoff in a more dynamic system than previously believed.

One apparent commonality, and possibly more important overall attribute, between all of the previously identified land use changes is the soil disturbance. Because of the strong relationship between water movement and soil characteristics, any changes in the properties of one entity can significantly alter the other (Zimmermann & Elsenbeer, 2009). In fact, many recent initiatives have been developed around the globe to better link land use alteration to water's soil erosive powers (Poesen et al., 2003). Vanacker et al., in 2005 went as far as to advocate that even fairly minor alterations to land cover and use may create a significant change in sediment creation on the watershed scale.

With many common soil disturbances come vegetative cover alterations – another important variable regarding water cycling and infiltration. Once the vegetation on the land has been removed through either land conversion or severe compaction, there will be fewer large and medium sized pores within the soil layers, resulting in a lower water adsorption than the same plot containing no biotic cover (Hayashi et al., 2006). Therefore, vegetation removal has been recently linked to both land use change and water infiltration.

In general, these projects have concluded that such alterations, particularly when the multitude of land change occurring due to the current population increase is considered, can have a detrimental impact on water and soil properties in the ecosystem.

Soil Erosion

"Soil is essentially a non-renewable resource and a very dynamic system which performs many functions and delivers service vital to human activities and ecosystems survival" (European Commission, 2006). However, this importance relating directly to soil status and availability has created a severe struggle between environmental, social, and economic benefits (Viglizzo et al., 2012) even as humans have attempted to more effectively understand the complex relationships between variables explaining soil degradation.

Soil erosion is typically first defined by the erosive agent – water or wind. During both processes, soil particles are separated into rudimentary units and displaced from their original location (Toy et al., 2002). Water erosion occurs primarily when the velocity of the water is able to create a shear strength great enough to overcome the cohesion between the soil particles, and is commonly worsened when the level of water flow cannot be adequately infiltrated into the surface. This buildup of unabsorbed water can occur due to multiple factors but is initially driven by causes such as rainfall and runoff accumulation. As the landscape is manipulated from a natural setting to a less pervious state, this runoff amount increases as it cannot be infiltrated quickly enough for unground movement or storage.

Multiple biotic and abiotic factors can be related to the amount of soil erosion likely to occur in a given location. For example, various soil types and textures are more prone to erosion. Soils with a high level of clay have been typically thought to erode less due to the strong bond present between each individual particle. On the other hand, soil with more fine sand will erode more easily (Dvořák & Novák, 1994) and therefore makes that zone more susceptible to water erosion. Erosion is also more likely to occur on sloped areas rather than in flat valley floors as water erosion from runoff is driven by a gravitational force.

Additionally, studies have found that soil erosion speeds are reduced exponentially with regards to vegetative cover (Gyssels et al., 2005) and that an inverse exponential relationship is apparent amongst mean sediment production and vegetation at the watershed level (Vanacker et al., 2007; Molina et al., 2008). Having this vegetative cover changes erosion amounts on two sub-levels: above and below ground. As previously mentioned, active vegetation creates a large amount of pores that infiltrate water more rapidly than soil without these root systems. Above ground, vegetation not only intercepts the initial rainfall of a region, but also slows down the velocity at which the water is traveling. This idea of above ground erosion protection is reviewed more thoroughly later in this document.

When all of these erosive variables are combined, not only can certain areas be identified as more vulnerable to soil erosion, but various levels or severity of erosion can also be determined. Since soil should be considered a non-renewable resource – particularly when the rapid pace of potentially permanent soil erosion is considered (Bazzoffi, 2009), it is of utmost importance to distinguish between these levels of erosion and understand their environmental impacts. With careful monitoring and limited human impact, however, some soils can withstand some degree of erosion by naturally replenishing the amount of soil lost (Bazzoffi, 2009). Determining where the line between slight and significant erosion lies for each soil type and plot is key for long-term sustainability of this resource.

Levels of Erosion

Certain natural levels of soil loss can be expected during a given timeframe regardless of the contributing factors in the surrounding area. For soils with minimal profile depth, loss should be no more than 1 ton ha^{-1} $year^{-1}$ while more established soils can handle a loss near 5 ton ha^{-1} $year^{-1}$ – though any amount over 1 ton ha^{-1} $year^{-1}$ is typically considered irreversible to soil worth within the human life expectancy (Bazzoffi, 2009). However, total soil loss does not always stay within this reasonable range. For this reason, common levels of erosion have been identified and defined regarding both formation qualities and erosion amounts ranging from splash erosion to gully erosion.

Types of Erosion

Splash erosion is typically recognized as the least erosion as its impact is isolated to the small area directly where the raindrop falls. This process can visually create minute craters in the soil but can usually be significantly decreased by not leaving the soil exposed directly to rainfall through means such as canopy cover. Next is sheet erosion where the top and commonly the most productive layer of soil is detached in sections down the slope as opposed to a channel formation (National Soil Erosion Research Laboratory, n.d.c). This process typically occurs early in the runoff formation before the water is able to concentrate into a narrower pathway.

As this concentrated flow develops, rill erosion is formed (U.S. Environmental Protection Agency, 2003). Rill erosion is the first type in which small channels or streamlets are created. With regards to agricultural settings, rill erosion can usually be removed via tillage practices and will not necessarily reform in the same location (Foster, 1986). These channels are smaller than ephemeral gullies and can visually be identified as multiple small, parallel streams that are disconnected from each other (Foster, 1986). In order to numerically separate ephemeral gullies from rill erosion, scientists use a threshold definition of 929 cm^2 for the cross-sectional area (Poesen et al., 2003). Therefore, if this area is less than 929 cm^2, the erosion is classified as rill, while cross-section areas greater than this value are classified as ephemeral gullies. Having a minimum depth near 0.5-0.6 meters and a minimum width of 0.3 meters can also help categorize the type of erosion present in the landscape (Imeson & Kwaad, 1980), but does not seem to be an absolute threshold. Visually, each rill channel is typically the same size and spaced approximately the same distance from each individual rill, therefore making this erosion type the transition between sheet erosion to the more noticeable gully erosion (Foster, 1986).

As rill channels progress and concentrate, they can eventually form more long-lasting and noticeable gullies. Ephemeral gullies are again typically resolved by tillage, but will reappear year after year in the same spot (Foster, 1986). As part of the erosional spectrum, ephemeral gullies are considered to be larger than rill erosion, but less than classical gully erosion. Unlike rill erosion, ephemeral gullies form along natural water courses where less powerful channels converge and their width is typically larger than the depth as the sidewalls to these ephemeral gullies are not distinct (Foster, 1986).

An interesting difference to note between rill, sheet, and gully erosion revolves around the potential for sediment transport. Since most of the sedimentation caused by rill and sheet erosion results in deposits along the base or in depressions throughout the landscape, only minute amounts of these particles are transported into rivers due to these forms of erosion (Poesen et al., 2003). Gully erosion, on the other hand, accounts for a large amount of this sediment transport into surrounding water bodies and therefore is particularly responsible for reservoir and basin infilling (Poesen et al., 2003). As a result, the amount of active gullies throughout a watershed seems to be a direct gauge of the amount of sedimentation in these catchments (Poesen et al., 2003).

One of the most markedly recognizable forms of erosion is the classical gully. As defined by Poesen et al. in 2003, gully erosion involves a rapid process of soil evacuation over a relatively narrow waterway at typically substantial depths. This level of erosion cannot be removed using standard tillage practices as these implements are unable to combat the depth and have an easily distinguishable headcut and sidewalls (Foster, 1986; Soil Science Society of America, 2013). Also, this is the first time in the spectrum of erosion levels that soft layers of bedrock may be susceptible to erosion (Foster, 1986). By comparing this definition to those of other types of gully erosion, it can be interpreted that gully erosion produces the most visually defining properties due to its quick development over a limited horizontal region. Numerically, classical gullies are defined by a measurement of over 0.5 meters (Soil Science Society of America, 2013) in depth, but no common agreement has been made for minimum width or cross-section.

As alluded to previously, real importance does not necessarily lie in the boundaries between the various types of erosion, but rather in the idea that a continuum is formed throughout the erosion amounts (Poesen, 1993). This idea has allowed erosion types to be more accurately described across environmental differences and is necessary when classifications are considered. Additionally, using certain signals within the landscape both with respect to chemical and biological factors can help determine the overall disruption of the environment (Waele, 2009).

Gully Development

In order to adequately understand gully erosion, the process through which a classical gully is initiated and formed must first be understood. Two core factors play a key role in gully development: headcutting and downcutting (Hancock & Evans, 2010; Ffollieott et al. 2003). Headcutting can be defined as an erosion process that lengthens the gully and progresses the initial knick point – the location of sharp variance in gradient – upslope (Ffollieott et al., 2003). Downcutting, on the other hand, relates to the width and depth within a gully and occurs via vertical erosion along the gully bed, oftentimes creating commonly identifiable steep side walls (Ffolliott et al., 2003; Hancock & Evans, 2010). As water flows over the gully head – the permanent knick point of the gully network, the edge of the bank is eroded as soil particles are loosened from their previous location. Additionally, as the water plummets over the wall, a plunge pool – a section of the gully bottom where scouring occurs as the water moves in a vertical direction – is oftentimes developed due to the increase in downward velocity of the water through gravitational forces. These particles then settle on the gully bottom and will either remain and create aggradation – become less deep – or move further down the watershed and cause the gully bottom to degredate – become deeper. Sediment deposit often arises in formed gullies when there is an increase in channel roughness or decrease in channel slope (Molina et al., 2009), which may help predict where these alterations in depth might typically be found. Subsurface flow can also alter the integrity of the gully walls and potentially accelerate undercutting along the sides of the gully (Ffolliott et al., 2003). This undercutting can then lead to gully sidewall failure or compromise the soil supporting the headcut and cause widening or upward migration of the channel.

As changes in width, depth, and headcut migration occur, soil is eroded and will ultimately be moved to another location further down the gully or the watershed. As a result of this sediment and water runoff transportation, gullies greatly increase the connectivity of a given environment by creating long-lasting pathways through which soil particles and other matter can be rapidly moved (Poesen et al., 2003). Therefore, gullies present not only a hazard to equipment or humans by being an unexpected physical cut into the assumed level surface, but are also outlets for nutrient and pollution transport into watershed outlets.

Normally, correction of gully formation is difficult once the initial development has begun, meaning that thorough understanding of the causes of gully initiation and relationships leading towards development is required (Prosser & Soufi, 1998). One predominantly important aspect of this initiation is finding the threshold between a stable cover and one that has been compromised far enough to allow erosive actions to take place. Prosser & Soufi (1998) found that in the deforested plot in humid temperatures, a threshold was apparent between gully erosion and the level of scour needed to uncover the underlying soil. Numerical associations, however, have been difficult to determine thus far regarding the exact threshold under which gully formation will begin.

Additionally, little is certain about any other factors that may lead up to gully initiation – particularly when compared to gully development. It is generally believed that initial formation is triggered by a compromise in vegetative cover, allowing for water accumulation and original channel development (U.S. Environmental Protection Agency, 2003). In some instances, this action may be caused by intentional grassland and scrub removal, but unintentional breaking of vegetative cover through vehicle crossings and rutting could also be the action starting the gully. When looking at aerial photos, pathways or established tracks appear to initiate gully location – giving a timeframe of when the erosion may have started (Sidorchuk et al., 2003). Therefore, while the variables leading up to gully initiation may not be fully understood, techniques are recently being used to better grasp gully movement and stability.

In order for gullies to be considered stable, both the gully bottom and gully walls must reach equilibrium and no longer vary over the time of the study (Sidorchuk et al., 2003). Active gullies are commonly seen with steep banks that have no vegetative cover, or in locations where water diversion is not likely due to the implementation of surface that cannot be eroded by the present surface runoff (Black, 1996). Some thresholds have been established to better and more consistently define a gully as stable or active. For example, gully bottoms are typically considered stable if they are at least twenty times the width of the flow of water at bankfull discharge (Sidorchuk et al., 2003). Moreover, the cross-sectional shape of a stable gully has characteristically been documented to have a trapezoidal formation (Sidorchuk et al., 2003). Two relationships have been proposed to empirically prove a stable gully system: stable bottom width versus discharge and width/depth ratio versus discharge (Sidorchuk et al., 2003).

A stable gully bottom width can be determined using the equation 2.1 from Sidorchuk et al.(2003) where A (m^2) represents the contributing watershed area and W_b (m) represents the gully bottom width. When the width of the gully bottom remains at this value determined by each different gully, the gully is thought to be stable through the following equation:

$$W_b = 0.5A^{0.3} \qquad \textit{equ 2.1}$$

where W_b = Gully Bottom Width (m),

A = Watershed Area (m^2).

A stable width/depth ratio can be determined using equation 2.2, relationship between width/depth ratio of a gully and discharge:

$$W/D = aQ^{0.2} \qquad \textit{equ 2.2}$$

where W/D = Width Depth Ratio (m/m),

ɑ = Soil Texture Variable,

Q = Discharge (m^3/s).

Visual signs aside from channel shapes and relationships have also been used to determine varying levels of gully stability. Recent studies have found that reestablished vegetation in the gully bottom, for example, may be a sign of stabilization (Molina et al., 2009). This thought began through the idea that with vegetation in the gully bed, roughly 25% of the sediment that would otherwise travel through the system will instead be slowed or stopped by these plants (Molina et al., 2009). In fact, conclusions have been taken as far as to directly relate short-term deposition of sediment and the complete stabilization of the gully (Molina et al., 2009), meaning that well established vegetation in the gully bottom can result in gully stabilization. This entire idea revolves around the above mentioned thought that as channel roughness increases, velocity of the water will decrease and be less likely to pick up soil or nutrient particles.

Factors Contributing to Erosion Rates

In various parts of the globe, soil loss rates caused by gully erosion range from 10% to 94% of the overall sediment production created from water erosion (Poesen et al., 2003). This range of sediment production does vary slightly (18% to 73%) in the United State of America (Poesen et al., 2003) (Table 2.1). This fact not only suggests that gullies have a varying degree of importance to the overall scheme of a region's erosion, but it also supports the idea that different variables with regards to soil properties, watershed characteristics, or common management practices in each state may be causing these variations in total erosion rates depending on the specific region of study.

Table 2.1 Soil Loss Rates in select U.S. States (adapted from Poesen et al., 2003)

Location	Soil Loss Rates by Gully Erosion (ton/ha*year)	Soil Loss Rate by Gully Erosion (%)
Alabama	19.7-35.9	50-60
Arizona	1.3-3.9	60-81
Delaware	5.6	71
Georgia	12	28
Illinois	11.6	42
Iowa	11.9	45
Kansas	17.9	27
Louisiana	13.5	25
Maine	11.5	31
Maryland	9.0	43
Michigan	2.7	21
Mississippi	16.8	30
New Jersey	11.6	42
New York	11.3	18
North Dakota	8.0	32
Pennsylvania	4.0	41
Rhode Island	8.3	29
South California	36.8	71
Vermont	13.7	58
Virginia	28.7	50
Washington	4.2	73
Wisconsin	9.4	35

Due to a lack of quantitative data, no reliable relationship based equation between governing features (soil type, land use, topography, etc.) and the morphological characteristics (depth, width, length) of various gullies has been established (Poesen et al., 2003). The most widely accepted quality of gully development and formation is that it occurs most commonly in sites with steep slopes (Park, 2001), but exceptions exist to this excessively general statement as well. However, various studies are still being completed that look solely at a single timeframe, contributing factor, or general region with regards to gully formation and initiation (e.g. Hancock & Evans, 2010; Ionita, 2006; Zhang et al., 2007). Nonetheless, some of the most highly recognized morphological attributes regarding gully formation and growth are as follows: slope location, time frame, soil type, land use, climate, and topography.

Slope Location

The location on the slope where the sample of erosion amount and rate is studied can produce drastically different results. In one study, zones at the peaks of hills were dominated by rill and sheet erosion, and resulted in gully erosion accounting for only 33% of the overall sediment movement in those sections (Poesen et al., 2003). As the study area moved further down the slope, gully erosion controlled the total sediment amount with nearly 85% of the loss (Poesen et al., 2003). This research first confirms that gully erosion process can be successfully found – with varying degrees of likelihood – throughout most topographies regardless of whether the site is located at the top or bottom of a watershed. Secondly, this study concludes that in areas downslope, gullies are generally more prone to establishment due to a comparatively larger concentration, amount, and velocity of water over one particular route than for rill or sheet erosion.

Relating to the location of the hillslope is the location of the gully headcut to the edge of the watershed formed by the sloping landscape. As gully headward growth occurs, the gully becomes self-limiting by decreasing the drainage area which flows into the gully network (Kirkby & Bracken, 2009). This concept is confirmed empirically through a study in southeast Spain focused on an abandoned agriculture plot approximately 200m wide by 500m long (Poesen et al., 2003). As the contributing watershed area grew smaller because the gully migrated further into the contributing area, less water could potentially traverse the gully, concluding that location within the watershed and on the slope greatly dictate gully growth.

Time Frame

The amount of time considered over the study appears to be related to the gully erosion seen throughout a catchment (Poesen et al., 2003). During the active stage, gullies will form over 90 percent of its headcut growth, 35 percent of its volume, and 60 percent of its overall area that will occur over the entire gully evolution (Sidorchuk, 2006). This erosion process involved repetitive gully bank slumping, gully bed widening, and headcut migration, but only occurs for roughly 5 percent of the time in which a gully evolves (Sidorchuk, 2006; Kosov et al., 1978). If a particular short-term study only captures that dormant stage, the gully could be improperly considered to be stage. However, a study resulting in measurements of excessive growth could by chance have selected the active time frame for a gully and incorrectly predict this amount of movement for all future time frames. As such, the duration of time considered during a study may not dictate whether erosion will occur, but could skew gully assessment.

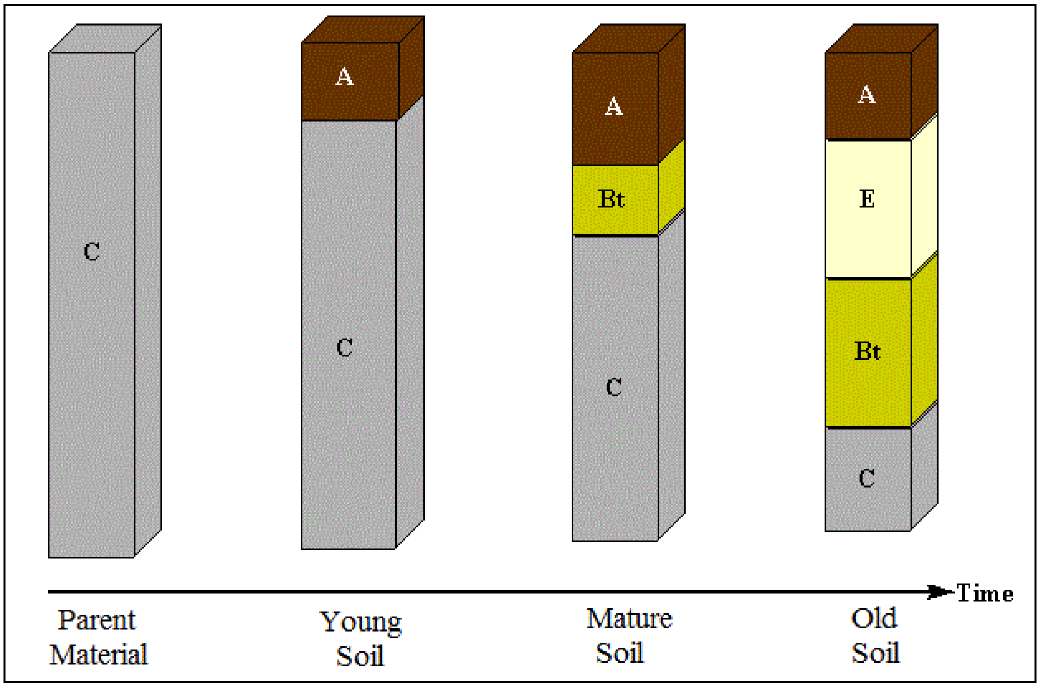
This problem arose in a study on the Iberian Peninsula conducted during a wet winter, where approximately 50% of the total sediment transport was caused by gully erosion (Poesen et al., 2003). However, when any 3 to 20 year period over the same location was analyzed, gully erosion accounted for closer to 80% (Poesen et al., 2003), suggesting that the short time frame skewed the likely growth predicted for these gullies. Ultimately, this change in percentage can likely be linked to different weather patterns and the conditions under which various types of soil erosion are likely to occur. For example, a wet winter may have resulted in a large amount of groundwater recharge and may have had an influence on the runoff that could have affected gully migration, but no definite conclusions were made in this study.

Soil Type

Generally speaking, various soil properties including texture, particle size distribution, and composition can increase or decrease the likelihood that certain soils will be eroded by water (U.S. Environmental Protection Agency, 2003). Additionally, some soil properties can also be linked to the above mentioned categories of soil erosion. For example, light soils, such as silty, coarse loamy or sandy varieties, are typically dominated by rill erosion (Poesen et al., 2003). Gullies initiated in extremely cohesive sediment are likely to exhibit greater headward growth and steep sidewalls than soils with a fragmented composition (Kirkby and Bracken, 2009). Therefore, knowledge pertaining to the soil texture of a given zone can be an important indicator when identifying locations for gully imitation and gully development.

Also, a study in central Belgium concluded that the volume of sediment produced specifically from gully erosion is 4-5 times higher when the soil profile lacks a Bt-horizon (Poesen, 1993). Bt-horizons are generally identified by their illuvial lattice clays (Pedosphere.ca, 2012), meaning that the bonding between the individual soil particles does not allow for a high degree of erosion. Bt-horizons are also more likely to develop prominently within older soil profiles as the area progresses away from its parent material as illustrated in Figure 2.2.

Figure 2.2 Stages of soil development in the central United States (adapted from University of Wisconsin-Madison, n.d.)



Lastly, soil textures heavily comprised of rock or large sediment in the upper level of the soil profile are more likely to be susceptible to gully erosion opposed to shallow laying and lower energy erosion such as sheet or rill (Poesen et al., 2003). This idea can likely be attributed to the energy within gully erosive waters, as lower forms of erosion require less energy to displace sediment and are not able to penetrate the upper level of rock.

Soil type can also in effect change the vegetative cover of the plot. For example, certain roots cannot grow in soils with high bulk densities (Gregory, 2006) where there are limitations on the pores sizes that will be found in these soil types. Certain pH levels or amounts of chemical components can also limit the types of vegetation that can establish in certain zones. Additionally, the compressibility, moisture, and temperature commonly associated with the soil type can alter the root densities, possibly changing the sediment production rate (De Baets et al., 2011).

Land Use

In disturbed locations, several soil components, the quantity of vegetation, and the volume of biomass have been linked to watershed properties such as erosion, runoff and infiltration (Spaeth et al., 1996). Anthropogenic factors relating to land use have also been proven to dictate location and progression of gully erosion including tractor ruts, furrows, and field borders (Zhang et al., 2007). Each of these factors – both natural and those initiated by humans – can have a varying effect on the erosive potential of the plot, therefore influencing the progress from an undisturbed to disturbed setting.

Some specific land use alterations can significantly change the infiltration and runoff rates during a given weather event. When man-made features such as drainage and irrigation canals or roads are built within a given watershed, gully formation is increasingly likely as a result of inadequate removal of water (Nyssen, 2001; Vanacker et al., 2003). A study conducted in Ethiopia confirms this idea. When a road was built within the catchment being monitored, the sediment movement due to gully formation increased from 33% to 55% as a result of the increased surface water (Nyssen, 2001). Therefore, watersheds with these alterations should be specifically monitored regarding potential gully development.

In many instances, land use will ultimately change the health and amount of vegetative cover in a catchment. Disrupting the natural vegetative cover creates a disconnected site that makes effective water movement and infiltration difficult (Molina et al., 2009). Even small intensification of vegetation (10-25%) can meaningfully reduce soil movement (60%) during short timeframes (Molina et al., 2008). Removal of vegetative cover directly parallel and adjacent to a gully location can rapidly increase the migration of the gully head and gully banks. However, the reverse process can also be claimed as reestablishment of forbs, grasses, and shrubs that had been previously eradicated on the soil surrounding an actively migrating gully can aid in quick stabilization of the system (Vanacker et al., 2003).

Vegetation explicitly decreases soil erosion potential in many ways. First, it increases the roughness of the ground and interrupts the water flow velocity (Styczen & Morgan, 1995), intercepts rainfall, and intensifies water infiltration (Gyssels et al., 2005). This concept not only deters gully erosion, but also limits raindrop, sheet, and rill erosion from occurring. Second, the root system alone can make a significant difference on sediment control (De Baets & Poesen, 2010). For example, fine-branched roots such as fibrous systems have proven to be able to significantly decrease water velocity and sediment movement; tap root systems are less effective (De Baets et al., 2011).

Vegetation cover located in the bed of the gully has also been related to gully growth and sediment movement. With a well-established vegetative cover, the gully bottom will be more secure from erosive mechanisms, exhibit better soil chemical and physical properties, and improve water infiltration (Prosser & Slade, 1994; Rey et al., 2005). Initial establishment of the cover is key to vegetation development as the gully bed typically collects a larger amount of both nutrients and water needed for the grasses and forbs to survive – making the gully bottom ideal for vegetation growth (Rey et al., 2005).

Overall, most literature involving research and analysis of vegetative cover and erosive abilities appear to link this variable to sediment yield along the entire watershed. It should be noted, however, that some studies, such as Rey (2004) seemed to determine that this relationship is in fact false and reported no relationship between watershed vegetation and erosion potential, but rather that there was a correlation between the soil movement and the vegetation in the gully bottom. This type of vegetation growth creates a grassed waterway as opposed to an open-flow channel, and slows down the water velocity through both above and below ground biomass.

Climate

It has been supported that large amounts of soil erosion – particularly gully formation – are not necessarily directly dependent on the total annual rainfall of a region. Rather, the occurrence of more intense events where runoff potential is high due to an array of environmental varibles – particularly decreased infiltration throughout the watershed – defines how and when a gully will develop. Thus far, no threshold exists that defines that exact limit between erosive rainfall intensities. Rain events with more than 50 mm of precipitation over a 5 day period however, are defined as potentially erosive amounts (USDA-SCS, 1972). Defining this limiting threshold for both intensity and amount will aid in both gully erosion prediction and determination of total erosion.

During times of intense rainfall, however, some studies have supported that gully erosion plays only a minimal role in the total sediment production over an entire watershed (Poesen et al., 2003), an important note to consider with soil erosion research. Belgium winter months, for example, experience low intensity rain events, but gully erosion is still the most predominant form of soil erosion (Vandaele & Poesen, 1995). However, the idea of intense rainfall for one area may not be representative of intense rainfall for another area, meaning comparisons between different sites are still difficult to quantify.

Properties of a region's climate can by extension affect the vegetative cover of the catchment. For example, when the temperature falls far enough to create frost, plants with tap root systems not only lose biomass above the soil, but their roots rapidly decay and offer much less soil strength (De Baets et al., 2011). Vegetation with fibrous roots, however, is able to withstand frost and therefore can protect the soil against water erosion at colder climates than tap rooted plants (De Baets et al., 2011). When combined together, the varying ways in which climate can affect soil erosion prove it is likely one of the most substantial factors regarding gully development.

Erosion Modeling Methods

Monitoring soil erosion, and to a wider scope, the hydrologic cycle, has an important place in environmental stability and prediction for two main reasons. First, to lessen the negative effects created by flood events and second, to escalate the infiltration of water through the soil profile (Bazzoffi, 2009). By decreasing the magnitude and occurrence of significant flood events, harm to down flow environments can be avoided. On a related issue, by increasing infiltration, groundwater levels can be replenished as opposed to re-entering the cycle through evaporation where environmental benefits are less direct. When applied to gully erosion, hydrologic modeling could assist in predicting the likely progression of the channel, but more empirical studies are needed detailing the process by which gullies are developed. Nonetheless, many models do exist today that can predict soil erosion loss, allowing for prediction of potential gully formation

Universal Soil Loss Equation (USLE)

Regarded as one of the most important improvements to soil and water conservation, the Universal Soil Loss Equation (USLE) was published in 1965 with an updated version in 1978 (USDA, 2009). The empirical equation is most commonly used to determine surface runoff and estimate soil erosion (USDA, 2009). Research for the development of this equation started in the 1940's, but when the first equation was derived, it only contained two explanatory variables (land slope and slope length) and a constant (USDA, 2009). This initial form expanded soon after in 1941 with cropping and support practice factors (USDA, 2009). Eventually, the USLE evolved into more complex equations with more intricate predictor variables, but the National Soil Erosion Research Lab in West Lafayette, Indiana still remains as the storehouse for data relating to this original erosion prediction model (National Soil Erosion Research Laboratory, n.d.b).

Revised Universal Soil Loss Equation (RUSLE)

One of the most widely utilized methods for prediction of soil erosion is the Revised Universal Soil Loss Equation (RUSLE) due to its ease of use and ability to be integrated into Geographic Information Systems (GIS) (Bazzoffi, 2009). The RUSLE contains many variables that can be altered to represent the soil, rainfall, and human activities to which an area is subjected (Figure 2.3). Each variable can be slightly altered, depending on the desired accuracy or range of outputs for the prediction. For example, it is common to consider both the maximum and minimum yearly rainfall on a given plot in order to calculate R – the rainfall erosivity factor (Bazzoffi, 2009). In one study, the maximum R value was considered to determine the amount of erosion that would occur using the highest amount of rainfall over a 50 year time while the minimum R value was used to isolate the specific areas that would witness erosion even with limited rainfall (Bazzoffi, 2009).

In 2010, many entities began to transition to the RUSLE2, a program similar to the original USLE, but with an advanced computer programming component. Unlike previous forms, this model utilized a more advanced integration formula instead of simply appoximations that had been used prior (USDA, 2010). Additionally, this version is able to make estimations based on timeframes as short as one day, whereas previous programs would move in a two week progression. As with other forms of this equation, the RUSLE2 estimates rill and interrill erosion (USDA, 2010). Therefore, this program focuses on the surface runoff caused by small channels – rills – throughout the landscape, as well as the area between nearby rills, and would therefore need to be altered for gully application.

Figure 2.3 Variable outline of Revised Universal Soil Loss Equation (RUSLE, 2002)

Revised Universal Soil Loss Equation (RUSLE)

$$A = R * K * LS * C * P$$

A = estimated average annual soil loss (tons/acre/year)

R = rainfall/runoff factor. Quantifying the effect of raindrop impact and the amount of rate of runoff associated with the fain, based on long term rainfall record

K = soil erodibility factor based on the combined effects of soil properties influencing erosion rates

LS = slope length factor, a combination of slope gradient and continuous extent

C = cover and management factor, incorporating influences of crop sequence, residue management, and tillage

P = practice factor, incorporating influences of conservation practices such as contouring or terraces

Water Erosion Prediction Project

The Water Erosion Prediction Project (WEPP) is another one of the most highly utilized soil erosion prediction models used in the United States and offers a large variety of potential types of outputs (Laflen et al., 2004). For example, WEPP produces outputs such as subsurface flow, vegetation growth, daily runoff, and sediment output, detachment, and deposition classified in various particle sizes. WEPP also allows for a variety of inputs that make prediction of erosion potential over an entire watershed more feasible by utilizing principals from erosion mechanics, hydrology, and plant science (Laflen et al., 1997). According to Flanagan et al. (2007), the WEPP model was originally created to eliminate the need for the USLE, but has clearly only spurred additional improvements to that method including the RUSLE and RUSLE2.

As with models of many kinds, WEPP has been progressing throughout the years as desire for a better, more workable method has become apparent. The interface alone of the program has undergone radical changes to accommodate all sizes of erosion plots and easy utilization on personal computers. Integration of digital elevation maps has also improved the workability of the program and made WEPP a program that can be run in Geographic

Information Systems (National Soil Erosion Research Laboratory, n.d.a). However, WEPP is still unable to predict gully erosion specifically.

Photogrammetry Monitoring and Ground Control Points

While this approach may not involve a specific equation to produce erosion loss, its analysis remains the same through utilization of infield points and digital analysis. Initially, ground control points (GCPs) are placed in clearly visible places at the gully location to offer a consistent datum for monitoring change (Marzolff and Poesen, 2009). Next, sequential aerial images and digital elevation models are produced of the desired gully network. These photographs and digital elevation models (DEM) can track the alterations both vertically and horizontally in and around the gully when matched with previously produced maps. In order to decrease many of the common errors associated with aerial monitoring, new features have been integrated to vastly decrease, if not eliminate entirely, some of the inaccuracies caused by lighting, angle of focus, and various other problems (Marzolff and Poesen, 2009).

While this comparison of progressive images allows the users to analyze the changes in gully volume and location by using various ArcGIS tools such as the cut/fill options, some details simply cannot be produced without infield data imagery collection. Undercutting from the headcut and along the banks of the gullies will not be sensed and therefore left out of the overall model. However, as with all common methods, acknowledging and understanding this disadvantage can greatly increase the accuracy of the overall soil loss prediction.

Other Models

Many popular models use what is referred to as a “runoff coefficient” which describes the ability of various land uses to negate flood events through soil infiltration (Bazzoffi, 2009). In detail, the runoff coefficient indicates how well various soil types can control the intensity and duration of a flood, as well as the soil’s effectiveness to infiltrate water throughout the hydrologic cycle (Bazzoffi, 2009). The SCS curve number is one popular technique used to predict this runoff coefficient and the direct infiltration or runoff created during a storms. This concept allows for a spectrum of infiltration to be classified were the location with the lowest runoff coefficient corresponds to the driest conditions while the highest runoff coefficient reflects a much wetter region (Sriwongsitanon & Taesombat, 2011).

Multiple methods can be used to predict erosion amounts that are based on this idea of a runoff coefficient. Generally, these types of programs are able to produce a wide variety of outputs including nutrient cycling. Analysis of this kind can begin by using many different methods including the implementation of hydrological models such as the Soil and Water Assessment Tool (SWAT) (Nie et al., 2011), or the Soil and Water Integrated Model (SWIM). SWAT, for example, focuses heavily on the implications of changes in management practices on chemical, sediment, and water outputs of various sized watersheds. This model is specifically useful for long-term estimation as it uses monthly to annual time increments. SWIM, on the other hand, was originally developed to integrate the successful attributes of SWAT with advantages seen in other programs. With SWIM, time steps on a daily basis can be implemented which allows for more short-term analysis. Additionally, the technical methodology used to derive desired outputs such as net photosynthesis and evapotransiration was in SWIM was altered from the previously used programs (Blackland Research & Extension Center, n.d.).

Gully Monitoring

While many models – including those previously mentioned – have been developed with respect to soil erosion over time, models specifically focusing on prediction and monitoring of gully erosion have been exceedingly rare. Therefore, gully erosion monitoring has been utilized as a more stable and reliable way to potentially predict the movement and erosive rate of gullies (Hancock & Evans, 2010; Ionita, 2006). Generally speaking, gully monitoring and observation can be separated into three timeframes: short-time scale or <1-10 years, medium-time scale of 10-70 years, and a long-time scale of more than 70 years (Poesen et al., 2003). Various field and laboratory techniques have been commonly used depending on the desired length of study.

Short-term research typically revolves around both airborne and ground-based field studies (Poesen et al., 2003) since the individual person or group leading the research will likely be present for that timeframe. Also, given the short period of time, it is feasible to directly measure the amount of soil lost by the gully systems, with this method being successfully utilized often in various cropland settings (Gyssels et al., 2002). Photogrammetric techniques – as discussed previously for modeling purposes – have been used to calculate the amount of soil transported by water erosion during this shorter time span (Poesen et al., 2003). Ritchie et al. (1994) was one of the first to be able to successfully place a laser sensor on an airborne craft to measure the cross-sections of multiple gullies. This data could then be converted and used to analyze the soil loss.

In order to combat some of the common errors associated with these sequential aerial techniques, however, field measurements have and can be integrated into this study time frame. Simple field measurements can be taken to monitor the gully head migration, aggradation or degradation throughout the gully bed, and changes in width location and span. By placing benchmark pins at the originally established headcut, measurements of change from the installed pin location can be recorded at regularly schedule intervals (Vandekerckhove et al., 2001; Oostwoud Wijdenes & Bryan, 2001). Reference pins can also be installed at the deepest and widest parts of the gully in order for these gully alterations to be accurately monitored throughout the study.

Medium-term research (10-70 years) relies less on direct field studies and rather on aerial photographs that depict the alterations in volume, area, and length of gullies (Poesen et al., 2003). This of course creates some difficulties with accurate depiction of sidewall undercutting erosion and seasonal variations in vegetation cover. One major drawback of this larger resolution data collection is that only gullies with significant changes over the observed timeframe can be adequately studied (Poesen et al., 2003). For example, gullies that may have started to develop additional headcuts may not be noticed on an aerial photograph, leaving that information omitted from the data for an extended period of time. However, Vanddekerckhove et al. (2001) has derived a method of estimation utilizing the exposure of roots, dead root ends, stems, browsing scars, and fallen trees within a given gully system. Identification of these minute details, though requiring a trained eye, will allow for a more advanced analysis of the gully even over a lengthy period of study.

Long-term research has been conducted using past data, several dating techniques and artifacts to determine substantial gully erosion throughout history (Prosser & Winchester, 1996). Many of these long-term studies require researchers to piece together various components of known data to be able to assess the formation and evolution of the gullies. For example, effective risk analysis of water runoff and soil erosion using GIS can pinpoint areas that are most susceptible to erosion (Bazzoffi, 2009). From this data, weather information can be used to determine the exact dates and locations that erosion likely occurred. While these techniques cannot give exact, detailed analysis of the gully erosion process or rate of erosion, they can give a good estimate of the long-term changes.

In all field studies regarding gully formation and progression, some processes simply cannot be adequately monitored such as plunge pool erosion, tension crack progress, and flow detachment (Poesen et al., 2003). With increased studies on gully erosion, however, these minute attributes may indeed be key factors in determining gully progression. As a result, laboratory studies involving human-made flumes have been established to better estimate the minute details and channel growth (Poesen et al., 2003). These small scale, human designs allow for the isolation of conditions that may not be possible in environmental field research and increase the ease through which plunge pools, tension cracks, and flow detachment can monitored.

Regardless of the amount of studies focused on monitoring and measurement of gully erosion, many restrictions still apply to these approaches (Poesen et al., 2003) as gully erosion is indeed an environmentally variable activity that cannot always be completely mimicked in laboratory settings. When the above mentioned flume design is reapplied to field gullies, various factors may change in importance.

Additionally, and on a more elementary level, there is a lack of standardized methods for gully erosion rates, meaning comparison of multiple sites presents numerous difficulties (Poesen et al., 2003). Establishment of these standards for gully growth assessment will more successfully decrease the worries of monitoring but will not effectively eliminate issues surrounding watershed to watershed comparison (Poesen et al., 2003). Each of these monitoring difficulties should be considered for future research and gully erosion development.

Military Activities and Impacts

Presented in 2004, “The Army Strategy for the Environment: Sustain the Mission, Secure the Future”, continued to outline the Army’s increasing interest in the need to comply with a sustainability-based agenda (Buck et al., 2011). Much of this recent concern was sparked by the monitoring results compiled by the Land Condition Trend Analysis (LCTA), later referred to as Range and Training Land Assessment (RTLA). This group was established in 1989 to examine 160 randomly stratified sampling plots on an annual basis for soil and vegetation properties (Singer et al., 2012). Measurements such as percent vegetation canopy cover and ground cover, vegetation height, and disturbance were recorded throughout the plots and extrapolated over the entire area (Singer et al., 2012). Results from these efforts seemed to prove that when military training intensity decreased, ground cover and canopy cover both increased and became more stable. Even with this data proving military influence on environmental conditions, many traditional and essential training activities must still occur regardless of environmental degradation. Therefore, important emphasis has been placed on analysis pertaining to military actions across the terrain through many researched based studies (Liu et al., 2007; Li et al., 2007; Althoff et al., 2006; Gatto, 2001).

Varying levels of military training intensity create different degrees of land use change and produce an altered hydrograph with variable peak discharges. Even small amounts of training can affect the sustainability of the area (Harmon & Doe, 2001) by compromising the wildlife habitat and decreasing the local underground water levels. Therefore, initiatives on multiple levels have been established throughout the Department of Defense to drive these sustainable efforts (Department of Defense, n.d). The Environmental Conservation Program of the Department of Defense, for example, outlined that any activities under its supervision, on United States territories, properties, and trusts must be in accordance with ecosystem management and preserve biological diversity whenever possible regarding military training (Walker, 1999). Many environmental variables including runoff and erosion potential, therefore, have been largely managed through these programs.

Understanding the variation in water runoff caused by different levels of military activity within a given watershed can be useful in determining both gully initiation and migration prediction. Field maneuvers, small arms fire, combat vehicle operations, and mortar and artillery fire have all been commonly identified as potential soil disturbing activities on military bases. At Fort Riley, most of this training activity is witnessed on the northern 75% of the base (Abel et al., 2009), making this area a prime location for measuring the degree of maneuvering impacts. Figure 2.4, taken in training area 98, is part of this high training intensity at Fort Riley.

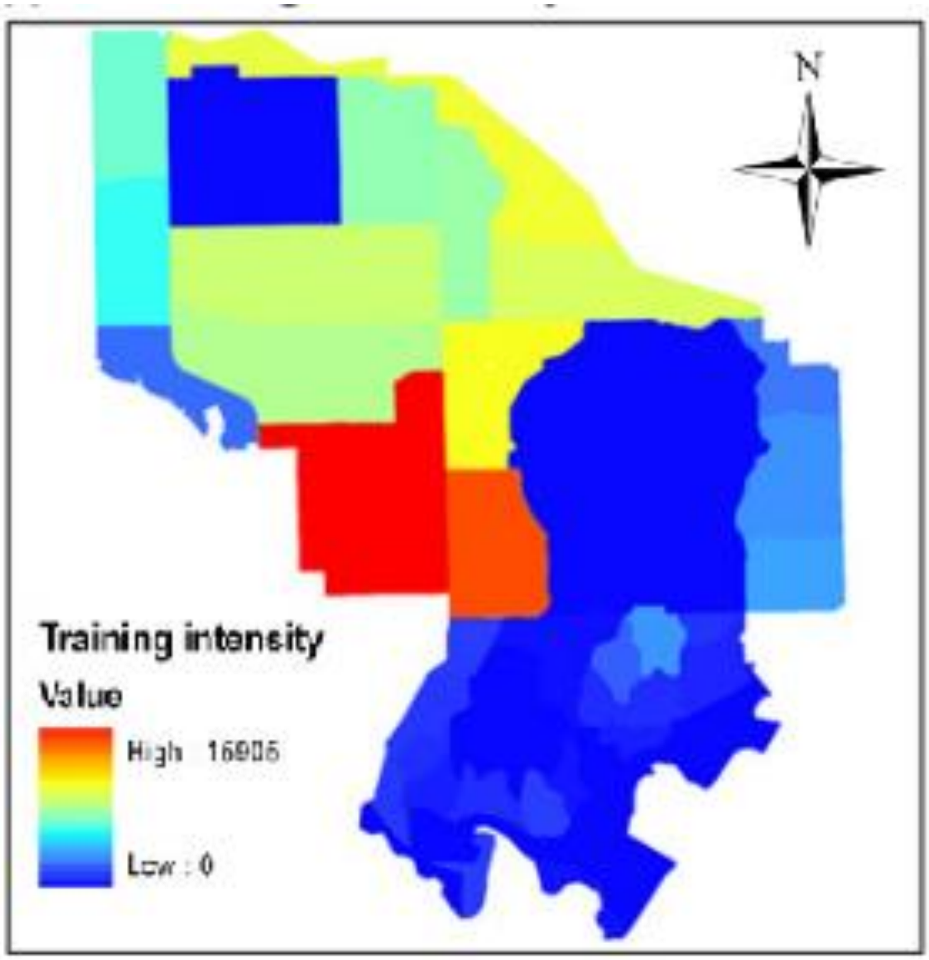
Figure 2.4 Fort Riley track curve located in training area 98 (Personal Photo, 2012)

Military Training

Because military personnel throughout the United States must be continually prepared for missions across the globe, certain levels of readiness training will always be required. Most specifically, trafficking – the term commonly used to encompass all levels of vehicle maneuvers on a certain plot – has been identified as a necessary component of military exercises and overall military readiness (Buck et al., 2011). As a result, various environmental properties are commonly compromised. In general, erosion caused by military training is closely linked to the overall ecological health of a plot and can dictate the zone’s ability to remain sustainable for future activity (Harmon & Doe, 2001). Reduction of vegetative cover and soil compaction are the two most commonly witnessed results of heavy military activity (Althoff et al., 2006; Milchunas et al., 1999). As mentioned before, once the vegetation surrounding a gully is compromised or the infiltration rate decreased due to soil compaction, gully progression will potentially progress into sever military safety issues.

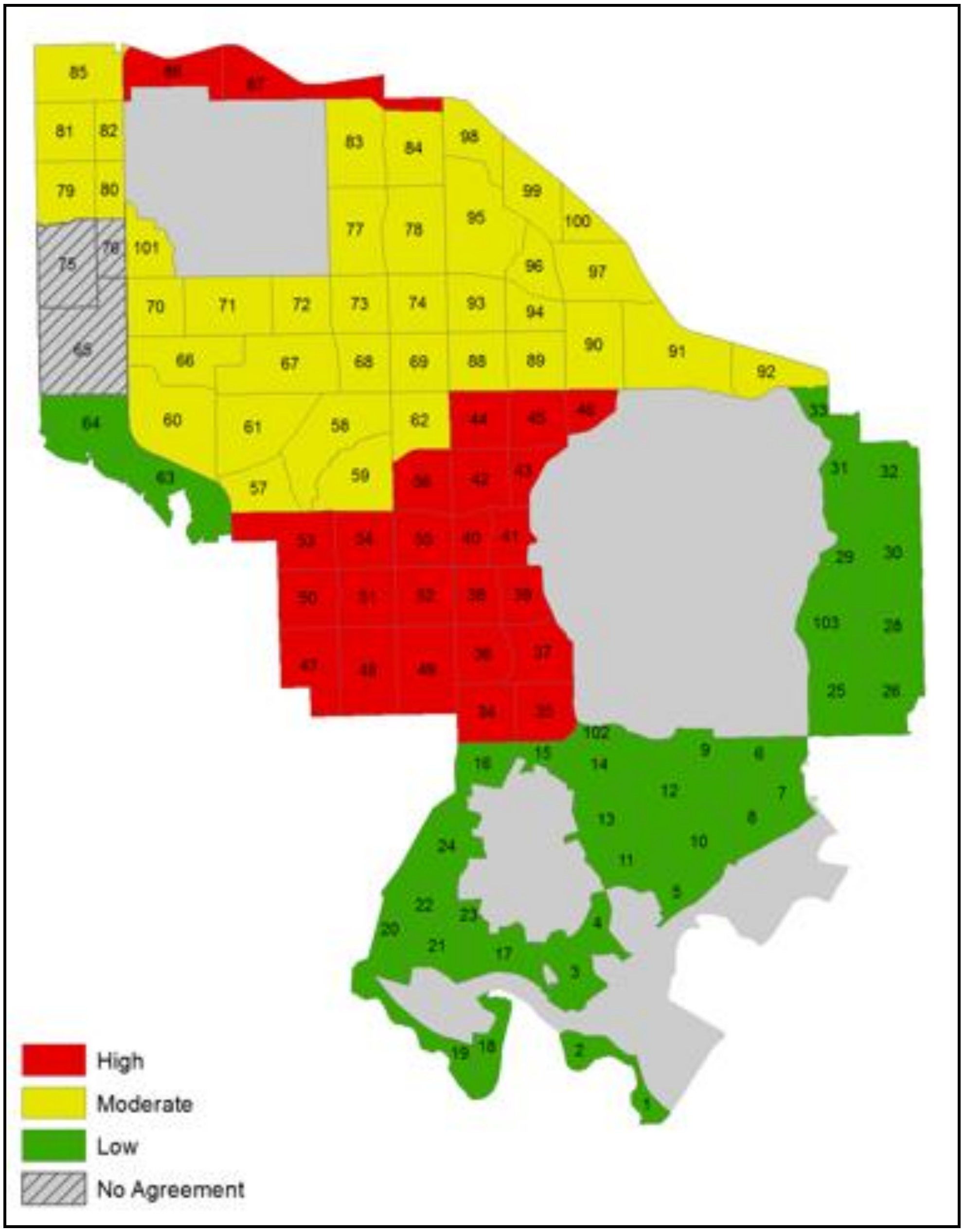
In order to better estimate the environmental change caused by military training intensity, total training days per year (TTD) were recorded regarding each training area. This measurement was calculated by combining all 24 hours periods in which a specific training area was scheduled for unit usage (Singer et al., 2012). If a training area was being used by various units, that zone would have more than one soldier training day for an explicit 24 hour timeframe (Singer et al., 2012). From this information, various maps have been created to illustrate the variation in military training intensity, such as Figure 2.5.

Figure 2.5 General zones of Training Intensity ranges at Fort Riley Military Base in Kansas (adapted from Johnson et al., 2011)



Due to occasionally inaccurate reporting of TTD and the effort needed to compile the yearly data, personal communications have been recently combined with previously established training intensity maps to produce more accurate representations. Figure 2.6 represents one of the most currently up-to-date estimates of training intensity at Fort Riley with personal communications from P. Denker and S Hutchinson.

Figure 2.6 Fort Riley Training Intensity Estimate (Denker (pers. comm.); Hutchinson (pers. comm.); Johnson et al., 2011)



However, the resolution of the exact training location using either of the above maps or techniques has left much to be desired as a single pass of a tank in one corner of the training area under these parameters would produce the same intensity as multiple passes with an entire brigade over the same 24 hours period using the TTD method.

In general, ground cover data – compiled by the LCTA and RTLA efforts – has seemed to decrease slightly with military training per year. This trend, however, might be somewhat time-delayed as the highest intensities do not represent the years with lowest ground cover percentage. For example, a significant decrease in ground cover may not be seen in the graph until a one to two year delay has occurred. This outcome is produced as the vegetation typically has a more difficult time with regrowth after intense disturbance. Nonetheless, general correlations between TTDs and ground cover can still be made.

While on-site erosion and water runoff is of utmost importance with respect to soldier safety and military equipment costs, the movement of sediment into locations further down the watershed or stream network is also of concern in military installation regions (Harmon & Doe, 2001). When coupled with the direct influences seen to the environment on many military bases across the United States, it becomes clear that erosion prevention through advanced research efforts is needed to negate the above mentioned issues.

Military Research

Prior to the year 2000, few conclusions could be made regarding military impacts on soil erosion, with the exception that the bigger and heavier the machinery vehicle used during training, the larger the ground level would be effected (Quist et al., 2003). Due to this low level of specific knowledge pertaining to military training and land use change, coupled with the strong initiatives to decrease degradation of the military lands, heavy amounts of research have since been conducted to better related activities on military installations to water runoff and soil erosion.

Soil Properties

While soil variance is extremely high and properties associated with one exact point can quickly change even with short distances, it is still important to understand what military and environmental conditions may lead to the most significant erosion changes. Therefore, tests monitoring changes in soil moisture, soil type, and varying vehicle maneuvers have been conducted and summarized here.

Soil strength measurements – taken in the first 15 cm of soil where the largest damage to soil is seen – help determine how well a certain soil can maintain trafficking (Buck et al., 2011). In general, as the terrain is subjected to trafficking, the soil strength increases due to amplified compaction, but begins to decrease once the plot of soil fails and decreases in compaction (Buck et al., 2011). When this level of failure is reached and the soil acts less as a compacted layer, it is likely that soil erosion will become more prominent. Some studies have utilized profilometers to measure the disturbance of the tracks with numerical values. Similar to instruments used in wind erosion studies, this devise contains rods with colored measuring increments along a flat, vertical plane. These rods are positioned vertically towards the ground cover and then released within the profilometers where gravitational force pulls each rod to the ground. Since the rods are loosely held in this vertical position by attached sections, the rods remain vertical and drop only as far as the soil has been disturbed. Measurements can then be taken from the single images to determine how far each section was disturbed numerically (Buck et al., 2011).

Utilizing these measuring methods, research has been conducted to examine multiple variables. In a study conducted by Anderson et al. (2006) at Fort Riley military installation, multiple conclusions were made regarding the weights of military vehicles and their cumulative soil impacts at this specific site.

First, the rate at which the military vehicles traveled had a minute effect on the soil impact width – the zone in which vegetative and soil disturbance was deemed important – with only a slight increase for heavier vehicles (Anderson et al., 2006). While this does not mean that heavier vehicles have the same soil impact as a lighter vehicle numerically, it does support that speed is not a significantly compounding variable with regards to soil impact. Also, the highest speed reached during each condition was dictated by the driver and therefore not constant throughout the entire study. For example, the operator would only reach as high a speed as was safe for the given soil conditions. In this study, this was a reasonable limitation, but may not always be implemented in training situations as soil conditions are not always a concern or focus of the training regimen.

Second, soil texture showed no substantial difference between the light and heavy vehicles (Anderson et al., 2006). Contradictory to previous claims, this data supports that soil texture is not a significantly important variable, at least when assessed on a military training base. A soil texture with larger amounts of clay, for example, compacted to the same level as any other soil tested which included loam, silt, and clay soils.

Third, soil moisture resulted in a significant variance with nearly an 80% greater (Table 2.2) cumulative impact on wet soil versus dry soil (Anderson et al., 2006). Of the conclusions made in this study conducted by Anderson et al., this one is possibly the most noteworthy for both military and research implications, suggesting that the deterioration of the training land may eventually reach a level that the negative effects from military training is not worth the benefits accrued by the activity. Additionally, this conclusion regarding soil moisture and compaction sparks researchers on soil water erosion to further explore the relationship between dry or wet conditions and gully erosion initiation.

Table 2.2 Gully erosion percentages and vegetation impact under dry versus wet conditions (adapted from Anderson et al., 2006)

Vehicle Type	% Increase from Dry Conditions	Vegetation Impact in Wet Conditions
M1A1	78.7%	20,298 m^2
APC	79.8%	5,688 m^2
HEMTT	75.8%	7,245 m^2
HMMWV	21.5%	2,188 m^2

M1A1 – M1A1 Abrams Tank; APC – Armored Personal Carrier; HEMTT – Heavy Expanded Mobility Tactical Truck; HMMWV – High Mobility Multipurpose Wheeled Vehicle

It is important to note, however, that the after effects of the passes completed in this specific Anderson research were not considered. The study focused on the immediate soil property effects during various conditions, but progression caused by storm events was not a factor. Future long-term studies will be needed to accurately track which conditions did produce large long-term levels of erosion and which showed initial problems, but never progressed into noteworthy problem zones.

Turning radius of any given vehicle is also an area of interest to many researchers at military bases. As might be expected, soil strength was measured to be less in locations were the vehicles applied a larger amount of shearing force, also known as the turning zones, compared to location where the ground was subjected to straight passes (Buck et al., 2011). The percent increase seemed to occur on an exponential basis, meaning that turning radius may be a more significant factor than many other variables regarding vehicle maneuvering.

Vegetative Cover

Measurements of vegetative disturbance are generally less technical as many results are interpreted visually. Some studies have created categories that visually place varying degrees of disturbance into groups (Anderson et al., 2006). For example, “Scrape” has been the term used to express that vegetation and soil were stripped from the study track while “Imprint” implies a site that simply witnessed soil and vegetative compression, but no removal of the actual ground cover (Anderson et al., 2006). Percentages have also been used to assess how detrimental the impact has been on the ground and vegetation. Once again, these categories seem to have been arbitrarily assigned and are read visually. Impact severity of roughly 20%, for example, is described as “some broken stalks/plants” that will not regain their rigid nature within a few days and will visibly remain a disturbed site for at least two months (Anderson et al., 2006). A 60% impact severity is classified by approximately two-thirds of the vegetation removed from the in-track site, coupled with exposed root systems of the remaining vegetation and large piling of displaced soil along the side edges of the vehicle track (Anderson et al., 2006).

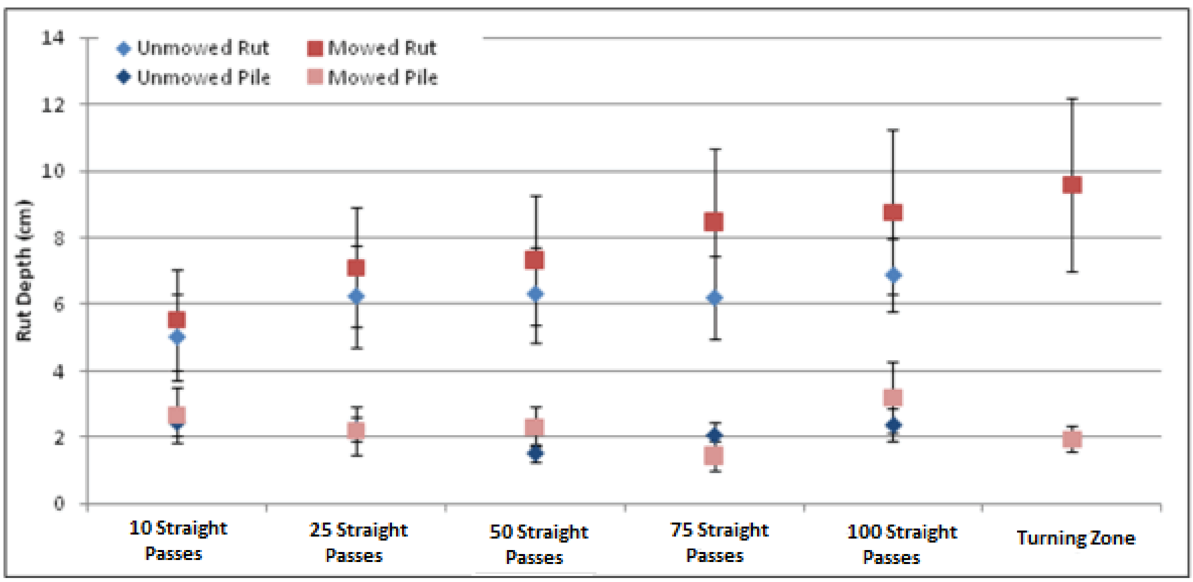
While these guidelines may leave ample room for error, Haugen et al.(2000) was the first group to define these standards which have been consistently used on military and agricultural lands for nearly fifteen years. Nonetheless, it is important to understand the level of error that may arise due to variables in the study – making replication of the site and conditions nearly impossible. For example, one researcher may look at a disturbed plot and categorize it as a 40% disturbance while another may label that section as 60%. Additionally, various field plants may react differently in varying regions or due to their characteristic structures. Claiming a certain number of passes will result in a certain level of impact severity, therefore, is extremely difficult and should be carried out with caution.

Vegetation cover can also dictate the soil strength of a certain area. For example, unmowed vegetation seemed to show a less steep increase in soil strength than terrain that had been mowed during a study conducted by Buck et al. (2011). With a lack of vegetation cover, the ground was left bare and more susceptible to compaction, therefore compromised the soil structure. A decrease in soil strength was recorded during the straight driving maneuvers on both covered and uncovered surfaces, which is in agreement with the idea of soil failure at a certain limit (Buck et al., 2011). Whether compressed with turning or straight maneuvers, a breaking point exists for soils that cannot be reversed regarding soil strength.

As with soil strength, shear strength initially increases with military activity, but decreases once a threshold of failure is reached. In mowed plots, only 25-50 passes were needed to reach the failure point (Buck et al., 2011). Before this limitation, the shear strength increased rapidly (Buck et al., 2011) and therefore supports the idea that shear stress, with its parallel movement, may have a greater level of influence on soil alteration than compaction which acts in the normal direction.

Certain environmental variables have often been isolated within studies to determine which military maneuver factors realistically affect terrain disturbance. Straight military trafficking, for example, has been recorded creating compaction rates averaging 9 cm per 100 passes with rut build-up on the exterior of the track of nearly 3 cm per 100 passes (Buck et al., 2011). During turning maneuvers, the compaction rate was even higher (Buck et al., 2011). In both instances, it was recorded that the compaction depths increased significantly during the initial 25 passes and more steadily after (Buck et al., 2011). This same trend has been seen on unmowed versus mowed plots regardless of the vegetative cover level (Figure 2.7). This idea implies that in all reality, the true significance of terrain disturbance may not lie in the total number of passes, but rather be found within the first 25 passes. After this initial disturbance, the rate of environmental compromise may ultimately plateau and reach a certain point where the region has been completely disturbed.

Figure 2.7 Unmowed versus mowed vegetative crops and their respective rut and pile alterations (Buck et al., 2011)



Research Objectives

Many studies have been conducted to better understand the processes by which gullies progress over time (Ionita, 2006; Sidorchuk, 2006; Hancock & Evans, 2010; De Baets & Poesen, 2010). The majority of this literature has focused on identifying the factors most likely to affect gully erosion (Kirkby & Bull, 2000; Valentin et al., 2005; Vanwallegham et al., 2005; Zhang et al., 2007; De Baets et al., 2011; Neary, 2012; Burylo, 2012) but few are able to place an accurate numerical weight on each of the predetermined factors. Additionally, limited data has been published specifically relating gully progression to military maneuvers at Fort Riley military base in Kansas. Therefore, the first goal of this study is to thoroughly assess gully formation with regards to significant controlling factors including common watershed characteristics and land management variables. The second goal is to develop an equation utilizing these factors to accurately predict future gully headcut growth at Fort Riley.

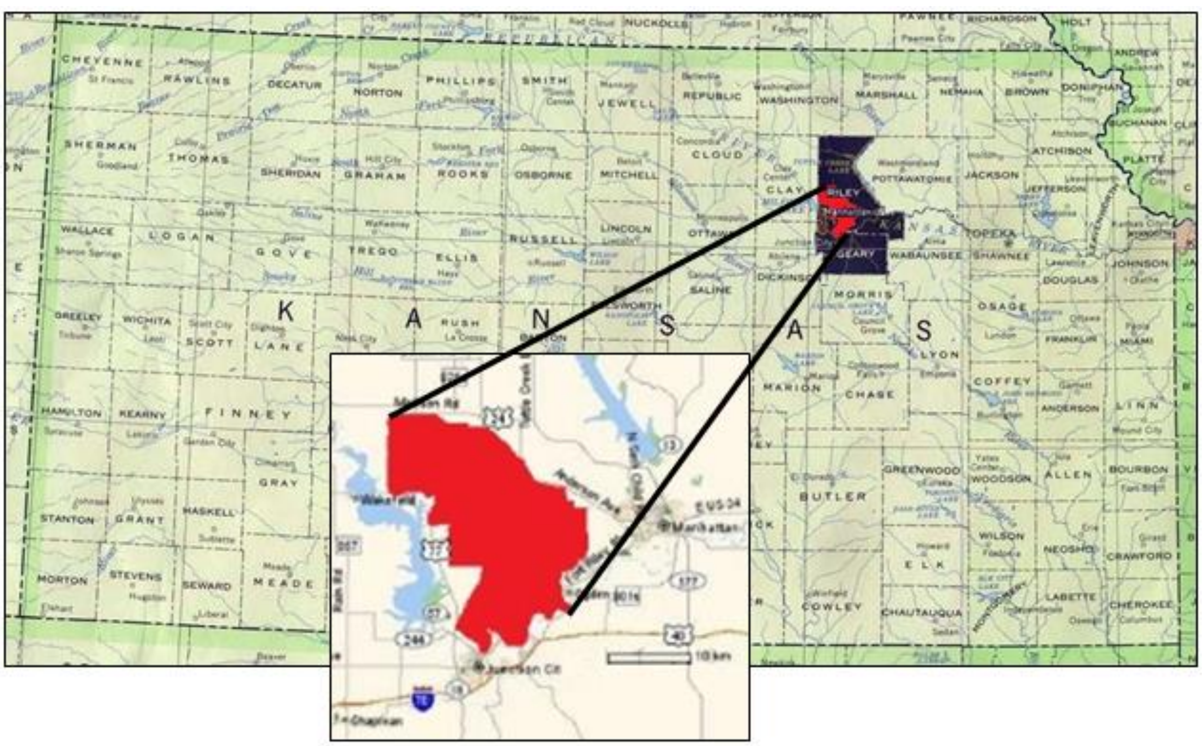
Chapter 3 - Methods and Materials

Description of site

Location and Topography

Located in Northeast Kansas, Fort Riley is a United States Army installation of approximately 41,154 hectares residing in Geary and Riley counties (Anderson et al., 2006) (Figure 3.1). Each day, approximately 25,000 people are present on base during daytime hours, making Fort Riley one of the larger army bases in the United States (US Military, 2008). Additionally, the base is located only 2 km North of Junction City – population of over 20,000 – and 10 km West of Manhattan – populations of 52,000 (City-Data: Manhattan, 2013; City-Data: Junction City, 2013).

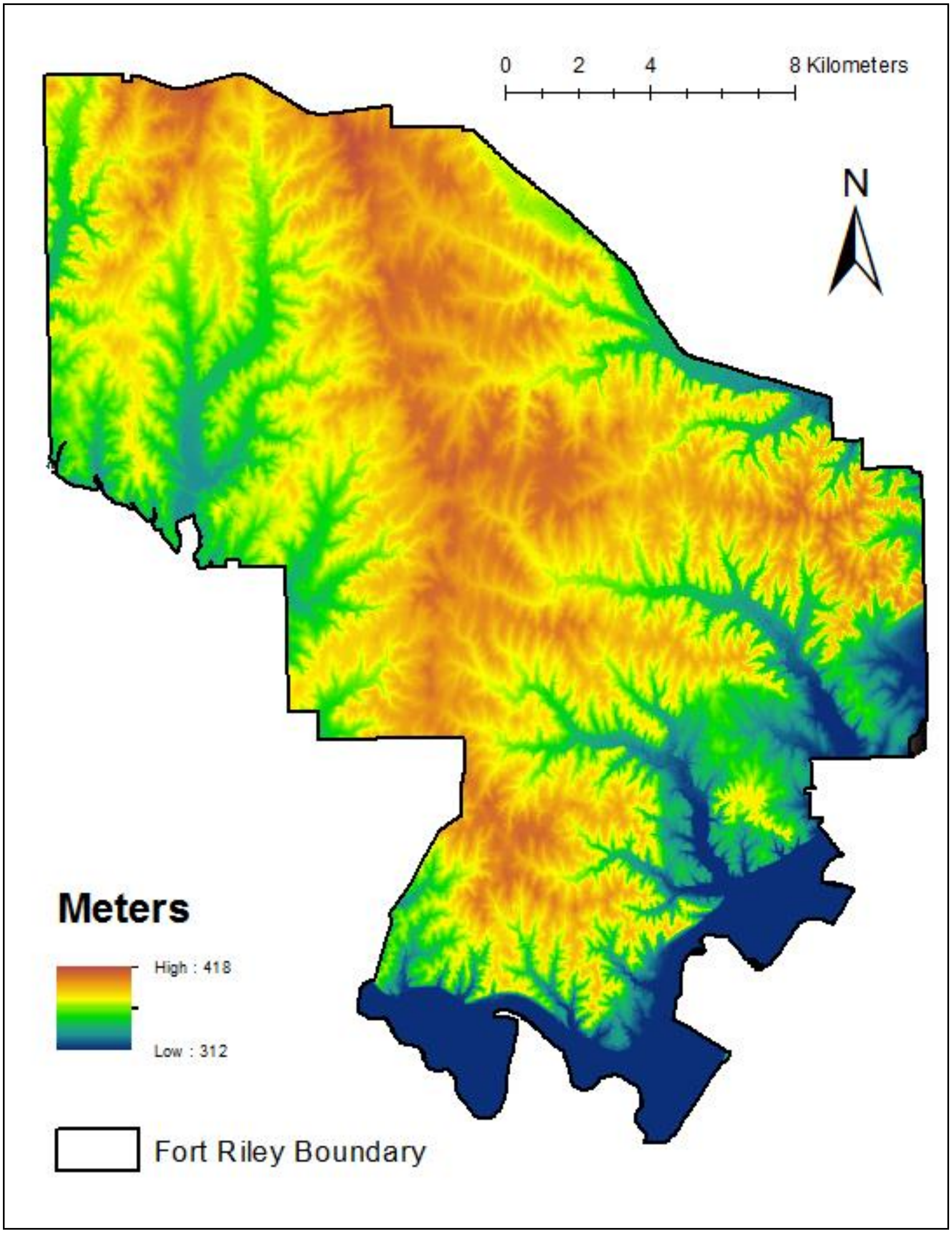
Figure 3.1 Location of Fort Riley and surrounding areas (Data Sources: The University of Texas at Austin, 2013 and Google Maps, 2013)



Fort Riley is positioned in the Tall Grass Prairie biotic zone and is classified under the Bluestem Prairie grouping (Bailey, 1976). This province is defined by its heavy population of grasses (80%), as well as it characteristic rolling plains transected by stream valleys (Althoff et al., 2005; Anderson et al., 2006). Additionally, Fort Riley is entirely encompassed in the Flint Hills Ecoregion, which contains approximately 1.6 million hectares of undisturbed tall-grass prairie (Bailey, 1995). This ecoregion spans a roughly 60 km wide strip of land from the northern edge of Kansas and into the state of Oklahoma, making it a significant zone within the borders of Kansas (Bailey, 1995).

The elevation of the base ranges from 312 to 420 meters above mean sea level (Data Source: Fort Riley Integrated Training Area Management Program, 2007). The highest elevation is located along an axis running north-south through the middle of the installation. Elevation generally decreases further south on this axis and outwards in both east and west directions with the southern border being of lowest general elevation with Milford Lake reservoir borders the installation to the west (U.S. Environmental Protection Agency, 2010).

Figure 3.2 Elevation map of Fort Riley based on a 3 meter spatial resolution digital elevation model (Data Source: Fort Riley Integrated Training Area Management Program 2007)

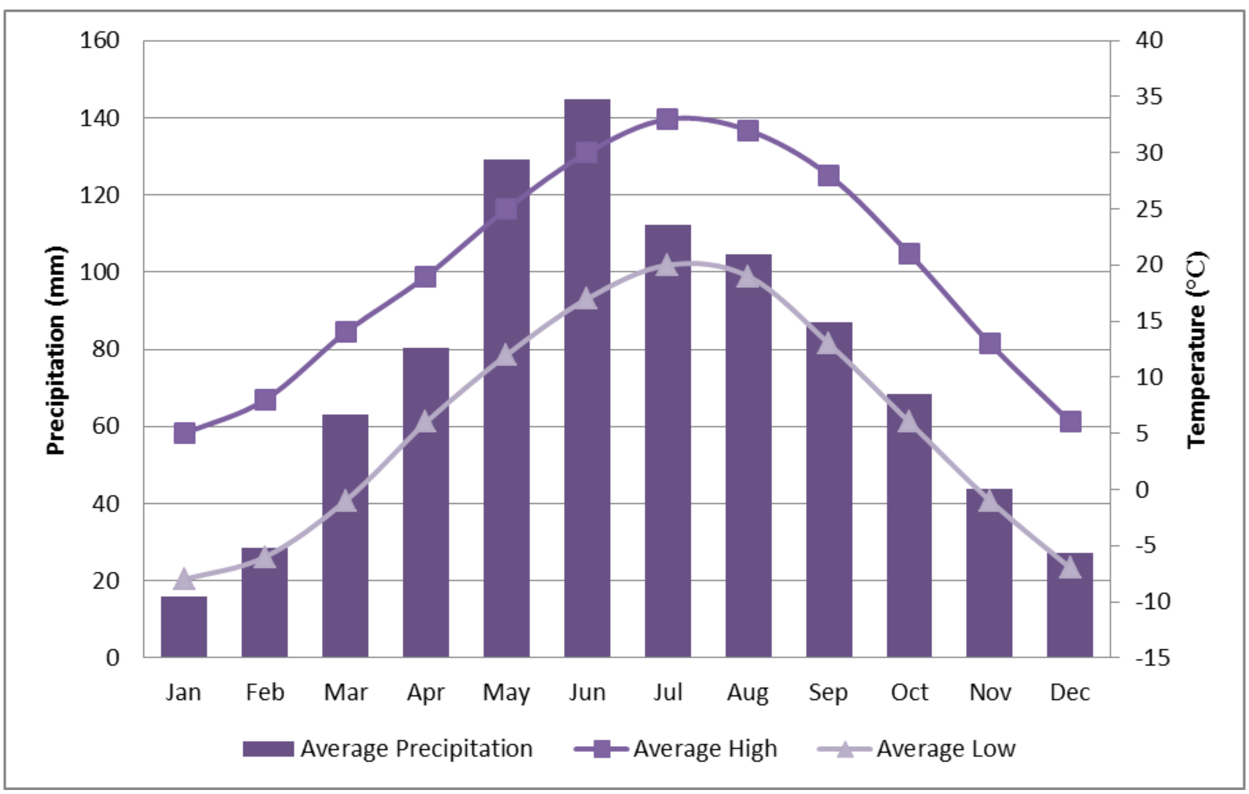


After the completion of World War II, Fort Riley became a base mostly used for military training (Singer et al., 2012). Expansions of land occurred in 1940 (roughly 13,000 hectares) and in 1966 with over 20,000 additional hectares reserved for training and education (Singer et al., 2012). Training occurs on approximately 70% of the installation, leaving 30% for various uses such as maintenance, houses, and offices (Singer et al., 2012).

Climate and Soil

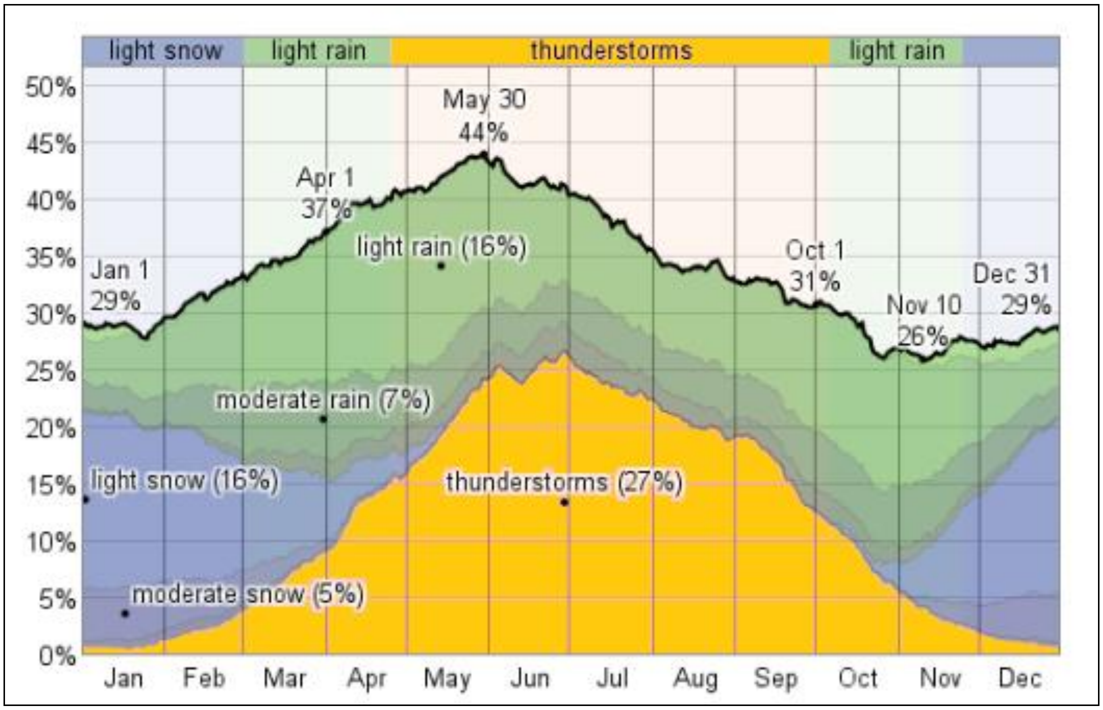
Being located in the Midwest region of the United States, Fort Riley experiences continental climate with large variations between seasonal temperature averages (Goodin et al., 1995). Within an average year, the warm season will occur from the beginning of June to early-September with peak temperatures near the end of July. The cold season, on the other hand, lasts roughly from the end of November to the very beginning of March with the coldest of days appearing early to mid-January (Goodin et al., 1995).

Figure 3.3 Climograph for Manhattan, Kansas based on monthly average temperature and precipitation data for the period of 1971-2000 (adapted from National Climatic Data Center, 2012)



Precipitation in the region varies as considerably as temperature with a daily likelihood between 25-45% depending on the time of year (NOAA, 2012). Spring and early summer months (April-June) experience the highest precipitation in the form of light rain in April with a transition towards thunderstorms into the summer months (NOAA,2012; Goodin et al., 1995). Throughout the entire year, 35% of precipitation is seen as thunderstorms with light rain, light snow, and moderate rain following with 28%, 14%, and 13% respectively (NOAA, 2012). Thunderstorms can range in intensity, but are generally defined in this region as rainfall rates of roughly 60 mm/hr (NOAA, 2012).

Figure 3.4 Probability of precipitation at some point in the day for Manhattan, Kansas (adapted from NOAA, 2012)



Soil properties within the region vary greatly from well drained sandy soils to significantly less permeable clays. At Fort Riley, however, the nearly half of the base is considered moderately well drained while the rest is primarily classified as well drained (SSURGO, 2012). The hydrologic groups found on the installation are comprised of a large majority of Class C and Class D (SSURGO, 2012). These groups represent a very high runoff potential, thus a high erosion potential. Particle size within the area falls almost entirely into the fine range (<2mm) with some regions being significantly smaller and grouped into a fine-silty classification (0.002 - 0.006 mm) (SSURGO, 2012). Average depth to bed rock varies greatly but tends to be between 0 and 11 meters for the higher elevation ranges (SSURGO, 2012). As the elevation decreases towards the Eastern edge, depths are highly variable and can be well over 100 meters in depth (SSURGO, 2012). Generally, limestone or shale comprise the bedrock in this region meaning that physically, the bedrock on base is quite impervious and compact (SSURGO, 2012).

Vegetative Cover

Generally speaking, Fort Riley is primarily covered by a mix of natural tallgrass, CRP (Conservation Reserve Program) grass, and a compilation of various trees such as cottonwood and oak (Delisle, 2012). Most of the urban areas are located in the southern part of the base, meaning that alterations due to increased nonporous cover are mostly only witnessed in the bottom third of Fort Riley.

Numerically, Fort Riley has been estimated to have or contain roughly 80% grass and 19% shrubs and wood lands (Althoff et al., 2005; Anderson et al. 2006). Most of these shrubs and heavily wooded areas, however, are concentrated in stream valleys throughout the base, leaving the rest of the installation to be covered with prairie grass. The most predominate species in the grassland regions are switchgrass (*Panicum virgatum*), little bluestem (*Schizachyrium scoparium*), big bluestem (*Andropogon gerardii*), and Indiangrass (*Sorghastrum nutans*) as various other plants inhabit a smaller portion of land (Delisle, 2012). Wooded areas are comprised of mostly black walnut (*Juglans nigra*), hackberry (*Celtis occidnetalis*), chinquapin oak (*Quercus muhlenbergii*), bur oak (*Q. macrocarpa*) and American elm (*Ulmus americana*) (Althoff et al., 2006). Nearly 79% of the prairie at Fort Riley is considered A-grade or B-grade, representing an increase of roughly 45% since a 2002/2003 study (Delisle, 2012). Five invasive weed species have been documented at Fort Riley, with four of the five (musk thistle, field bindweed, sericea lespedeza, and Johnsongrass) being found widely across the entire base (Delisle, 2012; US Army, 2010).

Previous Gully Installation

As a reassessment study focusing on the growth of previously acknowledged erosion locations at Fort Riley, gully identification was done using monumented gully sites from master's research conducted by Katie Handley in the summer of 2010 (Handley, 2010). Originally, these gullies were found by LiDAR (Light Detection and Ranging) imagery in March 2007, Fort Riley personnel, or field reconnaissance. While over 375 locations were identified as potential gullies, only 47 were thoroughly assessed during summer 2010. Therefore, these 47 locations became the initial set of gully sites for this study.

During the initial gully installation, two survey pins were placed at the visible headcut. These pins were arranged so that a straight line would transverse both pins in addition to the furthest edge of the gully head. This method allowed for future measurements that could monitor the growth in head location based on how far active erosion had occurred past this previous established line. During installation, important consideration had to be used regarding the perpendicular distance from the gully site to ensure that the pins would not be eroded out as the gully progressed both upwards and with regards to width, therefore the closest pin at all locations was then placed approximately one meter from the edge of the gully. The second pin was one meter away from the first reference pin unless bedrock prevented instillation. Once these locations were identified, half-inch rebar rods were driven into the soil and topped with orange or yellow plastic survey caps.

Additionally, the widest and deepest locations within the first section of active gully were identified using a plastic measuring tape. These spots were again monumented using rebar and survey caps for easy identification at later dates and installed perpendicular to water flow. As before, the pins needed to be placed far enough away from foreseeable erosion to prevent being washed out.

Lastly, a GPS point using a Trimble GeoXT 2005 Series Pocket PC was taken in the general area of each gully site and combined into a single shapefile. This document could then be used at a later time to aid in the location of each gully. For a majority of the gullies, GPS points were also taken at each rebar pin representing the widest and deepest points for easy identification. In a few cases, the widest and deepest points were at the same location in the gully and were therefore noted with only one survey pin and as a single point in the shapefile.

Gully Assessment

Each of the 47 previously installed gullies was reassessed during summer 2012 to monitor the change in headcut, width, and depth. As with the originally recorded data and study in 2010, gullies were defined as erosion channels that were at least one meter in width. This distance was deemed the appropriate span in 2010 because vehicles such as the M113 are not able to traverse a gap larger than 1.6 meters (Department of the Army, 1985) and approximately 80-85% of the military vehicles used at Fort Riley cannot traverse a break in the ground that is any wider than 1 meter (Hutchinson & Hutchinson, 2010). More generally, the term “military gap” was used in this study as this is the phrase used by the Army to define any channels that are too wide for military vehicles to independently bridge (Department of the Army, 1985). The exact depth of the gully was not defined numerically, but has been classified as the depth at which the gully cannot be overturned by normal tillage practices (Soil Science Glossary Terms Committee, 2008). It was also assumed that a gully with a width larger than one meter would not have a significant depth that would create difficulties for many military vehicles.

In order to produce the most accurate and applicable results within this study, gullies were additionally defined as linear erosive features. This linear definition was combined with the general military hazard definition used to identify gullies in Handley (2010) in order to better predict the progression of gully migration opposed to locating military gaps.

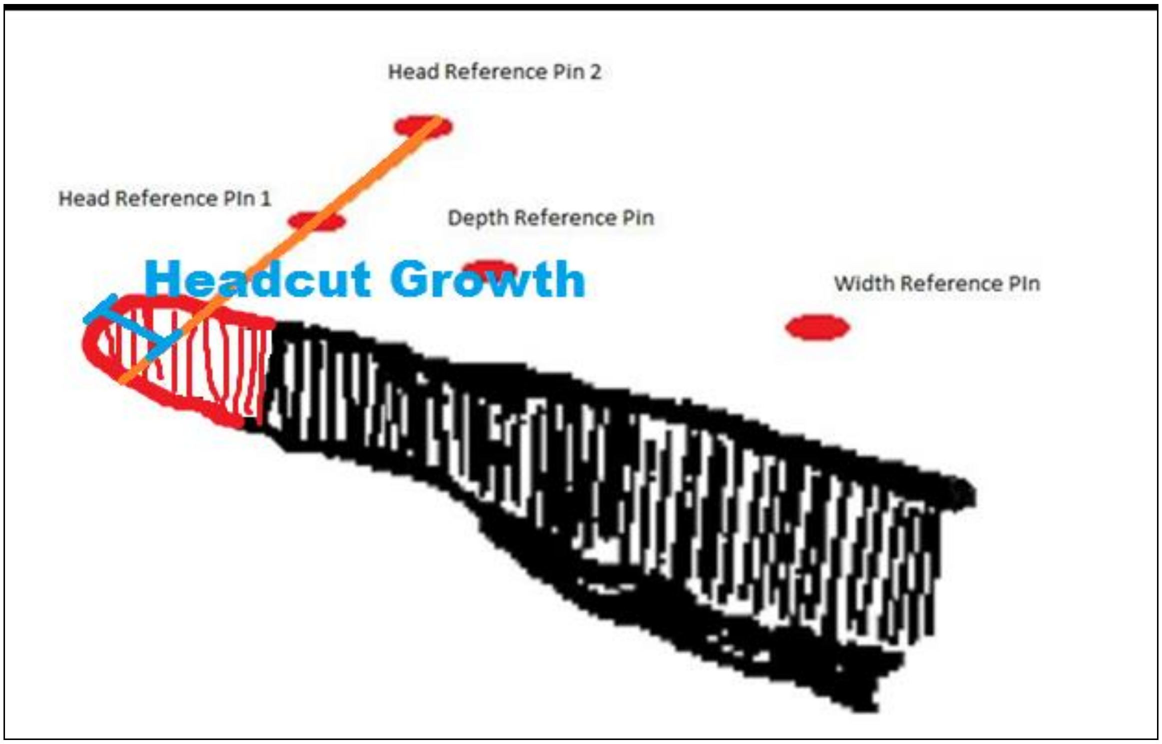
This additional definition was utilized to decrease any errors that could be created in this set or further sets of gully measurements at Fort Riley and to ideally more similarly cluster the qualifying gullies. Had gullies been included that required inconsistent or unreliable measurement techniques compared to the others in this data, the results may have been inaccurate and not reflected potential common trends. Had gullies been included that did not exhibit the linearity established in this study, the results may have been invalidated and proper assessment would have been skewed. Ultimately, these problems regarding specific gully characteristics and predetermined measurement techniques again emphasis the need for more consistent methodology with regards to gully and erosion growth.

Given this linear feature definition, some of the 59 gullies were in fact wide enough to be considered military gaps and therefore not traversable by many military vehicles, but not deemed appropriate for inclusion in this dataset. Under the umbrella of this linear erosive feature definition, various criteria were outlined prior to and during fieldwork that eliminated certain erosion networks. The most common criteria are analyzed below, but should act as a guide for future studies and not all inclusive regarding what might be defined as linear erosive features.

Headcut

Headcut migration was measured using a rigid surveying rod as a straightedge intersecting both erosion pins (Figure 3.6). A plastic measuring tape was used to determine the distance from the initially installed headcut pins. If no noticeable change had occurred, the measurement was recorded as zero. If any migration had happened since the original installation, the distance was recorded in tenths of meters. In some cases, the vegetative cover had regressed from the original headcut line, but the soil dropoff remained in the same location. This result was recorded as zero since gully dimensions were not based on vegetation presence. On gullies where the soil downward cut had migrated, measurements were always taken to the furthest edge of the soil – not the vegetative cover. Again, this was deducted as the most accurate way to measure the change as vegetation is a variable of gully erosion and not the defining characteristics of a gully's existence.

Figure 3.5 Methodology for remeasurement of headcut growth (adapted from Cleveland and Soleri, 1991)



Width and Depth

In order to maintain consistency regarding width and depth change measurements, remeasuring of width and depth was conducted at the same reference pins installed in 2010 even if it appeared another section of the gully had exceeded the original measurement to a greater amount. This allowed for consistent measurement instead of introducing potential error by moving the width and depth locations.

Additionally, side bank definition was not consistent on all gullies. For example, some gullies had one bank that had been formed by drastic cutting into the soil with what most would consider a typical gully bank. The other bank (Right bank in Figure 3.7) would not have these same attributes, however. Some banks would gradually slope into the above floodplain without revealing any clear downcut. This gradual increase starting at the gully bottom created issues regarding where to place the second width measurement and at what height to place the rod when measuring depth. In order to ensure accurate measurement between each gully, the smallest angle, or most prominent change in slope, was considered the measurement point (left bank on

Figure 3.7). The rigid rod was then placed at a perpendicular distance to the gully bottom as well as perpendicular to water flow and laid across the gully as seen in Figure 3.7. Also seen in Figure 3.7 is that the right bank does indeed have a shallower slope and no well-defined bank downcut. By using this defined methodology, consistent research can be completed, which has not been common thus far in gully research.

Figure 3.6 Rigid rod placement for gully network width and depth (Personal Photo, 2012)

Once the rigid rod was placed correctly (Figure 3.8), measurements were taken for width and depth. Width was measured using a plastic tape strung from the widest reference pin to the nearest bank indicated by the short side of the rigid rod. The plastic tape was then strung from the widest reference pin to the furthest bank indicated by the opposite end of the rigid rod. In the field, these two measurements were recorded on a field sheet as well as on the Archer Ultra

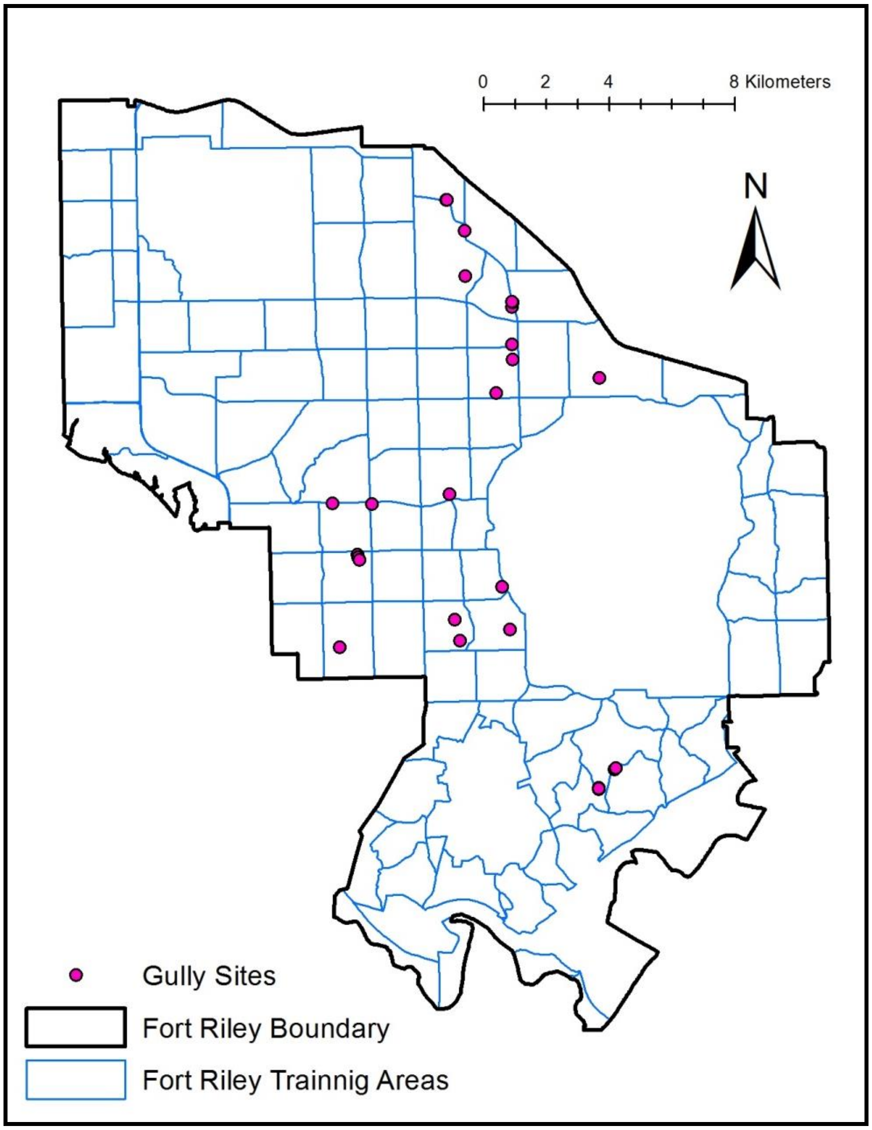
Rugged PDA (Juniper Systems) under the gully shapefile. Since each gully was associated with a GPS point taken at the nearest headcut reference pin, the two width measurements could be recorded for easy access and future identification. Once the data could be altered on a desktop computer, the shorter length was subtracted from the longer length to produce the overall gully width. This width value was finally subtracted from the width measurement taken in 2010 to determine the change in width for that respective gully.

Depth was remeasured using the same rigid rod, only now placed perpendicularly to flow between the two banks of the gully at the reference pin indicating greatest depth. Since the surveying rod was secured with each short edge securely laid on the top on the bank, measurements were taken from the bottom edge on the rod nearest the bed of the gully. A plastic measuring tape was then strung perpendicularly from the bottom of the rod to the deepest point in the gully along the rod. A handheld bubble level was used to ensure the procedure was plumb. This measurement was again recorded on field paper and the Archer under the respective GPS reference headcut pin in the shapefile and then subtracted from the depth measurement taken in 2010. Given this method of analysis, a negative output represented gully aggradation or sediment deposit in the gully bed. A positive output was therefore correlated with degradation or removal of soil in the gully bed to correlate with other positive outputs and removal of sediment.

Figure 3.7 Remeasurement technique of width and depth in gully system (Personal Photo, 2012)

At least two pictures were taken at each gully to compare with the previous photographs of the erosion sites. The first was above the headcut approximately one to two meters looking down the gully length. This allowed for the general properties of the gully such as sinuosity and width progression downstream to be captured. The second was below the headcut roughly three meters from the head looking toward the gully headcut bank. This distance provided details regarding the depth at headcut, any step pools in the gully, and any slough from the sidewalls of the gully. As with the previous study concerning these gullies at Fort Riley, additional pictures were taken if the gully length was more than five meters or if significant erosion features – such as undercutting or additional headcuts – had developed. These photographs were taken using a 5-megapixal iSight External Camera (Apple Inc.) that recorded the date, time, and spatial coordinates of the picture.

Figure 3.8 Twenty-one gullies locations remeasured and recorded for 2012 study at Fort Riley Military Installation



Seven new gullies were identified and monumented in summer 2012. However, only initial data measurements were recored, so the locations of the gullies were not included in the GIS layer development or in the statistical analysis. For exact details pertaining to the methodology of primary installation of these survey pins, see Appendix A.

Spatial Data Development

Gully Location

In order to create a GIS gully shapefile that could be utilized in data and statistical analysis, the GPS points taken directly over the top of the first headcut reference pin were uploaded onto a desktop GIS system as a point shapefile. This point shapefile was then the base for extracting the respective values associated with each gully site and for developing the watersheds associated with each point. The photographs taken of each gully system were also uploaded and stored in a file outside of GIS for future use and integration into interactive maps of Fort Riley. Each photograph contains an inbedded GPS coordinate so that the pictures can later be associated with their respective gully.

Topographic

Gully analysis was conducted using 10 of the most commonly accepted erosion factors considered in this study. These predictor variables include Watershed Characteristics (Watershed Slope, Watershed Area, Flow Accumulation, Drainage Density, Aspect, Clay Percentage) and Land Management Techniques (Training Intensity, Burning Frequency, Burning Seasonality, Change in Biomass).

A 3-m DEM derived from the 2007 LIDAR data was used to develop many of the above mentioned predictor variables. For each of these variables, the Fill function (commonly used to remove sinks in a surface and reduce small imperfections) was not utilized with the DEM to avoid reducing or smoothing the accurate representation of the realistic waterflow.

Initially, two layers were derived from the unfilled three meter DEM – flow direction and flow accumulation, with flow direction producing a summary of the direction in which each water droplet would flow and flow accumulation summarizing the number of pixels flowing into each pixel. These outputs were later used to delineate the watersheds associated with each gully GPS location.

Watershed Slope and Watershed Area

Watershed slope over the contributing area has been supported as a variable likely in influencing the rate of erosion over a landscape (Zhang et al., 2007). As the elevation change between the highest ridge point and the respective pour point increases, the velocity of the concentrated water should also increase. The slope of the contributing watershed will therefore be used to determine if a larger slope produces or is required to accumulate enough energy to create gully erosion.

Similarly, watershed area determines the amount of water potentially flowing into the gully network. As the contributing area increases, a larger amount of runoff should flow into the gully and produce the required energy amount to remove sediment from the accumulation location at the bottom of the watershed.

Both of these variables were numerically produced using geospatial analysis, with exact methods listed in Appendix B. The data collected was copied from the corresponding attribute table and added to the comprehensive variable table.

Flow Accumulation

One of the most highly studied variables likely effecting soil erosion is flow accumulation, or the total concentration of the water flow over a selected area. This variable has thus far been shown to directly relate to gully erosion with soil displacement increasing with an increase in flow accumulation.

This variable was again numerically produced using geospatial analysis, with exact methods listed in Appendix B. The data collected was copied from the corresponding attribute table and added to the comprehensive variable table.

Drainage Density

Drainage density, defined as the total length of all the streams in the desired area divided by the total area in the drainage basin was calculated using previously mentioned methods. The previously mentioned watershed area and flow length extracted within each watershed were placed in a spreadsheet file where the total stream lengths were divided by the total area for each watershed, respectively.

Clay Percentage

In order to determine the clay percentage representative at each gully location, Soil Survey Database (SSURGO) data and corresponding visual layers were downloaded from the Soil Survey Staff, NRCS (2012) for Riley and Geary Counties. Once this data was collected, the soil layers from Riley and Geary Counties were uploaded and analyzed using proper geospatial techniques. This extracted data was then copied from the corresponding attribute table and added to the comprehensive variable table with specific methodology relating to this study listed in Appendix B.

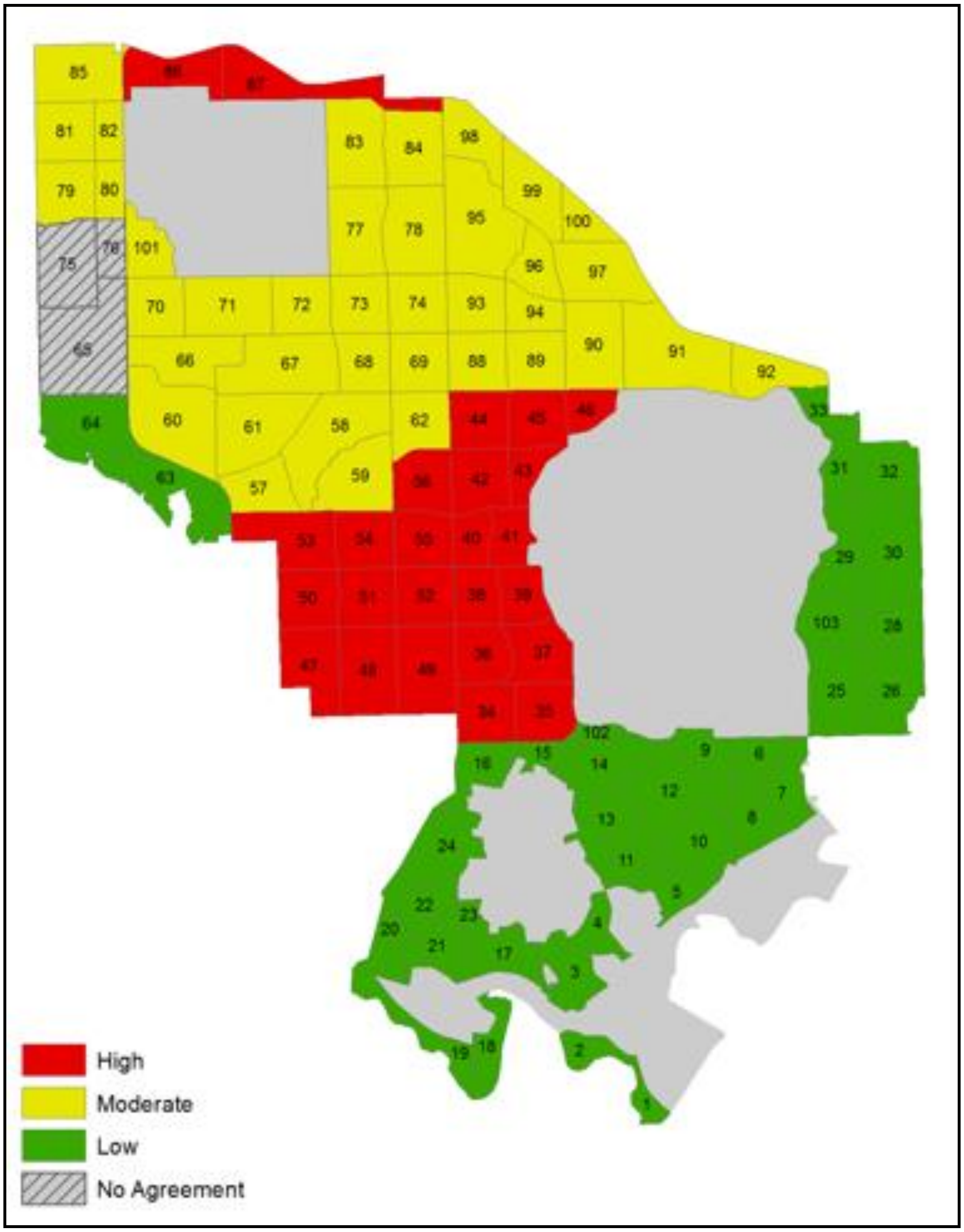
Aspect

Aspect identifies the downhill direction each cell faces with regards to the maximum rate of change to its neighbors. This variable is represented in degrees ranging from 0-360 with North correlating with the highest and lowest possible values. Using the above mentioned DEM, this variable was produced and the average value over the entire watershed was extracted with respect to each gully network. This data was then copied from the corresponding attribute table and added to the comprehensive variable table.

Training Intensity

Derivation of the military's modus of landuse change was based upon the visual map of Fort Riley from Johnson et al., 2010 and personal communications with Phillip Denker and Dr. Shawn Hutchinson. Since the map (Figure 3.13) contained identification of the training areas at Fort Riley, the training area in which each gully was found was simply compared with the representative training intensity. This data was then added to the comprehensive variable table.

Figure 3.9 Fort Riley Training Intensity Estimate (Denker (pers. comm.); Hutchinson (pers. comm.); Johnson et al., 2011)



Burning Frequency and Burning Seasonality

Over the past 10 years, burning throughout Fort Riley was recorded with regards to both frequency and seasonality. Each time a fire was initiated across the region, the frequency would increase and the seasonality considered with seasonality ultimately represented into one of the following categories: Never Burned, Fall/Winter Only, Mostly Fall/Winter, No Dominant Season, Mostly Spring, and Spring Only.

This data was then correlated with each watershed being considered in this study. If the watershed contained one of more burning frequency or burning seasonality, the value occurring most often was considered. This data was then added to the comprehensive variable table.

Change in Above Ground Biomass

In order to provide a numerical proxy representing vegetative cover throughout the watershed, above ground biomass was calculated. Using data collected during the 2010-2012 summers, average biomass found above the soil was determined for each watershed. The values correlating with the 2010 summer was then subtracted from the 2012 summer to produce the change seen in above ground biomass from the beginning to end of this study. This data was then added to the comprehensive variable table.

Chapter 4 - Results

Initial Data Assessment

In the summer of 2012, 43 previously monitored gullies installed with reference survey pins were revisited. Using the above mentioned methods, 16 additional gullies were visited and noted for future data collection with 7 of these gullies pinned for future study. Of the total 59 gullies visited, 38 did not meet the defined criteria required for this study. All gullies measurements are summarized in Appendix C with Table 4.1 below representing the corresponding 2012 activity.

Table 4.1 Summary table of gullies visited and accessed during summer 2012 at Fort Riley, KS

GN	TA	Widest 2010 (m)	Deepest 2010 (m)	Notes	2012 Action
0	95	8.46	1.57	Maneuver area closed during data collection period	No data collected
1	95	8.92	2.18	Gully network had been fixed using rock placement since initial reference point installation	No data collected
2	95	10.72	2.31	Gully network had been fixed using rock placement since initial reference point installation	No data collected
3	95	9.75	1.83	Gully network had been fixed using rock placement since initial reference point installation	No data collected
4	95	3.38	0.91	Maneuver area closed during data collection period	No data collected
5	98	2.36	0.91	Included	Data collected
6	98	2.46	1.22	Included	Data collected
7	95	10.41	2.44	Gully network had been fixed using rock placement since	No data collected

				initial reference point installation	
8	95	8.53	1.35	Gully network had been fixed using rock placement since initial reference point installation	No data collected
9	95	10.57	1.52	Gully network had been fixed using rock placement since initial reference point installation	No data collected
10	95	10.03	2.26	Gully network had been fixed using rock placement since initial reference point installation	No data collected
11	95	unpinned	unpinned	No distinct flow direction or headcut growth prominent	No reference pins installed
12	95	3.91	1.32	Only one reference headcut pin ever found. No width or depth pins located	No data collected
13	51	2.95	0.99	Included	Data collected
14	51	2.72	1.35	Included	Data collected
15	51	1.83	0.86	Included	Data collected
16	55	6.05	1.37	Included	Data collected
17	89	3.28	1.74	Included	Data collected
18	96	5.56	1.7	Included	Data collected
19	89	2.84	1.31	Included	Data collected
20	89	1.22	1.02	No GPS points or rebar pins ever located for widest and deepest measurements	No data collected
21	96	4.7	1.82	Included	Data collected
22	96	3.73	0.67	Included	Data collected
23	42	3.66	0.79	Included	Data collected
24	37	4.75	1.04	Included	Data collected
25	36	5.97	1.68	GPS points never located. 2012 width measurements were inconsistent with 2010 measurements. Large level of uncertainty in accuracy without GPS locations. Not	No accurately located data collected

				included in study	
26	49	4.22	1.27	Included	Data collected
27	77	3.1	1.31	Maneuver area closed during data collection period	No data collected
28	77	2.39	1.22	Maneuver area closed during data collection period	No data collected
29	77	3.38	1.02	Maneuver area closed during data collection period	No data collected
30	78	3.91	0.86	Maneuver area closed during data collection period	No data collected
31	41	unpinned	unpinned	Previously installed pins located in field, but no numerical values ever recovered	No data collected
32	61	3.02	0.91	Maneuver area closed during data collection period	No data collected
33	48	2.08	1.07	Included	Data collected
34	91	1.8	0.81	Included	Data collected
35	12	3.33	0.62	Included	Data collected
36	12	5.56	1.17	Inconsistent width and depth data recorded. Significant error imbedded in data collection process	2010 data could not be utilized. No data collected in 2012
37	12	8.69	0.72	Included	Data collected
38	11	3.43	0.81	Included	Data collected
39A	12	5.01	1.41	Included	Data collected
39B	12	3.61	0.81	Included	Data collected
41	78	unpinned	unpinned	No distinct headcut. Extremely long gully with rotating plunge pools and plateaus	No reference pins installed
42	78	unpinned	unpinned	Not included	Reference pins installed and width/depth measurements taken
43	51	unpinned	unpinned	Sideheadcut from previously installed gully	No reference pins installed
44	51	unpinned	unpinned	Sideheadcut from previously installed gully	No reference pins installed

45	54	1.47	1.45	GPS points never located. 2012 width measurements were inconsistent with 2010 measurements. Large level of uncertainty in accuracy without GPS locations. Not included in study	No accurately located data collected
46	49	1.07	1.35	GPS points never located. 2012 width measurements were inconsistent with 2010 measurements. Large level of uncertainty in accuracy without GPS locations. Not included in study	No accurately located data collected
47	36	0.76	1.17	GPS points never located. 2012 width measurements were inconsistent with 2010 measurements. Large level of uncertainty in accuracy without GPS locations. Not included in study	No accurately located data collected
48	94	1.83	1.88	GPS points never located. 2012 width measurements were inconsistent with 2010 measurements. Large level of uncertainty in accuracy without GPS locations. Not included in study	No accurately located data collected
49	86	unpinned	unpinned	Not included	Reference pins installed and width/depth measurements taken
50	77	unpinned	unpinned	No distinct headcut located. Long, old road that had developed into stable ditch	No data collected
51	45	unpinned	unpinned	Not included	Reference pins installed and width/depth measurements taken

52	43	unpinned	unpinned	Not included	Reference pins installed and width/depth measurements taken
53	43	unpinned	unpinned	Not included	Reference pins installed and width/depth measurements taken
54	57	unpinned	unpinned	Gully network never located even with GPS points. Possibly filled in with surrounding soil	No data collected
55	9	unpinned	unpinned	Gully network never located even with GPS points. Covered with soil mounds	No data collected
56	39	unpinned	unpinned	Not included	Reference pins installed and width/depth measurements taken
57	41	unpinned	unpinned	Not included	Reference pins installed and width/depth measurements taken
58	36	unpinned	unpinned	Gully network never located even with GPS points	No data collected

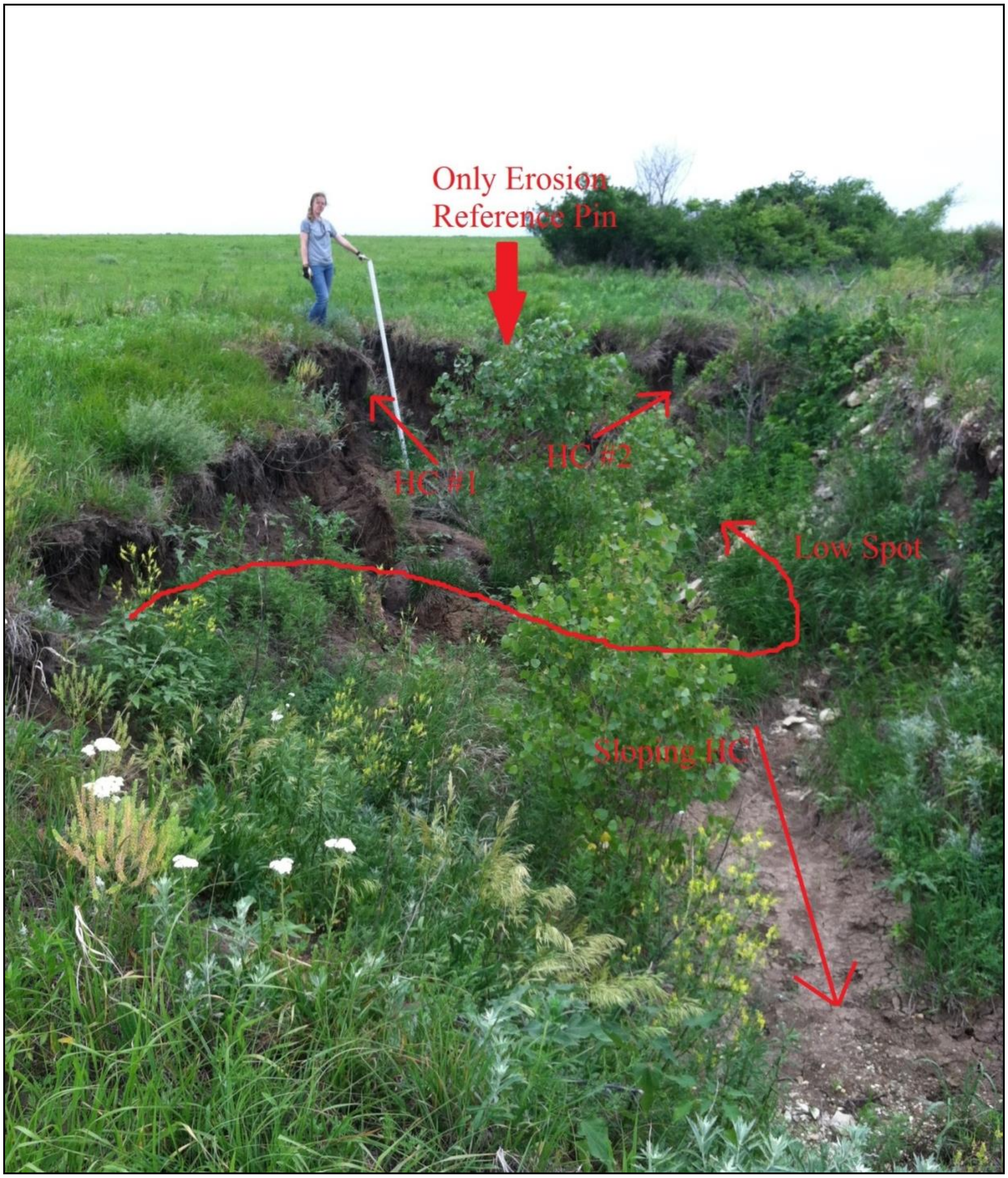
Seven gullies measured in 2010 had been filled with rock to reduce future erosion and prevent soldier injuries and equipment damage. Rock fill is commonly utilized at Fort Riley to fix the most hazardous or largest of military gaps. An example of this technique is seen in Figure 4.1 taken at a previously measured headcut during the Handley (2010) assessment.

Figure 4.1. Rock fixed gully implemented to deter soil erosion at Fort Riley, KS

Five gullies previously measured in 2010 did not exhibit a single erosion channel. In general, a clear headcut is needed within research appropriate gullies in order to assess the movement – or lack thereof – of the gully head location. However, this was not the case in all systems. In gully 41, multiple plunge pools were located in a line formation, but no significant headcut was ever visible. With a significant accumulation of runoff, however, any of these plunge pools may provide the initial nick point required for gully formation, but no gully feature was present in the 2012 visit. Similarly, in erosion network 50, the gully head slowly progressed into a gradually elevating watershed with no distinct downcut present. While it appeared the energy concentration over the area may be great enough to cause excessive sediment movement, a single headcut gully had not formed and therefore resulted in this system being inappropriate for this assessment.

Additionally, unpredictable headcut migration muddled the accuracy regarding gully growth measurements. In gully 11, headcut migration had not occurred in the predicted direction made in 2010 and had likely eroded one of the headcut reference pins. At this same location, at least one other notable headcut (gully 12) had been formed along the initially identified headcut, which made the measurable growth nearly impossible (Figure 4.2). In all situations where a single clear headcut was not present, regardless of potential military training hazard level, it was determined that useful, repeatable measurements could not be collected and that data collection would only produce invalid results regarding gully progression.

Figure 4.2. Unpredictable gully network (gully numbers 11 and 12, located in Training Area 95) with multiple headcuts, erosion features, and only one identifiable erosion reference pin



One unique situation arose for gullies in maneuver areas O and H, where limited accessibility during summer 2012 did not allow for proper measurement of the gullies; therefore these systems were not included in this study. As with any military installation, Fort Riley restricts access into specific training locations based on scheduled training. Each week, a schedule of training maneuvers and activities was published. From this, it was determined which areas were safe for access. In future studies, these gullies should be included if accessible.

Gully Evaluation

After each gully was individually analyzed regarding its appropriateness for this study, 21 remained for further assessment. Of the 21 gullies included in this study, the headcut did not migrate in 10 gullies while 4 gullies resulted in headcut growth of over 1.0 meters. One of the four gullies with significant headcut growth also produced significant aggradation in depth change (gully 21, depth change = -1.11 m), supporting the idea that the sediment produced from the downcutting of the gully head was deposited into the gully bottom.

Width change was seen in 18 of the gullies with 3 gullies resulting in slightly negative growths. This numerical error was likely due to minute errors in gully pin location or gully headcut identification, or simply due to insufficient precision. Of the 18 gullies that did show a change in width, none expanded more than 0.7 m over the two year time span. When analyzed with consideration to headcut, it was revealed that all but one gully with width change at or below 0.10 m had minimal headcut growth. The one exception was gully 13, which resulted in a headcut growth over 17 m. Further research is needed to confirm any relationships between width change and headcut growth for this gully set.

One gully resulted in no change in depth while 9 showed some degree of degradation (positive change) and 11 showed aggradation (negative change). Only two gullies resulted in depth change of more than 0.5 m (gully 21 = -1.11 m; gully 26 = -0.55 m). Both gullies, however, also resulted in width changes of over 0.40 m, suggesting that there is a relationship between depth and width growth. As the two gullies increased in width, they also produced increases in depth (gully 21, depth change = 0.43 m; gully 26, depth change = 0.48 m).

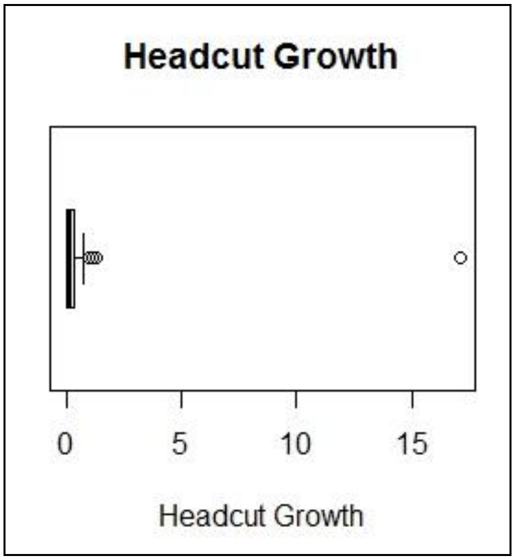
Table 4.2 Summary measurements from the 21 gullies included for 2012 study at Fort Riley

Gully Number	Training Area	Maneuver Area	Headcut Growth (m)	Width Difference (m)	Depth Difference (m)
5	98	P	0.15	0.46	0.26
6	98	P	0.00	0.54	-0.32
13	51	D	17.07	0.10	-0.13
14	51	D	0.00	-0.03	0.05
15	51	D	0.24	0.35	0.08
16	55	D	0.00	0.10	0.00
17	89	M	0.00	-0.08	0.11
18	96	P	0.00	0.10	0.21
19	89	M	0.00	0.70	-0.34
21	96	P	1.17	0.43	-1.11
22	96	P	1.27	0.21	0.02
23	42	E	0.08	0.66	-0.19
24	37	B	0.00	0.08	0.10
26	49	A	0.00	0.48	-0.55
33	48	A	0.15	-0.07	-0.05
34	91	M	0.21	0.23	-0.11
35	12	R	1.02	0.28	0.09
37	12	R	0.74	0.29	-0.11
38	11	R	0.00	0.08	-0.10
39A	12	R	0.36	0.13	0.01
39B	12	R	0.00	0.02	-0.09

In order to eliminate any extreme variations that may not have been removed from the data set initially, each variable was tested for outliers and distribution assessed via histogram. The three predictor variables (headcut growth, width channel change and depth channel change) are shown below.

Headcut growth produced four outliers – gully 13, gully 21, gully 22, and gully 35 (Figure 4.3). These four outliers were also the four gullies analyzed previously as the only gullies with significant headcut growth, suggesting that if these four outliers are indeed eliminated as is typically appropriate with outliers, the average value for headcut growth in this study will be extremely low and may not prove to even be significant or accurate. The fact that such a large number of gullies resulted in minute changes in headcut growth could also suggest some type of stability within a majority of these gullies during this particular timeframe and may require further analysis.

Figure 4.3 Headcut Growth boxplot with accompanying statistical summary for determining outliers (Inner Quartile Range: 0.36; Outlier Range: -0.54 to 0.90; Four outliers: gully 13, gully 31, gully 22, gully 35)

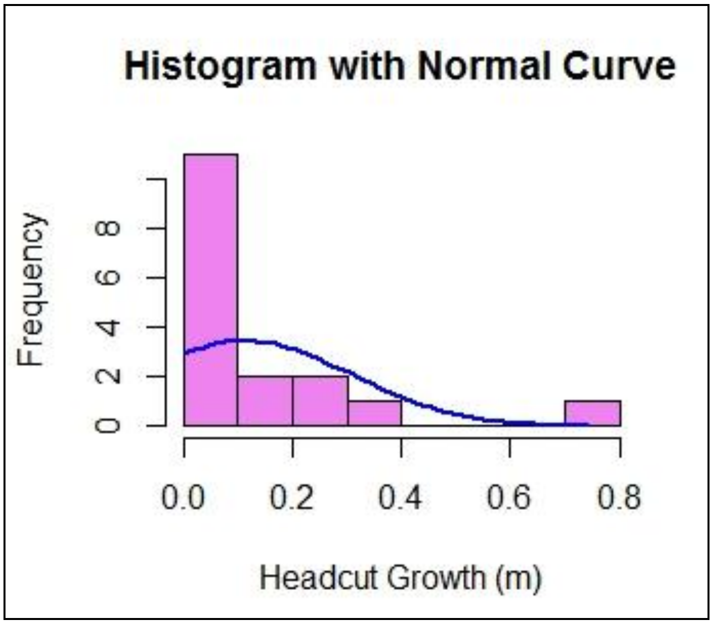


HCG
Min. : 0.00
1st Qu.: 0.00
Median : 0.08
Mean : 1.07
3rd Qu.: 0.36
Max. :17.07

Four Outliers: 17.07m (gully 13), 1.17m (gully 21), 1.27m (gully 22), 1.02m (gully 35)

When these four headcut growth outliers were eliminated to potentially produce a more appropriate summation of the gullies assessed, the resulting histogram (Figure 4.4) did not correlate with a normal distribution. Instead, the histogram proved the above idea that the data would be excessively skewed to the right (skewness = 2.15) due to the large number of gullies that showed minimal or no headcut growth during the two year study. This lack of even distribution suggests that gullies that did not exhibit classically defined headcut erosion may have resulted in an inappropriate skewing of the data set as there may be two different categories of gullies during this short study.

Figure 4.4. Histogram and Normal Curve of Headcut Growth frequency with four outliers removed



Skewness
HCG
2.1502494

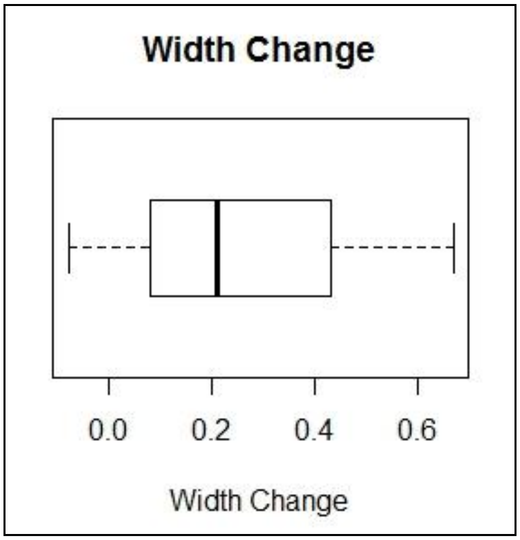
High positive value
Skewed right/Positively skewed

Kurtosis
HCG
7.269083

>3, Leptokurtic
Higher, sharper peak than normal curve
Tail longer and fatter

Width change did not produce any outliers within the 21 gullies being analyzed (Figure 4.5). This suggests that a fairly even or normal distribution is present within this variable and that including all gullies will result in an appropriate data set.

Figure 4.5. Width change boxplot with accompanying statistical summary for determining outliers (Inner Quartile Range: 0.35; Outlier Range: -0.445 to 0.955; No outliers)

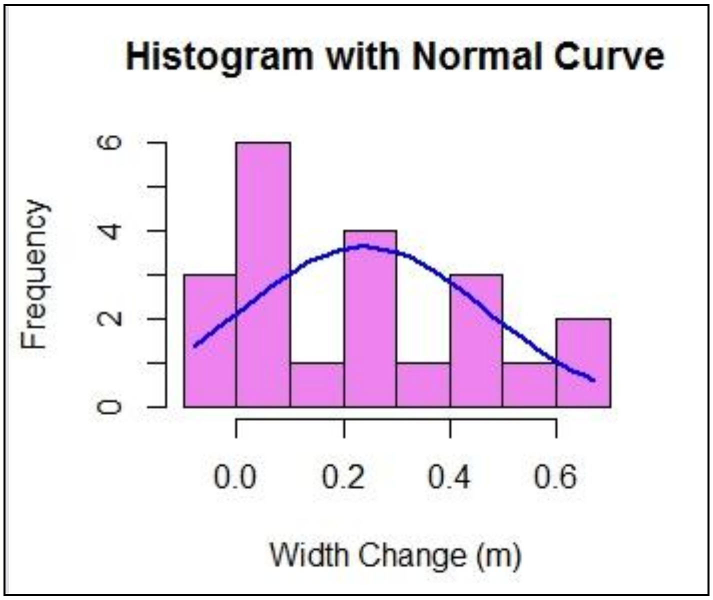


Width
Min.   :-0.0800
1st Qu.: 0.0800
Median : 0.2100
Mean   : 0.2395
3rd Qu.: 0.4300
Max.   : 0.6700

Zero Outliers

The width change histogram (Figure 4.6) confirmed the lack of outliers in the data set. As with headcut change, the width change was skewed to the right (skewness = 0.443), but not nearly as considerably as the previous headcut variable. Additionally, the kurtosis of the width change data was much closer to that of normal distribution (kurtosis = 2.099), suggesting that the data was indeed similar and that no outliers existed with regards to this specific variable.

Figure 4.6. Histogram and Normal Curve of Width Change frequency with no outliers removed



Skewness
Width
0.4425539

Positive value
Skewed right/Positively skewed

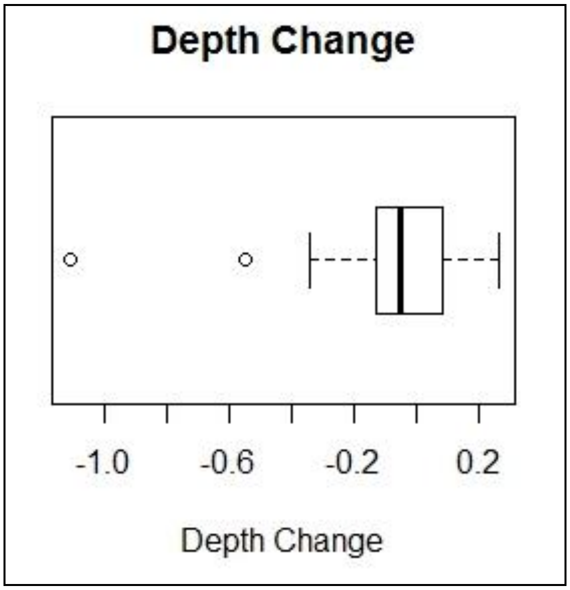
Kurtosis
Width
2.098761

<3, Platykurtic
Lower, broader peak than normal curve
Tail shorter and thinner

Depth change produced two outliers – gully 21 and gully 26 (Figure 4.7). These two outliers were also the two gullies analyzed previously as the only gullies with significant depth change greater than 0.5 m in either aggradation or degradation, suggesting that if these two outliers are indeed eliminated, the average value for depth change in this study will be extremely close to zero and may not prove to even be significant or accurate. The fact that such a large number of gullies resulted in minute variations in depth change could also suggest some type of stability within a majority of these gullies during timeframe of this study.

One of the outliers identified within depth change was also one of the four outliers regarding headcut growth. This correlation suggests that while these data points are indeed outliers within their respective variable, they may still hold importance regarding any growth trends throughout the gully set. Additional techniques for analysis are needed to confirm or deny this relationship.

Figure 4.7. Depth change boxplot with accompanying statistical summary for determining outliers (Inner Quartile Range: 0.21; Outlier Range: -0.445 to 0.395; Two outliers: gully 21, gully 26)

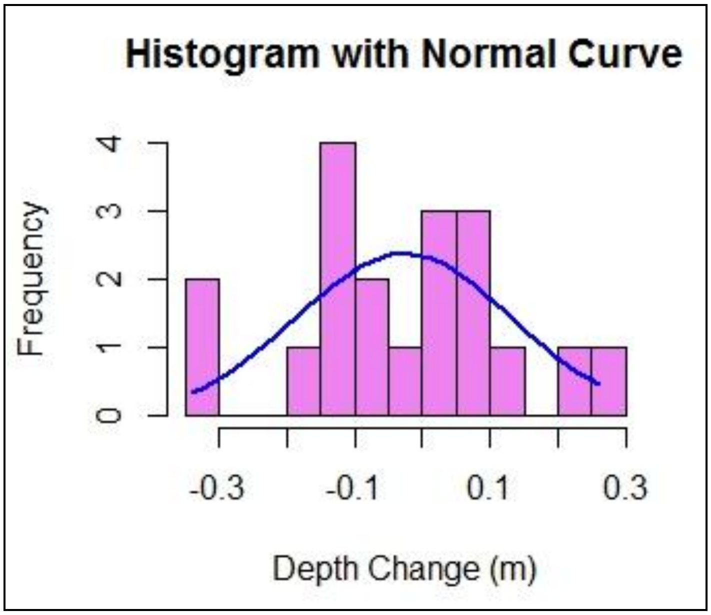


Depth
Min. :-1.1100
1st Qu.:-0.1300
Median :-0.0500
Mean :-0.1033
3rd Qu.: 0.0800
Max. : 0.2600

Two Outliers: -1.11m (gully 21),
-0.55m (gully 26)

Unlike the two previous output variables, depth resulted in a negatively skewed histogram (skewness = -0.260) (Figure 4.8). This result suggests that even with outliers eliminated from the group of 21, a slight tendency towards the left – aggradation – is seen for depth change. Two significant mechanisms are likely to have caused this aggradation. The first being headcut growth in which sediment was dislodged at the gully head and deposited into the gully bottom. The second is channel sidewall failure, less formally referred to as sloughing. Differentiating between these triggers is important within this study as only gullies with single headcut erosive features should ideally be included for consistent representation of gully progression. As a result, further analysis techniques are needed to determine the similarity amongst gullies that produced traditionally defined gully headcut growth and those that did not.

Figure 4.8. Histogram and Normal Curve of Depth Change frequency with two outliers removed



Skewness
Depth
-0.2601579

Negative value
Skewed left/Negatively skewed

Kurtosis
Depth
2.666359

<3, Platykurtic
Lower, broader peak than normal curve
Tail shorter and thinner

Headcut Gully Progression

Since the outliers produced using the 21 gullies did not result in significant normal curves with regards to headcut and width change, some gullies may be skewing the data and invalidating the relationships seen over this short timeframe and other factors may more appropriately define significant variations within the data set. Therefore, gullies without any growth regarding headcut progression were eliminated from the dataset. This was done to isolate the gullies that exhibited gully erosion as linear features as previously defined from the gullies that did not produce single headcut growth.

Ten gullies did not have any headcut migration during the two year study period (Table 4.3). Of the ten gullies that did not exhibit headcut growth, three did produce significant width change. These three gullies (6, 19, 26) also showed significant aggradation in the bed of the gully. This suggests two important points. First, as large amounts of sediment were dislodged from the sidewalls of these gullies, the particles were deposited along the gully bottom. This relationship is common in gully evolution, particularly over the entire lifetime of a gully, but does not meet the single headcut progression this study analyzes. This change in width with the absence of headcut migration suggests that the flow of water may not be in the direction of the initial nick point. Width change without headcut progression could also suggest that there is a natural barrier in the headcut that is prohibiting the gully from migrating further. Both of these explanations do not correlate with single headcut progression of a gully as the formation of a second headcut potentially skews the nature of this study.

Second, while these gullies did not produce the single headcut gully erosion feature defined in this study, other types of erosion within the gullies are occurring at Fort Riley. This erosion might be a result of unique land management practiced including fire regimes and military training, but again promotes sideheadcut formation as opposed to migration of the initial gully headcut. Individual trend analysis regarding such variables is needed to determine if this sidewall erosion can be explained by land management, change in water flow, or a natural barrier to the current headcut.

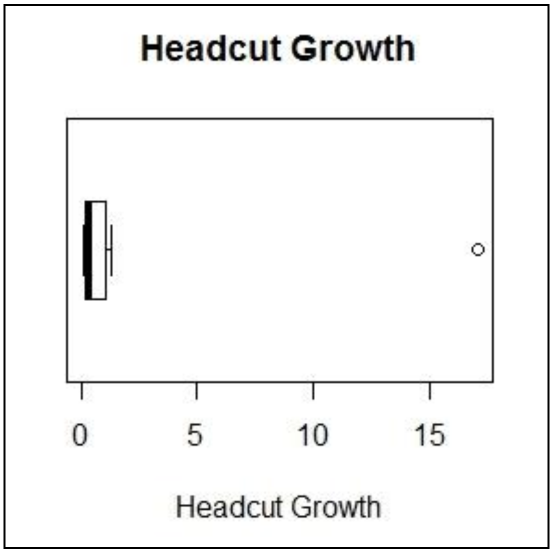
Table 4.3. Summary table of 21 gullies included in study with selections of the 10 gullies without headcut growth

Gully Number	Headcut Growth (m)	Width Difference (m)	Depth Difference (m)
5	0.15	0.46	0.26
6	0.00	0.54	-0.32
13	17.07	0.10	-0.13
14	0.00	-0.03	0.05
15	0.24	0.35	0.08
16	0.00	0.10	0.00
17	0.00	-0.08	0.11
18	0.00	0.10	0.21
19	0.00	0.70	-0.34
21	1.17	0.43	-1.11
22	1.27	0.21	0.02
23	0.08	0.66	-0.19
24	0.00	0.08	0.10
26	0.00	0.48	-0.55
33	0.15	-0.07	-0.05
34	0.21	0.23	-0.11
35	1.02	0.28	0.09
37	0.74	0.29	-0.11
38	0.00	0.08	-0.10
39A	0.36	0.13	0.01
39B	0.00	0.02	-0.09

Prior to extensive data analysis regarding the differences between including the gullies with no headcut growth over this two-year period, an assessment of the appropriateness of this elimination was required. First, all variables were tested for normality using boxplots and the outcome variables were additionally tested utilizing histograms. The headcut results are below (Figures 4.9 and 4.10) while the remaining diagrams can be found in Appendix D.

When the gullies without headcut migration were eliminated from the data set, only one gully was deemed an outlier with a headcut growth of over 17 m (gully 13). This alteration in gullies analyzed also significantly changed the statistical data as the quartiles, mean, and median all increased substantially.

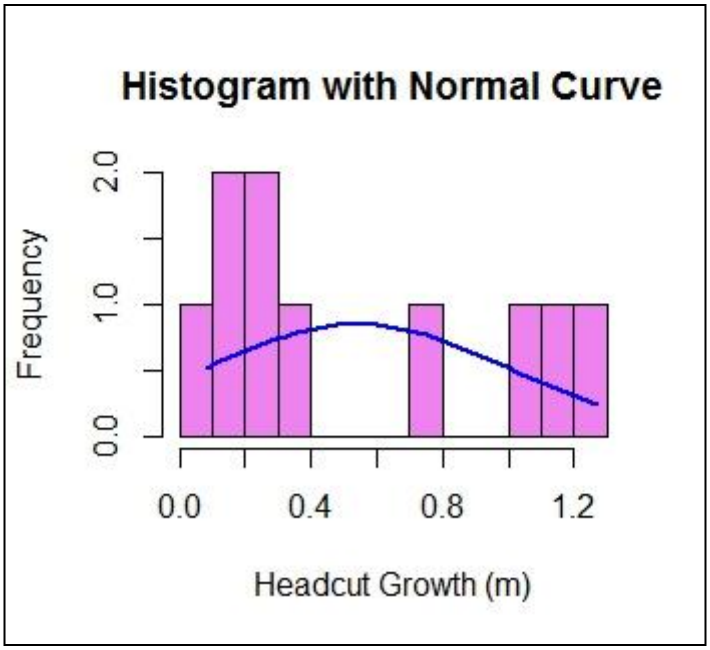
Figure 4.9. Headcut Growth boxplot of 11 gullies resulting in headcut migration with accompanying statistical summary for determining outliers



	All Gullies	Only with HCG	Change between two groups
1st Q	0.00	0.180	Inc.
Median	0.08	0.360	Inc.
Mean	1.07	2.042	Inc.
3rd Q	0.36	1.095	Inc.
IQR	0.36	0.915	Inc.

When analyzed utilizing a histogram for frequency, the data set with only gullies exhibiting headcut growth (Figure 4.10) changed drastically from the histogram considering all 21 gullies. The skewness decreased dramatically and was much closer to no skew (value = 0) when compared with the skewness of the 21 gully data set. Additionally, the kurtosis completely changed direction as the graph now depicts a platykurtic distribution where the curve is lower and contains a broader peak than a normal curve. Since a normal curve exhibits a kurtosis of roughly 3, eliminating the gullies that did not result in headcut change seems to be more appropriately valid with regards to these histograms.

Figure 4.10. Histogram and Normal Curve of Headcut Growth frequency utilizing gullies resulting in headcut growth with one outlier removed



	All Gullies	Only with HCG	Change between two groups
Skewness	2.150	0.557	Dec.
Kurtosis	7.269	1.609	Dec.

From the statistical analysis completed using histograms and boxplots, the elimination of the gullies with zero headcut growth was deemed appropriate. While some of the variables do not yet meet the required skewness, kurtosis, and outlier requirements in certain situations, a majority of the variables do improve and therefore result in a better relationship between the remaining gullies than if all 21 gullies were potentially considered.

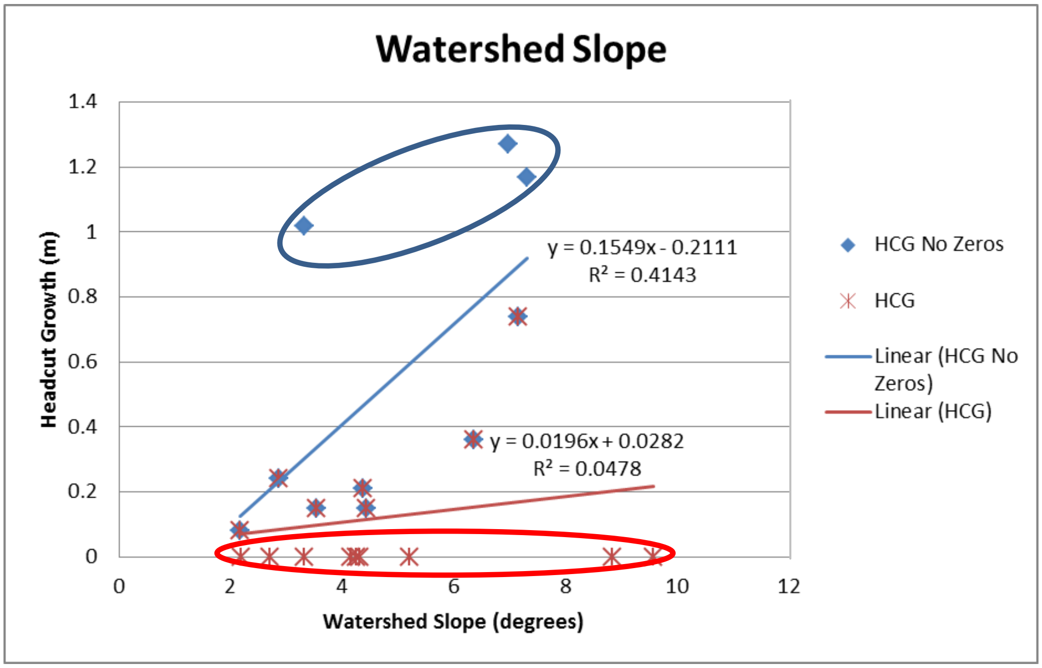
Variable Analysis

In order to further analyze the measurement changes, each gully was correlated with 10 predictor variables: Watershed Slope, Flow Accumulation, Watershed Area, Drainage Density, Aspect, Clay Percentage, Training Intensity, Burning Frequency, Burning Seasonality, and Above Ground Biomass Change.

The first six variables are considered watershed characteristics and are unlikely to be significantly altered in short periods of time. Watershed slope, the amount of change in elevation over the accompanying watershed length, is commonly used to predict likely erosion within an area. As the slope of the watershed increases, the energy input becomes larger and results in an increased potential for soil erosion via water movement. The gullies studied at Fort Riley support this relationship (Figure 4.11). When all 21 gullies were originally considered (outliers omitted), the correlation was insignificant. However, when gullies that did not result in any headcut growth (respective outliers again omitted) were eliminated from the data set, the 10 remaining gullies resulted in a stronger relationship between gully headcut growth and watershed slope.

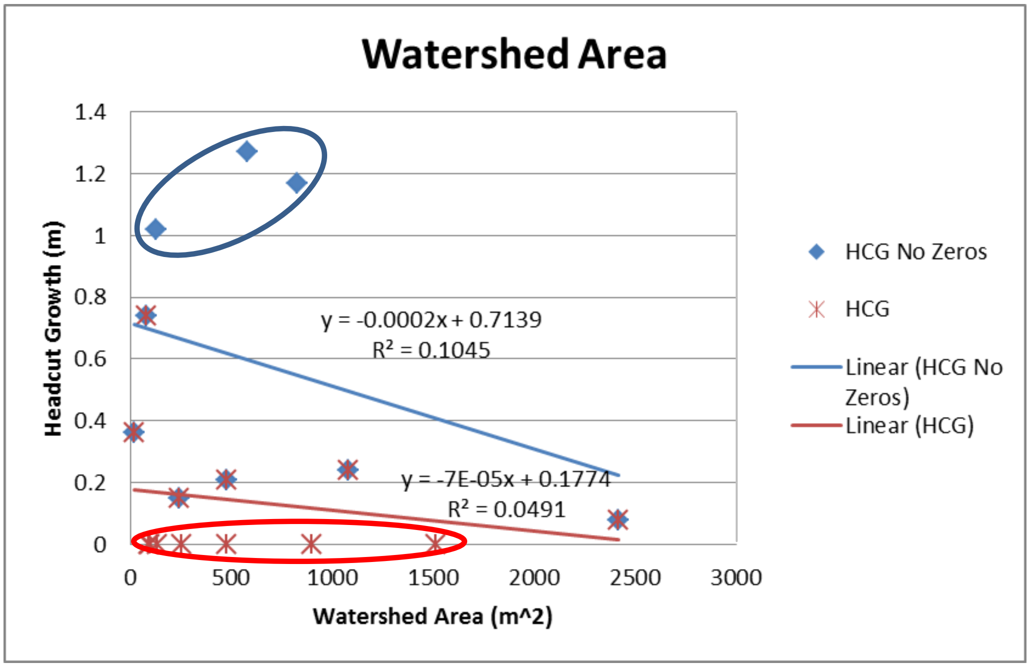
The gullies eliminated from the second data set – outlined in a red circle in Figure 4.11 – are of particular interest in the fact that two of the gullies resulted in the two largest watershed slope amounts. This result is in opposition to literature in the fact that the highest slopes should produce larger amounts of headcut growth (Mohammadkhan et al., 2011 Vijith et al., 2012). However, these gullies did not yield any headcut growth over this two year period – suggesting that other factors could be contributing to this reverse expectation.

Figure 4.11. Watershed Slope versus Headcut Growth with data set including all 21 gullies and data set including only gullies with headcut change. Blue circle indicates three outliers not included in Linear HCG trendline and Red circle indicating gullies not exhibiting Headcut Growth



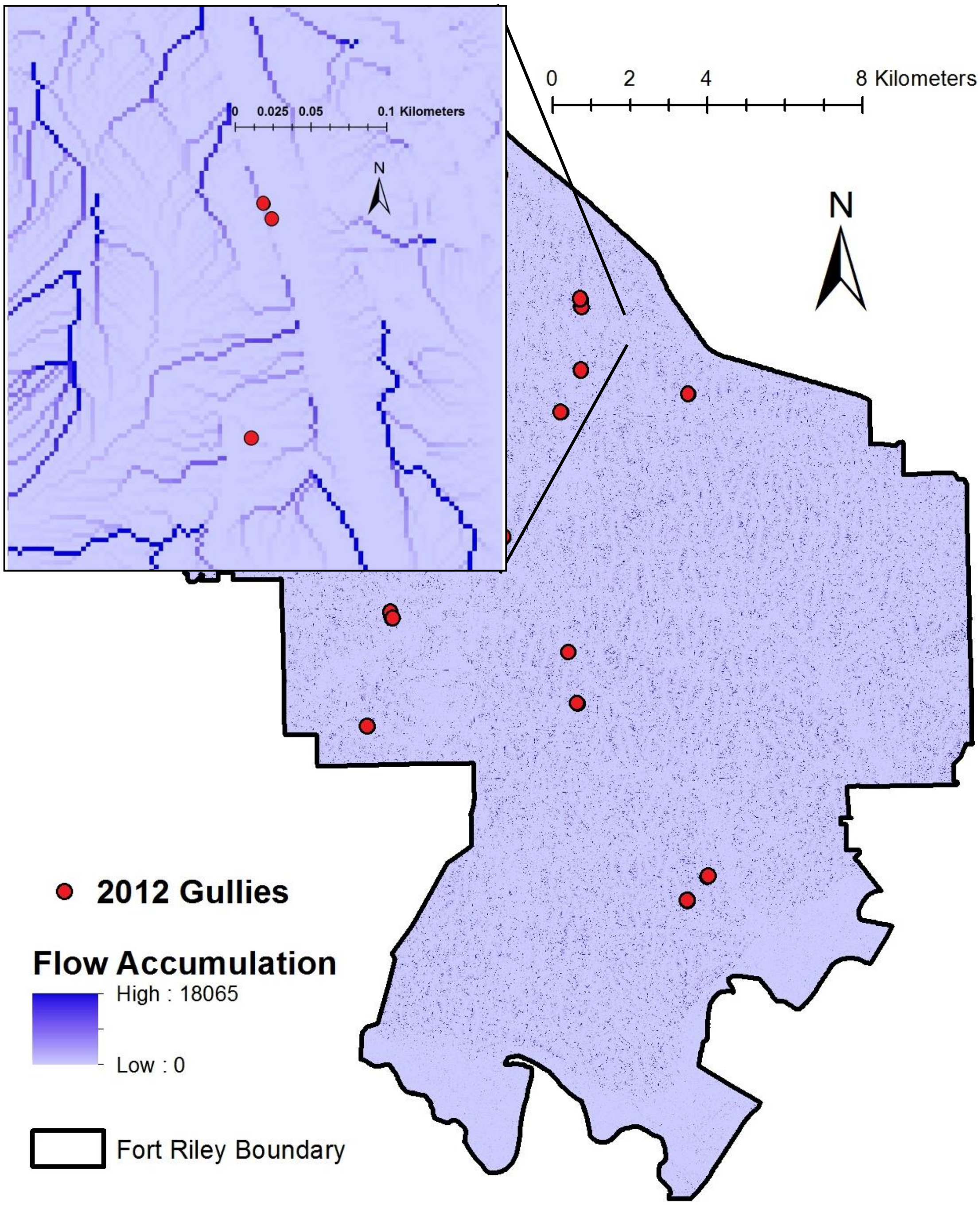
The next erosion variable commonly considered on the watershed scale was watershed area. As with watershed slope, soil erosion via water should increase as the watershed area increases. When the original 21 gullies were plotted (Figure 1.12) to correlate watershed area and headcut growth (outliers omitted), a negative relationship was revealed – opposite of the claims supported in current literature (Chaplot, 2013). Once the gullies without headcut growth were eliminated, the correlation between these independent and dependent variables do not change association, but the relationship does become more closely associated. This change is supported by an increase in the R^2 value which calculates the difference between the chosen data points and the line of best fit. As the R^2 value approaches one, the line becomes more closely fit, suggesting the data is also more closely related. While the orientation of the trend line is still opposite the expected relationship, the correlation relationship does become stronger with the elimination of the gullies without single headcut erosion. This suggests that watershed area is an important explanatory variable regarding headcut growth within this data set, but that some other factors may be heavily influencing the negative relationship seen below. This idea is additionally supported by the gullies with zero headcut growth circled in red (Figure 4.12). Unlike with watershed slope, these gullies are not the maximum values associated with the gully data set, suggesting that the general trend that lower watershed area values should produce a lower amount of headcut growth.

Figure 4.12. Watershed Area versus Headcut Growth with data set including all 21 gullies and data set including only gullies with headcut change. Blue circle indicates three outliers not included in Linear HCG trendline and Red circle indicating gullies not exhibiting Headcut Growth



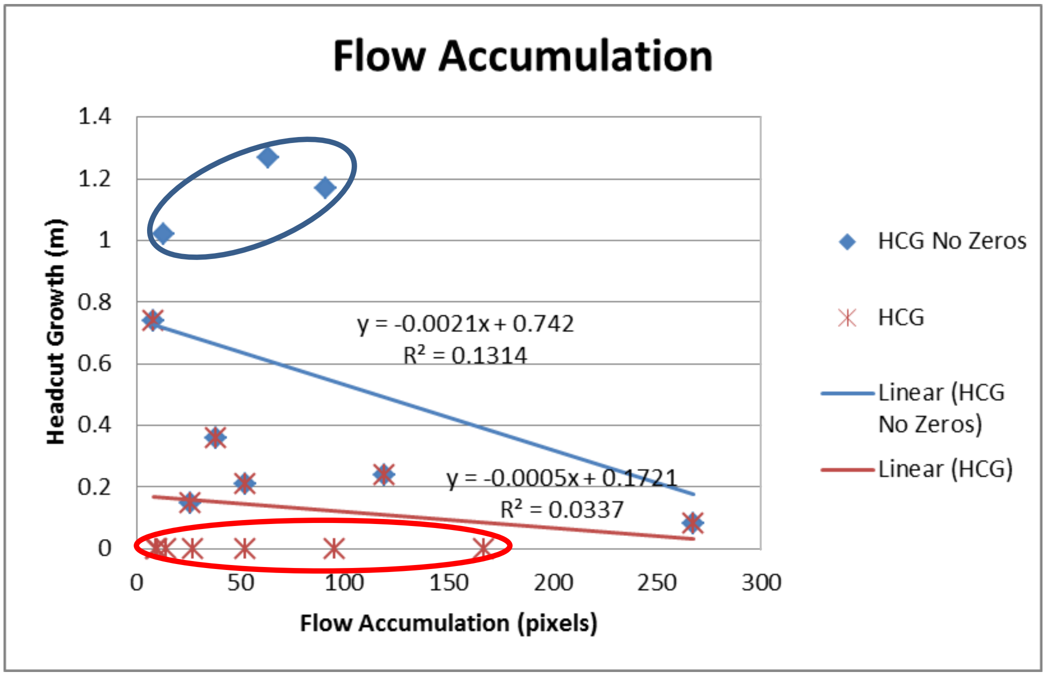
Flow accumulation, the next variable considered, is another highly studied factor known to explain soil erosion. As the flow accumulation changes, the amount of water potentially entering the specified pour point is altered, meaning that as the accumulated water increases, a larger amount of energy can flow into the system and there is a higher amount of potential soil erosion. The flow accumulation throughout Fort Riley is represented in Figure 4.13.

Figure 4.13 Flow Accumulation represented over Fort Riley boundary with locations of 21 studied gullies (Data Source: Fort Riley Integrated Training Area Management Program, 2007)



As with watershed area, when plotted against headcut growth, flow accumulation (Figure 4.14) showed no relationship. However, when the gullies with zero headcut growth were removed, the relationship between the gullies increased, suggesting that it was appropriate to remove the gullies that did not erode.

Figure 4.14. Flow Accumulation versus Headcut Growth with data set including all 21 gullies and data set including only gullies with headcut change. Blue circle indicates three outliers not included in Linear HCG trendline and Red circle indicating gullies not exhibiting Headcut Growth



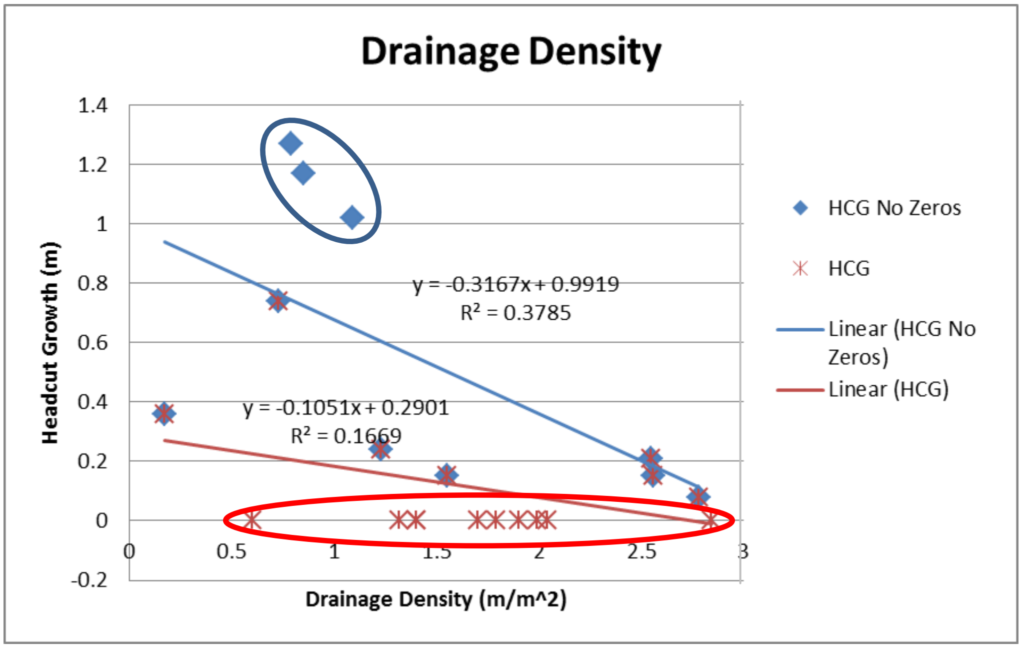
As with many of the other watershed characteristics analyzed in this study, headcut growth was expected to increase as the drainage density over the watershed increased. This relationship occurs because of the soil permeability and underlying type of rock that can affect the infiltration rate of the water throughout the watershed. If the drainage density is higher, more water is accumulating on the surface of the soil as opposed to infiltrating into the soil profile – therefore producing a higher likelihood of soil erosion due to the energy concentration that creates a peak along the hydrograph of a given storm.

The relationship produced when the gullies in this study were analyzed with respect to headcut growth (Figure 4.15) was opposite what was expected regarding common literature (Vijith et al., 2012) – with a negative slope in the trend lines for both data sets. However, when the gullies with zero headcut growth were eliminated, the relationship between the remaining gullies increased and supported the removal of these gullies to more accurately analyze gully progression.

The relationships between the minimum and maximum values, as well as the outlier (circled in blue) and zero headcut growth gullies (circled in red), were significant. For example, the minimum drainage density value was near the middle of the data sets as it produced an average amount of headcut growth. Also, the maximum value was a gully that did not exhibit any headcut growth, again contradicting most literature, and suggesting other variables may play a more important role when regarding headcut growth explanation. Additionally, the outliers circled in blue were not in a positive trend line as with the previous variables analyzed, suggesting that a positive correlation should not be expected when added into the data set.

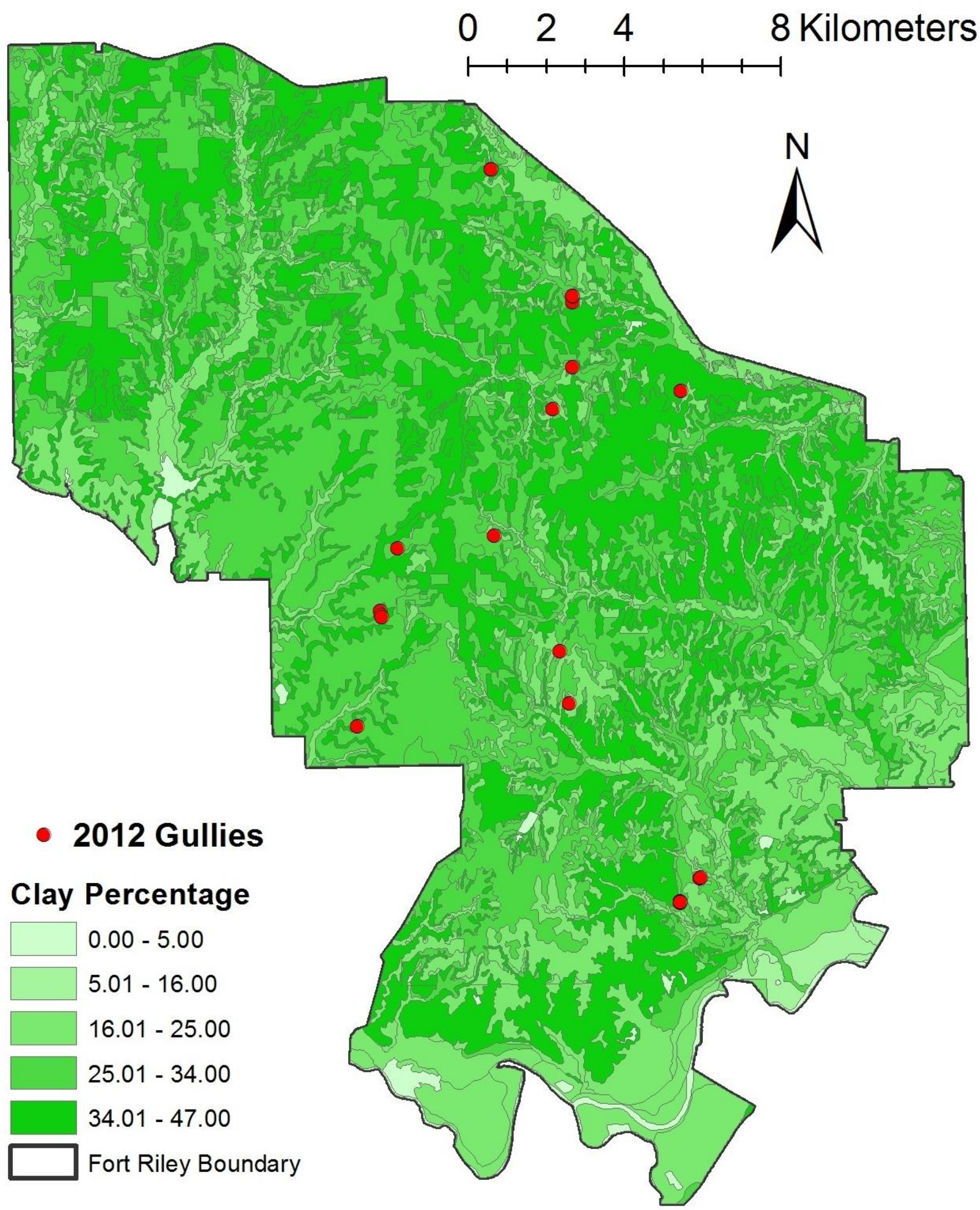
Overall, this combination of results contradictory to common literature brings to light the idea that drainage density may not be of great significance in this study during this short timeframe and that other variables may be more accurately explanatory.

Figure 4.15. Drainage Density versus Headcut Growth with data set including all 21 gullies and data set including only gullies with headcut change. Blue circle indicates three outliers not included in Linear HCG trendline and Red circle indicating gullies not exhibiting Headcut Growth



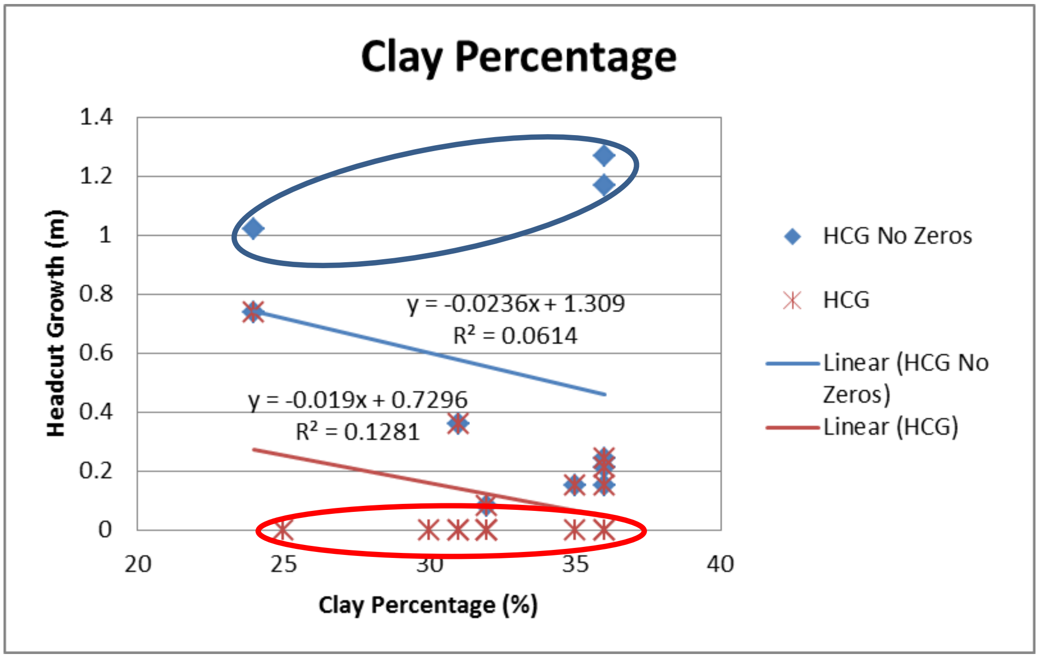
The next variable considered regarding watershed characteristics was clay percentage – an additional way to numerically represent the infiltration rate among a watershed. As with drainage density, the erosion potential and headcut growth should increase as the clay percentage increases. This occurs because clay has a lower infiltration rate as compared to loam or silt soils. With this lower infiltration rate comes an increase in surface runoff and an increase in soil erosion potential. The clay percentage throughout Fort Riley is shown in Figure 4.16.

Figure 4.16 Clay Percentage represented over Fort Riley boundary with locations of 21 studied gullies (Data Source: Fort Riley Integrated Training Area Management Program, 2007 and STATSGO, 2009)



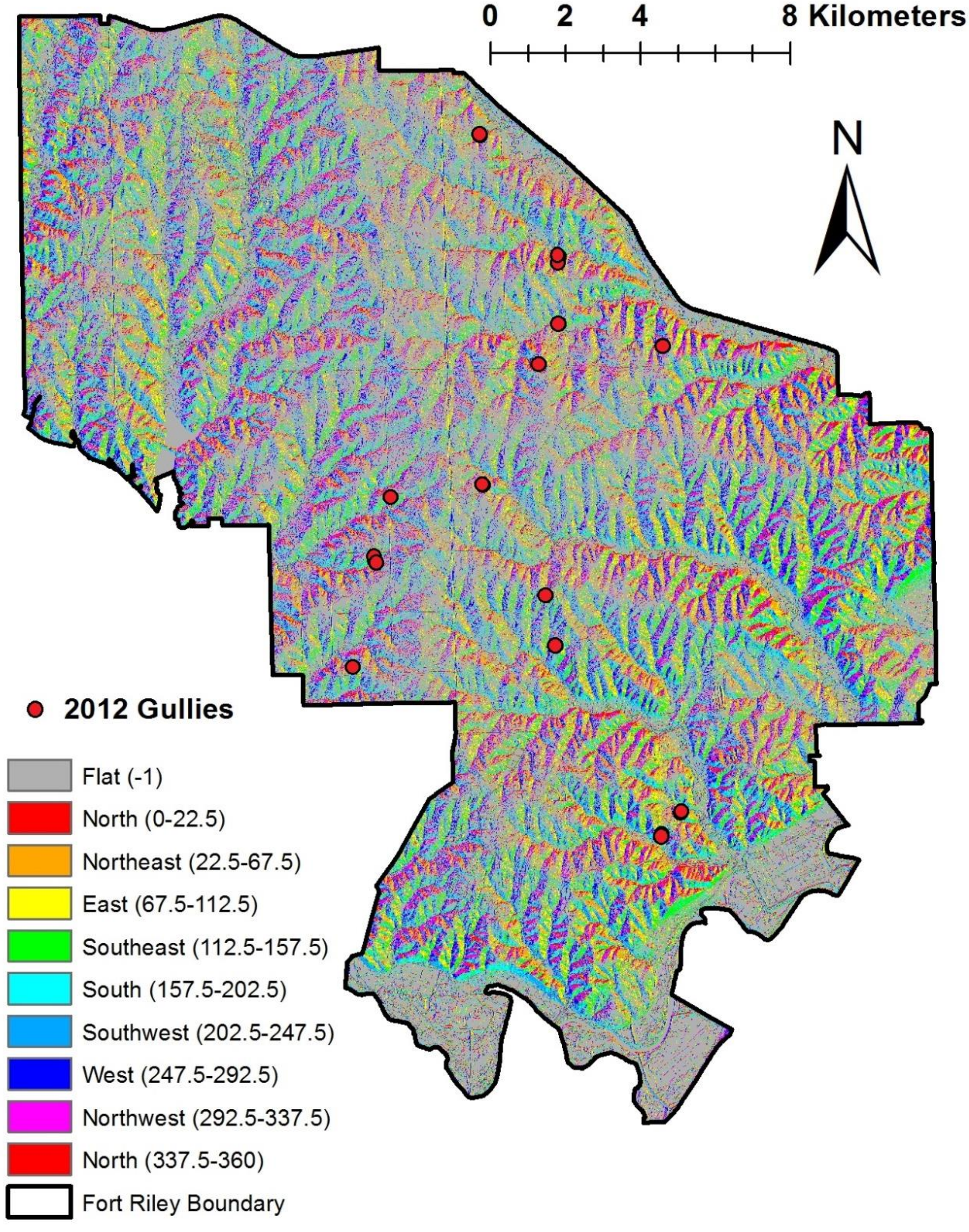
When plotted (Figure 4.17), it was shown that both data sets had no correlations with headcut growth as the literature (Chaplot, 2013) would suggest. Additionally, with the removal of the zero growth gullies, the relationship loses strength and becomes less correlated than when all 21 gullies are considered. This unexpected relationship suggests that clay percentage may be less important regarding headcut growth and could instead play a more predominant role in other erosion processes. It could also suggest that clay percentage does play an important role in determining whether a gully will progress regarding headcut growth as opposed to what amount of progression may occur. Further analysis is required to determine whether this correlation is true.

Figure 4.17. Clay Percentage versus Headcut Growth with data set including all 21 gullies and data set including only gullies with headcut change. Blue circle indicates three outliers not included in Linear HCG trendline and Red circle indicating gullies not exhibiting Headcut Growth



While little to no literature directly related aspect to headcut growth, the basic principles of the variable suggest some type of relationship may exist. For example, mountainous regions experience extremely different soil moisture and biomass presences depending on the direction in which the watershed is oriented. If a watershed is facing a southern direction, it will receive a higher amount of solar radiation as opposed to northern facing slopes. As a result, water will be removed from the soil more quickly on southern facing watersheds, meaning the antecedent soil moisture may be higher on northern facing areas. This increase in antecedent soil moisture may then influence the potential for soil erosion. Aspect throughout Fort Riley is shown in Figure 4.18.

Figure 4.18 Aspect represented over Fort Riley boundary with locations of 21 studied gullies (Data Source: Fort Riley Integrated Training Area Management Program, 2007)

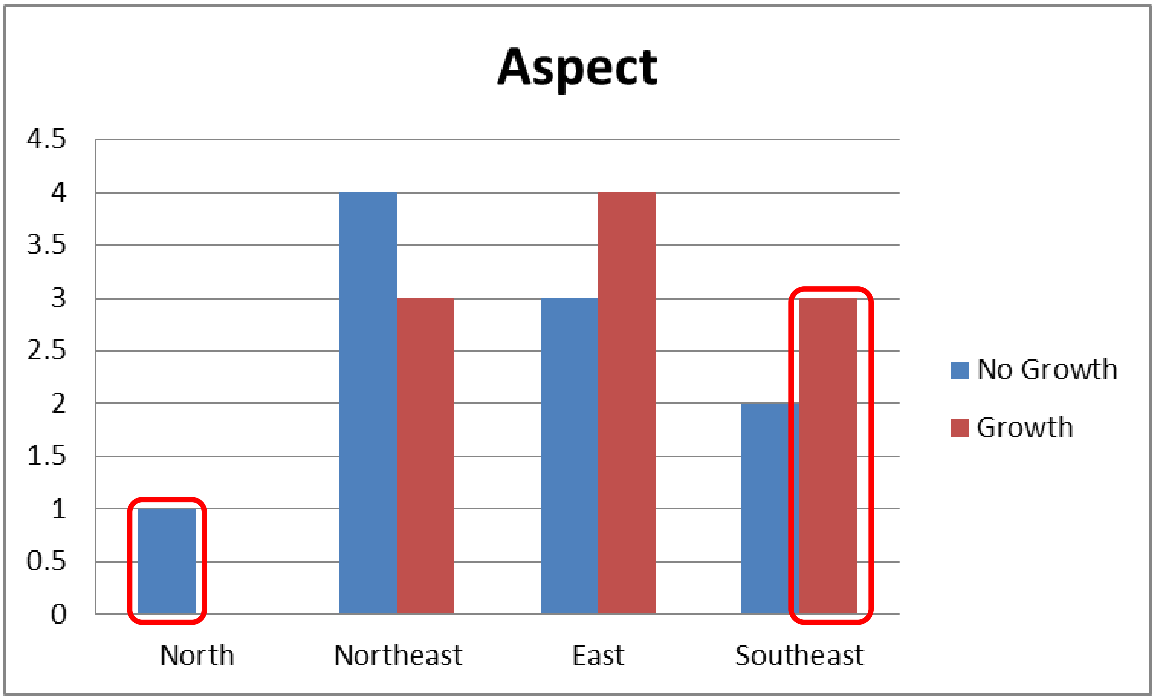


When plotted with respect to aspect frequency and headcut growth (Figure 4.19), relationships were slightly skewed in both directions. Gullies that exhibited headcut growth were more likely to face towards the south while gullies that did not produce headcut growth tended to face in a northern direction.

More significantly, all of the gullies meeting the definitions for this study ranged from approximately 0-160 degrees with no gullies forming on a western facing watershed. In Kansas, storms typically move from west to east with no prominent north or south movement. As these storms progress across the state, watersheds located with an east or west orientation will remain under the storm for a longer period of time as opposed to gullies with north or south facing watersheds. These gullies, therefore, likely receive a larger amount of precipitation and runoff, a fact that is supported by the orientations of gullies in this study. Additionally, with all included gullies facing with an east direction, this study would suggest that the increase in energy potential accumulated as the water flows down the watershed is significant as opposed to watersheds facing west. These watersheds would indeed receive an increase in precipitation amount, but would not necessary receive the larger amount of energy potential.

Nonetheless, this analysis does not definitively rule-out or include aspect as an erosion predictive variable. At Fort Riley, the general terrain is not considered mountainous or significantly hilled in many locations. As a result, there are few locations in which significant shadowing from surrounding hills may exist as well as few watersheds that present significantly different directions and could instead be classified as flat terrain.

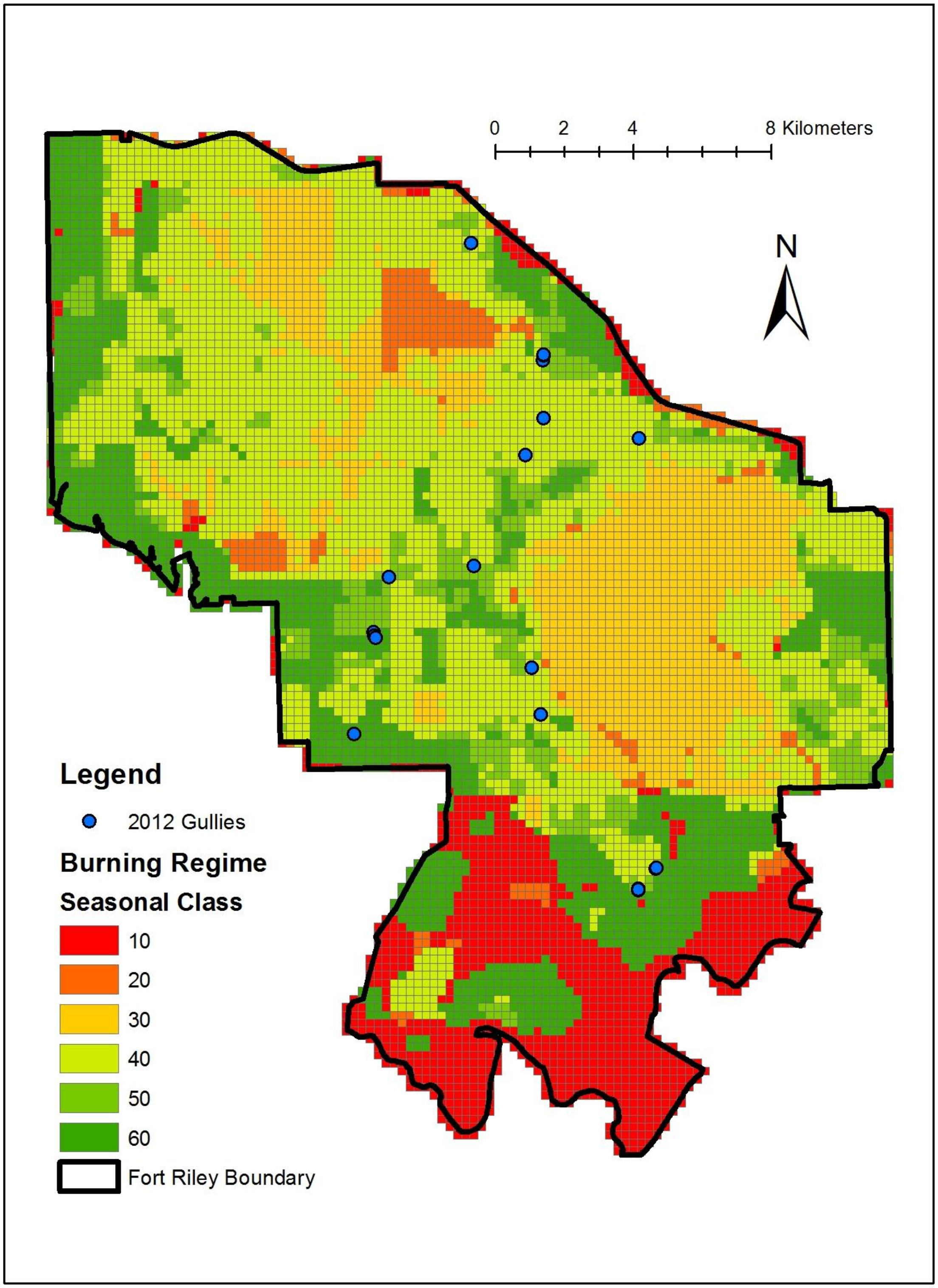
Figure 4.19. Aspect versus Gully Frequency including all 21 gullies (omitting gully 13) separated with respect to headcut growth or no headcut growth including red highlights for significant trends in either category



The remaining four variables were land management factors as opposed to watershed characteristics. These four variables – burning seasonality, burning frequency, training intensity, and above ground biomass – are more likely to change values over shorter periods of time and may not remain static during the entire lifetime of the gully.

Burning seasonality was divided into six different categories measured in multiples of ten. These values are 10 – never burned, 20 – Fall/Winter only, 30 – Mostly fall/winter, 40 – No dominant season, 50 – Mostly spring, 60 – Only spring. One of the most significant ways in which burning seasonality may affect gully headcut growth is the change in biomass that is accelerated depending on the burning time. For example, burns that occur in spring months allow for warm season grasses to increase growth potential as they do not have to compete with the forbs and shrubs in the area for sunlight. When a burn occurs in the fall or winter, growth of varying vegetation is not necessarily hindered, but it is not potentially accelerated as in with a spring burn. When plant properties are applied to soil erosion, literature suggests that grasses are more adequate at holding soil particles in place and decreasing the potential for soil erosion (De Baets & Poesen, 2010; Fattet et al., 2011).

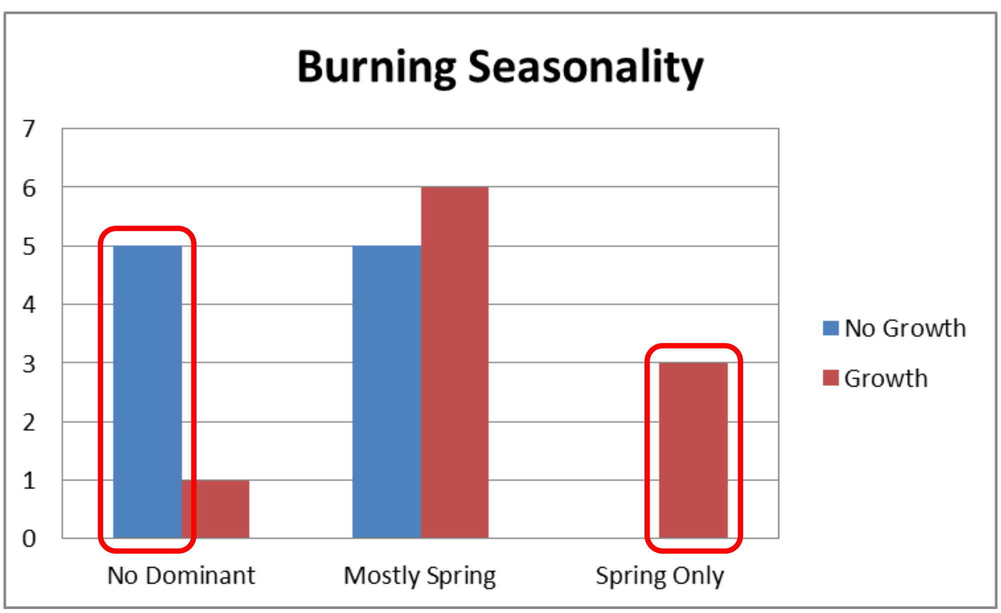
Figure 4.20 Burning Seasonality represented over Fort Riley boundary with locations of 21 studied gullies (Devienne et al., 2013)



When plotted to analyze frequency (Figure 4.21), two tails can be seen in trends regarding growth and no growth gullies. Within gullies that experienced headcut growth within the two-year timeframe, more of the gullies tended to be dominated by spring only burning. Additionally, gullies without headcut growth did not contain a dominant season. This relationship was opposite of what has been supported within the literature when common plant and soil properties are applied.

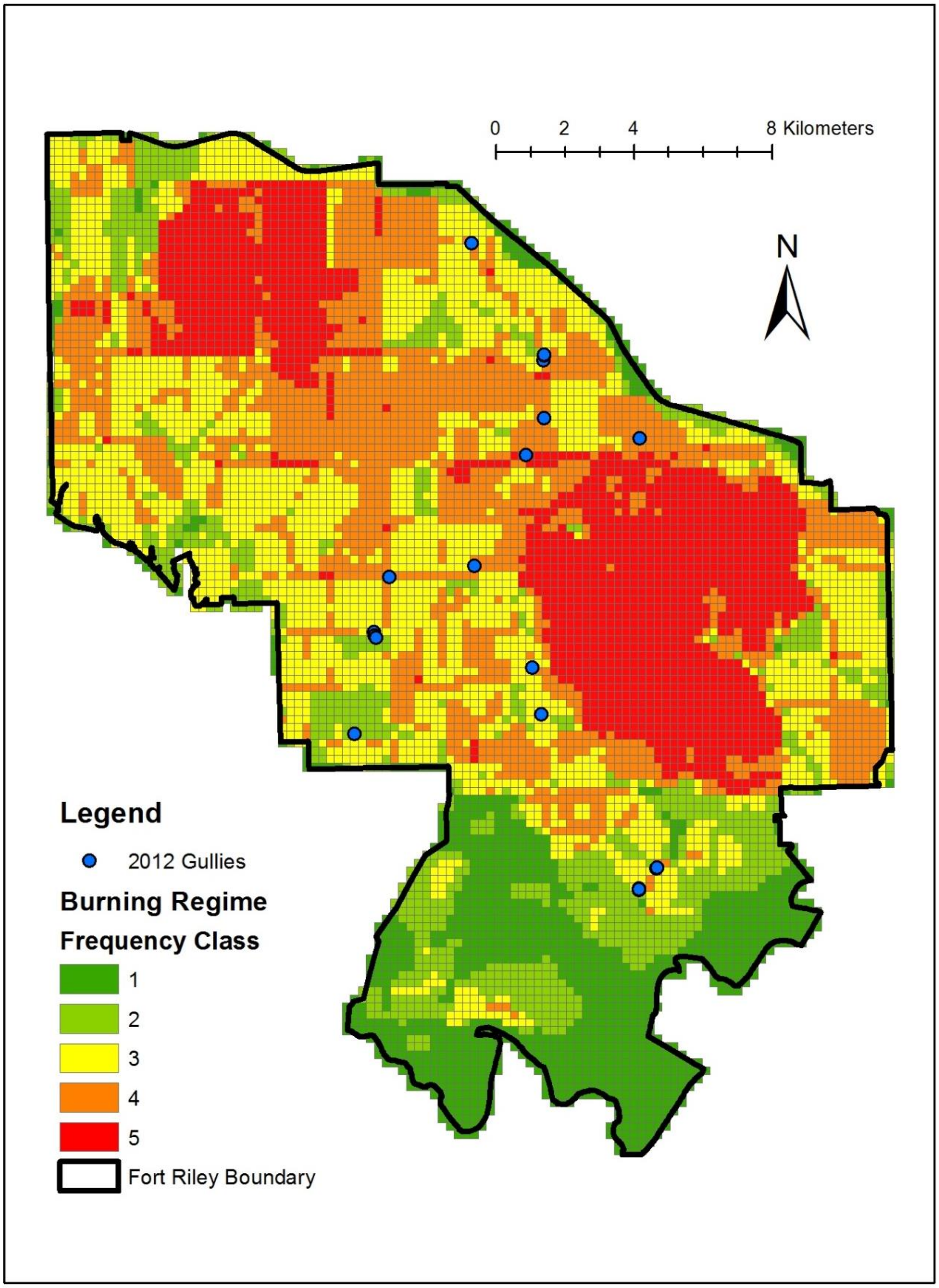
However, this opposite relationship does not entirely negate the possibility that burning seasonality may play a role with regards to gully headcut growth. While plant growth above the ground can aid in disruption of direct water flow over the soil, root structure and amount may instead be a more significant variable and could be affected by the burning seasonality. Also, since the initial gully erosion was not documented and could have occurred decades before this study, it is impossible to know what the burning seasonality may have been at that time. Therefore, burning seasonality could still be considered a factor regarding gully initiation and formation.

Figure 4.21. Burning Seasonality versus Gully Frequency including all 21 gullies (omitting gully 13) separated with respect to headcut growth or no headcut growth including red highlights for significant trends in either category



Burning regimes are typically considered in multiple ways, including both seasonality and frequency. As the burning frequency increases over a watershed, the above ground biomass is more frequently removed and no longer present to decrease the water that could progress to cause soil erosion. In other research initiatives, it has been suggested that as the burning frequency within a watershed increases, gully headcut erosion should increase as less biomass exists to slow the energy of the water flowing into the system.

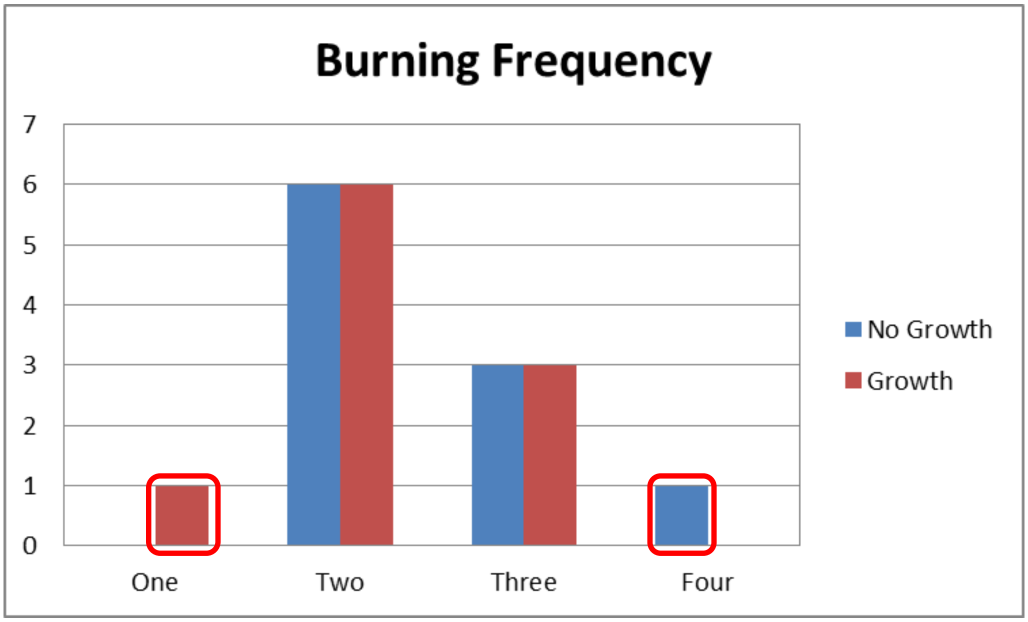
Figure 4.22 Burning Frequency represented over Fort Riley boundary with locations of 21 studied gullies (Devienne et al., 2013)



When the gullies considered in this study (excluding gully 13 with a headcut of over 17 m), there was an opposite trend of what was expected regarding burning frequency and erosion progression. Compared with the group that exhibited growth during this two year study, the gullies that did not produce any gully headcut migration was skewed more towards a higher number of burns within the past ten years. As highlighted in Figure 4.23 with red circles, the two extremes of both groups mirror each other, but in the opposite direction as expected.

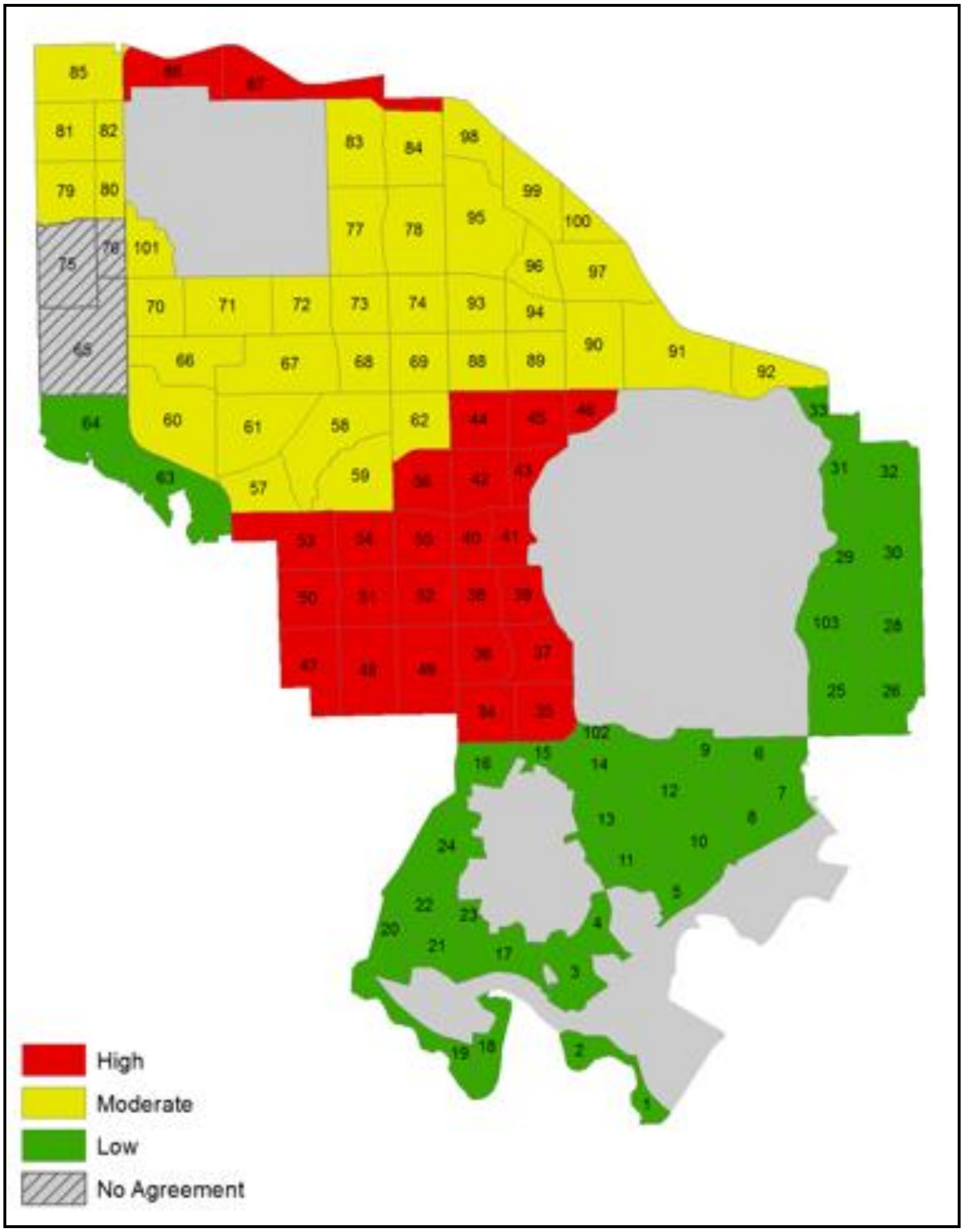
As with burning seasonality, the timeframe during the gully initiation may not be included within the ten year time during which this frequency was recorded. Additionally, other forms of erosion may still be occurring that are not reflected in this study as only gully progression with a single headcut was considered. As analyzed before, three of the ten gullies that did not experience single headcut erosion did produce significant width change, meaning some degree of erosion did happen outside of the defined gully progression.

Figure 4.23. Burning Frequency versus Gully Frequency including all 21 gullies (omitting gully 13) separated with respect to headcut growth or no headcut growth including red highlights for significant trends in either category



One of the most unique variables present at any military base is training intensity, a common means to represent the amount of military impact that might occur across the installation. As the training intensity increases from low to high, the gully erosion should too increase as the anthropogenic impact has changed to become more significant.

Figure 4.24 Fort Riley Training Intensity Estimate (Denker (pers. comm.); Hutchinson (pers. comm.); Johnson et al., 2011)

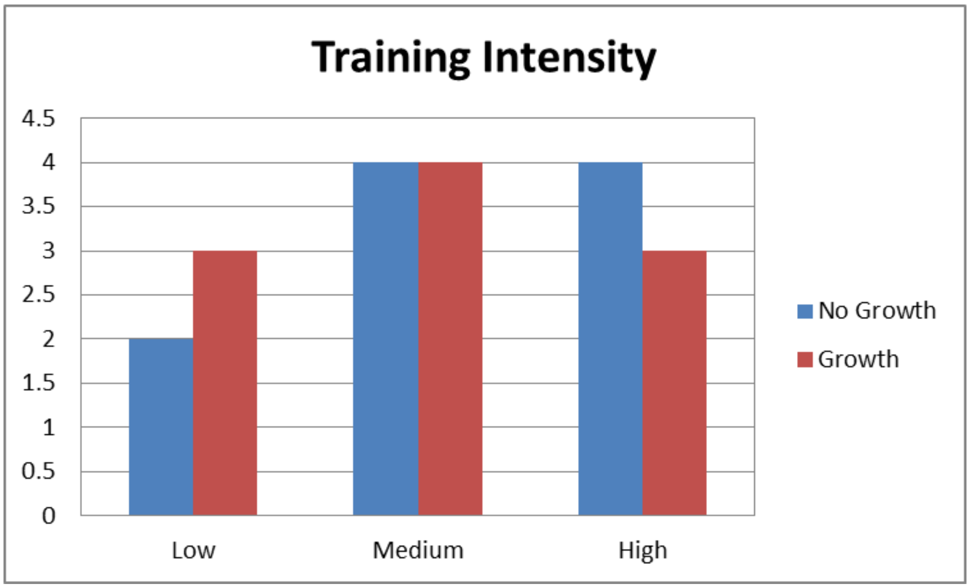


When analyzed using the two data sets, no significant trend was seen that differed between gullies that resulted in headcut progression and those that did not (Figure 4.25). This result suggests that training intensity does not have a significant influence on gully headcut growth at Fort Riley during this specific timeframe.

Multiple reasons could explain why this variable did not have as strong an impact as previously believed. First is the spatial resolution through which training intensity was acquired as opposed to the spatial resolution of the gullies. The gullies are in general 50 m to 200 m in length, whereas the training intensity resolution was assessed at a training area level. The extreme difference between these two measurements creates an excessive amount of error simply due to the inaccuracy of the training layer. While the general training area might be considered to be in high intensity, the exact location at which the gully is located could instead be different depending on where the training actually occurred.

Second, the temporal resolution may play a part in how the gully headcut migration may have occurred. For example, the soil moisture content during which the training happened can alter the effects on the soil erosion. If a higher amount of water was contained in the soil when the training occurred, the soil would become highly compromised and therefore possess a higher potential for erosion.

Figure 4.25. Training Intensity versus Gully Frequency including all 21 gullies (omitting gully 13) separated with respect to headcut growth or no headcut growth



The final predictor variable analyzed in this study is above ground biomass change. This factor offers a unique look at land management by reflecting the direct impact human choices have on the landscape of the watershed. As with the other land management variables considered in this study, change to the above ground biomass can happen quickly relative to the watershed characteristics but is still able to potentially correlate with the gully movement witnessed at Fort Riley in this two-year study.

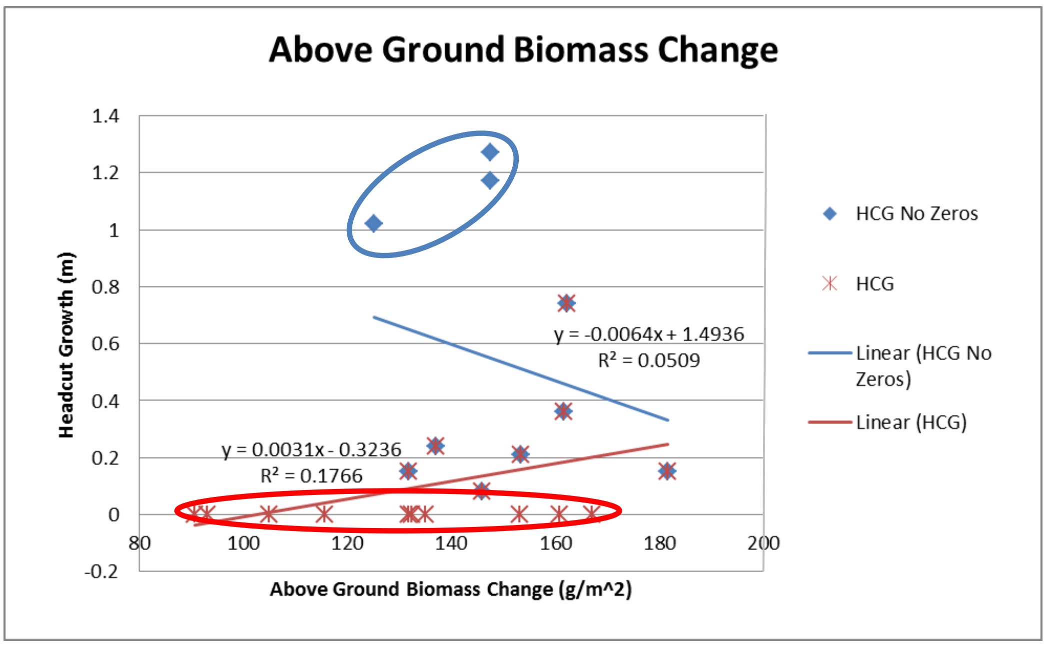
Generally, above ground biomass change will be higher in areas that output the largest amount of erosion. This is due to the amount of plants present in the watershed that are available to deter the erosive movement of the water and keep the soil from detaching. If there is a great amount of biomass change throughout a watershed, this chance for erosion increases and has been supported in increasing the likelihood of gully erosion.

When plotted (Figure 4.26), however, the two data sets outputted vastly different relationships with regards to both direction of correlation and effectiveness of relationship. When all gullies were considered, the correlation was one of the highest of all variables and in the positive direction as supported by literature (Fattet et al., 2011). When only gullies with headcut growth were eliminated, the relationship dropped significantly and the trendline switched to a negative correlation.

These changes in correlations suggest a few possible relationships that cannot necessarily be proven from this study alone. First is that above ground biomass may indeed be an important factor in stabilizing the headcuts of the gullies and keeping them from experiencing any migration. In Figure 21, the gullies with no headcut growth (circled in red) do not greatly skew the relationship between all of the gullies as is seen in many of the previous variables. This result therefore gives support that there may be additional reasoning as to why the above ground biomass change is strongly related to the gullies without headcut growth as opposed to those that experienced that change.

Second, the lack of relationship between above ground biomass change and headcut growth only suggests that this variable is incorrect in establishing a relationship between biomass and gully migration – not a confirmation that no relationship exists. While some literature does support the expected relationship between these two variables, more studies have actually correlated root structure and below ground biomass with gully erosion (Fattet et al., 2011). As water flows along the top of the soil throughout a watershed, some energy will be dissipated due to the compact nature of the above ground biomass. However, with gully erosion, the subsurface flow is at times more important as the runoff seeps horizontally through the soil profile. This movement predominantly occurs when flow reaches bedrock or another form of hardened soil that does not allow for vertical infiltration, forcing the water to move in a horizontal direction and interact with the root systems of the watershed plants. Therefore, other measurements regarding biomass accumulation or change might present a stronger relationship with gully erosion, but were not assessable during this study.

Figure 4.26. Above Ground Biomass Change versus Headcut Growth with data set including all 21 gullies and data set including only gullies with headcut change. Blue circle indicates three outliers not included in Linear HCG trendline and Red circle indicating gullies not exhibiting Headcut Growth



After individually analyzing the 10 predictor variables in this study, there was no one gully variable that directly related to headcut growth for the gullies at Fort Riley during this two-year study. However, many important relationships were established and possible correlations between watershed characteristics and land management tactics have been suggested.

Of the most prominent would be the interaction between watershed characteristics and land management techniques at Fort Riley. With many of the variables in this study, the relationship with headcut growth was in the opposite direction as would be suggested. Since gully erosion has occurred in some gullies during this study, it is unlikely that the networks do not to some degree follow the proven relationships between the variables, but rather another explanation exists.

One reason could be that integration of multiple variables at once could reveal a correct correlation between variable change and headcut growth. In many studies, natural gullies are used as the baseline for gully progression, where watershed characteristics are the only input factors affecting gully growth. In these cases, it is extremely likely that the relationships regarding gully growth would in fact be true. Since the gullies at Fort Riley are by no means natural gullies and are under some type of human influence, the land management layer may indeed offer a strong enough influence to radically alter the expected relationship between headcut growth and watershed characteristics.

In order to rudimentarily assess multiple variables that could be producing certain trends in watershed characteristics and land management, a few gullies were specifically analyzed (Figure 4.27). Two gullies without headcut growth (gullies 19 and 38) and three gullies resulting in headcut growth (gullies 5, 23, and 37) were each analyzed individually with regards to each explanatory variable to better understand the possible reasoning for variations in headcut outputs.

Watershed slope, the first variable analyzed with each of the five selected gullies, revealed a range of gully headcut outputs. Gully 23 was among the lowest watershed slopes within this data set and also produced one of the smallest headcut growths, though its change was not zero. Gullies 5 and 19 both contained watershed slopes of approximately double that of gully 23, but one gully resulted in no headcut growth while the other did show some change. This fact suggests that some other factor significantly played a role with these two gullies and dictated the difference in headcut growth. Gully 37, with a watershed slope again approximately double that of gullies 5 and 19 produced a headcut growth of nearly three times that of the change seen in gully 5. Additionally, gully 37 was one of the highest watershed slopes of the group with headcut migration, which would suggest that it should also have some of the highest values regarding other watershed characteristics. Gully 38, the other gully without headcut being individually analyzed, resulted in the highest watershed slope. This placement suggests that some other factor is significantly influencing the potential for headcut growth as this large value in watershed slope should have correlated with the greatest headcut migration.

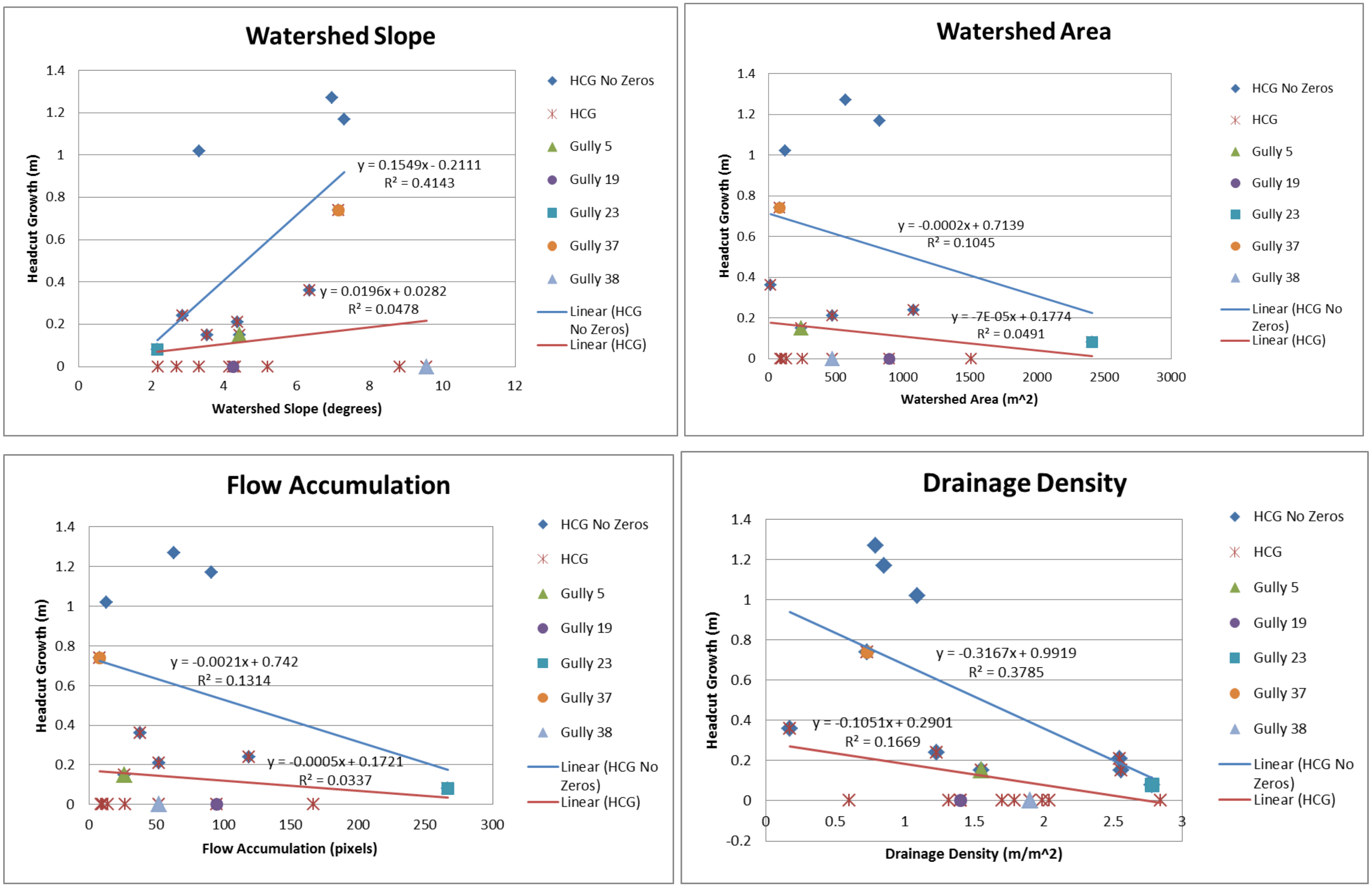
The next variable, watershed area, flipped many of the correlations seen with watershed slope. For example, gully 37 – one of the gullies with the largest watershed slope, was among the lowest in watershed area. Gully 5 also correlated with an extremely low watershed area even though the headcut growth relating to this gully was approximately a fourth of that of gully 37. Lastly, gullies 23 and 38 essentially switched locations with each other with gully 23 representing a watershed area of nearly five times that of gully 38. While the three gullies with the highest headcut growth did not act as predicted with regards to watershed area, some of the gullies without headcut migration did associate with lower values of watershed areas and therefore support the previous literature on erosion and watershed area (Chaplot, 2013).

Flow accumulation exhibited results very similar to watershed area in the thought that the individually assessed gullies were located in opposite locations as watershed slope. Gully 23 again correlated with one of the largest values – approximately 5 times that of gully 38 – but produced a headcut growth of much lower than the other gullies resulting in headcut migration. This continual reversal of expected values particularly with one gully suggests that watershed slope is the underlying importance. Within reasonable limits, the watershed area and flow accumulation are not significant unless the slope of the watershed is large enough to accelerate the energy of the water slow

The next variable, drainage density, generally resulted in opposite trends as supported by current literature (Vijith et al. 2012). Additionally, the relationships between each individual gully analyzed and their output headcut growth was less realistic with regards to the results expected. For example, many of the gullies that produced zero headcut migration were near the middle of the pack within this data set as opposed to at the lower end. Also, the three largest headcut growths were again amongst the lowest drainage densities, suggesting that infiltration potential of a watershed is not as significant with regards to gully erosion at Fort Riley during this two-year study as previously contested. This thought is again supported by gully 23 correlating with one of the highest values of drainage density, and yet one of the lowest headcut growths. Without a significant watershed slope, enough energy cannot be accumulated to accelerate the water to gully erosion levels, no matter the infiltration or water amount assembled.

Ultimately, it appears that watershed slope has an even greater influence on determining the potential headcut gully growth than previous assessed. Some of the gullies individually analyzed that followed proven trends with regards to watershed slope, for example, produced significantly opposite correlations for other watershed variables. Additionally, the largest of the headcut growths continually related to lower values regarding watershed are, flow accumulation, and drainage density, yet the two most significant headcut migrations were well over the average watershed slope in this data set. Both of these trends suggest that without a significant watershed slope, extreme headcut growth is not likely to occur.

Figure 4.27 Watershed Characteristics including linear trendlines for the gully subset including gullies without single headcut progression (red) and for the gully subset excluding gullies without single headcut progression (blue)



Watershed characteristics are not the only types of factors that can potentially effect gully soil progression at Fort Riley military base. As a location utilizing occasional burning regimes and vehicle training, the land management variables could play an important role in dictating the level of erosion occurring throughout the installation.

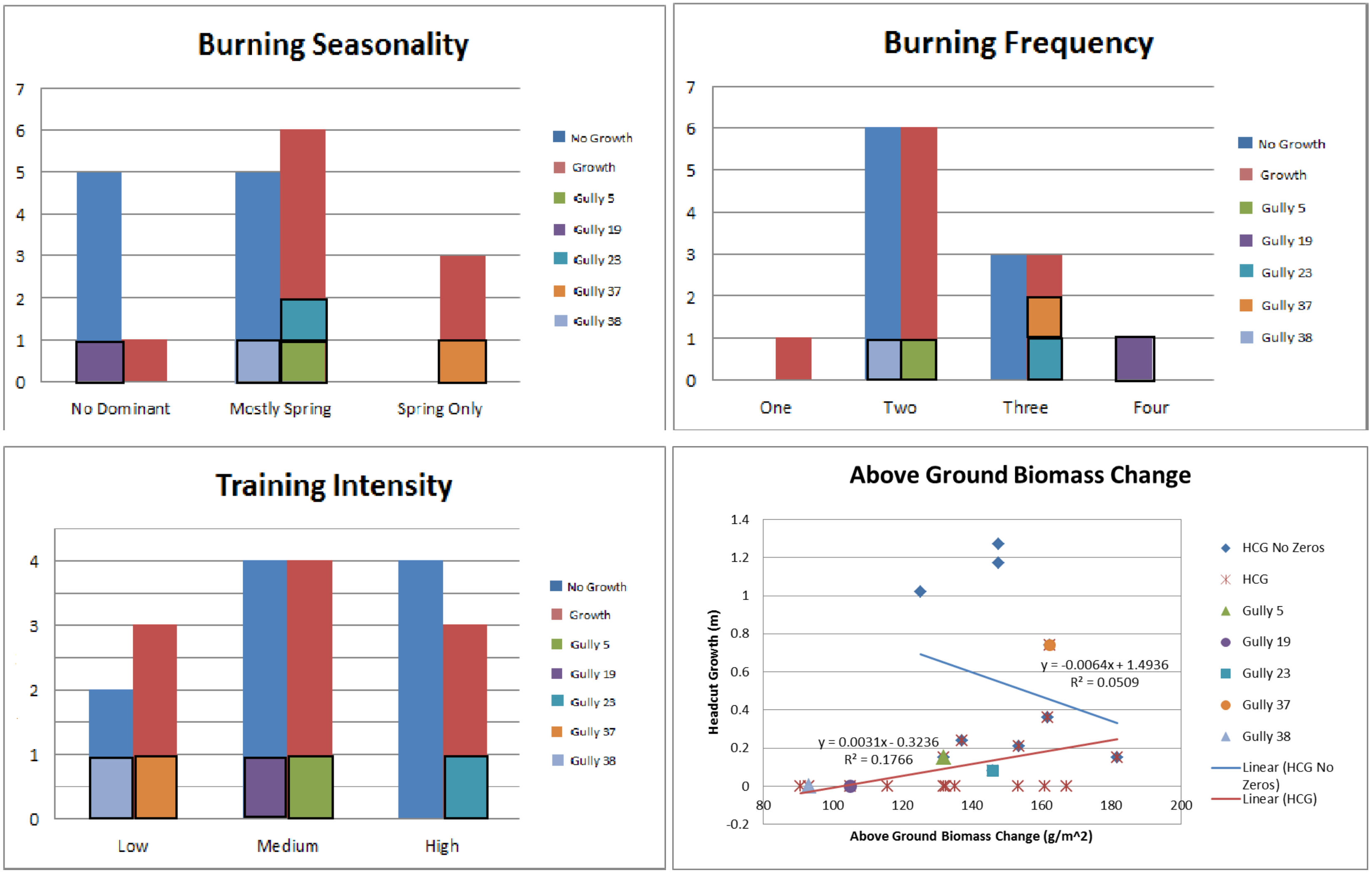
Burning regimes at Fort Riley can be categorized into two different variables – burning seasonality and burning frequency. When the individual gullies were analyzed via burning seasonality, gully 37 correlated with spring only burns even though this gully produced one of the highest amounts of headcut migration. When this gully was assessed for burning frequency, it was also one of the gullies with the highest number of burns during the past year. These largely contradictory results suggest that burning factors may not play an important role in determining gully headcut growth, or that the burning variables are indirectly altering another variable that could be effecting gully headcut migration. This thought is supported by the fact that gully 19, a gully with no headcut growth, is located in a zone that was burned 4 times during the past 10 years, again going against the suggested trends in the literature (Cawson et al., 2012).

The most unique variable analyzed in this study – training intensity – did not offer much explanation regarding why certain gullies experienced headcut migration and others did not. For example, gully 23 – one of the lowest values with regards to headcut growth, was located in a training area identified with high levels of training intensity. Had this gully correlated with lower intensities than the other gullies experiencing extreme headcut growth, training intensity could have been the variable uniquely explaining the differences in results. No trends were available to differentiate between gullies with or without headcut growth either.

Change in above ground biomass, the final land management variable examined in this study, relates the biomass conditions to the timeframe during which the change in headcut migration occurred. As the change becomes greater, the headcut growth should to be greater. The most notable trends presented through this specific variable is the variance between gullies 5 and 19 – the two gullies with approximately the same watershed slope. With each other variable, there did not appear to be a logic reason for why the two correlate with the same watershed slope, the watershed characteristic appearing to be most important for gully headcut erosion at Fort Riley. However, these two gullies did experience reasonably different changes in above ground biomass with gully 5 – the gully resulting in headcut growth – relating to a larger change in above ground biomass. Additionally, gully 37 was among the gullies with the highest change in above ground biomass with gully 23 landing roughly in the middle of the data set. These correlations between the individually analyzed gullies give support that there is indeed some trend between change in biomass and headcut growth.

Ultimately, it does not appear that any land management variables, on an individual gully analysis level, are extremely explanatory of gully headcut progression at Fort Riley during this two year study. This could be a result of an inability to properly analyze all variables at once instead of on individual basis, or it could suggest that an incorrect set of predictor variables were chosen. The above variables, while all supported as important erosion factors or logically sound possibilities, do not represent all of the influences possible on the military base. All of the variables, for example, were required to be quantitative so to provide numerical support for or against strong correlations. This meant that many visual observations recorded while in the field could not be represented in the above data. However, photographs taken in the field do allow for qualitative interpretations of factors such as in channel vegetation and soil compaction.

Figure 4.28 Land Management Techniques including linear trendlines for the gully subset including gullies without single headcut progression (red) and for the gully subset excluding gullies without single headcut progression (blue)



One intriguing variable with regards to gully erosion is the amount of vegetation in the gully channel. Some of the gullies, such as gully 5 in Figure 4.29, contained very little vegetation within the channel. Additionally, the few clumps that did exist in the channel, their roots were not secured into the soil. Other gullies, such as gully 19 in Figure 4.30, had large amounts of vegetation throughout the entire gully bottom and were secured permanently with root systems in the gully soil.

Figure 4.29 Gully exhibiting Headcut Growth with significantly little vegetation and no well-established flora

Figure 4.30 Gully exhibiting No Headcut Growth with medium vegetation in the gully bed containing well established root systems

When this observation was applied to all of the gullies in this study, a slight trend appeared between gullies that did or did not produce headcut change. Of the group of ten gullies that did not experience headcut growth, seven contain medium or extreme vegetation in the gully channel bottom. Additionally, within the group of 11 gullies that did produce some degree of headcut growth, seven were observed as having very little to medium vegetation in-channel. This trend suggests there may be a correlation that as the vegetation becomes more established within the gully bottom, headcut growth is less likely.

In some instances, such as gully 19 in Figure 4.30 above, some of the vegetation may have recently fallen in from sidewall failure (circled in red). This observation suggests that vegetation in the gully channel may actually be more closely related to the width change seen over this two-year study, and thus advocating that gullies with high amounts of gully bottom vegetation should be monitored for width change and not necessarily headcut migration.

Table 4.4 Summary table of in-channel vegetation in the 21 gullies studied at Fort Riley, KS

Gully Number	In-Channel Vegetation
5	Very little vegetation
6	Very little vegetation
13	Very little vegetation
14	Some vegetation
15	Medium vegetation
16	Extreme vegetation
17	Medium vegetation
18	Medium vegetation
19	Medium vegetation, Healthy
21	Some vegetation
22	Very little vegetation
23	Very little vegetation
24	Extreme vegetation
26	Medium vegetation
33	Medium vegetation
34	Extreme vegetation
35	Very little vegetation
37	Very little vegetation
38	Very little vegetation
39.1	Extreme vegetation, Established trees
39.2	Medium vegetation

Compaction and infiltration are two other common erosion assessment tools that allow for proper evaluation and prediction of soil movement potential. While no quantitative data was taken directly relating to either variable, qualitative photos and observations can again be used to support general trends throughout certain sets of gullies.

In gully 23 in Figure 4.31, the gully bottom is bedrock controlled, as opposed to gully 26 in Figure 4.32, where the gully bottom is much softer and offers a surface more prone to infiltration. With bedrock controlled gullies, water cannot penetrate the solid layer and is less likely to infiltrate in a vertical direction. This water is then left to flow in a horizontal direction, accelerating headcut migration in the direction of the flow path. In gullies with more absorbent soils, infiltration in a vertical manor can occur and therefore deters the water from transporting the soil located at the gully headcut.

Figure 4.31 Gully exhibiting Headcut Growth at Fort Riley with bedrock bottom and headcut

Figure 4.32 Gully exhibiting No Headcut Growth at Fort Riley with soil gully bottom and headcut

When applied to all 21 gullies in this study, the trend is supported through gullies with and gullies without headcut growth as 5 of the 6 gullies identified as having bedrock controlled bottoms were also gullies that resulted in headcut growth. This trend is supported by the above logic relating bedrock layers to water flow direction.

Weather Data

Gully erosion is dependent on not only physical factors and the terrain, but also the input factor of erosive energy, primarily overland runoff from excess precipitation. Without water flow into the gully system, the network will not show any type of growth, therefore potentially dictating the type of analysis required. One of the most effective ways to determine the level of erosion within an area is by calculating the runoff potential of a region.

Two necessary criteria are needed in order to calculate the runoff potential for a given storm. These are storm intensity and prior precipitation. Without intensity, there will not be enough energy behind the water flow to adequately dislodge the soil particles from the surrounding soil. Without precipitation build-up, the soil will be dry enough to infiltrate a large amount of the runoff transporting over the gully system instead of traveling along the soil surface. This soil sum is referred to as the antecedent soil moisture. When this value reaches a 5 day precipitation accumulation of more than 50 millimeters, the storm has reached the threshold and has the potential of creating water runoff. However, there is not a generally accepted threshold that defines erosion potential for intensity during a certain time period. In order to provide a reasonable estimation of erosion causing storms, an intensity of more than 10 millimeters per hour was used in this study. From this criterion, it was determined that 7 storms between the dates of May 1, 2010 and August 31, 2012 were significant enough to potentially create soil erosion via water transport (Table 4.6).

Table 4.5 Hourly precipitation data significant enough to potentially create soil erosion (adapted from Kansas State University: Research and Extension, 2013)

Events	Date	1 Hour Intensity (mm/hr)	2 Hour Intensity (mm/hr)	3 Day Precipitation Sum (mm)	5 Day Precipitation Sum (mm)
1	06/13/2010	17.8	10.0	60.6	60.6
2	06/16/2010	20.6	10.3	51.3	91.9
3	06/20/2010	10.4	9.8	33.8	74.4
4	05/25/2011	12.5	6.5	45.2	56.9
5	06/02/2011	22.9	15.5	99.3	99.3
6	03/21/2012	10.4	5.7	47.7	47.7
7	08/25/2012	14.5	11.2	80.8	81.0

Two important notes were considered when viewing this weather data and applying it successfully to the field data collected regarding gully progression. First, seven events is the best estimate for each gully even though some gullies were installed or resurveyed inside of this weather range. For example, some gully reference pins were installed late in June 2010, meaning the rain events prior to that data would not have an effect on the observed gully change. Also, some gullies were remeasured before August 2012, meaning that the final rainfall event may have again occurred outside of the change timeframe.

Second, this data was recorded at the North Agronomy Farm located along the northern border town of Manhattan and 30-45 kilometers from Fort Riley depending on the exact location being considered. Precipitation intensity can drastically change within a much smaller range, even within a couple of kilometers. Therefore, a great deal of error likely exists between the intensity measurements taken at the airport and the runoff intensities realistically witnessed at each gully location. This lack of precise weather data creates a substantial issue for erosion studies and makes prediction and modeling nearly impossible due to the large span of errors that could potentially be associated with each site.

When this data was applied to the output results measured at each gully network, the lack of significant change seems realistic and supported. For example, since there were relatively few erosion causing precipitation events during the two year span of this study, it would not be realistic to expect excessively high or extreme width, depth, or headcut changes. Therefore, the frequency of zero or low change over this two year time is ultimately to be expected.

Statistical Analysis

Previous studies have used both field and design erosion processes to produce predictive equations regarding gully progression (Sidorchuk et al., 2003; Torri & Borselli, 2003). From this research, it has been established that most erosive patterns exhibit some type of non-linear relationship with regards to the independent variables chosen and the dependent erosion analyzed. Additionally, a majority of this research focused on only a few predominant factors – sometimes with only one at a time – opposed to determining a predictive equation encompassing both watershed characteristics and land management techniques. Therefore, producing a multiple relationship regarding the following independent variables (Watershed Slope – WSS, Watershed Area – WSA, Flow Accumulation – FA, Drainage Density – DD, Training Intensity – TI, Burning Frequency – BF, Above Ground Biomass Change – AGBC) was performed with specific R Programming code listed in Appendix E.

Prior to outputting a predictive equation for Headcut Growth at Fort Riley, KS, the assumptions made regarding multiple regression were assessed. These assumptions included the following:

- linear relationship between the dependent and each independent variables
- independent variables unrelated to the error
- homoscedasticity
- residuals normally distributed
- lack of outliers

The first three assumptions were assessed using scatterplots for each independent variable with regards to the dependent variable of headcut growth. Figure 4.33 displays one of the most definitive independent variables – Watershed Slope. This variable produced a generally linear progression when plotted versus Headcut Growth and did not show any major jumps or outliers in error, suggesting error had no effect on the dataset. The scatterplot representative of each independent variable is listed in Appendix F.

Figure 4.33 Scatterplot of Watershed Slope vs Headcut Growth used to assess linearity, error trends, and homoscedasticity of variables

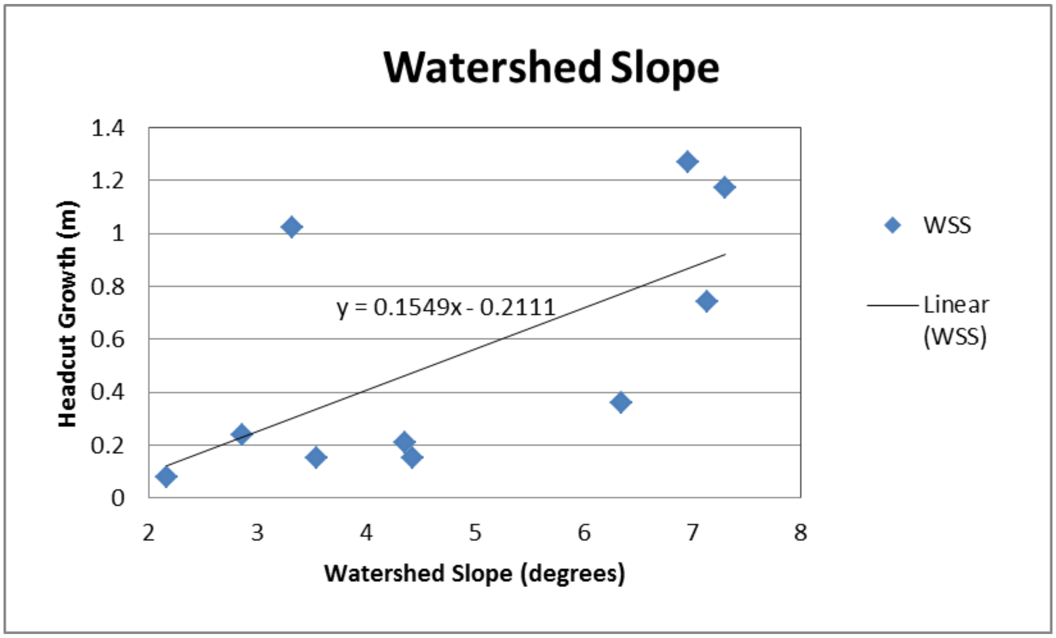
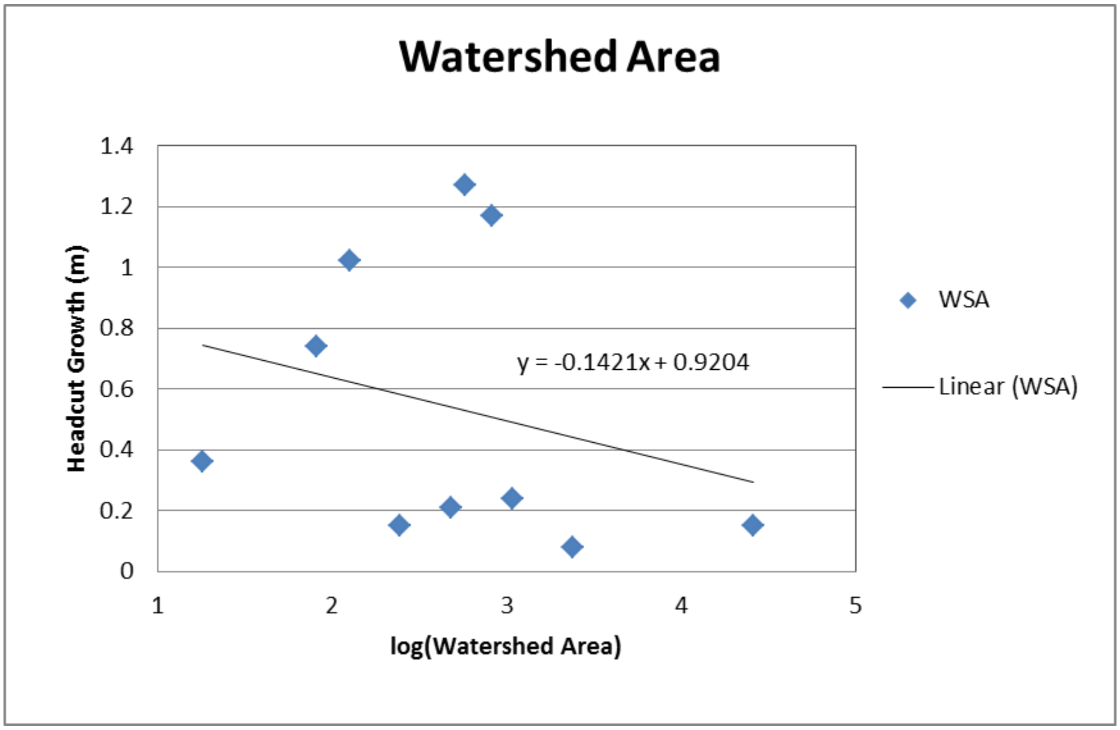


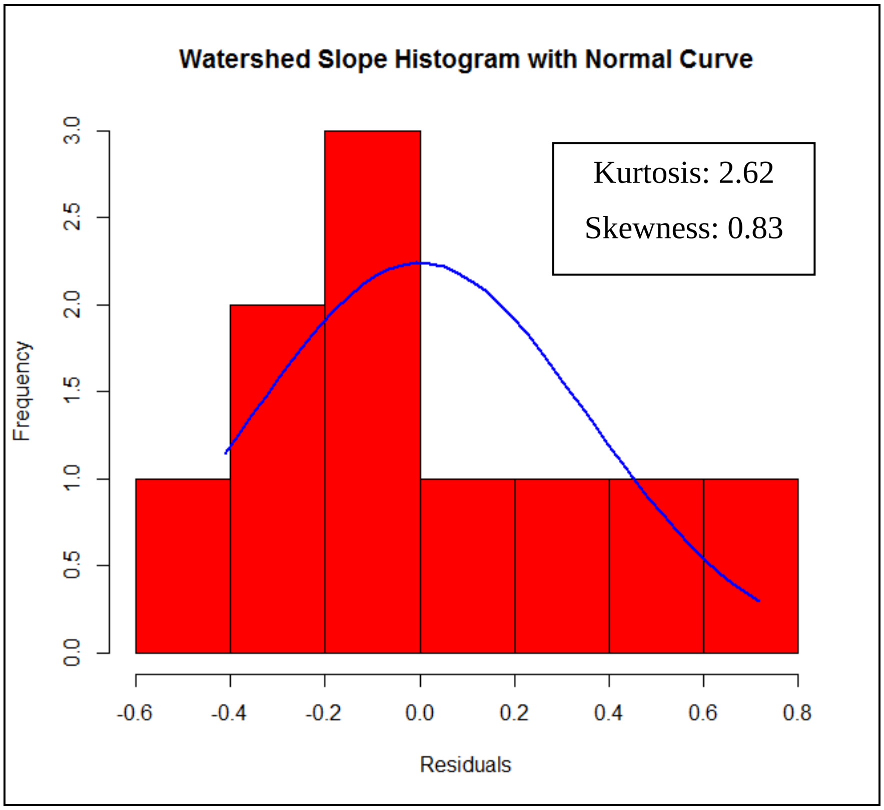
Figure 4.34 represents a variable – Watershed Area – with a less definitive linearity and homoscedasticity. The independent variable, when plotted versus Headcut Growth, showed a less significant linear trend. Additionally, the error in the data may have an influence on the relationship as the distance between the trend line and actual values decreases as the log of the Watershed Area increases. Regardless of the small variations in the scatterplot assessments, all seven independent variables were deemed appropriate for multiple regression with respect to linearity between the dependent and independent variable, error trends, and homoscedasticity.

Figure 4.34 Scatterplot of log(Watershed Area) vs Headcut Growth used to assess linearity, error trends, and homoscedasticity of variables



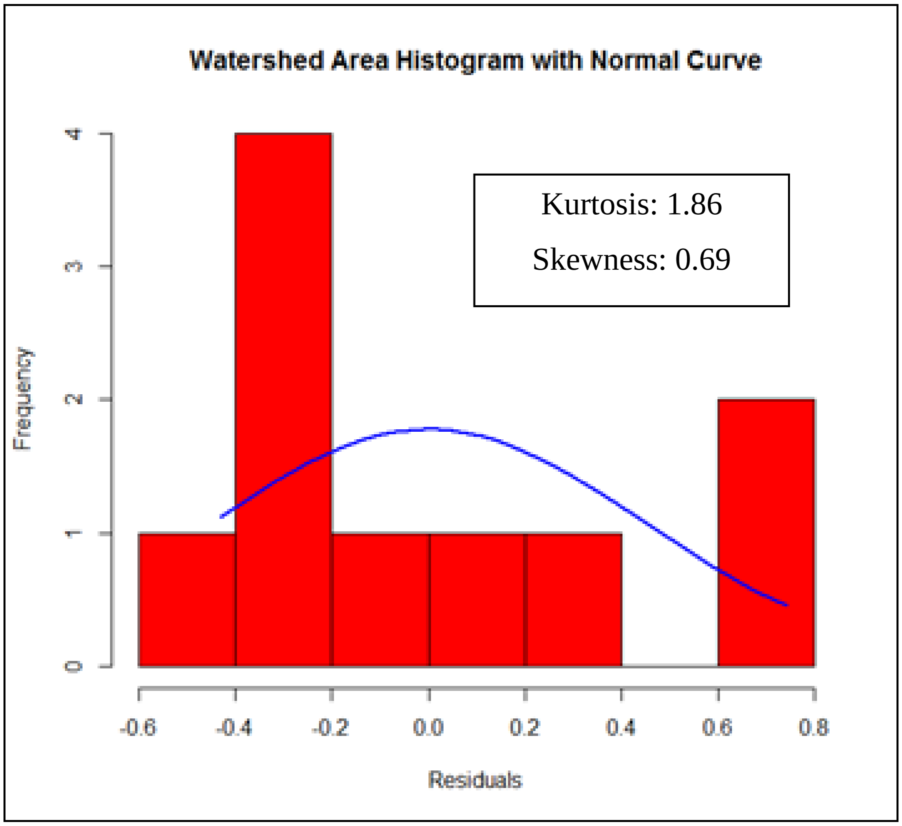
The fourth assumption, normal distribution of residuals, was assessed using histograms and normal curves for each independent variable. Figure 4.35 depicts one of the variables most closely related to a normal distribution. This is supported visually using the actually bar graph and its similarity to a normal distributed dataset, as well as numerically through kurtosis and skewness. For Watershed Slope, kurtosis proved to be 2.62 with a value of 3.0 being the ideal amount for a normal distribution, with the variable's skewness being 0.83 with 0.0 being the value associated with a normal dataset. The histogram representative of each independent variable is listed in Appendix F.

Figure 4.35 Residual plot of Watershed Slope with Normal Curve to determine dataset distribution



As with the first three assumptions, some independent variables were less ideal with regards to the criteria required for accurate multiple regression. Figure 4.36 displays one of the independent variables that did not produce an exact correlation with a normal distribution of residuals. The log of Watershed Area resulted in a kurtosis further from the ideal value of 3.0, but did prove to be less skewed than some of the other variables in this study. Additionally, only a few values are ultimately restricting this variable from producing a normal distribution, deeming this independent variable, and the seven total being assessed, appropriate with regards to the fourth multiple regression assumption.

Figure 4.36 Residual plot of log(Watershed Area) with Normal Curve to determine dataset distribution



The fifth and final assumption commonly made regarding multiple regression states that a lack of outliers exist within the dataset. In this study, only 11 gullies successfully met the criteria outlined for single headcut gully progression, with one of those gullies being an outlier with regards to headcut growth. Therefore, only 10 gullies were assessed for each independent variable. If outliers had been properly assessed and eliminated from the dataset with respect to each independent variable, even fewer data points would have been available for representative analysis. This decrease in data would have further skewed and invalidated the predictive ability of this study, so a lack of outliers was not necessarily guaranteed for all variables. Nonetheless, this assumption was deemed met and multiple regression could be performed. All additional variable graphs for multiple regression analysis are included in Appendix D.

Using an automated multiple stepwise regression in R Programming, the following equation was produced using the above mentioned seven variables regarding Headcut Growth at Fort Riley, KS:

$$HCG = 0.666 + 0.137(WSS) - 0.478(TI) + 0.757(\log[WSA]) - 0.278(DD) - 0.0138(AGBC) + 0.187(Bfreq) \quad (R^2=0.902) \qquad \textit{equ. 4.1}$$

where WSS = Watershed Slope (degrees),

TI = Training Intensity,

WSA = Watershed Area (pixels),

DD = Drainage Density (m/m^2),

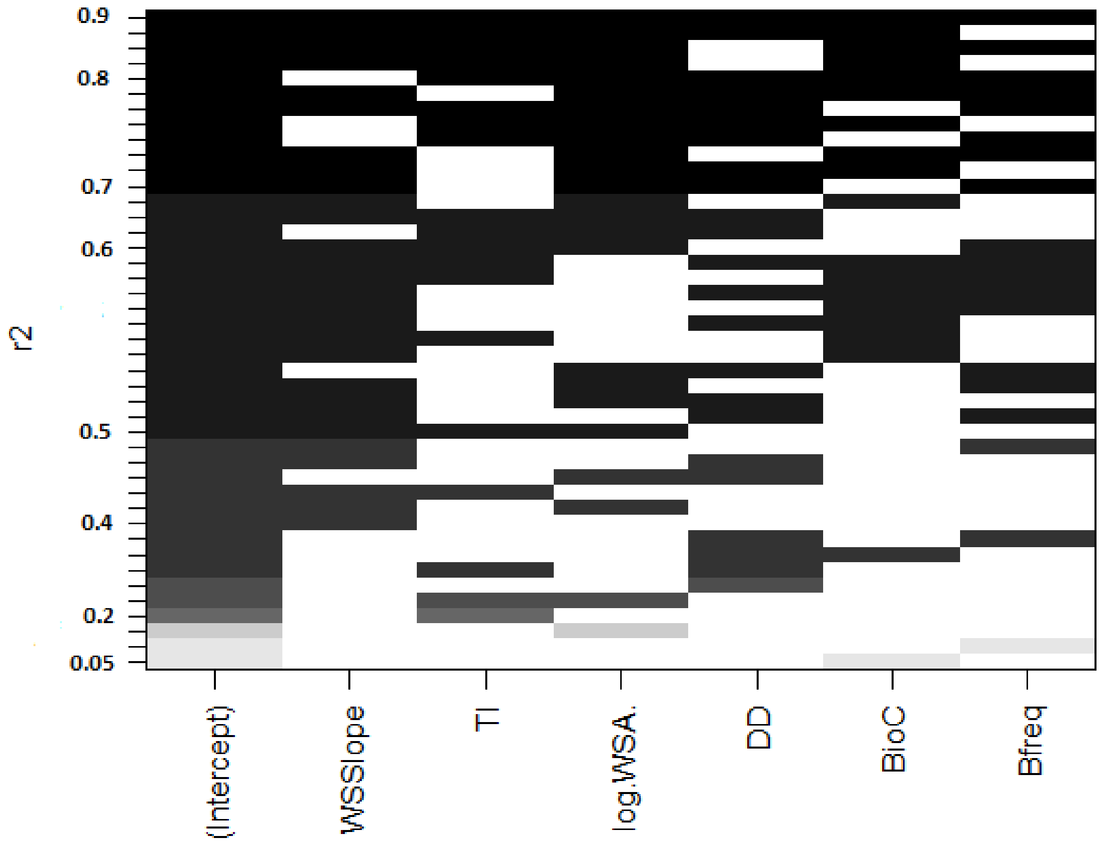
AGBC = Above Ground Biomass Change (g/m^2)

Bfreq = Burning Frequency (years).

Only one variable, the log of Flow Accumulation, was eliminated from the seven total input independent variables. This elimination is supported by the scatterplot derived for Flow Accumulation and Headcut Growth, where the relationship supported by literature is not produced by this dataset. As one of the most fundamental driving forces behind erosion potential – the amount of water flowing into the network – it is logical that the opposite correlation would not benefit a predictive equation regarding gully erosion.

With a multiple R^2 value of 0.902, just over 90% of the relationship between these independent variables and the independent variable (Headcut Growth) is explained by this set of six factors. Figure 4.37 – an all subsets regression in R Programming – was used to confirm this combination of variables produces the best predictive equation. When all six variables are considered, the R^2 value reaches its peak value.

Figure 4.37 Independent Variable Selection Matrix with [HeadcutGrowth = Intercept + WatershedSlope + TrainingIntensity + log(WatershedArea) + DrainageDensity + AboveGroundBiomassChange + BurningFrequency] as the most predictive equation

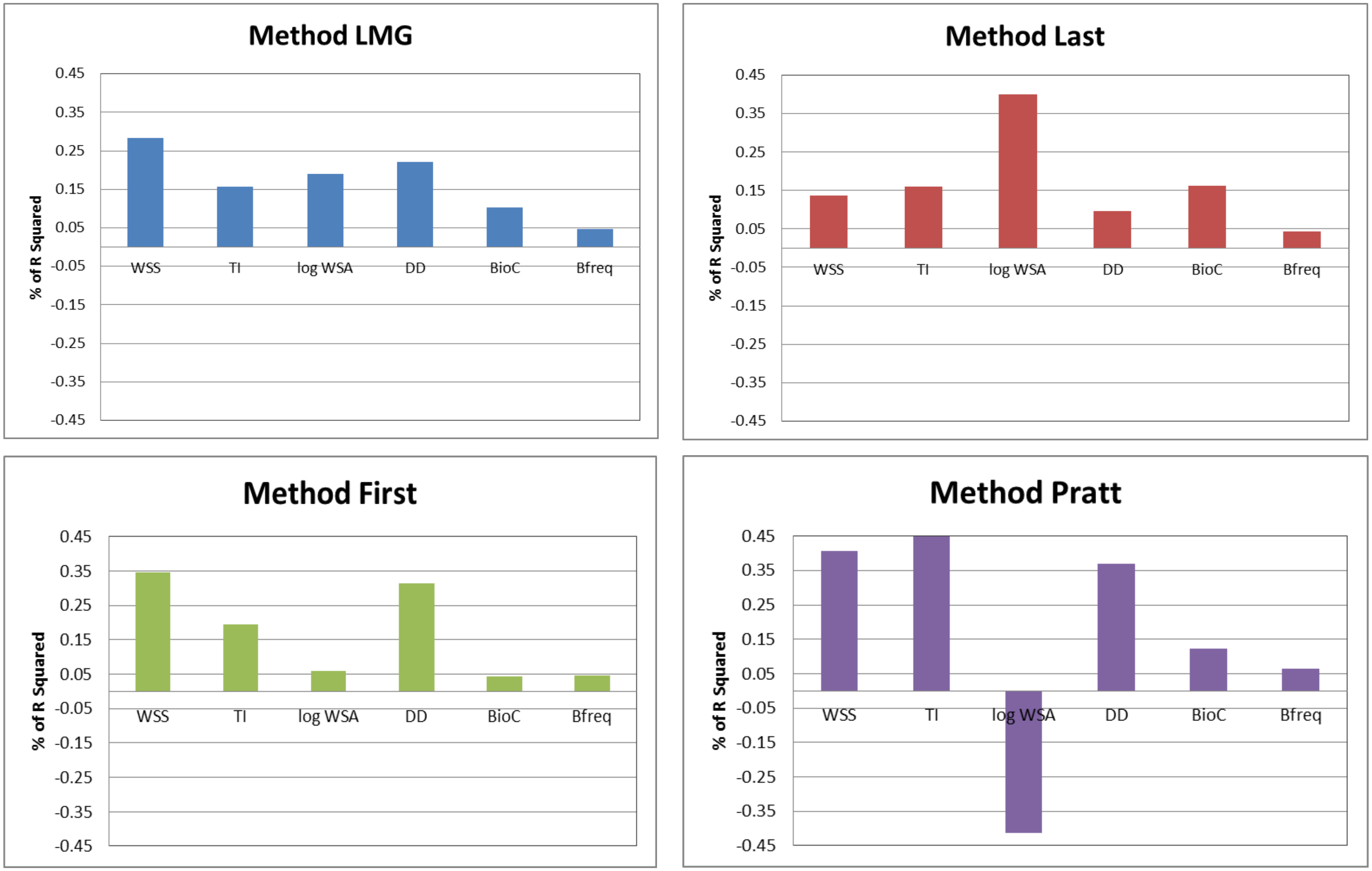


Once the most predictive model was determined, as assessment of the importance of each independent variable could be completed. Four common methods (LMG, Last, First, Pratt) were utilized to accurately represent the most significant variable with all four results displayed in Figure 4.38.

Of the six independent variables included in the predictive Headcut Growth equation, Watershed Slope proved to be the most significant in two methods (LMG and First) and the second most significant in one other method (Pratt). Drainage Density was the second most important variable in two of the methods (LMG and First). In all four methods, Burning Frequency was among the least significant independent variables, suggesting that its influence on the overall predictive ability of the Headcut Growth equation is not as important.

Generally, watershed characteristics more consistantly displayed a significant portion of the predictive ability of the Headcut Growth equation. Land management techniques, while showing some spikes in significance using the Pratt Method, were more consistantly found in the middle to low important range regarding the six total independent variables considered. This result suggests that at Fort Riley, land management techniques are not as important in predicting the headcut growth produced over this specific timeframe.

Figure 4.38 Independent Variable Relative Importance to Predictive Headcut Equation represented in percentage of R Squared value ($R^2 = 0.902$)



Ultimately, Watershed Slope representing a large percentage of the total R^2 of this predictive equation is supported throughout this study.

An R^2 value of 0.902 is one of the most significant relationships produced with regards to other studies focused on predictive equations and gully erosion. This value could be improved, however, by utilizing different variables in place or in addition to the seven considered in the multiple regression analysis.

One significant variable potentially absent from the predictive equation and accounting for the missing 10% is compaction. Multiple proxy variables have been developed to estimate the overall compaction of a watershed or determine the exact value at a specific point including clay percentage, soil type, distance to bedrock, and land management techniques. Regardless of the estimation used, total soil compaction is difficult to accurately represent, but has continually proven to alter the erosion potential of an area.

Vegetative cover is another absence partially represented in this study. However, determining the below ground biomass may be the more important technique to represent vegetative cover, and therefore partially represent the missing 10% of the predictive equation for Headcut Growth.

Chapter 5 - Summary and Conclusions

Land management changes significantly impact the environmental properties of a landscape and lead to devastating alterations in the soil and water cycle processes. These changes can result in extreme levels of soil erosion that cannot be reversed. Some research has been conducted to access the relationships between this degradation and land management, but very little of this research has been done regarding military installations and maneuvering. This study focused on gully erosion progression on military training bases not only because of this lack of previous research, but also because the threat it produces towards soldier safety and equipment maintenance. A better understanding of the relationships between various environmental factors and gully formation will significantly contribute to a decrease in solder injuries, equipment damage, and environmental degradation caused by gully erosion.

The goal of this study was to record and assess gully erosion progression occurring on Fort Riley by correlating measured response variables with attribute predictor variables. Three response variables – headcut growth, depth change, and width change – were calculated by utilizing data pins installed during the summer of 2010. Additionally, 10 commonly accepted erosion causing factors were paired with each gully data site and used to determine any relationships that may exist categorically or numerically between the gullies.

In order to produce the most accurate and useful erosion model possible, as well as analyze any significant trends within the recorded data, all response and predictor variables were run through a set of frequency analyses techniques with regards to the 21 gullies meeting definition criteria. Initially, outliers for each variable were calculated using Inner Quartile Ranges to determine which gullies were outside of the dataset. Each variable was then tested for normal distribution and assessed on a scatterplot versus headcut growth. In support of the research objectives of this study, this process was again completed, but this time only for gullies that produced single headcut growth.

Of the watersed variables assessed (Watershed Slope, Watershed Area, Drainage Density, Flow Accumulation, Clay Percentage, Aspect), some notable trends were extracted. Watershed Slope was the one variable that was highly correlated to headcut growth in the direction supported through current literature. This relationship suggests that at Fort Riley, watershed slope is the most significant watershed variable needed to predict headcut progression over this short timeframe. Aspect also produced an interesting trend as all of the 21 gullies considered in this study face with an Eastern orientation. When combined with the storm progression typically seen in Kansas where weather front move from west to east, it can be concluded that gullies are more likely to form in watershed oriented horizontally.

The second group of variables considered was land management techniques including Training Intensity, Burning Frequency, Burning Seasonality, and Above Ground Biomass Change. Some trends did result from the analysis of each variable to headcut growth, but more significant conclusions can be made with the representation of land management.

First, times during which high levels of training occur also need to be monitored to better assess in what conditions might have a more significant impact on gully progression. For example, above ground biomass change was only a once-a-year proxy for the amount of total vegetative cover throughout the watershed. Vegetation, however, is more likely to significantly change during the seasons and not just between the same dates two years apart. Since training intensity is not segregated depending on seasonality, any correlation between this presence or absence of vegetative cover cannot be effectively made. Weather and soil conditions relating to precipitation also cannot be strongly correlated with training levels. One particular area of interest would be to determine the level of causation between soil moisture and military training and to determine to what magnitude wet soil conditions impact gully progression. Without knowing more about the timing of training passes, however, these relationships will remain unknown.

Second, there is a need for more accurate spatial and temporal training monitoring and data accumulation within military installations. In this study, some of the most recent assessments of military foot and vehicle traffic were used. Nonetheless, this data still required that the training intensity be generalized over an entire training area. By assigning an intensity to an entire training area (some ranging near 1 km by 1 km), minute changes in track passes are severely generalized. When the size of this study area is compared to the size of the average gully in this study, the difference allows for significant estimation of the resulting compaction and deterioration of the soil. Comparing the training area size to the average watershed size within this study also hints towards the production of large, inaccurate training impact representation.

Third, vegetative relations to gully progression should be numerically represented. In this study, visual comparisons are made between many gullies exhibiting headcut growth against those that did not. One of the most significant conclusions is that gullies with bedrock bottoms produced a large amount of headcut growth. If water is not allowed to move vertically through the soil profile, the water will significantly move horizontally throughout the gully network and create a higher potential for gully growth. Additionally, gullies without headcut growth typically contained a larger amount of in channel vegetative cover. This conclusion not only suggests a relationship between biomass within a gully bottom, but also between root structure and presence to negate the shear stress caused by water movement. These significant conclusions support an addition of numerical representation of each variable in future studies.

Lastly, with regards to land management technique variables, compaction was not accurately considered in this research. While some variables such as training intensity, soil structure, and biomass can potentially be used to estimate the compaction of an area, the accuracy of each proxy can be questioned.

Numerical modeling was conducted using Multiple Variable Regression Analysis. Using backwards stepwise comparisons, an equation containing six of the possible seven independent variables was produced. This equation, Headcut Growth = 0.666 + 0.137(Watershed Slope in degrees) – 0.478(Training Intensity) + 0757(log[Watershed Area in pixels]) – 0.278(Drainage Density in m/m^2) – 0.0138(Above Ground Biomass Change in g/m^2) + 0.187(Burning Frequency in number of years), proved to significantly predict the progression in gully headcut movement with an R^2 value of 0.903.

Four models were then used to determine the importance of each variable with regards to headcut growth progression during this study. In two of these models, Watershed Slope proved to be the most important, and was the second most important in a third model. As suggested in the individual linear analysis, Watershed Slope was therefore the most predictive of the independent variables used to calculate headcut growth at Fort Riley.

While the predictive equation produced in this study is statistically significant, the gully experiencing more than 17 meters of headcut migration, may indeed not be considered an outlier, but rather the norm during a greater number of rain events. Had more erosion causing precipitation events occurred, more gullies would have likely output the same intensity of headcut change, making the 17 meter gully migration less of the exception and rather more of the overall expected value. Kansas, for example, was considerably behind in precipitation values throughout this study, suggesting the dry weather of the recent studies could alter whether outliers should realistically exist. As a result, further long-term studies are needed that allow for significant rainfall events to occur that produce both the needed precipitation and intensity for gully erosion to occur.

Gully erosion located at military installations presents a unique and treacherous hazard to both training equipment and soldiers. To accurately and effectively avoid these issues created by degradation of the soil and interlocking environment, gully erosion progression must be better understood. This study was the first of its kind to intertwine various underlying causes of gully erosion and the physical changes witnessed at the gully locations. This could be improved by studying a more extensive set of gullies at Fort Riley. As a result, the frequency analysis and model prediction could prove to be more accurate.

Erosion progression models are capable of ultimately determining which gullies will likely pose the greatest of threats to soldier safety and equipment management. Additionally, gully categorization will allow for cross comparison of gully networks. Both of these study outputs will together keep soldiers safe and decrease the cost associated with equipment damage caused by gully erosion. Once gully development is better understood, it can aid in the acceptance of sustainable training exercises throughout military installations. This alternate approach to sustainable practices will alter the land management techniques utilized and ultimately slow the negative effects seen from environmental degradation.

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Appendix A - Gully Reference Pin Installation Methodology

New Gully Installation

While all of the gullies directly utilized in this study via headcut, width, and depth growth were previously pinned in 2010, some additional gullies had been located but not installed with reference pins during the 2010 research. This was either because the gully did not meet the predefined gully definition or because there was not enough time to visit and adequately install pins late in the season. Therefore, gullies that now met the one meter in width definition were equipped with headcut, width, and depth reference pins in 2012 so to begin monitoring for further studies.

Identical instilation methods were mimiced from the 2010 study with only minor changes in materials. As with in the 2010 study, gullies had to meet the one meter in depth definition before they would be installed with gully pins. All pins installed in 2012 were created using half-inch rebar that had been cut to two foot-long lengths. Two reference headcut pins were placed at a perpendicular angle to the water that flows into the gully head. The closest pin was installed approximately one meter from the current headcut. This point was recorded on the Archer Handheld GPS while a second reference pin was placed one additional meter from the headcut in a perpendicular line to the current gully head.

An erosion pin was also installed at the widest location along the gully. To avoid losing the pin to erosive forces, the pin was inserted at least one meter from the current gully edge. If bedrock or another barrier was located at the one meter marker, the pin would be moved further away in a perpendicular direction to the aparent flow of water. Measurements were then taken from the installed erosion pin to the outer bank and from the instilled erosion pin to the inner bank. The difference between the two would then be considered the current width of the gully. This data, along with a GPS point location, were all incerted into the Archer Handheld GPS.

Another pin was installed at the deppest reference point. The pin was again located approximately one meter from the gully bank to avoid erosion loss or military interaction during military manuevers. The location of this pin and depth measurements at this location were recorded in the Archer Handheld GPS.

Appendix B - Detailed Spatial Data Methods

Gully analysis was conducted using 10 of the most commonly accepted erosion factors considered in this study. These predictor variables include Watershed Slope, Watershed Area, Flow Accumulation, Drainage Density, Clay Percentage, Aspect, Training Intensity, Burning Frequency, Burning Seasonality and Above Ground Biomass Change.

A 3-m DEM derived from the 2007 LIDAR data was used to develop many of the above mentioned predictor variables. The Fill function (found under Spatial Analysis > Hydrology in ArcGIS 10.0) was not utilized with the DEM to avoid reducing or smoothing the accurate representation of the realistic waterflow.

Initially, two layers were derived from the unfilled three meter DEM – flow direction and flow accumulation. The Flow Direction tool under Spatial Analysis > Hydrology in ArcGIS 10.0 was used to produce a summary direction of each water droplet within the Fort Riley boundary using the DEM as the "in surface raster". Flow Accumulation was then derived using the Flow Accumulation tool under Spatial Analysis > Hydrology in ArcGIS 10.0 with the Flow Direction layer as the "in flow direction raster". These outputs were later used to delineate the watersheds associated with each gully GPS location.

Flow accumulation was utilized in conjunction with the gully point shapefile created directly from field data to delineate watersheds. A snap pour point was first designed for each gully site. Using the Snap Pour Point tool under Spatial Analysis > Hydrology in ArcGIS 10.0, each gully was placed in its own individual shapefile and granted a snap distance of 5 meters. These 5 meters allowed the point to move diagonally one pixel measuring 3 meters by 3 meters to the pixel with the highest flow accumulation for the gully system.

The watershed tool (Spatial Analysis > Hydrology > Watershed in ArcGIS 10.0) was utilized with Flow Accumulation as the raster and each individual pour point as the output point to produce gully watershed. Since each gully was currently represented in a different shapefile, this process was run 21 times and simplified using the ModelBuilder approach in ArcGIS 10.0. The resulting watersheds were then used as the base outline for many of the following predictor variables.

Watershed Area and Slope

The watershed area variable began with the derived Flow Direction map at 3 meters as the "in flow direction raster" and each of the 21 snapped gully pour points as the "in pour point data" locations. This method was placed into a ModelBuilder in ArcGIS 10.0 to simplify the process. Once each watershed was created, the area was derived by adding an Area Data column to the attribute table of each watershed. This data was then copied from the GIS attribute table and added to the comprehensive variable table.

The watershed slope variable was similarly derived using the same Model developed in ArcGIS 10.0 for watershed area. The Slope Tool found under Spatial Analyst > Surface Toolset in ArcGIS 10.0 was used with each watershed representing the input surface raster. No output measurements or z factors were used. This data was then copied from the GIS attribute table and added to the comprehensive variable table.

Flow Accumulation

The previously developed flow accumulation layer was overlaid with each snapped gully pour point and analyzed using the Extract Values to Points tool found under Spatial Analyst > Extraction Toolset in ArcGIS 10.0. This data was then copied from the GIS attribute table and added to the comprehensive variable table.

Drainage Density

Using the Flow Length Tool (Spatial Analyst > Hydrology in ArcGIS 10.0), the previously created Flow Direction map was utilized at the "in flow direction raster". The output map was then run through the Extract by Mask Tool (Spatial Analyst > Extraction in ArcGIS 10.0) with the Flow Length map as the "in raster" and each watershed outline as the "in mask data". This input feature defines the area in which data is to be extracted and places this information in an output data table. The output result then creates a summary of the flow lengths which can either be visually summed or run through the Zonal Statistics Tool (Spatial Analyst > Zonal) and selecting the total value. The second method was used in this study. This total flow length was then copied from the GIS attribute table and added to the comprehensive variable table. This value was then divided by the total watershed area to determine the drainage density for each watershed.

Clay Percentage

In order to determine the clay percentage representative at each gully location, Soil Survey Database (SSURGO) data and corresponding visual layers were downloaded from the Soil Survey Staff, NRCS (2012) for Riley and Geary Counties. Once this data was collected, the soil layers from Riley and Geary Counties were uploaded into ArcGIS 10.0, along with an installation outline of Fort Riley. Using the Clip > Extract Toolset > Analysis Toolbox, the soil layer was clipped to the corresponding Fort Riley outline.

Once the soil layer was representative of the Fort Riley boundary, the layer was joined with the first layer of clay data from the 2009 STATSGO database. This information was representative of approximately the first 20-30 cm below the soil surface and unique to each polygon in the soil layer. This created a data layer representative of the clay percentage throughout For Riley.

By using the Extract Values to Points tool under Spatial Analyst > Extraction Toolset with each gully snap point as the input point and the clay percentage shapefile as the input raster, the value directly under each gully headcut was found. This data was then copied from the GIS attribute table and added to the comprehensive variable table.

Aspect

To calculate this variable, the 3 meter DEM was used as the “in raster” within the Aspect Tool under Surface > Spatial Analyst in ArcGIS 10.0. To transform individual pixel values into a watershed sized variable, the Zonal Statistics Tool (Spatial Analyst > Zonal Toolset in ArcGIS 10.0) with each watershed shapefile as the “in zone data” was used. These boundaries outlined the desired area to be analyzed, and with the output aspect map as the “in value raster”, the majority aspect within the watershed was determined. This data was then copied from the GIS attribute table and added to the comprehensive variable table.

Training Intensity

The previously developed training intensity layer from Denker (pers. comm.); Hutchinson (pers. comm.); Johnson et al., 2011) was overlaid with each snapped gully pour point and analyzed using the Extract Values to Points tool found under Spatial Analyst > Extraction

Toolset in ArcGIS 10.0. This data was then copied from the GIS attribute table and added to the comprehensive variable table.

Burning Frequency, Burning Seasonality

Each snapped gully pour point was overlaid with the Burning Frequency layer and Burning Seasonality layer from Devienne et al., (2013) and analyzed using the Extract Values to Points tool found under Spatial Analyst > Extraction Toolset in ArcGIS 10.0. This data was then copied from the GIS attribute table and added to the comprehensive variable table.

Above Ground Biomass Change

The previously developed Above Ground Biomass layers were overlaid with each snapped gully pour point and analyzed using the Extract Values to Points tool found under Spatial Analyst > Extraction Toolset in ArcGIS 10.0. This data was then copied from the GIS attribute table and added to the comprehensive variable table, where the 2010 value was subtracted from the 2012 value for each point to produce the change.

Appendix C - Detailed Gully Data

Gully Number	Training Area	Maneuver Area	Widest 2010 (m)	Deepest 2010 (m)	Width 2012 (m)	Depth 2012 (m)	Width Change (m)	Depth Change (m)	Headcut Growth (m)
0	95	L	8.46	1.57	N/A	N/A	N/A	N/A	N/A
1	95	L	8.92	2.18	N/A*	N/A*	N/A*	N/A*	N/A*
2	95	L	10.72	2.31	N/A*	N/A*	N/A*	N/A*	N/A*
3	95	L	9.75	1.83	N/A*	N/A*	N/A*	N/A*	N/A*
4	95	L	3.38	0.91	3.566	0.762	0.186	-0.148	19.02
5	98	P	2.36	0.91	2.8956	1.1938	0.5356	0.2838	0.15
6	98	P	2.46	1.22	2.4384	1.016	-0.0216	-0.204	0.00
7	95	L	10.41	2.44	N/A*	N/A*	N/A*	N/A*	N/A*
8	95	L	8.53	1.35	N/A*	N/A*	N/A*	N/A*	N/A*
9	95	L	10.57	1.52	N/A*	N/A*	N/A*	N/A*	N/A*
10	95	L	10.03	2.26	N/A*	N/A*	N/A*	N/A*	N/A*
11	95	L	unpinned	unpinned	N/A**	N/A**	N/A**	N/A**	N/A**
12	95	L	3.91	1.32	2.83464	1.1887	-1.0753	-0.1313	0.13
13	51	D	2.95	0.99	2.4384	0.762	-0.5116	-0.228	17.07
14	51	D	2.72	1.35	2.2556	1.01498	-0.4644	-0.3350	0.00
15	51	D	1.83	0.86	2.37744	0.9144	0.54744	0.0544	0.24
16	55	D	6.05	1.37	6.18744	1.27	0.13744	-0.1	0.00

17	89	M	3.28	1.74	3.47472	1.7	0.19472	-0.04	0.00
18	96	P	5.56	1.7	3.9624	1.73736	-1.5976	0.03736	0.00
19	89	M	2.84	1.31	3.048	1.7272	0.208	0.4172	0.00
20	89	M	1.22	1.02	N/A+	N/A+	N/A+	N/A+	N/A+
21	96	P	4.7	1.82	4.4196	1.2446	-0.2804	-0.5754	1.17
22	96	P	3.73	0.67	5.0292	0.6096	1.2992	-0.0604	1.27
23	42	E	3.66	0.79	3.84048	0.635	0.18048	-0.155	0.08
24	37	B	4.75	1.04	1.8288	1.28016	-2.9212	0.24016	0.00
25	36	B	5.97	1.68	6.0707	1.8288	0.1007	0.1488	1.02
26	49	A	4.22	1.27	4.572	1.0922	0.352	-0.1778	0.00
27	77	O	3.1	1.31	1.2192	0.889	-1.8808	-0.421	0.28
28	77	O	2.39	1.22	2.37744	0.8382	-0.0125	-0.3818	0.76
29	77	O	3.38	1.02	2.4994	0.9398	-0.8806	-0.0802	0.00
30	78	O	3.91	0.86	4.8768	0.8636	0.9668	0.0036	0.00
31	41	E	unpinned	unpinned	1.73736	0.762	N/A++	N/A++	N/A++
32	61	H	3.02	0.91	3.9877	1.03632	0.9677	0.12632	0.38
33	48	A	2.08	1.07	1.9558	1.0414	-0.1242	-0.0286	0.15
34	91	M	1.8	0.81	2.01168	0.6985	0.21168	-0.1115	0.21
35	12	R	3.33	0.62	3.3528	0.4572	0.0228	-0.1628	1.016
36	12	R	5.56	1.17	2.6162	0.6858	-2.9438	-0.4842	8.47
37	12	R	8.69	0.72	2.34696	0.8128	-6.3430	0.0928	0.74

38	11	R	3.43	0.81	2.80416	0.6858	-0.6258	-0.1242	0.00
39A	12	R	5.01	1.41	5.14	1.4732	0.13	0.0632	0.36
39B	12	R	3.61	0.81	3.63	0.7874	0.02	-0.0226	0.00
41	78	O	unpinned	unpinned	N/A^	N/A^	N/A^	N/A^	N/A^
42	78	O	unpinned	unpinned	2.07264	1.7018	N/A^^	N/A^^	N/A^^
43	51	D	unpinned	unpinned	N/A’	N/A’	N/A’	N/A’	N/A’
44	51	D	unpinned	unpinned	N/A’	N/A’	N/A’	N/A’	N/A’
45	54	D	1.47	1.45	3.3528	1.2192	1.8828	-0.2308	0.00
46	49	A	1.07	1.35	4.05384	1.34112	2.98384	-0.0088	1.07
47	36	B	0.76	1.17	4.51104	1.1811	3.75104	0.0111	0.00
48	94	M	1.83	1.88	8.50392	1.84404	6.67392	-0.0359	1.86
49	86	Q	unpinned	unpinned	3.53568	0.7112	N/A^^	N/A^^	N/A^^
50	77	O	unpinned	unpinned	N/A”	N/A”	N/A”	N/A”	N/A’’
51	45	E	unpinned	unpinned	3.1242	0.9652	N/A^^	N/A^^	N/A^^
52	43	E	unpinned	unpinned	N/A°	N/A°	N/A°	N/A°	N/A°
53	43	E	unpinned	unpinned	4.1148	0.85344	N/A^^	N/A^^	N/A^^
54	57	H	unpinned	unpinned	N/A°°	N/A°°	N/A°°	N/A°°	N/A°°
55	9	R	unpinned	unpinned	N/A°°	N/A°°	N/A°°	N/A°°	N/A°°
56	39	B	unpinned	unpinned	2.5146	0.889	N/A^^	N/A^^	N/A^^
57	41	E	unpinned	unpinned	4.8768	0.6604	N/A^^	N/A^^	N/A^^
58	36	B	unpinned	unpinned	N/A°°	N/A°°	N/A°°	N/A°°	N/A°°

* - Gully had been fixed since initial reference point installation. No data was collected in 2012

** - No distinct flow direction in water or headcut growth was prominent. No reference pins were installed in 2012

+ - No GPS points or rebar pins were ever located for widest and deepest measurements. No data was collected in 2012

++ - Pins were found for depth, width, and headcut, but not numerical data was ever associated with the shapefiles. No data was collected in 2012

^ - No distinct headcut. Extremely long gully with rotating plunge pools and plateaus. No reference pins were installed in 2012

^^ - Newly pinned in 2012. No data taken in 2010

‘ - Sideheadcut from previous gully. No data taken in 2012

“ - No distinct headcut. Old road that had developed into stable ditch

° - Gully network was never assessable during summer 2012

°° - Gully network never located even with GPS points

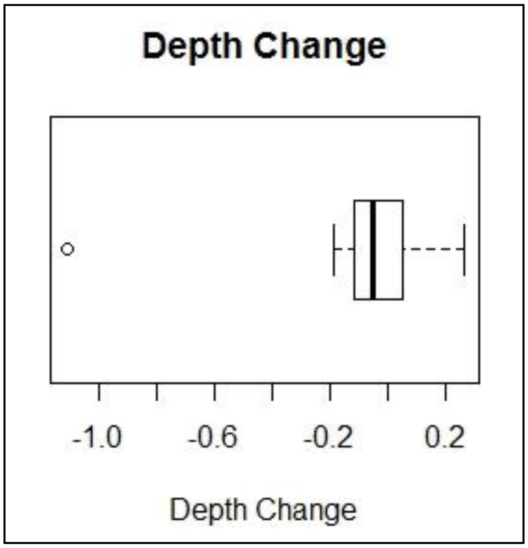
Appendix D - Boxplot and Outlier Analysis

Prior to statistical analysis with regards to the predictive ability of the dependent or independent variables, possible outliers were determined using boxplots. All 11 gullies exhibiting single gully headcut growth were included in each boxplot to determine individual outliers regarding each of the 13 total variables. Outliers were determined using the equation for the inner quartile range [IQR = Third Quartile – First Quartile] followed by the Lower Fence and Upper Fence [Lower Fence = First Quartile – 1.5*IQR; Upper Fence = Second Quartile + 1.5*IQR]. Any gully with an attribute above the upper fence or below the lower fence was deemed an outlier with respect to that variable.

Width
Min.   :-0.0700
1st Qu.: 0.1700
Median : 0.2800
Mean   : 0.2791
3rd Qu.: 0.3900
Max.   : 0.6600

IQR: 0.39-0.17 = 0.22
First Quartile – 1.5*0.22 = -0.16
Third Quartile + 1.5*0.22 = 0.72

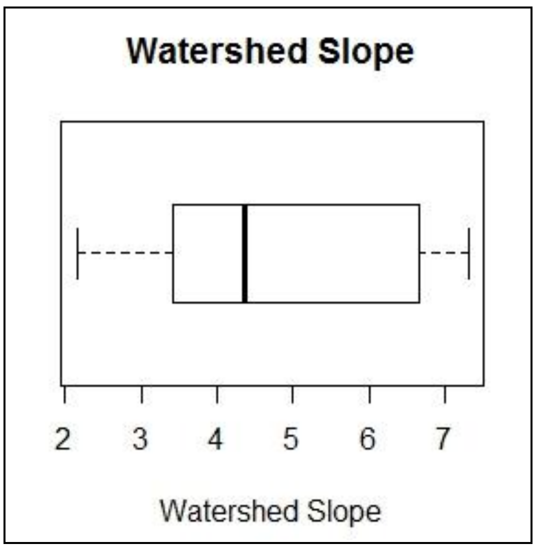
Zero Outliers



Depth
Min. :-1.1100
1st Qu.:-0.1200
Median :-0.0500
Mean :-0.1127
3rd Qu.: 0.0500
Max. : 0.2600

IQR: 0.05--0.12 = 0.17
First Quartile – 1.5*0.17 = -0.375
Third Quartile + 1.5*0.17 = 0.305

One Outlier: -1.11m (gully 21)



WSSlope
Min. :2.160
1st Qu.:3.430
Median :4.360
Mean :4.795
3rd Qu.:6.655
Max. :7.300

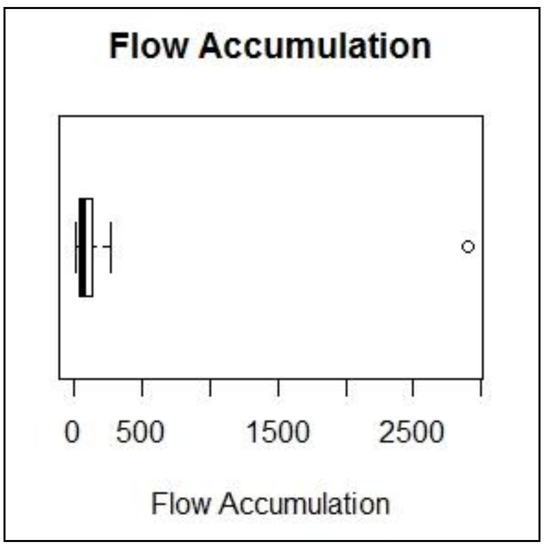
IQR: 6.655-3.43 = 3.225
First Quartile – 1.5*3.225 = -1.4075
Third Quartile + 1.5*3.225 = 11.4925

Zero Outliers

TI
Min. :1.000
1st Qu.:1.500
Median :2.000
Mean :2.091
3rd Qu.:3.000
Max. :3.000

IQR: 3-1.5 = 1.5
First Quartile – 1.5*1.5 = -0.75
Third Quartile + 1.5*1.5 = 5.25

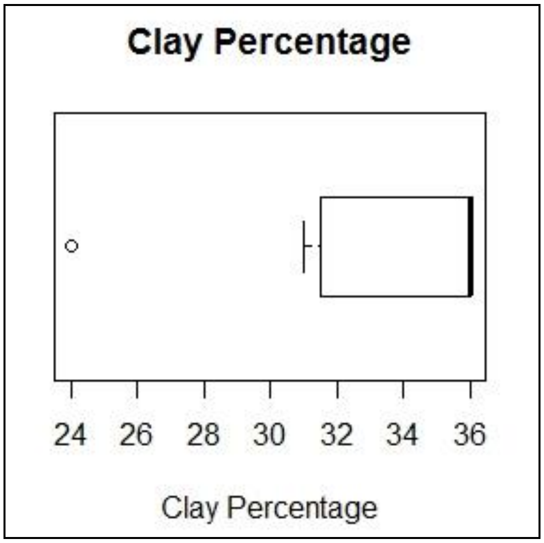
Zero Outliers



FA
Min. : 8.0
1st Qu.: 32.0
Median : 63.0
Mean : 338.2
3rd Qu.: 132.0
Max. :2898.0

IQR: 132-32 = 100
First Quartile – 1.5*100 = -118
Third Quartile + 1.5*100 = 282

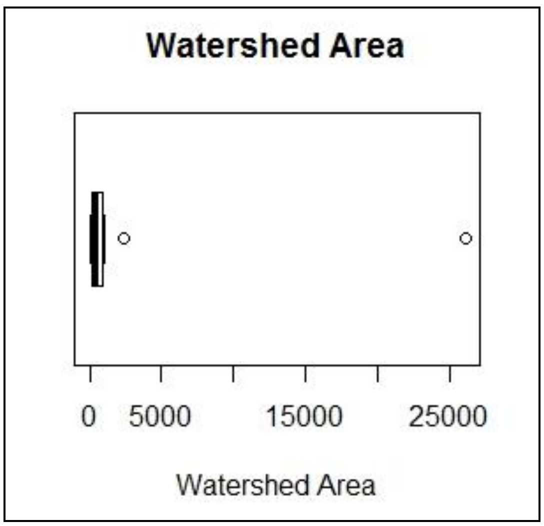
One Outlier: 2898 (gully 33)



Clay
Min. :24.00
1st Qu.:31.50
Median :36.00
Mean :32.91
3rd Qu.:36.00
Max. :36.00

IQR: 36-31.5 = 4.5
First Quartile – 1.5*4.5 = 24.75
Third Quartile + 1.5*4.5 = 42.75

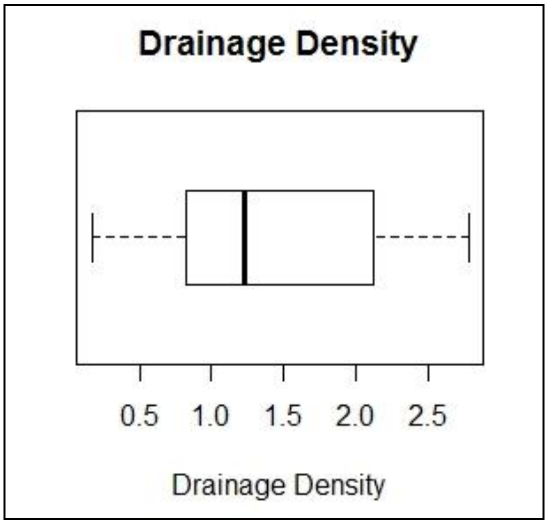
Two Outliers: 24 (gully 35), 24 (gully 37)



WSA
Min. : 18.0
1st Qu.: 184.5
Median : 477.0
Mean : 2925.8
3rd Qu.: 954.0
Max. :26091.0

IQR: 954.0-184.5 = 769.5
First Quartile – 1.5*769.5 = -969.75
Third Quartile + 1.5*769.5 = 2108.25

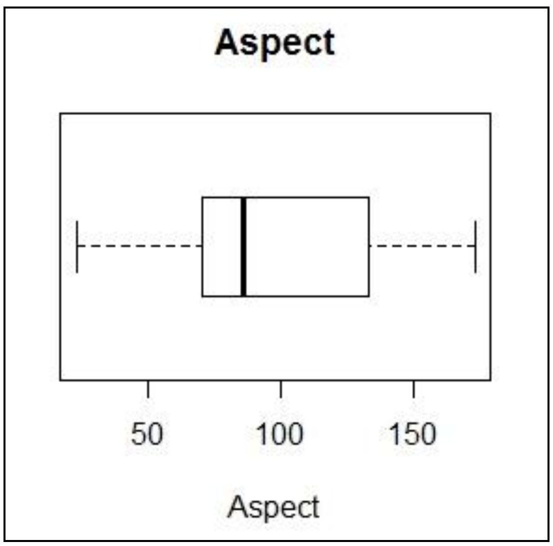
Two Outliers: 2412 (gully 23), 26091 (gully 33)



DD
Min.   :0.170
1st Qu.:0.820
Median :1.230
Mean   :1.455
3rd Qu.:2.125
Max.   :2.780

IQR: 2.125-0.82 = 1.305
First Quartile – 1.5*1.305 = -1.1375
Third Quartile + 1.5*1.305 = 2.0825

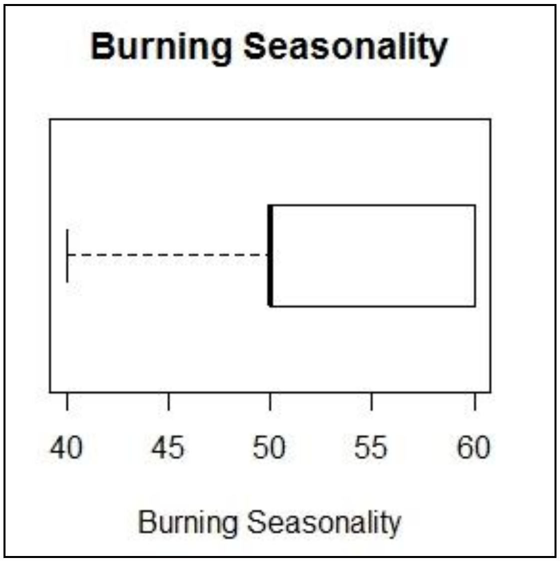
Zero Outliers



A
Min.   : 23.03
1st Qu.: 70.66
Median : 86.31
Mean   : 97.10
3rd Qu.:133.35
Max.   :173.35

IQR: 133.35-70.66 = 62.69
First Quartile – 1.5*62.69 = -23.375
Third Quartile + 1.5*62.69 = 227.385

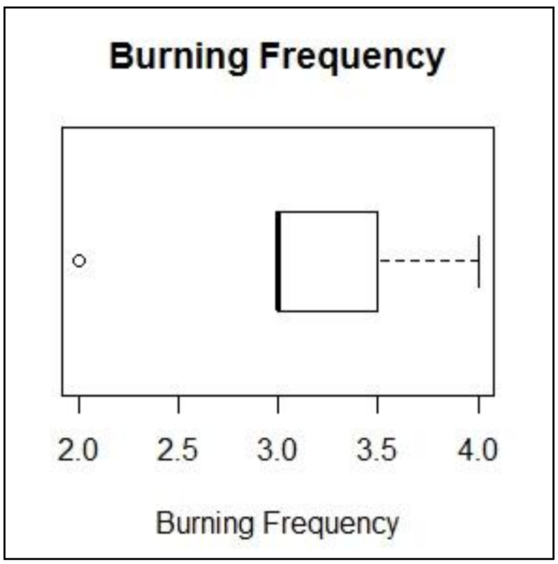
Zero Outliers



Bseas
Min. :40.00
1st Qu.:50.00
Median :50.00
Mean :52.73
3rd Qu.:60.00
Max. :60.00

IQR: 60-50 = 10
First Quartile – 1.5*10 = 35
Third Quartile + 1.5*10 = 75

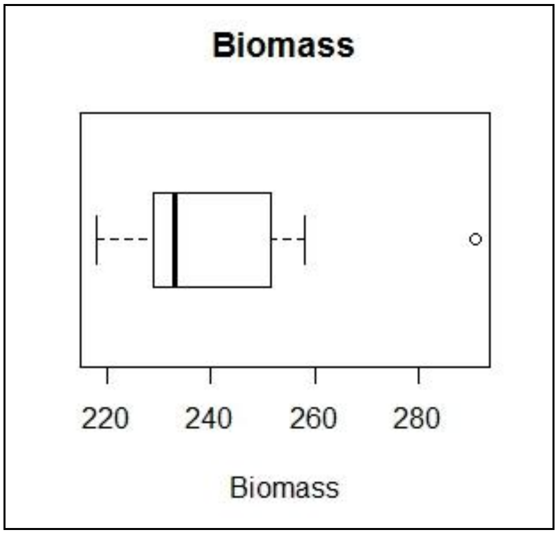
Zero Outliers



Bfreq
Min. :2.000
1st Qu.:3.000
Median :3.000
Mean :3.091
3rd Qu.:3.500
Max. :4.000

IQR: 3.5-3 = 0.5
First Quartile – 1.5*0.5 = 2.25
Third Quartile + 1.5*0.5 = 4.25

Two Outliers: 2 (gully 13), 2 (gully 33)



BioA
Min. :217.8
1st Qu.:228.8
Median :233.0
Mean :241.1
3rd Qu.:251.5
Max. :290.8

IQR: 251.5-228.8 = 22.7
First Quartile – 1.5*22.7 = 194.75
Third Quartile + 1.5*22.7 = 285.55

One Outlier: 290.83 (gully 33)

Appendix E - Statistical Code for R Programming

Various statistical codes were utilized throughout this study to produce the analysis and equations needed to adequately assess the research questions previously stated. All codes are listed and referenced below.

Histograms:

```
x <- mtcars$mpg
h<-hist(x, breaks=10, col="red", xlab="Miles Per Gallon",
  main="Histogram with Normal Curve")
xfit<-seq(min(x),max(x),length=40)
yfit<-dnorm(xfit,mean=mean(x),sd=sd(x))
yfit <- yfit*diff(h$mids[1:2])*length(x)
lines(xfit, yfit, col="blue", lwd=2)
```

(Quick-R Histograms and Density Plots, 2012)

Boxplots:

```
boxplot(mpg~cyl,data=mtcars, main="Car Milage Data",
  xlab="Number of Cylinders", ylab="Miles Per Gallon")
```

(Quick-R Boxplots, 2012)

Multiple Regression Variable Selection (using stepwise selection):

```
library(MASS)
fit <- lm(y~x1+x2+x3,data=mydata)
step <- stepAIC(fit, direction="both")
step$anova
```

(Quick-R Multiple Linear Regression, 2012)

Multiple Regression Variable Selection (using all-subsets regression):

```
library(leaps)
attach(mydata)
leaps<-regsubsets(y~x1+x2+x3+x4,data=mydata,nbest=10)
# view results
summary(leaps)
```

(Quick-R Multiple Linear Regression, 2012)

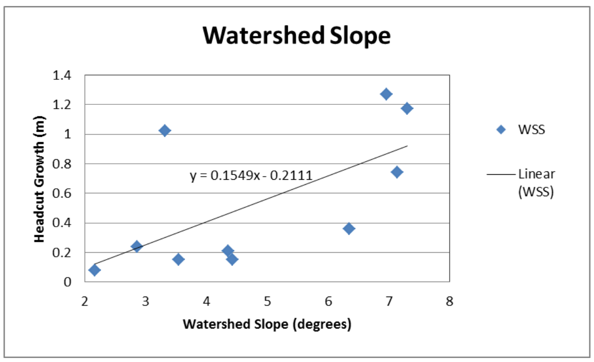
Multiple Regression Variable Relative Importance:

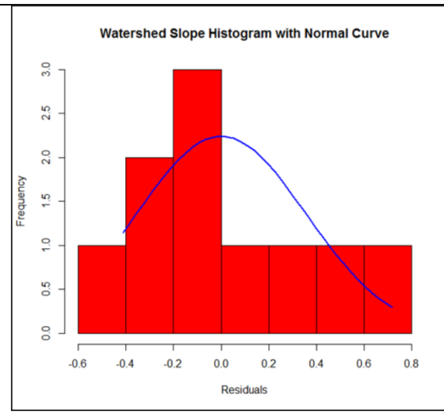
```
library(relaimpo)
calc.relimp(fit,type=c("lmg","last","first","pratt"),
  rela=TRUE)
```

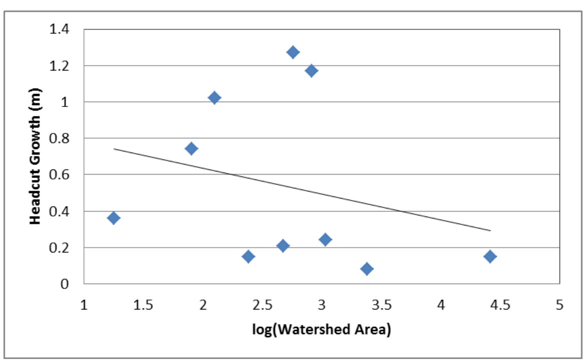
(Quick-R Multiple Linear Regression, 2012)

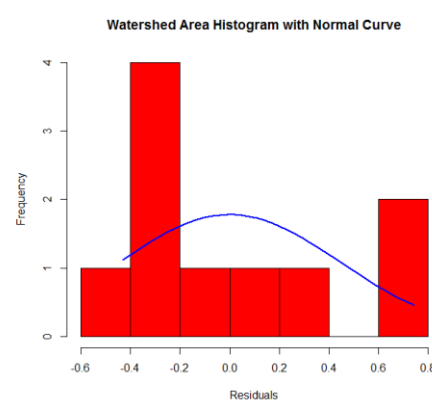
Appendix F - Multiple Regression Assumption Analysis

Before Multiple Regressions analysis could be completed for the select seven independent variables, the variables needed to be check for the assumptions made within this regression analysis. Below are the results from the tests run including linear relationship with headcut growth, homoscedasticity, and distribution of residuals.

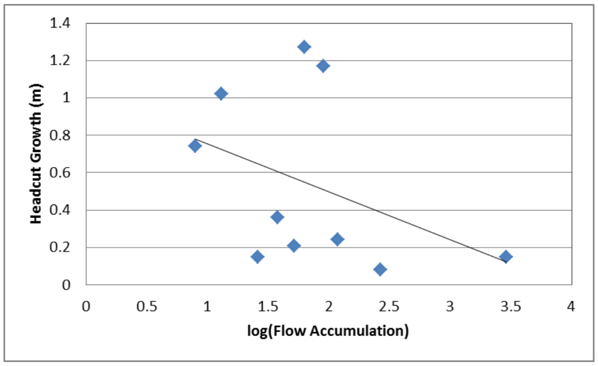
<table>
<tr><th>Variable</th><th>Linear Relationship
and Homoscedasticity</th><th>Distribution of Residuals</th></tr>
<tr><td>WSS</td><td>


</td><td>


Kurtosis: 2.62
Skewness: 0.83</td></tr>
<tr><td>WSA</td><td>


</td><td>


Kurtosis: 1.86
Skewness: 0.69</td></tr>
</table>

<table>
<tr>
<td>FA</td>
<td>
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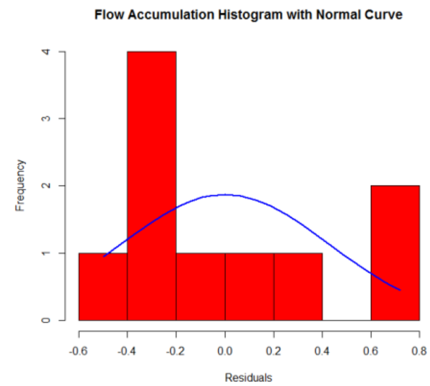
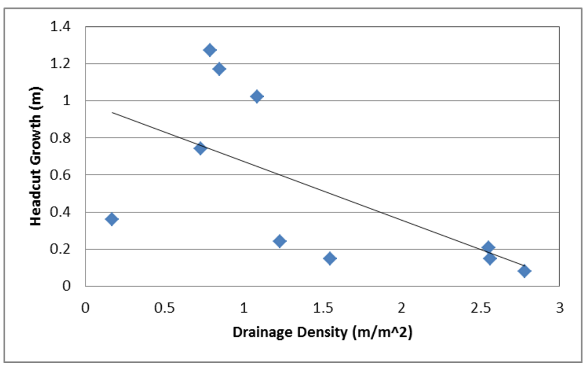
<td>

Kurtosis: 2.09
Skewness: 0.69</td>
</tr>
<tr>
<td>DD</td>
<td>
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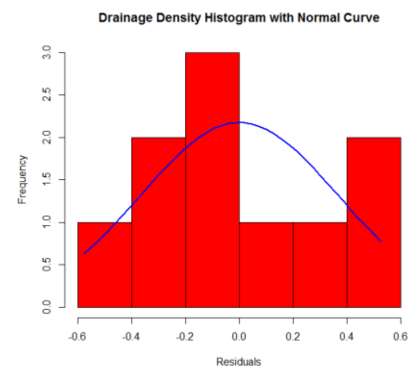
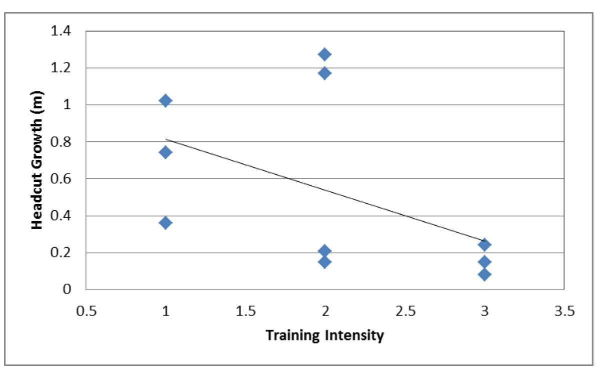
<td>

Kurtosis: 1.92
Skewness: 0.012</td>
</tr>
<tr>
<td>TI</td>
<td>
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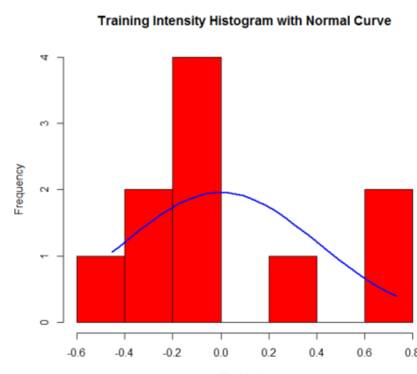
<td>

Kurtosis: 2.35
Skewness: 0.79</td>
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<table>
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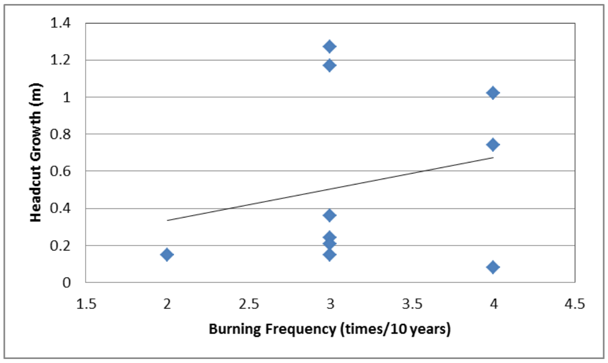
<td>BF</td>
<td>
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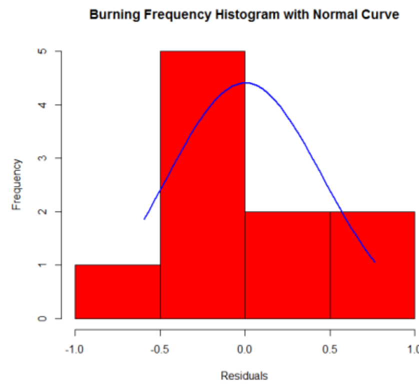
<td>

Kurtosis: 2.08
Skewness: 0.60</td>
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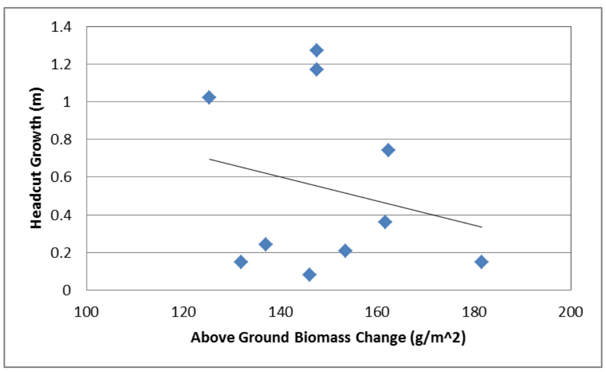
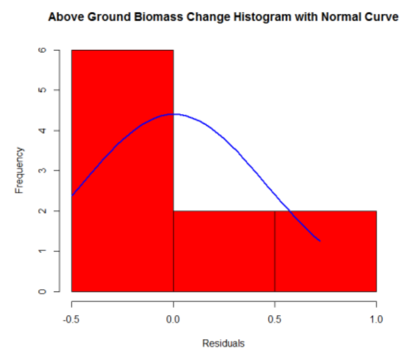
<tr>
<td>AGBC</td>
<td>
</td>
<td>

Kurtosis: 1.69
Skewness: 0.43</td>
</tr>
</table>