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September 2013, Colorado Front Range Flooding, and Impacts on Agriculture and Irrigation Infrastructure: A Case Study in the Left Hand Ditch System, Boulder County, Colorado

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Capstone Project

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Abstract

Flooding can cause massive harm to the agricultural sector by flooding fields and damaging the infrastructure that is essential for agricultural activities. Crops are often lost and repairs may be necessary to restore irrigation systems to functional status. This research aims to quantify the damages and losses experienced from the unprecedented September 2013 flooding event in Boulder County Colorado's Left Hand Ditch Company service area. Damages are cataloged and Geographic Information Systems (GIS) technologies were used to estimate economic impact and determine the landscape characteristics of lands where the highest rates of flooding occurred. Alfalfa and non-alfalfa hays experienced the greatest losses with flooding most common in Western Great Plains Riparian Woodlands and Shrublands and Agricultural lands. Flooding was most common in lower elevation areas with shallower slopes. Manter sandy loam, Calkins sandy loam, and Niwot soils were the soil types for that experienced the most widespread flooding.

Introduction

Flooding is a common natural hazard, defined by the United States Geological Survey (USGS) as "any high flow, overflow, or inundation by water which causes or threatens damage."(2013). Floods vary in their size, intensity, and the damage they cause. Floods can develop over the course of a few days or rapidly in the case of a flash flood. A flood can impact a sizeable area and a large number of people and the infrastructure they depend on in all aspects of life.

In September 2013, parts of the Colorado Front Range experienced an unprecedented precipitation event that caused widespread flooding and tremendous damage, warranting a federal disaster declaration by the Federal Emergency Management Agency (FEMA) (2013). Ironically, Colorado had been exceptionally dry preceding the flood and many were hopeful for rain when the storm was first forecasted (Coleman 2014). On September 9, 2013 tropical moisture from Mexico's Pacific coast reached Colorado's Front Range and collided with another air mass of humid air from the Gulf of Mexico. As these moisture laden air masses collided, a slowly-circulating low pressure system became stationary, circulating over Colorado's Eastern Slope and held the moisture-rich air over the area for most of the week, creating a recipe for the perfect storm for Front Range flooding.

During the week-long period from September 9 through September 16, 2013, heavy rainfall caused flooding affecting 17 counties in Colorado. The most rainfall fell in parts of Boulder County and the city of Boulder, where seven-day totals exceeded 17 inches of rain in places (Norman et al. 2013). September 12, 2013 broke the record for most rain ever recorded in one day in the city of Boulder, with 24-hour rain totals over 9 inches (National Oceanic and Atmospheric Administration 2013). Boulder typically experiences 20-30 inches of rain annually, leading the National Weather Service to describe the event as "biblical" (Freedman 2013).

Boulder County's higher elevation areas in the western part of the county such as Nederland and Ward, along the Peak to Peak Highway, experienced even more rain with totals up to 23 inches, adding to the already large volume of water that flooded the lower elevations as it flowed downstream (Coleman 2014). Some eastern areas where rainfall totals were insubstantial were badly flooded simply due to upstream floodwaters flowing into them (2014). Climate statisticians estimate the September 2013 flooding in Colorado as a one in 1000 year event (Freedman 2013). Figures 1 and 2 show total rainfall estimates and totals for daily rainfall for Boulder County for the storm that lasted from September 10, 2013 to September 16, 2013, respectively.

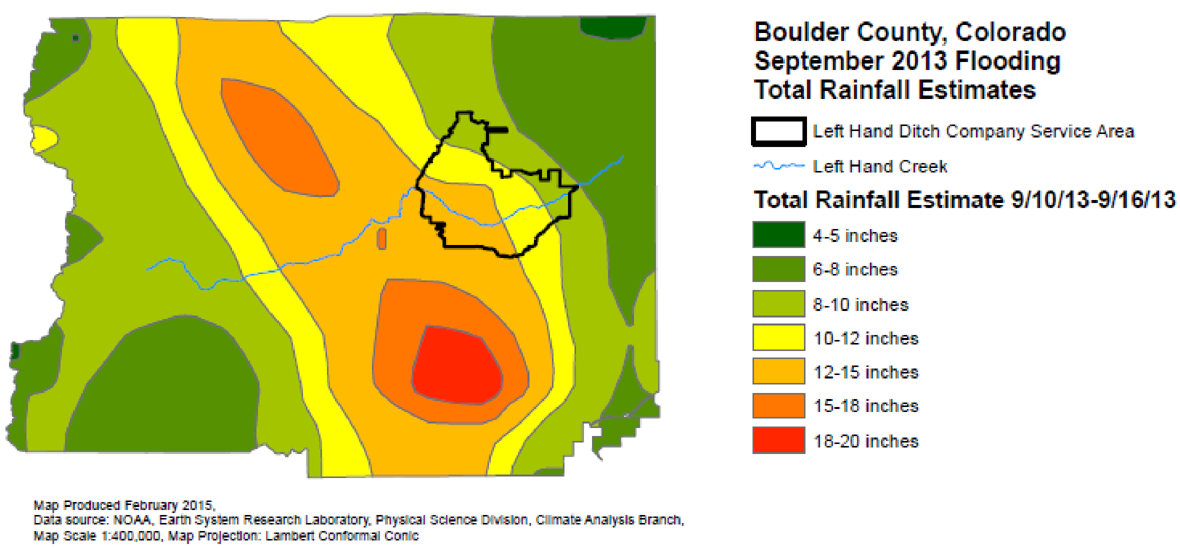


Figure 1: Boulder County, Colorado Total Rainfall Estimates – September 2013 Flood.

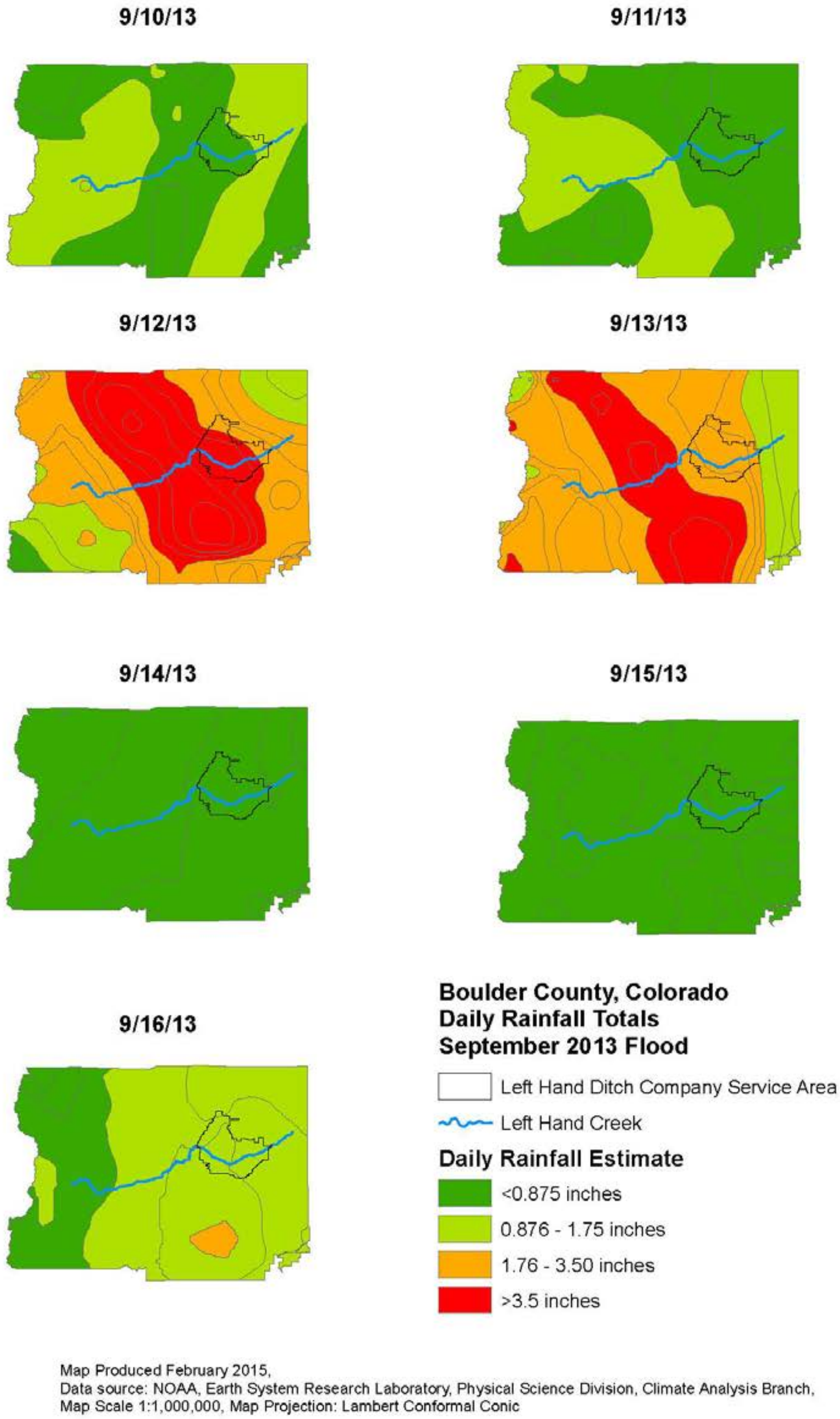


Figure 2: Boulder County, Colorado Daily Rainfall Totals – September 2013 Flood

Agriculture is essential to human life on Earth; if we cannot produce food, we will be unable to survive and human life on earth will perish (Simpson and Ogorzaly 2001). Agriculture is dependent on water and in the arid west water is usually the limiting resource for agriculture. Often the water related agricultural dilemma in dry climates is drought like Colorado was experiencing in 2013 before the flood, when there was not enough water (Coleman 2014). In the case of the September 2013 floods, there was too much water.

Many ditches and irrigation related infrastructure were damaged or destroyed and thousands of acres of farm land were flooded, killing crops and furthering losses (Coleman 2014). Additional losses were experienced in the 2014 growing season due to damaged infrastructure that was still under repair. 223 irrigation ditches were reported to the state of Colorado as damaged, with 19 of them not ready for water by the start of the 2014 irrigation season. This resulted in an estimated 9,000 acres of lost irrigated land for 2014. Likewise, 76 of the 207 dams that required inspection in Colorado following the September 2013 flood raised concern to engineers and 19 of these were not repaired by the start of the 2014 irrigation season.

Much of the destruction that was experienced occurred in Boulder County, whose unique geography provided conditions that threatened large areas of agricultural land during the flooding (Norman et al. 2013). Narrow canyons funneled large amounts of water that fell in the mountains directly to agricultural areas and cities downstream causing immense damage (Coleman 2014). This research focuses on the Left Hand Ditch Company (LHDC), whose service area includes areas between the Boulder, Lyons, and Niwot (Plummer 2014). The LHDC service area experienced massive damages to their water delivery infrastructure, many of which were not repaired until after the 2014 growing season had started. Figure 3 shows the LHDC service area and the hydrography of the St. Vrain River Basin in Boulder County, Colorado.

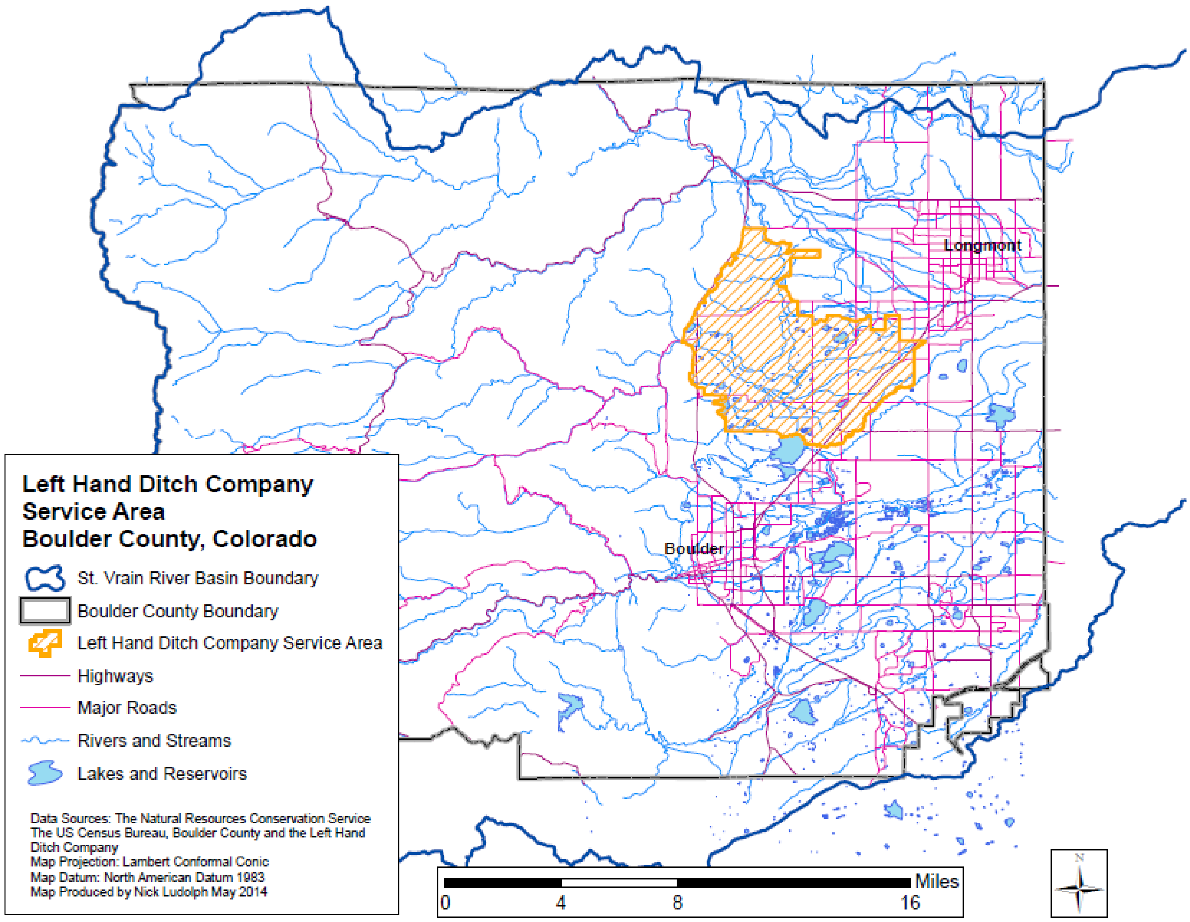


Figure 3: The Left Hand Ditch Company Service Area

This research identifies the landscapes and their characteristics where flooding was most common within the service area of the Left Hand Ditch Company in Boulder County, Colorado following the September 2013 flooding. It also assesses the damages incurred to agricultural lands and to the ditch irrigation infrastructure. Geographic

Information Systems (GIS) technologies have been utilized to catalog and measure these damages and GIS techniques in polygon overlay were employed to analyze landscape characteristics.

Project Definition

The USDA's National Resources Conservation Service (NRCS) has classified the entire country into different divisions of hydrologic units (n.d.). Hydrologic units that intersect the United States but contain portions of Mexico and Canada are also designated using this system because they are geographic features and do not follow arbitrarily established political boundaries. These NRCS hydrologic units are described by hydrologic unit codes abbreviated HUC. This hydrologic unit classification system contains several scales of differentiation between hydrologic units including regions, subregions, basins, subbasins, watersheds, and subwatersheds in decreasing size relative to each other.

The entirety of the Left Hand Ditch Company service area is contained within the Missouri River Region, the South Platte River Subregion, the Upper South Platte Basin, and the St. Vrain Subbasin. The Left Hand Ditch Company Service Area is contained entirely within two watersheds, Left Hand Creek and Boulder Creek-St. Vrain. Five subwatersheds overlap with the LHDC service area, Indian Mountain-St. Vrain Creek, McIntosh Lake-St. Vrain Creek, Dry Creek, Lower Left Hand Creek, and Boulder Reservoir. Figure 4 shows the watersheds and subwatersheds of the LHDC service area using the NRCS hydrologic unit classification system.

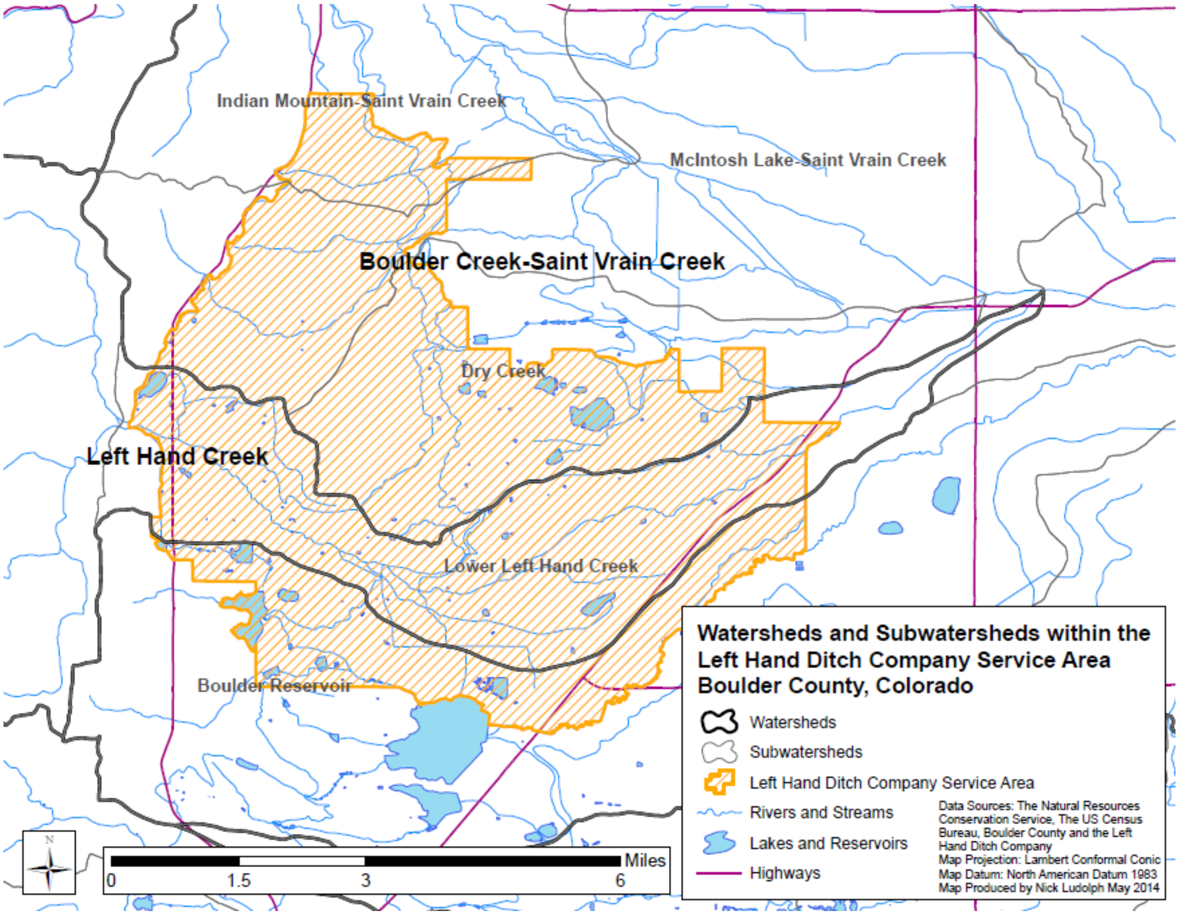


Figure 4: Watersheds and Subwatersheds of the Left Hand Ditch Company Service Area

Agriculture is critical to humans' existence on this planet. In 2012, the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS) estimated Colorado's agricultural sector to be worth almost $8 billion annually with Boulder County's agricultural sales estimated at around $34 million annually. Additionally, the agriculture industry is estimated to supply $40 billion to the State's economy in direct and indirect contributions annually and employs an estimated 173,000 people yearly, making it Colorado's second largest industry after tourism (The State of Colorado 2014). The agricultural sector is also the largest water user in

Colorado and uses on average 20% more water than other areas perfoming the same type of agricultural activities due to Colorado's dry climate.

Boulder County and much of Colorado have a rich agricultural heritage dating back to early pioneer settlements in the 19th century (Wolfenbarger 2006). Left Hand Ditch was Boulder County's first irrigation ditch and is one of the oldest irrigation systems in Colorado, with its first diversion dating to the 1860's. Unlike most irrigation ditch systems, Left Hand Ditch is not actually a ditch, but a natural creek, Left Hand Creek, with a flow rate that has been greatly increased by anthropological diversion projects. The Left Hand Ditch Company service area feeds fourteen ditch systems (Plummer 2014). A large amount of Boulder County's Agricultural Land lies within the Left Hand Ditch Company service area.

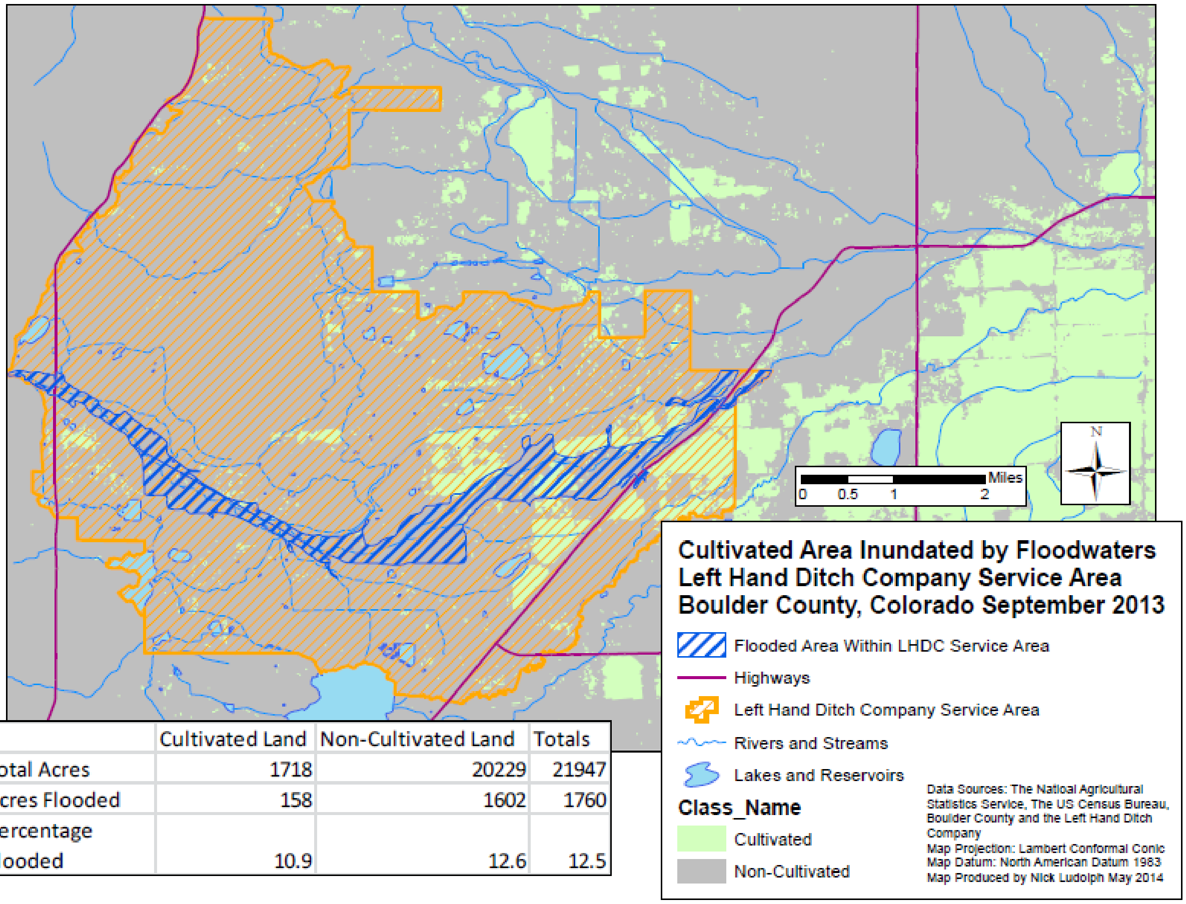
Left Hand Ditch is an extremely important ditch system in the history of water rights in the western United States. In 1882, the landmark Colorado Supreme Court Decision Coffin v. Left Hand Ditch granted the Left Hand Ditch Company enough water to irrigate approximately 20,000 acres and established the Colorado Doctrine, also known as Prior Appropriation, which has become the basis for water law in the western United States (Black 2009). Water rights based on Prior Appropriation exist in most of the western U.S. and differ from Riparian Water Rights which govern water in most eastern states, where water rights are associated with land ownership and users are considered to have equal rights to water (The State of Colorado 2014; Energy and Environmental Research Center n.d.). Prior appropriation, established in response to the limited water resources in the West, is often described using the phrase "first in time

– first in right." It ignores the relationship between land and water and allows the first person or corporation to divert water for beneficial use, the right to that water, giving those who hold older or more senior water rights preference often even over the landowners who have that water flowing through their properties.

Since water is governed in the West using the Prior Appropriation Doctrine, ditch and reservoir companies such as the Left Hand Ditch Company have been established to privately manage these water resources and to provide a medium for cooperation between water users (The State of Colorado 2014). Many of the agricultural water activities in Colorado would not be possible without such infrastructure and organization in place. Ditch companies operate and maintain ditches and manage the legal implications of water use in Colorado while making sure water users in their service areas receive the water they have legal rights to (The State of Colorado 2014; McKenzie 2014; Plummer 2014).

Ditch companies oversee the water rights held by their members and utilize ditch irrigation infrastructure such as head gates and laterals to control the flow of water to different water users and channel water to the right locations (McKenzie 2014; Plummer 2014). In Colorado these water users are primarily farmers and municipalities with some industrial water users (The State of Colorado 2014). Without ditch companies such as the LHDC, accurately maintaining and governing who gets what water under the Prior Appropriation Doctrine would be nearly impossible (Plummer 2014). Left Hand Ditch Company and its members hold some of the earliest established water rights in the west, giving them priority over more junior water rights holders.

Agriculture utilizes a large area of land in Boulder County. In 2012 Boulder County had an estimated 855 farms with over 132,000 acres in farms (USDA NASS 2012). Farmland is estimated to be steadily increasing in Boulder County where farmers grow a range of crops with the vast majority of agricultural land established for forage agriculture. Forage is defined as "any part of the plant that can be consumed by a grazing animal or that can be harvested for feeding" and refers to "any pasture, hay silage or green-chop" (The University of Georgia 2012). Other major crops grown in Boulder County include wheat, corn, barley, and vegetables. Additionally, over one fourth of farms in Boulder County are estimated to have livestock and/or poultry operations (USDA NASS 2012). Figure 5 shows cultivated lands in the LHDC service area that were inundated by floodwaters in the September 2013 flooding.



	Cultivated Land	Non-Cultivated Land	Totals
Total Acres	1718	20229	21947
Acres Flooded	158	1602	1760
Percentage Flooded	10.9	12.6	12.5

Figure 5: Cultivated Land Inundated by floodwaters within the Left Hand Ditch Company Service Area, September 2013

Boulder County and the Left Hand Ditch Company Service Area contain a relatively large area of agricultural lands that are classified as significant (Boulder County Government (BCG) 1997). These levels of significance are outlined in the Boulder County Comprehensive Plan and have been identified since the early 1980's (BCG 1983). Significant agricultural lands of national importance were identified by the Soil Conservation Service, now called the Natural Resources Conservation Service (NRCS). Significant Agricultural Lands of statewide importance were identified by the State Soil Conservation Board, a division of the Colorado Department of Agriculture and Natural Resources. Lastly, Significant Agricultural Lands of Local Importance were identified by Boulder County and the Boulder Soil Conservation District. There are over 88,000 acres of significant agricultural land in Boulder County (BCG 1997).

Water is often a limiting factor when growing crops in the arid western United States and irrigation has proven to be an essential aspect of successful and productive farming in Colorado's dry climate (Colorado State University (CSU) 2011). The United States Department of Agriculture National Agricultural Statistics Service (USDA NASS) defines irrigated land as "all land watered by an artificial or controlled means, such as sprinklers, flooding, furrows or ditches, sub-irrigation, and spreader dikes" (2012). Water and irrigation are extremely important to agriculture in western states such as Colorado where in the exceptionally dry climate water brings not only beauty, but productivity and stability to the land (CSU 2011).

In 2012, the Agricultural Census estimated that Boulder County irrigates over 30,000 acres on 547 farms (USDA NASS 2014). That means that around two thirds of farms and the area covered by farmland in Boulder County are irrigated, making irrigation an essential aspect of the agricultural process and infrastructure. Ditch irrigation is the main method used to transport water from natural sources such as rivers and lakes to farms for use for irrigation (CSU 2011). In Boulder County and across the State of Colorado, elaborate systems of ditches such as the Left Hand Ditch system exist to distribute water to farms. Figure 6 shows the headgates and laterals that make up the Left Hand Ditch Company Service Area. This infrastructure can easily become damaged in extreme flood events such as the Front Range September 2013 Floods (Coffman 2013).

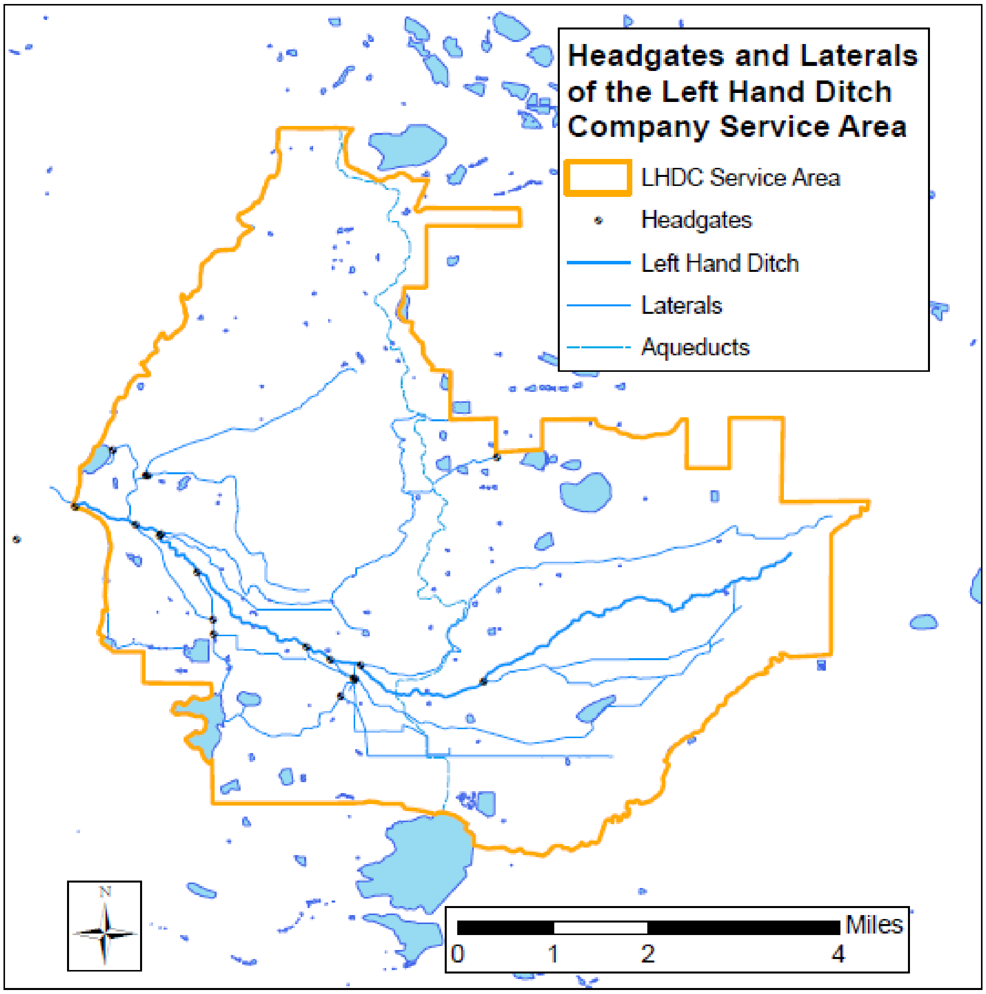


Figure 6: Headgates and laterals of the Left Hand Ditch Company Service Area

Flooding often has a substantial effect on the agricultural sector because of the large area that agricultural lands cover and their often close proximity to water (Colorado Foundation for Water Education 2013). Irrigation ditches utilized by agricultural operations may make them even more susceptible to damage from flooding by actually funneling floodwaters directly to farms. In Boulder County, many of these irrigation ditches and laterals are over 150 years old and difficult to maintain during normal stream flow conditions making them easily damaged during large flood events (Wolfenbarger 2006). Left Hand ditch system was no exception; due to its unique geography and the lack of headgates to close along the creek itself, the ditch system experienced widespread damage from the September 2013 Flooding (McKenzie 2014, Plummer 2014).

In 2014, the State of Colorado estimated the damages to water conveyance systems to be at $42,129,284, over 75% of the total estimated economic impact to agriculture. Other agricultural impacts included crop loss, private farm clean up, and pasture and range loss. The Colorado Water Conservation Board (CWCB) reported approving over $40 million in emergency loan funding to ditch and reservoir companies in Colorado including a $3.3 million loan to the Left Hand Ditch Company to repair damages to the LHDC irrigation infrastructure (2013). This loan was the largest approved by the CWCB for a ditch and irrigation company because the damages to the LHDC irrigation infrastructure were so catastrophic. The damage to these irrigation and water delivery systems may never fully be documented due to the complexity of natural disasters from flooding although this research strives to quantify these damages.

The farms most affected by the September 2013 flooding took the steps immediately necessary to remove contaminated produce and animal feed. Despite the measures taken immediately following the flood, pollutants carried by the floodwaters could affect soils and therefore potential crop safety and yields for years to come (Franzen 2010). This will not be quantifiable for several years until more growing seasons have passed and the results of lost topsoil can be measured.

Forage makes up most of the agricultural land in Boulder County (USDA NASS 2012). Non-harvested forage lands are often recoverable if they have not come in contact with contaminants carried by the floodwaters (UFIFAS 1998). Its close proximity to the mountains and upstream position from many anthropological activities prevented LHDC's service area from becoming extremely contaminated. LHDC's service area was spared from much of the contamination experienced further east from the September 2013 flooding, where floodwaters picked up contaminants from cities and other anthropological activities as they inundated areas and destroyed much of what were in their paths (McKenzie 2014, Plummer 2014).

Literature Review

Immediate concerns typically threaten agricultural areas inundated by flood waters (Hellevang 2011). Alderman et al. explain that flood waters can carry contaminants that make food unsafe for consumption (2012). Some crops can be salvaged after flooding but proper steps must be taken to test water and remove contaminated produce from farms affected by floods containing contaminants (The Produce Safety Alliance 2013; Kandel 2010). Hay and other food sources for livestock must also be removed to prevent livestock from getting sick (Cotton and McBride 2010). Harvested forage such as hay bales which have been submerged in flood waters are unusable and must be disposed of immediately, before livestock feed on them (Norman et al. 2013).

Flooding also affects crops that have not yet been harvested. Submersion has a range of effects on different species of plants (The University of Florida Institute of Food and Agricultural Sciences (UFIFAS) 1998). Warmer temperatures cause damage to occur much quicker to waterlogged plants because dissolved oxygen in the soil water typically depletes at a faster rate from increased respiration (Drew 1983). Because the 2013 flooding in Colorado occurred late in the growing season after hot mid-summer temperatures had mostly ended, the rate of damage can be expected to be lower than a flood of the same magnitude in the middle of the summer. Seminal research on flooded crops suggests that in general waterlogged plants tend to have reduced shoot and fruit weights and are not as productive with some species facing mortality (Justin and Armstrong 1987).

In a 1990 review in the journal, *Aquatic Botany*, Ernst explains the effect of waterlogged soils on plants. The article describes that the primary effect of waterlogging is reduced soil oxygen. As soils are waterlogged for a longer period of time, speciation occurs where elements in the soil become isolated and change from an oxidized to a reduced state, making regular plant function more difficult. Ernst explains that a reduction in photosynthesis will occur almost immediately following waterlogging but also acknowledges the strong relationship between waterlogging duration and degree of damages.

Ernst also stresses that waterlogging will affect glycolysis, the process by which a plant breaks down glucose to use as energy (1990). The extent of these effects depends on how widespread anoxia or lack of oxygen is in the soil. Not surprisingly, the longer the soil is flooded, the more infiltration of water into the soil, causing more anoxia and thus greater damage to waterlogged plants. Adaptations are common in plants that are waterlogged frequently but since the LHDC service area rarely floods, especially not at this magnitude, plants possessing adaptations to waterlogging are not expected to be common in the study area if they existed at all.

In 1993, Castonguay et al. found that alfalfa, a major crop grown in the LHDC service area, experiences a reduction in yields under waterlogged conditions. They found that when alfalfa is waterlogged, it undergoes significant decreases in its production due to reduction in root growth. Concentration of nitrogen, phosphorous, and potassium, major minerals elements used by plants, were reduced dramatically in leaves and potassium was reduced in roots. Not surprisingly, the study also found that alfalfa plants' resilience for regrowth after waterlogging declined with the duration of waterlogging. An increase in free abscisic acid and large accumulations of starch in the leaves of waterlogged plants was observed, the result of abnormal plant function from the anoxic conditions. A decline in leaf stomatal conductance, or intake of carbon dioxide, was also observed; in other words, the alfalfa could not breathe. We can expect other crops to experience similar effects to alfalfa in waterlogged soils.

In a 2011 article from the Journal of Natural Hazards, Qi and Altinakar examine the complexity surrounding flood damage assessment and indicate that flood damage assessment reaches beyond solely measuring exposure to flood waters. Other factors come into play such as the value of what was affected by floodwaters. For example, agricultural lands could be regarded as highly valuable to society because of their role in food production, therefore, a loss of agricultural land could be considered more destructive than a loss of the same area of open space land. Similarly, quantifying economic crop loss due to flooding easily becomes complex due to varying stages of crop production and varying market values between crop species and even the same crop at different times of the year. Many variables can be assessed when analyzing a flood with GIS. Westen suggests taking several flood characteristics into account including depth of water, flood duration, velocity, rate of rise and decline and frequency of floods in the area (2002). This data was unavailable in a usable form for this research but this has been identified as an area for further research.

In a 2008 article in *Applied Geography*, several techniques are employed to assess damages incurred southern France from flash flooding events in November 1999 and September 2002 (Vinet 2008). Vinet stresses the importance of considering agricultural assets such as farm houses and greenhouses that were damaged as well as damaged irrigation infrastructure and lost crops to conduct a more accurate analysis. Vinet analyzed damages from two different floods, one occurred before the harvest and the other after crops had already been harvested. Not surprisingly, he found that the economic impact was much higher in the 2002 flood which occurred prior to the harvest because crop losses, mostly grapes in this case, were so much higher.

While reporting damages assessed in floods experienced in Illinois in 1996, Changnon suggests flooding caused a reduction in crop yields and high rates of soil erosion, washing away many of the land's nutrients (2002). Both of these articles and their techniques in flood damage assessment emphasize the importance of utilizing reliable and precise agriculture loss data and accounting for crop type in an economic analysis. Meyer et al. suggest assessing not only direct costs and costs due to business interruption for farms, but also indirect both monetarily tangible and non-tangible costs

(2013). For example, a complete economic analysis would take non-tangible effects into consideration such as fluctuations in commodity prices as a result of flood affected crops not going to market (Downton 2005). To conduct this analysis precisely is of course very difficult suggesting inherent bias and inaccuracy to some degree in any economic disaster analysis (Smith and Katz 2013).

Scientists and emergency managers have long improved methods of mapping flood damages but recent advances in remote sensing technology and Geographic Information Science technology have made more accurate methods of impact assessment much more readily available (Jeyaseelan 2003). Flood loss modeling is an important component of the rebuilding process following a major flood event because it helps officials determine where to send resources. Still, assessing damages to agricultural land and infrastructure have not been heavily emphasized (Tapia-Silva et al. 2011). In 2011 CWCB released its Risk MAP program in collaboration with FEMA to quantify the flooding risk in one of these analytical models for pre-flood risk assessment (The State of Colorado 2011). Many areas that were flooded in September 2013 were classified as high flood risk under this model but due to the magnitude of this particular flood event, many areas that flooded were not considered at risk.

Analytical models to perform flood damage assessments have been developed for several different geographic areas following major flooding events. This research utilizes some of these models for reference and direction but acknowledges limitations from differences between the unique geographies of both our area of interest, the Left Hand Ditch Company service area, in Boulder County, Colorado, and the areas of interest for these other geographic areas. Some case studies in flood damage assessment examine a specific crop, some of which do not exist in Colorado but can still provide an excellent framework for quantifying agricultural flood losses.

Spatial data overlay is a common GIS technique that when implemented correctly can be a powerful spatial analysis tool (Burrough and McDonnell 1998; Bolstad 2008). By combining spatial and attribute data in an overlay, the GIS scientist can generate new data and analyze the spatial relationship between thematically different data. This is the main technique used in this research to assess crop losses and determine the landscapes and their characteristics where flooding was most common. Bolstad describes overlay as “the vertical stacking and merger of spatial data” (2008). When overlaying data, new geometry is often formed. For this research, a geometric output was not necessary so the *Tabulate Area (Spatial Analyst)* tool was utilized, which outputs a table.

Choosing an appropriate coordinate system is an extremely important aspect of accurate overlay operations. Bolstad stresses the importance of using a common coordinate system between inputs to produce a meaningful and accurate output in overlay operations and suggests first determining what the overlay operation is being used for (2008). In this case we are using the overlay to calculate area so it is important that we use an equal area projection. Zeiler and Murphy describe how equal area projections are designed to maintain area measurements and are ideal for middle latitudes (2010).

Zeiler and Murphy suggest that an Albers Equal Area Conic Projection is often best suited for area calculations because it minimizes distortion to area measurements by utilizing two standard parallels which add complexity and reference to the coordinate system (2010). These standard parallels are places where the conic shape of the projection touches the globe's surface. In the ArcGIS 10.1 Help, Earth Systems Research Institute (ESRI) suggests using 29°30' and 45°30' as standard parallels for maps that lie in the conterminous United States (2013).

Design and Implementation

The primary methods of this research catalog irrigation infrastructure and integrate vector and raster data overlay analysis to estimate agricultural resources lost and determine the landscapes and their characteristics where flooding was most common. The results of this analysis illustrate which areas were more susceptible to agricultural losses and irrigation infrastructure damage from flooding. The intent is that they can ultimately be utilized for future planning in the Left Hand Ditch Company service area, Boulder County, Colorado's Front Range, and in other geographic areas.

This research utilizes publically available GIS data from Federal, State, and Local Government agencies and collects additional data using in person interviews with the executive director and contractor responsible for repairs on the Left Hand Ditch Company's service area. The Environmental Systems Research Institute (ESRI) *ArcGIS 10.1* software suite with was used for all analyses and in the production of all maps. Many steps of the analysis utilize tools available in the *Spatial Analyst Extension*.

Initially, flood extent data was acquired from several sources such as the Federal Emergency Management Agency (FEMA), The University of Colorado Hydrology Department, The Colorado Department of Emergency Management, and Boulder County Government GIS Department. When utilized, the data acquired from FEMA portrayed the flooding extent in significantly more detail than other sources and was therefore deemed to be the most accurate representation of the flooding extent in the LHDC service area. Although the FEMA data was most detailed in its spatial representation of the flooding, none of the acquired flood data described depth, flood duration, velocity, or rate of rise accurately at a reasonable scale for the study area. These flood characteristics were not taken into consideration and this has been identified as an area requiring further analysis.

Hydrologic unit data was acquired from the National Resources Conservation Service's National Hydrography Dataset. Land cover data were acquired from the National Gap Analysis Program (GAP). Agricultural land, building footprint and storm rainfall estimate data were all acquired from the Boulder County Government GIS Department. Irrigation infrastructure and the LHDC service area boundary were acquired from the City of Boulder. The accuracy of the City of Boulder's irrigation infrastructure data for the LHDC service area were confirmed by Terry Plummer, the Executive Director of LHDC, and Scott Aschenbrenner, the contractor responsible for repairs to the ditch system following the flooding. Crop data was acquired from the United States Department of Agriculture's National Agriculture Statistics Service.

Landscape characteristic data were also obtained for analysis. Soil characteristic data were acquired from the United States Department of Agriculture National Resource Conservation Service (USDA-NRCS)'s Soil Survey Geographic Database known as SSURGO. It contains data collected over more than a century by the National Cooperative Soil Survey and covers most of the United States (USDA-NRCS 2015). The soil survey data contains a large amount of information about the soil. This research examines some of these characteristics: known flood frequency, water storage capacity at several depths, drainage class, and hydrologic class, as they are described in the soil survey data. Some soil characteristics were omitted such as bedrock depth and water table depth because they were incomplete for some map units in the study area. Other characteristics such as farmland suitability, and erosion potential were initially analyzed but omitted due to relative homogeneity within the study area.

Soil characteristics can greatly impact how a flood affects an area and how much damage is caused. In their 2010 Flash Flood Early Warning System Reference Guide, the University Corporation for Atmospheric Research (UCAR) describes how different soil compositions can behave very differently under flooding conditions. They explain considering three main factors, soil moisture, soil permeability, and soil profile. Soil moisture played a large role in the September 2013 floods in Colorado because with the large volume of water falling as rain, the soil eventually became completely saturated and did not allow water to infiltrate, forcing it to flow on the surface (Coleman 2014).

Soil permeability is another soil characteristic that affects flooding (UCAR 2010). Permeability can be described using texture or the relative proportion of different sizes of particles in the soil. UCAR explains how sandy soils allow for the quickest infiltration because of the larger particles that make up the soil, with more space in between the particles for water, making them less susceptible to flooding. Silty soils have more medium-sized grains that offer an intermediate rate of infiltration, while clay soils have the smallest particles and are therefore more susceptible to flooding because water cannot infiltrate as quickly. This is described in the soils survey data qualitatively in the soil unit names (USDA-NRCS 2015).

UCAR suggests also considering soil profiles but stresses that profiles can have a minimal affect once the soil becomes saturated (2010). This was the case with the September 2013 flooding due to the duration of the storm and abnormally large volume of water that fell over the area as rain. The bedrock depth and water table depth are two crude measurements used to understand profiles. Unfortunately due to incomplete data for these characteristics in the soil survey data, bedrock depth and water table depth were not taken into consideration. Water storage capacity can also be used to understand soil profile. Water storage capacity refers to how much water the soil can store and is measured in centimeters cubed of water (USDA NRCS 2015). The NRCS data measures water storage capacity at several depths, 0-25 cm, 0-50 cm, 1-100 cm and 0-150 cm. Not surprisingly, soils with a greater water storage capacity and water storage capacities that extend deeper into the soil profile are less susceptible to flooding.

Known flood frequency is another characteristic described in the soil survey data indicates how frequently an area has been known to flood over time. Drainage class describes and quantifies the natural drainage condition of the soil, indicating the degree, frequency, and duration of inundated water on the soils over time. The soil survey data also indicates hydrologic group, a classification system that is used to determine the potential for runoff over a particular soil type, ranging from A to D, increasing in the amount of runoff. UCAR explains that land cover greatly affects flooding and runoff over the landscape (2010). For example urbanization creates more impermeable surfaces and compacted soils which decrease infiltration and increase runoff drastically influencing how water interacts with the landscape.

For this research, elevation data was acquired in a digital elevation model (DEM) raster from the USGS at a 10m resolution, the highest resolution publically available in the study area. To utilize the DEM, first it was projected appropriately for analysis involving area calculations in the Left Hand Ditch Company service area. Then the spatial analyst tools in *ArcGIS 10.1* were used to generate slope and aspect data from the projected raster DEM. The elevation, slope, and aspect data were then clipped to the study area, the LHDC service area, using the *Extract by Mask (Spatial Analyst)* tool and a polygon feature class representing the LHDC service area, acquired from the city of Boulder.

To utilize the elevation, slope and aspect data the Integer, or *Int (Spatial Analyst)* tool, had to be used to convert the floating point raster datasets into integer raster datasets that could be used in an overlay operation. Classes also had to be established for area tabulations. Using this methodology, five classes were established for elevation, using equal interval spacing, measured in meters above sea level: <1550, 1550-1600, 1600-1650, 1650-1700, and >1700. Aspect utilized the classes created in the data's generation that describe the cardinal directions N, NE, E, SE, S, SW, W, NW and flat ground, but the *Int (Spatial Analyst)* tool was still necessary to convert to an integer raster. The generated slope data was reclassified to use the USDA-NRCS' slope classes described in the National Soil Survey Handbook: Nearly Level (<2%), Gently Sloping (2-6%), Strongly Sloping (6-14%), Moderately Steep (14-25%), and Steep (>25%) (2015).

The USDA NRCS describes how elevation can play a role in how soils develop, their chemical composition, and can also affect drainage within the landscape (2015). Aspect, another important soil characteristic, defines which direction the land faces and can affect the way soil behaves in various conditions because different aspects interact with their surrounding environment differently. Slope has a large effect on soils during a flooding event. As expected, steeper slopes do not have as high rates of infiltration making shallower slopes more susceptible to flooding and leading to higher rates of runoff for steeper slopes (UCAR 2010).

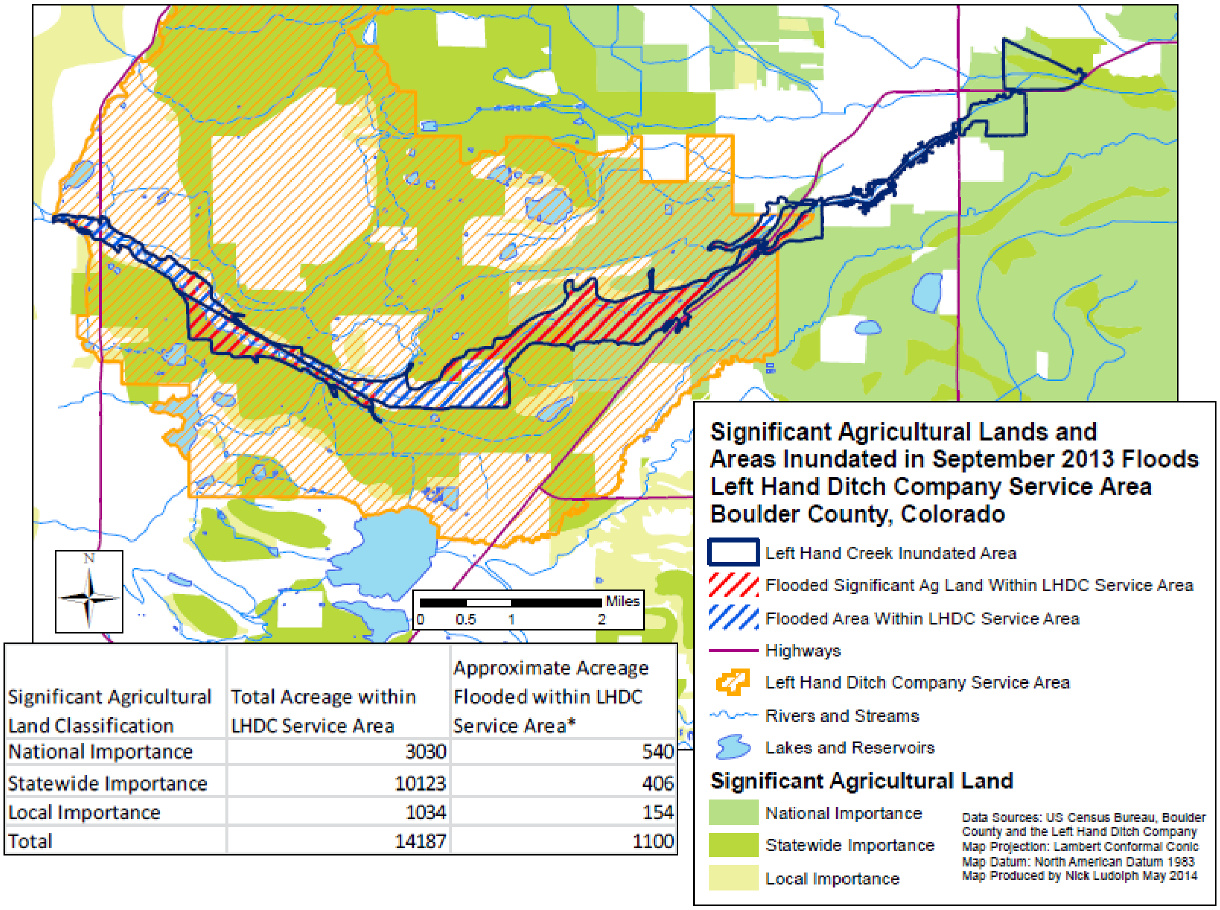
For this research an Albers Equal Area Conic Projection that is ideal for area calculations in the Left Hand Ditch Company service area was created by utilizing appropriate standard parallels and centering the projection on the study area. Following ESRI's guidelines, standard parallels were set at 29°30' and 45°30' (or 29.5 and 45.5 in decimal degrees). Then the *Feature to Point (Data Management)* tool was used in ArcGIS to convert the polygon feature representing the LHDC service area to a point, representing the center point or centroid of the LHDC service area. Next, new fields were created for latitude and longitude and the *"Calculate Geometry"* feature was used in the attribute table to calculate these values for the LHDC service area center point in decimal degrees. The center point was found to be at 40.126161 N, 105.221139 W. The centroid's coordinates were then used to center the new Albers Equal Area Conic Projection on the LHDC service area by setting 105.221139 W or -105.221139 as the Central Meridian and 40.126161 N as the Latitude of Origin. This ensures that area calculations are calculated most accurately. The Albers projection that was created utilizes the North American Datum from 1983 (NAD83).

The next step in the overlay analysis was to project all feature classes involved in the analysis into the newly created LHDC Albers projection. Raster datasets were also projected into the Albers Equal Area projection designed for area calculations in the LHDC service area. For most of this analysis, the *Tabulate Area (Spatial Analyst)* tool was used to determine what crops were lost as a result of the flooding as well as the landscapes and their characteristics where flooding was most common within the Left Hand Ditch Company service area.

Results

Geographic Information Systems technologies, using techniques in polygon overlay analysis were used to determine the area within the Left Hand Ditch Company service area that was inundated by floodwaters. Using flood inundation data from the Federal Emergency Management Agency (FEMA) it was found that over 1,700 acres of the approximately 22,000 acres in the Left Hand Ditch Company service area were flooded equaling approximately 12.5% of the total service area of the ditch company.

Polygon overlay analysis was also used to determine significant agricultural lands within the Left Hand Ditch Company service area. The LHDC service area contains a large area of significant agricultural lands with over 3,000 acres of national importance, over 10,000 acres of statewide importance, and over 1,000 acres of local importance together totaling over 14,000 acres. These significant agricultural lands cover about two thirds of the total Left Hand Ditch Company service area. Figure 7 shows lands in the LHDC that are classified as significant and the area that was inundated by floodwaters in the September 2013 flooding.



Significant Agricultural Land Classification	Total Acreage within LHDC Service Area	Approximate Acreage Flooded within LHDC Service Area*
National Importance	3030	540
Statewide Importance	10123	406
Local Importance	1034	154
Total	14187	1100

Figure 7: Significant Agricultural Lands Inundated by floodwaters within the Left Hand Ditch Company Service Area, September 2013.
**Acreage calculated with polygon overlay using ArcGIS 10.1 software. Data Sources for overlay: the Federal Emergency Management Agency (FEMA), the Boulder County Government, and the Left Hand Ditch Company.*

Terry Plummer, Executive Director of the Left Hand Ditch Company, took preventative measures into his own hands before the peak of the flood to protect farms and landowners' buildings in the LHDC service area (Zaffos 2014). On September 12, 2013, he put his own life in danger in the direct line of rising floodwaters, racing to build berms to protect from rapidly rising flood waters and divert water away from precious irrigation infrastructure and homes. Despite his arguably heroic efforts, hundreds of buildings in the LHDC service area were flooded.

Utilizing the Boulder County Government's building footprint data and using GIS techniques in overlay with FEMA's flood inundation data, it was found that 663 known buildings in the LHDC service area were flooded during the September 2013 flood. Some experienced minor damages while others were completely destroyed (Plummer 2014). Figure 8 shows known buildings and the inundation extent of the September 2013 flooding in the Left Hand Ditch Company service area. There are map insets for several areas that experienced the greatest concentrations of flooded buildings.

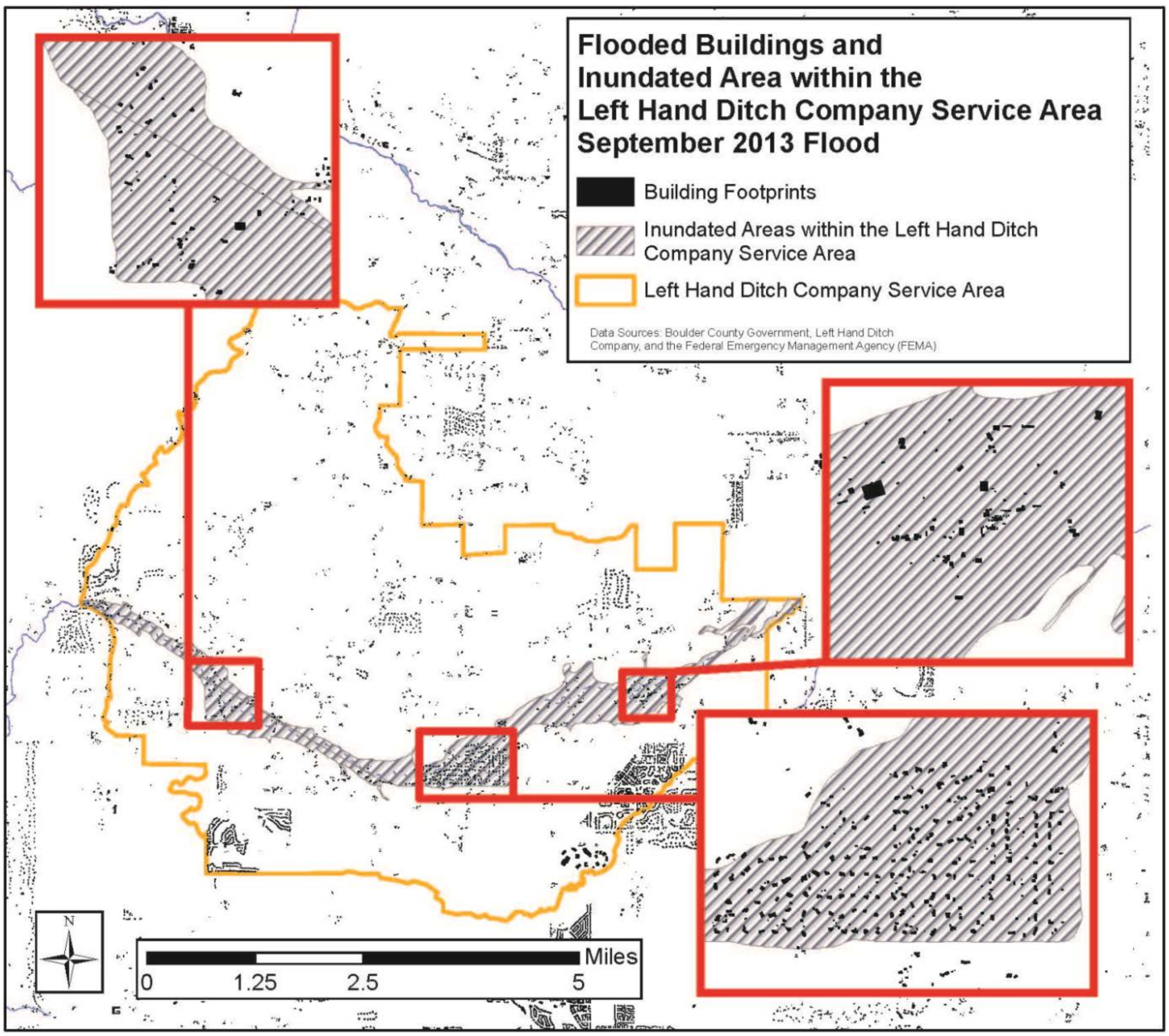


Figure 8: Flooded buildings in the Left Hand Ditch Company Service Area

Many crops became waterlogged before being harvested following the September 2013 flooding in Colorado. Results of an overlay analysis using GIS software determined that the major crops grown in the LHDC service area are hays other than alfalfa, alfalfa, corn, winter wheat, sorghum, and barley. Of these crops, the USDA's National Agricultural Statistics Service reports that all types of these crops would still be in the ground and therefore face damages and losses from flood waters, excluding winter wheat which is typically harvested by the end of July. See table 1 for harvest dates of major crops grown in the Left Hand Ditch Company service area. Crops are listed in order of most to least acres grown in the LHDC service area.

	Colorado Harvest Dates		
	Beginning of harvest	Most Active	End of Harvest
Hay (non-alfalfa)	6/6	4/5-7/10	9/15
Alfalfa	5/23	5/30-10/6	11/9
Corn	9/28	10/8-11/13	11/22
Winter Wheat*	6/27	7/2-7/21	7/29
Sorghum	9/29	10/11-11/18	11/29
Barley	7/20	7/29-9/6	9/14

Table 1: Harvest dates of major crops grown in the Left Hand Ditch Company service area.
Data source: United States Department of Agriculture National Agricultural Statistics Service (USDA NASS), 2010.
**The winter wheat crop was not affected by the September 2013 flooding because it had already been fully harvested in Colorado (USDA NASS 2010).*

The time for ideal harvest of the winter wheat crop had already passed so 2013's winter wheat crop in the Left Hand Ditch Company service area was not affected (USDA NASS 2010). Despite this, the 2014 crop may have experienced some effects from the flooding. Winter wheat is typically planted in the fall for the following growing season (USDA NASS 2010). The Colorado Crop Progress Report from September 22, 2013 suggests that some farmers may have wanted to replant winter wheat as a result of the flooding (USDA NASS 2013).

The September 2013 flooding occurred at the very beginning of the range of when winter wheat is typically planted in Colorado (September 1- October 11) so it is difficult to determine how much of the winter wheat in the LHDC service area had already been planted (USDA NASS 2010). The range of winter wheat planting dates for Colorado provided by the USDA NASS takes all of the state's geography into account, including much higher elevations than the LHDC service area, where winter wheat needs to be planted earlier. This research assumes minimal impact to the 2014 winter wheat crop in the LHDC service area because it is likely that none or only a small amount had been planted already because of the relatively lower elevations. Additionally, if winter wheat that had been planted for 2014 was affected, the cost to replant would be significantly less than the value of the other crops that were affected since the winter wheat hadn't started growing yet.

The water conveyance systems within the Left Hand Ditch Company service area experienced immense damages that took several months to repair. Miraculously, due to Executive Director, Terry Plummer, and Contractor, Scott Ashcenbrenner's efforts and prompt response, all major repairs in the Left Hand Ditch Company service area were completed prior to the start of the 2014 irrigation season (St. Vrain and Left Hand Water Conservancy District (SVLHWCS), 2014). This was not the case for all ditch companies in Colorado and was made possible largely due to the $3.3 million dollar low interest loan that was made available to LHDC from the Colorado Water Conservation Board

(CWCB 2013). Table 2 shows damages to the ditches and irrigation infrastructure in the Left Hand Ditch Company service area, their repair status, and estimated cost for the repairs. Repair cost is underestimated here due to missing repair estimate data from several ditches and laterals in the system. Even with this underestimate in cost, repairs are estimated at almost $4.3 million for the Left Hand Ditch and associated laterals and ditches that it feeds.

Ditch or Irrigation Infrastructure	Diversion structure Damages	Headgate Structure Damages	Measuring Structure Damages	Repaired by 2014 Irrigation Season	Repair Estimate (if available)*
Allen's Lake Filler	Destroyed	Destroyed	Buried	Yes	$84,000
Allen's Lake (with Diversion)	Diversion destroyed (no damage to lake)	Destroyed	Destroyed	Yes	$436,123
Bader Ditch	Destroyed	Destroyed	Intact	Yes	$4,000
Busch Ditch				not damaged	
Crocker Ditch	Destroyed	Destroyed	Buried	Yes	$25,000
CRO-John Ditch				not damaged	
Dry Creek				not damaged	
Gold Lake Filler Canal	Damaged	Intact	Damaged	Minor Repairs needed After Start of irrigation	$10,000
Haldi Ditch		Buried	Destroyed	Yes	$480,000
Hinman "Old Hinman" Ditch	Buried	Buried	Buried	Yes	$1,000
Holland Ditch				not damaged**	$1,000
James Ditch				not damaged**	$1,000
Johnson Ditch				not damaged	
Lake Ditch				not damaged	
Lake Valley Golf Course Diversion				not damaged	
Left Hand Ditch	Destroyed	Destroyed	Destroyed	Yes	$3,250,000
Left Hand Valley Reservoir	Damaged	Damaged		Yes	Unknown
New Hinman Ditch	Damaged	Damaged	Damaged	Yes	Unknown
New Table Mountain Ditch	Destroyed	Damaged		Yes	Unknown
North Toll Gate Ditch		Main Headgate Destroyed; Other Headgates Intact		Yes	Unknown
Old Star Ditch	Destroyed	Destroyed	Destroyed	Yes	Unknown
Peck Ditch					
Recorder Station	Destroyed	Destroyed	Destroyed	Yes	Unknown
South Toll Gate					
Star Ditch					Unknown
Williamson Cavey Ditch	Damaged	Damaged		Yes	$6,000
Total					**$4,298,123***

Table 2: Damages, repair status, and estimated repair cost to ditches and laterals in the Left Hand Ditch Company service area.
Data Source: St. Vrain and Left Hand Water Conservancy District, 2014.
**This total cost estimate in underestimates actual cost due to missing data for several ditches in the system*
***Some ditches listed as not damaged still incurred cleanup costs to reach usable status*

Utilizing spatial data from the USDA NASS' cropland data layer an overlay analysis was performed to determine what crops grow in the LHDC service area and which crops were flooded (2010). Using the acreages found in the overlay and non-spatial data describing the economic value of various crops in Colorado, also from the USDA NASS, a crude economic analysis was performed (2014). Table 3, shows the results of this analysis. Winter wheat was not included because it is assumed that all winter wheat for 2013 had already been harvested (USDA NASS 2010). Hay other than alfalfa was found to have experienced the most flooding with almost 470 acres of the 5191 acres grown in the LHDC service area inundated with floodwaters.

Crop	**Total Acres**	**Acres Flooded**	**Approximate Harvest Date in Colorado***	**Price Per/Acre****	**Harvested*****	**Estimated Profit Lost**
Other Hay (non-Alfalfa)	5191.4	469.7	15-Sep	$364.80	No	$171,345.53
Alfalfa	666.5	99.9	9-Nov	$687.30	No	$68,630.43
Corn	309.6	4.2	22-Nov	$603.91	No	$2,551.82
Winter Wheat***	59.4	3.3	29-Jul	$174.75	Yes	N/A
Sorghum	49.8	1.8	29-Nov	$183.84	No	$327.08
Barley	30.5	6.7	14-Sep	$762.09	No	$5,084.54
Other Crops	7.3	0				
Fallow Idle Cropland	64	1.3				
Total	6378.5	586.9				**$247,939.40**

Table 3: Crops grown and estimated crops lost to flooding in the Left Hand Ditch Company Service area due to the September 2013 flooding.
**Source: United States Department of Agriculture, Agricultural Statistics Service, Agricultural Handbook 628.*
***Source: United States Department of Agriculture, Agricultural Statistics Service, Colorado State Agriculture Review 2013.*
****The winter wheat crop had already been harvested by the time of the flood.*

Using these measurements and 2013 commodity prices for Colorado, it is estimated that farmers in the LHDC service area experienced $171,345 of lost profits due to the flooding non-alfalfa hay (USDA NASS 2014). Almost 100 acres of the 666 acres of alfalfa grown was inundated by floodwaters, resulting in an estimated $68,630 loss of profit. Other major crops grown in the LHDC service area include corn, winter wheat, sorghum, and barley but this analysis found impacts to these crops' harvest to be insubstantial in numbers compared to alfalfa and non-alfalfa hay. Overall this basic economic analysis found that almost a quarter million dollars in profits were lost due to flooded agricultural lands in the Left Hand Ditch Company service area. Most crops had not yet been harvested and many were far along in their growing cycles, almost ready for harvest, maximizing the economic impact (USDA NASS 2010).

A similar overlay operation was used to determine what land cover types exist in the LHDC service area and which were affected most heavily by the September 2013 floods. This portion of the analysis used data from the USGS' National GAP Analysis Program. Table 4 shows the results of this overlay listed in order of most flooded to least flooded land cover type. When land cover data were overlaid with the study area and the area inundated by floodwaters within the study area, it was found that land classified as agricultural land experienced by far the most flooding with 1,099 acres flooded of the 12,135 total acres in the LHDC service area, around 9% of the total area covered by land classified as agricultural.

Land cover Type	Total Acres	Acres Flooded	Percentage of Total Flooded
Invasive Annual Grassland	18.89	15.48	81.98
Western Great Plains Riparian Woodland and Shrubland	1278.91	451.60	35.31
Agriculture	12135.50	1099.09	9.06
Developed Open Space	943.41	81.69	8.66
Western Great Plains Floodplain Herbaceous Wetland	518.84	41.28	7.96
Invasive Perennial Grassland	3245.67	66.48	2.05
Rocky Mountain Ponderosa Pine Woodland	59.14	1.19	2.02
Developed	333.31	4.82	1.45
Western Great Plains Foothill and Piedmont Grassland	1329.85	4.93	0.37
Western Great Plains Shortgrass Prairie	894.53	1.07	0.12
Rocky Mountain Lower Montane Foothill Shrubland	398.51	0.00	0.00
Western Great Plains Sandhill Shrubland	20.48	0.00	0.00
Recently Burned	1.78	0.00	0.00
Open Water	627.95	N/A	N/A

Table 4: Land cover types of the Left Hand Ditch Company Service Area and the area of land cover flooded by type
Data Source: National GAP Analysis Program Land Cover Data

Western Great Plains Riparian Woodlands and Shrublands also had high rates of flooding with 451 acres flooded of the 1278 total acres in the LHDC service area, over 35% of the total area covered by that land cover type. Developed open space and Western Great Plains Floodplain Herbaceous Wetland land cover types also experienced high rates of flooding with around 8% of their total areas inundated by floodwaters, although their acreages are insignificant when compared to agricultural lands and Western Great Plains Floodplain Herbaceous Wetlands. Conversely, Invasive Perennial Grasslands, Western Great Plains Foothill and Piedmont Grassland, and Western Great Plains Shortgrass Prairie cover larger areas of the study area but were found to be more flood-resistant than other land cover types, with relatively small portions of their areas inundated by floodwaters.

The next portion of the overlay analysis involved soil characteristics provided by the USDA NRCS' national soil survey data. Results of this portion of the analysis are shown in tables 5 and 6. Figure 9 shows the various soil types identified by the soil survey and their extents across the LHDC service area. Niwot soils experienced the most flooding with 386 of the total 450 acres inundated by floodwaters, over 85% of their total area in the LHDC service area. Calkins sandy loam also experienced high rates of flooding with around 320 acres flooded in each slope class, 0 to 1 percent and 1 to 3 percent, totaling 640 acres inundated with water. Manter sandy loam also encountered widespread flooding with 226 of the 243 acres in the study area flooded, over 93% of the total area covered by that soil type.

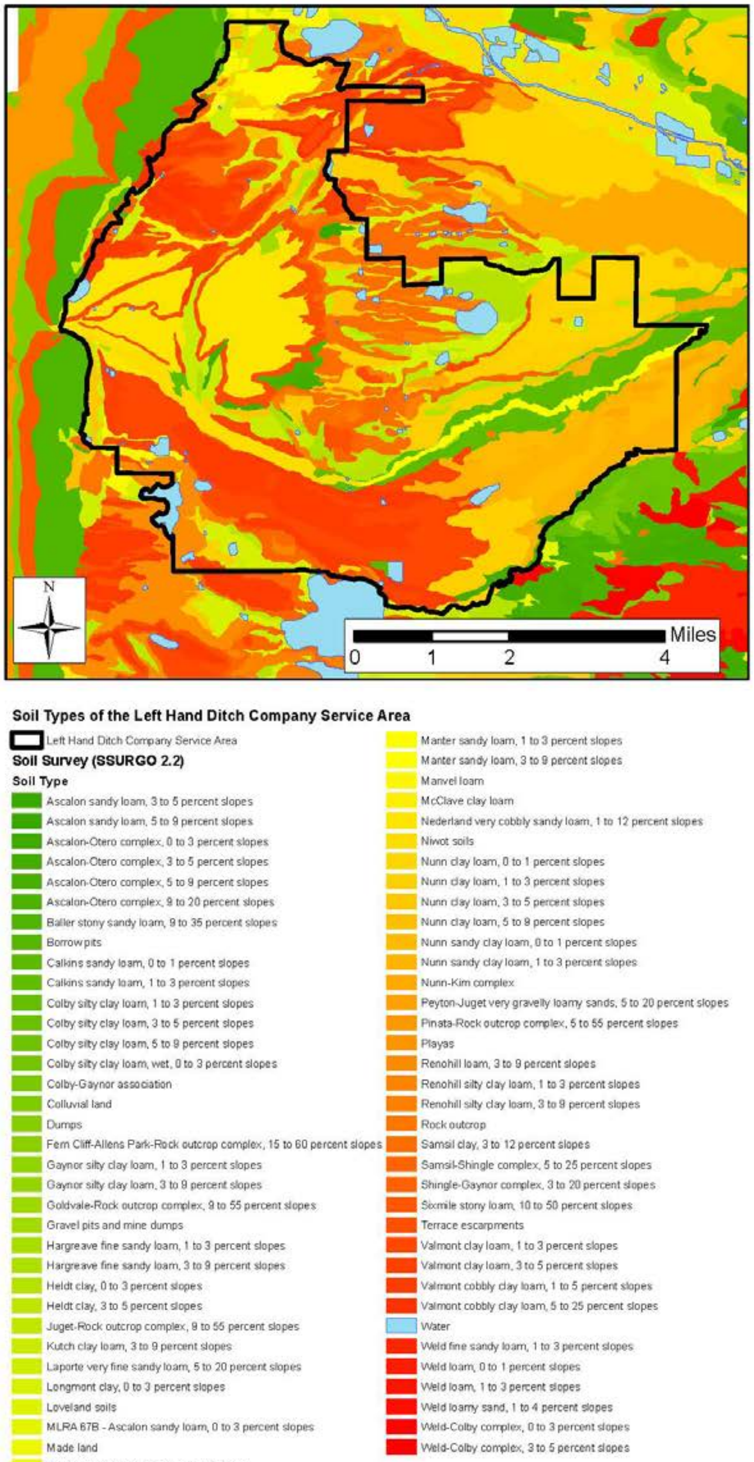


Figure 9: National Soil Survey Units in and around the Left Hand Ditch Company Service Area
Data source: National Soil Survey (SSURGO)

Soil Type and Slope	Soil Composition	Water Storage Capacity 0-25 cm	0-50 cm	0-100 cm	0-150 cm	Acres in LHDC	Acres Flooded	Percent Flooded
Manter sandy loam, 1 to 3 percent slopes	Sandy Loam	3.4	6.47	11.97	17.47	243.79	226.81	93.04
Niwot soils	Loam	3.75	6.1	8.6	11.1	450.59	386.62	85.8
Calkins sandy loam, 1 to 3 percent slopes	Sandy Loam	3	6	12	18	417.4	319.53	76.55
Calkins sandy loam, 0 to 1 percent slopes	Sandy Loam	3	6	12	18	627.14	321.15	51.21
Gravel pits and mine dumps	N/A	0.5	1	2	3	58.32	10.08	17.28
Nunn sandy clay loam, 0 to 1 percent slopes	Clay Loam	4	8.11	17.61	27.11	832.53	62.06	7.45
Valmont clay loam, 1 to 3 percent slopes	Clay Loam	4.69	8.69	14.35	17.85	1991.52	138.34	6.95
Nunn sandy clay loam, 1 to 3 percent slopes	Clay Loam	4	8.31	17.81	27.31	990.98	59.97	6.05
Valmont cobbly clay loam, 1 to 5 percent slopes	Clay Loam	3.8	7.8	11.84	15.34	1883.08	97.36	5.17
Heldt clay, 0 to 3 percent slopes	Clay	3.75	7.5	16.96	26.46	533.51	24.42	4.58
Baller stony sandy loam, 9 to 35 percent slopes	Sandy Loam	1.5	2.41	2.41	2.41	35.67	1.5	4.2
Nunn clay loam, 1 to 3 percent slopes	Clay Loam	4.75	8.5	16.96	26.46	1776.04	48.49	2.73
Renohill silty clay loam, 3 to 9 percent slopes	Clay Loam	4.54	9.14	14.08	14.08	403.96	5.71	1.41
Nederland very cobbly sandy loam, 1 to 12 percent slopes	Sandy Loam	1.64	3.64	6.66	9.66	2230.07	29.03	1.3

Table 5: Soil characteristics of soil types that experienced the most flooding in the September 2013 Flooding.
Data Source: United States Department of Agriculture National Resources Conservation Service National Soil Survey

Soil Type and Slope and Abbreviation	Known Flood Frequency	Drainage Class	Hydrologic Class	Acres in LHDC	Acres Flooded	Percent Flooded
Manter sandy loam, 1 to 3 percent slopes (MdB)	None	Well drained	B	243.79	226.81	93.04
Niwot soils (Nh)	Occasional	Poorly drained	C	450.59	386.62	85.80
Calkins sandy loam, 1 to 3 percent slopes (CaB)	Occasional	Poorly drained	C	417.40	319.53	76.55
Calkins sandy loam, 0 to 1 percent slopes (CaA)	Occasional	Poorly drained	C	627.14	321.15	51.21
Gravel pits and mine dumps (GP)	None		A	58.32	10.08	17.28
Nunn sandy clay loam, 0 to 1 percent slopes (NnA)	None	Well drained	C	832.53	62.06	7.45
Valmont clay loam, 1 to 3 percent slopes (VaB)	None	Well drained	C	1991.52	138.34	6.95
Nunn sandy clay loam, 1 to 3 percent slopes (NnB)	None	Well drained	C	990.98	59.97	6.05
Valmont cobbly clay loam, 1 to 5 percent slopes (VcC)	None	Well drained	C	1883.08	97.36	5.17
Heldt clay, 0 to 3 percent slopes (HeB)	None	Well drained	C	533.51	24.42	4.58
Baller stony sandy loam, 9 to 35 percent slopes (BaF)	None	Well drained	D	35.67	1.50	4.20
Nunn clay loam, 1 to 3 percent slopes (NuB)	None	Well drained	C	1776.04	48.49	2.73
Renohill silty clay loam, 3 to 9 percent slopes (ReD)	None	Well drained	C	403.96	5.71	1.41
Nederland very cobbly sandy loam, 1 to 12 percent slopes (NdD)	None	Well drained	B	2230.07	29.03	1.30

Table 6: Soil Characteristics of soil types that experienced the most flooding in LHDC in the September 2013 Flooding II

Data Source: United States Department of Agriculture National Resources Conservation Service National Soil Survey

The last portion of the landscape characteristic overlay analysis involved elevation, slope, and aspect. Results of this portion of the analysis are shown in table 7. The lowest elevation class, <1500 meters, had 586 acres that flooded, over 19% of the total area covered by this elevation class. Similarly elevations in the 1500-1550 meter class experienced 616 acres of flooding, over 8% of the total area covered by this elevation class. The amount of area within the study area flooded decreased with increasing elevation. North and northeast facing slopes were found to have higher rates of flooding. Lastly, the relationship between slope and flooding was observed. Shallower slopes experienced the highest rates of flooding with nearly level slopes (<2%) experiencing over 10% of their area flooded, and gently sloping areas (2-6%) experienced over 8% flooding in the LHDC service area. Areas with a slope steeper than 6% experienced significantly less flooding that decreased with increasing slope.

Elevation Class (meters)	**Total Acres in LHDC**	**Acres Flooded in LHDC**	**Percent Flooded**
<1550	2934.12	586.28	19.98
1550-1600	7599.33	616.55	8.11
1600-1650	5512.12	303.65	5.51
1650-1700	4628.74	238.03	5.14
>1700	1152.28	23.85	2.07
Aspect	**Total Acres in LHDC**	**Acres Flooded in LHDC**	**Percent Flooded**
Flat	296.44	0.00	0.00
North	2406.22	251.89	10.47
Northeast	4714.53	431.46	9.15
East	6271.18	471.26	7.51
Southeast	4250.71	322.53	7.59
South	2300.92	200.81	8.73
Southwest	525.37	23.13	4.40
West	368.62	8.74	2.37
Northwest	692.60	58.54	8.45

Slope Class	Total Acres in LHDC	Acres Flooded in LHDC	Percent Flooded
Nearly Level (<2%)	9868.27	1069.96	10.84
Gently Sloping (2-6%)	7644.60	631.51	8.26
Strongly Sloping (6-14%)	3136.70	60.53	1.93
Moderately Steep (14-25%)	827.44	5.50	0.66
Steep (>25%)	349.58	0.87	0.25

Table 7: Elevation, slope and aspect and their relationship to flooding in the Left Hand Ditch Company service area during the September 2013 floods

Discussion and Areas for Further Research

The overlay analyses performed in this research provide new insights on the landscape conditions that allow for the most damage to agricultural lands and irrigation infrastructure in a flooding event. Although this analysis does not account for all factors, this research is still important for simply cataloging the damages incurred to irrigation infrastructure and agricultural lands in Boulder County Colorado's Left Hand Ditch Company's service area. It will also aid in the future design of irrigation ditches for storm water conveyance in extreme flooding events.

Not surprisingly, the areas inundated by floodwaters were found to be clustered around the Left Hand Creek itself and the systems water conveyance such as ditches that are designed to deliver water to farmers. Field s of hay other than alfalfa were found to have experienced the most flooding of any of the crops grown in the LHDC service area. This is not surprising considering hay other than alfalfa is by far the most commonly grown crop in the LHDC service area with between 8 and 9 times as much area covered as alfalfa, the next most commonly grown crop.

Of the soil types that experienced the most flooding, sandy loam and loam soils tended to be more likely to flood than clay loam soils. This is surprising because in UCAR's Flash Flood Early Warning System Reference Guide, they report that sandy soils tend to allow more infiltration and flood less easily (2010). This illustrates that soil permeability and therefore infiltration rate were less important factors in determining what areas were more likely to experience flooding in September 2013 because the soil had already become saturated. This is consistent with the magnitude of the precipitation event and large volume of rain that fell.

Also surprising, there was no discernable correlation between water storage capacity and areas where flooding was most likely to occur and no substantial relationship between the USDA's hydrologic class, used to describe infiltration rate, and flooding. This is another indication that the soil had become completely saturated, making the infiltration rate and permeability insubstantial factors in flooding extent. In a smaller flood event we could expect these factors to have a greater affect as they probably did at the beginning of the flood, before soils had become saturated, forcing water to flow on the surface.

The USDA's soil survey data also describes known historical flooding frequency. All soil units in the study area are classified as having a flood frequency of "occasional" or "none." Not surprisingly, soil types that experienced the most flooding have a known flooding frequency classified as "occasional" while soils that experienced less flooding tended to have their known flooding frequency classified as "none." The low statistical probability of this particular flood, estimated at a 1 in 1000 year event, meant that several areas classified as having no known flood frequency were still inundated by floodwaters (Freedman 2013). Similarly and not surprisingly, soils classified as "poorly drained" under the USDA's drainage class experienced much more widespread flooding than those classified as "well drained."

Using the equal interval elevation classes, the lower elevation areas tended to allow for higher rates of flooding. This is no surprise considering that water typically flows to lower elevation areas. North and northeast facing slopes tended to experience more flooding. The preference of north facing slopes may be due to drier soils on south facing slopes when the precipitation event started, allowing for more infiltration in south facing slopes before soils became saturated. Other aspects of this analysis suggest that the volume of water was large enough that this would not have an effect. Not surprisingly, shallower slopes tended to experience the most flooding because water tended to pool instead of runoff.

Combining results of the various economic analyses performed, it is estimated that the Left Hand Ditch Company experienced over $4.5 million in damages and losses as a result of the September 2013 flooding. This takes into consideration a basic accounting of crop losses and damaged irrigation infrastructure. Several areas have been identified for further research. Fluctuations in commodity prices and the economic effects experienced from crops not going to market were not accounted for. Damaged agricultural structures were not accounted for in the analysis either because their value could not be accurately quantified. Flood characteristics such as depth, velocity and rate of rise were also not accounted for and would provide new insight about crop losses if this data becomes available. It is recommended that this flood characteristic data is collected if possible in future flood events involving inundation of agricultural lands.

Results from the landscape characteristic overlay analysis showed that flooding was more likely to occur on lands with particular soil types and land cover types. Several other characteristics that were expected to be more indicative of flooding did not show a meaningful relationship. Soil composition, water storage capacity, and hydrologic class were predicted to have a strong correlation, observable when compared to areas that flooded but this was not the case. This unexpected disassociation is likely due to the large volume of water that fell during the storm. Once the soil was fully saturated, these soil characteristics that affect infiltration and permeability were no longer relevant, causing water to flow on the surface over all types of soil.

Although the landscapes where flooding was more common in LHDC service are have been determined, and their characteristics identified, further research is necessary to fully understand floodwaters and their interaction with the landscape and anthropologically altered lands such as those used for agriculture. Prompt response by the Left Hand Ditch Company has been identified as a major factor in the LHDC's speedy recovery to their water conveyance systems following the flood damages. The author recommends analyzing landscape characteristics when building and assessing flood risk for agricultural lands in flood prone areas but acknowledges the limitations of this research's results simply due to varying geographies between study areas.

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