Arroyo Incision in Central Washington

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Introduction

Management of soil resources is important in many parts of the world for sustainable land use. This is especially true in many of the arid and semiarid regions of the world where sparse vegetation growth leaves the soil vulnerable to erosion. One common landform associated with soil erosion is an arroyo. These landforms form in drainage basins and form steep-sided gullies incised into the landscape after massive amounts of erosion has taken place. These landforms create problems for land use management through soil losses, making agricultural land unproductive, and negatively affecting water availability in an environment. The primary causes behind arroyo incision as well as the spatial distribution of arroyos are not completely understood.

To address these problems, I identified and mapped the distribution of arroyos in central Washington as of 2005. I first identified areas that have experienced arroyo incision and then mapped arroyo extents. I did this in order to address why certain areas are vulnerable to erosion. I hoped to answer what is the primary cause behind arroyo incision, whether it is substrate or human land use. To study this topic, I examined arroyo incision that has taken place in Douglas, Grant and Adams Counties. This semiarid region has seen numerous instances of arroyo incision that create problems for management of soil resources.

Arroyos in central Washington should be studied because of the drastic changes that they have caused to the landscape. By examining this entire area and mapping all arroyos we may be able to better understand why these arroyos initially formed. This can help in identifying areas that could be susceptible to further arroyo incision, soil erosion and water quality problems. Also, cataloging all areas of arroyo incision could aid in future study of arroyo incision in central Washington.

Study Area

As mentioned before, the area being studied is located in central Washington. The study area was defined as Douglas, Grant and Adams Counties (Figure 1). This study area features common characteristics in geomorphology, climate, vegetation, and land use. This area's semi-arid shrub-steppe environment is ideal for the development of arroyos and arroyos have already been identified here in the past.

The geomorphology of the study area has been influenced mostly by lava flows, continental glaciation, and glacial outburst floods. Much of the parent material that makes up this region is made up of basalt that was laid down 14 million years ago by lava flows. During the Pleistocene continental glaciers covered much of the northern portion of Douglas County

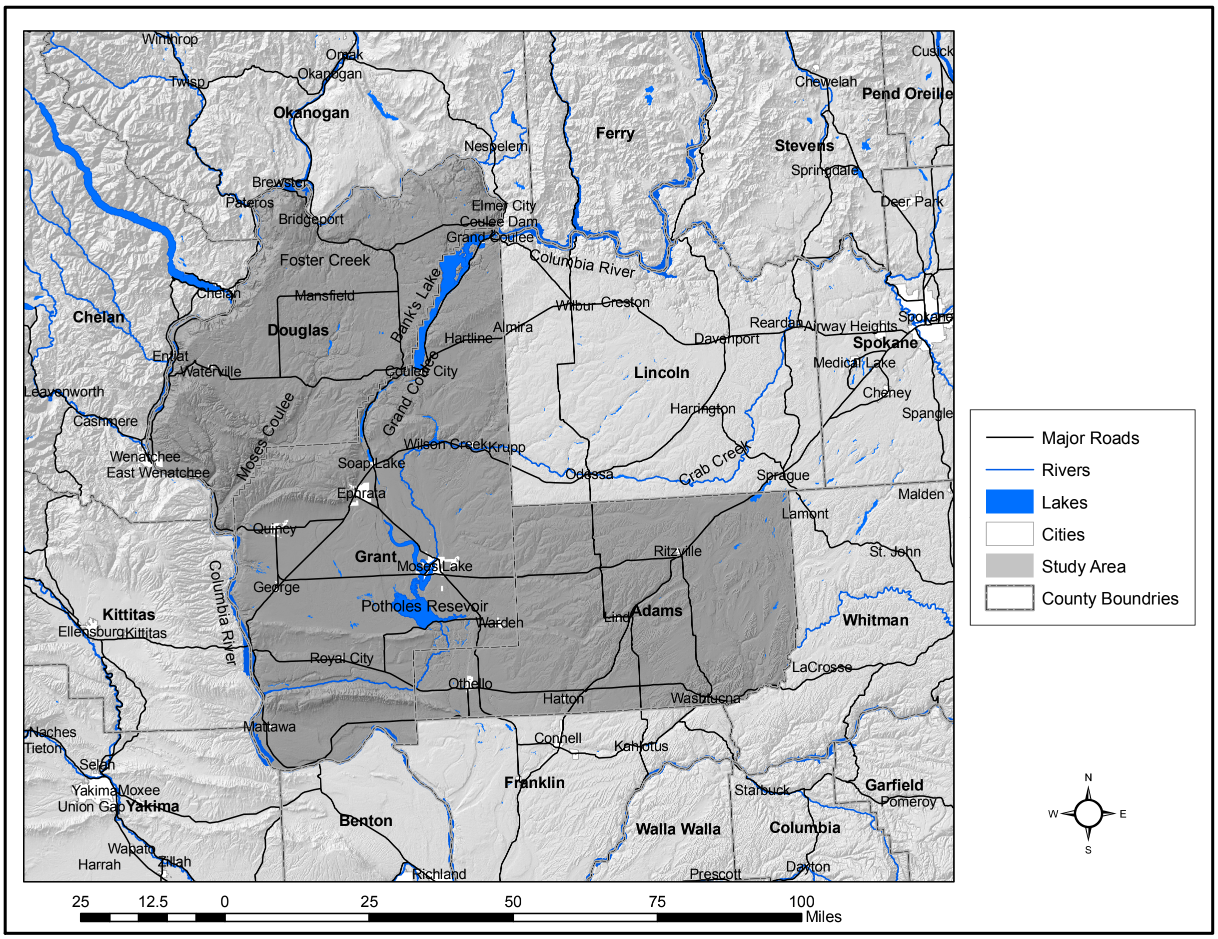

Figure 1: Study Area of Douglas, Grant and Adams Counties in central Washington

with deposits of glacial till, outwash and loess. The glacier that covered this area was known as the Okanogan Lobe and it extended south to Moses Coulee in Douglas County. At the end of the Pleistocene, glacial floods caused by the melting of glaciers produced coulees that make up the Channeled Scablands, which cover much of eastern Washington and the study area. This includes Moses Coulee, Grand Coulee in Douglas and Grant Counties (Figure 1) as well as Rocky, Farrier, Weber, Bauer and Lind Coulees located further east in Adams County. These floods also brought large deposits of sand, silt and gravel to the Channeled Scablands. Continental glaciation also contributed to the deposition of glacial lake sediments. Much of this sediment is found adjacent to the Columbia River (Figure 1). These sediments are influential in the formation of arroyos as it has a tendency to form vertical joints that can eventually become arroyos (Blanton, 2004).

The climate of this area varies widely depending on location but most of the region is characterized by a dry, continental climate with hot summers and cold winters. Climate data from Moses Lake shows that temperatures vary from an average of 29ºF in January to 70ºF in July (WRCC, 2005). The entire area receives most of its precipitation during the winter months. Most of the precipitation in this area falls during the winter months with summers in the region being very dry. There is also a peak in precipitation that occurs during the spring from thunderstorms. These storms bring a high amount of water flow, especially when falling on snowpack, and can be a major contributor to arroyo incision (Blanton, 2004). Also, large convective thunderstorms bringing high amounts of precipitation during the summer and have caused much of the observed soil erosion in the study area (Blanton, 2004).

The vegetation of the study area is characterized as a shrub-steppe environment and is dominated mostly by bunchgrasses and sagebrush. Riparian areas feature species of red Ossier dogwood, willows and mock orange. Wildlife in this area includes populations of mule deer, ducks, coyote, beaver, weasels, badgers, mountain lions and bobcats. Beaver are a common part of the riparian environments of the study area and can be seen as promoting arroyo incision by removing riparian vegetation making channels more vulnerable to erosion. Despite this, they can also be seen as having a positive impact on the environment because dams can help to regulate water flow and help in floodplain development in incised areas (Blanton, 2004).

Land use in the area is dominated mostly by agriculture and hydroelectric power along the Columbia River. Land use and settlement of the area intensified mostly around the beginning of the 20th century. This included mostly dryland wheat agriculture and livestock grazing, which could be attributed as a major cause of arroyo incision. A major change to the area occurred during the 1950s with the Columbia Basin Irrigation Project, which produced Potholes Reservoir and brought irrigation to much of the Columbia Basin. Hydroelectric power in the area began along the Columbia River in the 1930s. The study area has a sparse human population with larger settlements in the cities of Ephrata, Quincy, Othello and Moses Lake.

Literature Review

There has been extensive study of arroyos in the western United States as well as similar landforms in other parts of the world. These studies help to show how arroyos can be identified, how they can be assessed, and what caused them to initially form. Not much research has been done on arroyo development in eastern Washington. Understanding causes and the processes that have led to the formation of arroyos in other places is crucial to understanding how they have developed in eastern Washington.

Schumm and Hadley (1957) studied arroyos in Wyoming and New Mexico by examining the longitudinal profile of arroyo floors. The arroyos that they studied were discontinuous because valley floors often went through periods of incision followed by deposition. Periods of incision often began after deposition built up to a critical angle. This critical angle is dependent on the discharge of the stream being studied and is inversely related to the size of the drainage basin. This leads to landscapes where arroyo incision will not be present along all parts of a drainage channel. The authors also suggest that arroyos are common in arid environments because of the increased buildup of alluvium as water flow decreases when it is absorbed into a channel.

Pavish (1973) examined the arroyos in Bock Spring and the Rye Grass Coulee near Vantage, Washington. The arroyo located in the Rye Grass Coulee is located in the meridian of Interstate 90. He studied the arroyos by examining the stratigraphy of the arroyo walls. He dismissed the influence that human activity, particularly overgrazing, could have had on arroyo incision and attributed it mostly to long-term changes in climate because arroyos have existed in this area since before large-scale human settlement.

Cochran (1978) examined arroyo development on Johnson Creek also located near Vantage, Washington. He also studied the stratigraphy of the arroyo and was mainly concerned with using the information to reconstruct the environment of the immediate area for a better understanding of archeological remains found in the area. He also attributed incision to long-term changes in climate because arroyos have existed in this area since before large-scale human settlement.

Balling and Wells (1990) examined arroyo incision along the Zuni River in New Mexico. They compared timings of incision with changes in precipitation. They statistically tested historical changes in rainfall over the last century to see if changes in precipitation coincide with historical changes in arroyo incision. They attributed arroyos in this area mostly to climate changes because arroyo incision has occurred in this area since before the arrival of Spanish or Anglo-Americans. They found that incision usually occurred during periods with frequent intense summer storms and deposition occurred when rainfall was much less intense.

Finlayson and Brizga (1993) studied arroyos that developed along the Nagoa River in Queensland, Australia. This river has changed from an anastomosing river to one single channel incised into the sediment. They noted the landforms similarities to arroyos that have formed in the United States and the similar environments that they have formed in. They noted one of the common characteristics for these landforms in both Australia and the United States is that they are both located in areas that are highly variable in terms of rainfall and the occurrence of floods. These areas are highly sensitive to changes in land use. They also noted that in these arid regions livestock will usually graze in moist valleys and riparian zones, which puts more pressure on these areas.

Fanning (1999) looked at gullies in an arid region of New South Wales. She examined the relationship between erosion on surrounding hills from increased land use and the build up of alluvium in a valley. This alluvium is very susceptible to erosion and will eventually become incised. She attributed the development of gullies here to the introduction of sheep grazing to Australia.

Gonzalez (2001) studied arroyo incision along the Little Missouri River in North Dakota and was primarily concerned with how the timing of arroyo incision coincided with climate variations. This area of North Dakota has experienced large scale erosion that has led to the formation of the Little Missouri Badlands. He did this by studying the dendochronology of riparian cottonwood trees that typically grow in recently deposited alluvium after large-scale floods. He found that incision usually occurred after a period of extensive drought repressed vegetation growth leaving the area open to erosion during intense storms and attributes arroyo incision mostly to climate changes.

Boardman, et al. (2003) used airphoto interpretation to examine the soil erosion that has taken place in the arid region of Sneeuberg, Great Karoo, South Africa. The area has experienced extensive erosion creating gullies and badlands were erosion is most severe. The authors give a chart describing how to determine the severity of erosion from airphoto interpretation, whether it is sheet, rill or gully erosion. They use this chart to classify different parts of their study area based on the severity of erosion.

Blanton (2004) studied arroyo incision in West Foster Creek in northern Douglas County, Washington. He did his study with airphoto analysis over eight different time periods and was trying to determine what has caused arroyo incision in this area. He concluded that it was a combination of land use, substrate, and climate. The timing of arroyo incision in the area coincides with the spread of land use in the area. He concluded that this area was already predisposed to erosion because the soil was made up mostly of unconsolidated sediments, which included very erodible glaciolacustrine sediments. Also important is the dry climate of the area that leaves sparse vegetation growth leaving the area susceptible to erosion. This area also experiences many storms that bring unusually high amounts of precipitation that led to widespread erosion.

No previous research has been done to map all of the existing arroyos in central Washington. Of the previous research listed here, none used orthophotos as part of their research. Finlayson and Brizga (1993), Boardman et al. (2003) and Blanton (2004) used airphoto analysis as part of their study but focused on temporal changes in local areas. None of these studies focused on the spatial extent of arroyos over a large area.

Methods

To study this topic I examined arroyo incision that has taken place in Douglas, Grant and Adams Counties. I mapped all of the present arroyos located in this area. Identification of arroyos was done with Google™ Earth, digital orthophotos and ArcGIS™ to create georeferenced maps of the extent of arroyos. Mapping arroyo incision was done with Google™ Earth and ArcGIS™.

<u>Identification</u>

To help in identifying areas of incision I examined areas where previous research has been done to see areas that others have identified as incised. By looking at airphotos of arroyos that other people have identified it is possible to determine the criteria they used to identify arroyos. Pavish (1973) identified the Rye Grass Arroyo by locating shadows caused by depth and exposed sediments on the walls of the arroyo. Parts of the arroyo now have vegetation growing which shows that the floor may have stabilized and is not currently being incised. Cochran (1978) used similar criteria as Pavish (1973) to identify arroyos but the arroyos identified featured much more exposed sediments, which may show that the area has undergone arroyo incision much more recently. Blanton (2004) used high amounts of exposed sediments adjacent to the stream as criteria to identify arroyos in the Foster Creek Watershed. He also noted the problems with distinguishing between areas that were undergoing incision and areas that were not, particularly when incision stopped and an arroyo floor stabilized. He did this by looking for areas of floodplain development identified by large amounts of riparian vegetation near the stream and evidence that the stream has migrated laterally. He still mapped areas as an arroyo if it featured riparian vegetation and was not actively undergoing incision. He didn't map areas as an arroyo if they had been completely filled with sediments.

Arroyos were identified by areas were depth and small steep walls on either side of the stream that have created shadows, as well as the presence of exposed sediments and the removal of riparian vegetation (Smith, 1943). Arroyos were still identified in areas that do feature riparian vegetation growth if they still exhibited shadows and exposed sediments.

Mapping

The mapping of the spatial extent of arroyos in the study area was done with airphoto analysis. Areas of arroyo incision were first identified using Google™ Earth. After these areas were identified they were examined further with digital orthophotos. The digital orthophotos were color images taken by the National Agricultural Imagery Program (NAIP) in 2005. To cover the entire study area, arroyos were identified by systematically following drainage lines throughout the study area. Arroyos were mapped and digitized using ArcGIS™ and digital orthophotos to create ArcGIS™ shapefiles so that measurements of total arroyo incision lengths could be made accurately.

Arroyos that were identified were mapped into two different categories. This includes incised and probable incision. Incised areas include areas where we can be sure from the airphotos that incision has taken place. These areas feature very distinctive shadows and exposed sediments. Probable areas include areas that feature exposed sediments but where shadows are not visible because of the angle of the sun or they are obscured by vegetation growth.

Analysis

Analysis of the effects of substrate was done using ArcGIS™. Shapefiles created showing arroyo incision were overlayed with a shapefile showing surface geology obtained from the Washington State Department of Natural Resources. This allowed for measurement of arroyo incision that has taken place in a particular type of substrate. This helped in determining if arroyo incision occurs in a particular type of substrate.

Land use was also be mapped and digitized using ArcGIS™ to assess the effects that it could have on arroyo incision. Land use was mapped into three different categories: irrigated agriculture, dryland wheat agriculture and rangeland/natural vegetation. Agricultural land was identified by its very smooth and uniform texture. Irrigated agriculture should be much darker green than dryland wheat, with much more distinctive rows. Fields may form circles if it is center-pivot irrigation. Much of the natural vegetation in this area would be described as shrub-steppe, which would have a much more coarse texture when viewed on airphotos (Avery and Berlin, 1992). Much of agriculture in this area should also feature linear patterns to distinguish it from natural vegetation (Avery and Berlin, 1992).

Results

The results of mapping shows that arroyos are located throughout the entire study area, but there are many large areas that do not feature arroyo incision. The total amount of incision identified was 69563 meters and the total amount of probable incision identified was 20007 meters. In this study, arroyos were identified in three major areas: the Foster Creek watershed, upper and lower Moses Coulee, and western Adams County. In these areas the total amount of incision was over 20000 meters with the most incision occurring in the large area east of Moses Lake (Table 1). A small amount of incision was also found in northern Grant County (Table 1). (Figure 2)

Table 1: Incision and probable incision in the Douglas, Grant and Adams Counties

Incised		**Probable**	
Area	Length (meters)	Area	Length (meters)
Foster Creek Watershed	20617	Foster Creek Watershed	5652
Lower Moses Coulee	11617	Lower Moses Coulee	1799
Upper Moses Coulee	10894	Upper Moses Coulee	4824
East of Moses Lake	24948	East of Moses Lake	3652
Northern Grant County	1487	Northern Grant County	4080
Total:	**69563**	**Total:**	**20007**

Geology

After incision was identified, it was overlayed with a layer of surface geology (Figure 3). Arroyos were identified in the Foster Creek watershed where they had been previously identified by Blanton (2004). These arroyos were found in both East and West Foster Creek. West Foster Creek features the most continuous incision and most easily identifiable on airphotos. The incision in West Foster Creek is located in mostly glaciolacustrine deposits and glacial drift. Incision in East Foster Creek was much less continuous and was mostly in alluvium that had formed in the central valley. Incision was also identified in glacial outwash in both the central valley and the surrounding hills. (Table 2)

Table 2: Incision and probable incision in the Foster Creek Watershed by Geologic Map Unit

Incised		**Probable**	
Geologic Map Unit	Length (meters)	Geologic Map Unit	Length (meters)
Qgl	6827	Qa	2797
Qgd	5206	Qgl	1271
Qa	5170	Qgd	1051
Qgo	2152	Mc(e)	370
Mc(e)	1036	Mv(gN2)	117
Mv(wpr)	209	KJog(cj)	46

Mv(gN2)	71	**Total:**	**5652**
KJog(cj)	9		
Total:	**20617**		

Arroyos were found in two areas in Moses Coulee: lower Moses coulee, near the Columbia River, and upper Moses Coulee, near the center of Douglas County. Arroyos that were identified in Lower Moses Coulee were identified in nearly the center of the coulee in McCarteney Creek from between roughly four to sixteen kilometers northeast of the Columbia River. The coulee floor is made up of mostly gravel from the Missoula Floods that occurred at the end of the Pleistocene as well as alluvium deposited afterwards. These outburst floods are what initially created the coulee and many of the other coulees in central Washington that make up the Channeled Scablands. The sides of the coulee also feature mass wasting deposits from the steep coulee walls as well as alluvial fan deposits from drainages in the surrounding area. Almost all of the arroyo incision that has occurred here occurred in alluvium.

Incision that was identified in upper Moses Coulee approximately 50 kilometers up the coulee from the Columbia River and 15 kilometers south of the city of Mansfield. The coulee floor is made up of mostly alluvium and glacial drift. Gravel from glacial outburst floods makes up gravel bars along the sides of the coulee. Incision here was found mostly in the alluvium and glacial drift along McCarteney Creek. A large amount of arroyo incision was also identified in Dutch Henry Draw to the northwest of Moses Coulee, where the surface geology is mapped as Miocene basalts (Figure 3). This area should be seen as a probable place of error because, according to the geologic map incision occurred into bedrock and not into soft sediments. It could be that incision did occur into soft sediments above the basalt bedrock but this is not shown because of the scale of the map. (Table 3)

Table 3: Incision and probable incision in the Moses Coulee by Geologic Map Unit

Lower Moses Coulee

Incised		Probable	
Geologic Map Unit	Length (meters)	Geologic Map Unit	Length (meters)
Qa	10808	Qa	1798
Qls	573	Qfg	1
Qfg	206	**Total:**	**1799**
Qaf	30		
Total:	**11617**		

Upper Moses Coulee

Incised		Probable	
Geologic Map Unit	Length (meters)	Geologic Map Unit	Length (meters)
Mv(gN2)	6232	Mv(gN2)	2613
Qa	3320	Qa	1484
Qgd	2475	Qgd	727
Mv(wpr)	1086	**Total:**	**4824**
Mv(wfs)	747		
Ql	34		
Total:	**10894**		

The last major area where incision was identified was a large area approximately 25 kilometers east of Moses Lake and Potholes Reservoir that comprises most of western Adams County and the eastern edge of Grant County (Figure 3). These arroyos are all found in east to west trending coulees that are part of the channeled scablands that formed during the Missoula Floods. The coulees in this area that feature incision are Rocky, Farrier, Weber, Bauer and Lind Coulees. These Coulees are made up of mostly alluvium as well as sand, silt and gravel from glacial outburst flood. The majority of the area surrounding the coulees is made up of mostly loess and basalts. The majority of the incision occurred in alluvium in the center of the coulees and in loess and basalt in the surrounding region. (Table 4)

Table 4: Incision and probable incision east of Moses Lake by Geologic Map Unit

Incised		**Probable**	
Geologic Map Unit	Length (meters)	Geologic Map Unit	Length (meters)
Qa	15001	Qa	2578
Mv(wr)	5004	Mv(wr)	309
Mv(wfs)	2643	Ql	302
Ql	1871	Qfg	257
Qfs	305	Qfs	110
Qfg	124	Mv(wfs)	96
Total:	**24948**	**Total:**	**3652**

A small amount of incision was also identified in areas of northern Grant County. Most of the incision here was identified in isolated areas around the Beezley Hills located in Northwest Grant County (Figure 3). Most of the incision occurred in the Lynch Coulee located northeast of the Columbia River and further to the east near the city of Ephrata. This area is made up of mostly loess, basalts and a small amount of alluvium. Much of the incision here is located in alluvium and basalts. A very small amount of incision was also found in northeastern Grant County near the city of Wilson Creek in gravel from glacial outburst floods. (Table 5)

Table 5: Incision and probable incision in northern Grant County by Geologic Map Unit

Incised		**Probable**	
Geologic Map Unit	Length (meters)	Geologic Map Unit	Length (meters)
Mv(gN2)	739	Qa	2397
Qa	684	Mv(gN2)	1476
Qfg	64	Qfg	207
Total:	**1487**	**Total:**	**4080**

The examination of geology's influence on arroyo incision shows that incision is strongly tied to the Missoula Floods that occurred during the end of the Pleistocene and almost all arroyos have formed in the Channeled Scablands that formed as a result of the floods. These floods carved away the much less erodible basalt bedrock and created channels where the soft sediments could be deposited. All of the arroyos, with the exception of the Foster Creek Watershed, are all located south of the terminal moraines of the last glaciations. They all received deposits of glacial drift and glacial outwash as the continental glaciers were melting. They also received deposits of sand, silt and gravel as massive amounts of water flowed through the coulees during the successive Missoula Floods.

In many of the areas where incision was identified it was located mostly in alluvium. Schumm and Hadley (1957), Pavish (1973), Cochran (1978), Balling and Wells (1990), Fanning (1999), Gonzalez (2001) and Boardman (2003) all identified incision into valley fills of late Holocene alluvium. Incision identified in central Washington occurred not only in to late Holocene alluvium but also alluvial deposits from the glacial outburst floods. The reason for incision in these areas is the frequent deposits of sandy and silty sediments.

The Foster Creek Watershed not only received sediments from the Missoula floods but also glaciolacustrine sediments from the damming of the Columbia River during the late Pleistocene. The watershed is located within an area that was previously glaciated. Incision occurred within the watershed approximately 30 kilometers north of the terminal moraine of the Okanogan Lobe, which extends to the northern edge of Moses Coulee. Glaciation brought with it erodible deposits of glacial drift that extends over much of what is northern Douglas County. What is more important in the development of arroyos in this area are deposits of silty glaciolacustrine sediments. Blanton (2004) noted that these sediments experienced the most and the deepest incision throughout the entire study area and largely controls where incision takes place. These glaciolacustrine deposits are located in many other areas outside of the study area mostly in areas adjacent to the Columbia River. Finlayson and Brizga (1993) also identified incision in silty lacustrine deposits from ancient lakes.

As mentioned before there is a possibility of error in examining the geology of this area because of the scale that the map was produced at. There are several instances were incision was identified in areas of basalt bedrock. This incision could have been into softer sediments in top of the bedrock, which was not shown on the map because it was only found in small local areas. Boardman et al. (2003) noted incision that has occurred in thin deposits of colluvium on top of bedrock. In these cases incision was limited to one or two meters and stopped at the bedrock. There are also instances were incision was identified in areas of gravel from glacial outburst floods. The incision could have occurred in sand or silt from glacial outburst floods not shown here because of the scale of the map, which would be more probable.

<u>Land Use</u>

The result of mapping land use is shown in Figure 4. The results show that irrigation is most prevalent in Grant County where it is spread throughout a majority of the area surrounding Potholes Reservoir and Moses Lake. This is the result of the Columbia Basin Irrigation Project of the 1950s. Irrigation is also present spreading into the western edge of Adams County and small areas along the Columbia River in Douglas County. Dryland wheat agriculture is prominent in most of Douglas and Adams Counties and northern Grant County. Rangeland/natural vegetation makes up all of the other land in the study area. This type of land cover is found sporadically throughout the entire study area especially Douglas County. It is especially present were terrain is too steep or rocky to allow for agriculture. This type of land cover can also be found in previously cultivated areas that were converted to natural vegetation as part of the Conservation Reserve Program. This program began in the 1980s and compensated farmers who took their land out of cultivation in areas that could experience high amounts of soil erosion.

By examining the map (Figure 4) it is apparent that there seems to be a relationship between incision and what type of land use is being practiced, particularly whether or not the predominant land use in the area is irrigated agriculture or dryland wheat agriculture. Although incision in the study area mostly occurs in rangeland/natural vegetation, incision occurred where the surrounding land use in the area was predominately dryland wheat agriculture. Incision is notably absent in areas of predominately irrigated agriculture. The only area that this isn't true is in lower Moses Coulee where irrigated agriculture and incision is present in parts of the valley floor.

The absence of arroyos near areas of irrigated agriculture can possibly be explained by irrigation's effects on the hydrology of a region. It seems to be counterintuitive that irrigation could decrease the amount of arroyo incision because of the increased amount of runoff that irrigation produces. However, irrigation will also artificially raise the water table and increase the water available for riparian vegetation growth. One of the main factors that has been attributed to the development of arroyos is the thinning of vegetation caused by drought or overgrazing. The raising of the water table in a nearby field will promote the growth of denser vegetation. One piece of evidence for this is in lower Moses Coulee were both incision and irrigated agriculture are present (Figure 4). In areas where McCarteney Creek enters an area of irrigation there is no incision along the stream and the stream displays the growth of riparian vegetation. This is not true in portions of McCartney Creek that flow through non-irrigated portions of Moses Coulee where incision occurs and no riparian vegetation is present.

The presence of dryland wheat agriculture can influence the development of arroyos and cause an increase in soil erosion simply from the removal of natural vegetation with crops that do not keep the soil in place as well. Also, much of the cropland will be left fallow for long periods of time, usually less than one year, leaving the soil vulnerable to erosion from surface runoff with very little vegetation cover.

Grazing has also been suggested as a major factor in the development of arroyos. Most of the incision in the study area occurred in land cover classified as rangeland/natural vegetation and grazing should be considered as a major factor in incision. Pavish (1973) pointed out the negative impact that grazing has on central Washington's shrub-steppe environment. The most important impact is that grazing causes sagebrush to become a much more prominent species as opposed to bunchgrasses. Bunchgrasses, which are much more prevalent naturally, have much more tightly spaced roots than sagebrush, which is important in keeping the soil in place (Pavish, 1973). Sagebrush does not have tightly spaced roots and plants are not located close to one another.

Absence of Arroyo Incision

Although arroyo incision has occurred in many portions throughout the study area there are also many other areas were arroyos are not present. These areas should be taken into account in determining causes behind the development of arroyos. Many areas throughout the study area that do not feature arroyo incision are very similar in geomorphology, geology, vegetation and land use as areas that have experienced incision.

As was stated before, much of Grant County in the area surrounding Moses Lake and Potholes Reservoir does not feature arroyo incision (Figure 2, 3 and 4). Much of this is an alluvial fan created during the Missoula Floods and is made up of mostly silt, sand and gravel from glacial outburst floods. Sand and silt deposited from glacial lake outburst floods is very erodible and is found in many of the areas identified as incised. This could be explained by the fact that land use in this area is predominately irrigated agriculture. The water table would have been artificially raised from irrigation and the filling of Potholes Reservoir. Another explanation is that it is a very large low-relief area. This could be explained by the large alluvial fan that it is located on and the leveling of the land for irrigation. Arroyos were almost always identified in coulees and other areas where water would have gathered and deposited alluvium. Fanning (1999) cited the increased buildup of alluvium as a major cause behind gully incision. The author found that areas that were usually prone to gully erosion were areas where livestock grazing has increased erosion and subsequent deposition of alluvium. Schumm and Hadley (1957) also discussed the importance of the deposition of alluvium in creating erosional thresholds where the alluvium builds up to a critical angle, which initiates incision. This area does not feature much land devoted to rangeland or many deposits of alluvium, which may help to explain the absence of incision here.

Arroyo incision is also absent in the area of northern Grant County by Grand Coulee (Figure 2, 3 and 4). Many of the low-lying areas in this region where water would gather are rocky Miocene basalt flows and contain no soft sediments that could be incised. Also many of these areas have been filled with water as a result of the Grand Coulee Dam. The eastern area of Adams County also does not feature arroyo incision because all of the low-lying areas are made of basalt and there is very little glacially deposited material except for gravel from glacial outburst floods, which would not be very erodible (Figure 3).

In drainage basins where arroyo incision has been identified, areas upstream of arroyo incision should be considered as future areas of incision. Schumm and Hadley (1957) note that once incision initially occurs, the arroyo will spread upstream with very little incision occurring downstream.

<u>Effects of Arroyo Incision</u>

Arroyo incision can have lasting effects on a landscape that go beyond just losses in soil resources. This includes changes in hydrology and in vegetation. After an arroyo forms, water is confined to a narrow channel and cannot be absorbed into the soil, which negatively effects vegetation growth. Incision can also result in the lowering of the water table (Blanton, 2004). Flooding can usually be beneficial for floodplains, but after arroyo incision large flows of water are confined to a narrow channel. These changes on a landscape not only inhibit vegetation growth but leave a landscape vulnerable to more erosion in the future.

Conclusion

With this research project, I wished to address the problem of arroyo incision in semiarid environments. I analyzed this by identifying areas of Douglas, Grant and Adams Counties where arroyo incision is present. Incision was also compared with the surface geology of the study area to determine what materials are inclined towards erosion and arroyo incision. Arroyo incision and different land use practices were identified by airphoto analysis. This was done to try and determine if incision was spatially associated with a certain type of land use.

This research project has given insight into the geomorphology and the development of arroyos in central Washington. Airphoto analysis has shown that:

- Arroyo incision in central Washington is strongly associated with the Channeled Scablands and has formed in landforms that were initially created by the glacial lake Missoula outburst floods.
- Incision occurred in mostly material from glacial outburst floods, glacial lakes, other glacially deposited material from the late Pleistocene or late Holocene alluvium.
- Incision is absent in areas with predominately irrigated agriculture.
- Incision occurred mostly in land cover identified as rangeland/natural vegetation in areas where the surrounding land use was predominately dryland wheat agriculture.

Further Research

After analysis of the study area many questions still remain regarding incision that need to be addressed in further research through this area. This research project only dealt with the present spatial extent of arroyos in this area. A temporal study of arroyos identified in this project with successive airphotos would be a more powerful method of addressing land use and its effects on arroyo incision. A temporal study examining the study area before the Columbia Basin Irrigation Project would also be useful in determining if in fact irrigation has helped to discourage the development of arroyos. A temporal study of arroyos could be improved with statistical analysis of arroyo extent with land use and climate changes.

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