# HISTORICAL ARROYO DEVELOPMENT IN THE WEST FOSTER CREEK WATERSHED, WASHINGTON: SPATIAL EXTENT, TIMING, CAUSES, AND MANAGEMENT IMPLICATIONS

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A Thesis

Presented To

The Graduate Faculty

Central Washington University

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In partial fulfillment

of the requirements for the degree

Master of Science

Resource Management

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by

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August 2004

# ABSTRACT

# HISTORICAL ARROYO DEVELOPMENT IN THE WEST FOSTER CREEK WATERSHED, WASHINGTON: SPATIAL EXTENT, TIMING, CAUSES, AND MANAGEMENT IMPLICATIONS

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September 2004

Arroyos, common in semiarid environments, are little studied in the Pacific Northwest. This study used airphotos, climate data, and newspaper accounts to analyze arroyo incision in Central Washington's West Foster Creek watershed between 1939 and 2002 and its management implications. Impacts of incision on West Foster Creek included riparian degradation, stream sedimentation, and structure damage. Factors identified included substrate, land use, and weather and climate. Incision increased most between 1939 and 1955. Incision was not caused by a single factor, but likely was the result of increased intensity of land use on erodible substrate, combined with the trigger of large flash flood events, particularly in 1922 and 1948. Changing land use emphasis towards wildlife management and the Conservation Reserve Program has reduced incision since the 1980s. However, riparian restoration efforts are hampered by wildlife interference, particularly deer. Replanting upland areas to provide deer habitat would lessen stress on riparian vegetation.

# ACKNOWLEDGEMENTS

Special thanks to:

Dr. Karl Lillquist
Dr. Morris Uebelacker
Dr. Anthony Gabriel
Central Washington University Graduate Studies
Northwest Science Foundation
Central Washington University Department of Geography
Foster Creek Conservation District
Dan Petersen, Wells Wildlife Area
My parents

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# CHAPTER I

# INTRODUCTION

## Problem

Arroyos, or stream channels entrenched in unconsolidated sediments with steep walls and flat sandy floors, are common in arid and semiarid environments (Cooke & Reeves, 1976; Waters, 1992). Arroyo incision is most commonly associated with the American Southwest (Waters, 1992), but is found in other regions where substrate, climate, and land use conditions are favorable for arroyo development (Gonzalez, 2001; Slaymaker, 1982). Arroyo formation is a function of the interaction between geomorphic processes and the factors of climate, substrate, and land use (Cooke & Reeves, 1976; Graf, 1988). The cause of arroyo incision in particular locations has long been controversial, with researchers proposing a variety of hypotheses to explain their formation (Graf, 1988). The management of watersheds with arroyo incision is similarly complex. Structural (e.g., weirs) and non-structural (e.g., land use restriction) techniques at instream, slope, and upland locations are more or less appropriate for given watershed conditions. While stream erosion and deposition are part of a larger cyclical process and may likely result in the renewal of the riparian landscape, this healing may be too slow for human management objectives. Although arroyos have been extensively studied in other parts of the world, little research has been conducted on arroyos in the semi-arid environments of the Pacific Northwest.

## Purpose

West Foster Creek, located in semi-arid central Washington State, is a small stream with severe incision. This study analyzes arroyo incision in the West Foster

Creek watershed (Figure 1) from 1939 to present. The objectives of this study are to 1) describe the general character of the arroyos, 2) map the spatial extent of the arroyos, 3) determine the timing of arroyo incision, 4) assess the cause(s) of arroyo incision in the study area, and 5) assess the impacts of arroyo incision and generate management recommendations for the West Foster Creek watershed.

## Significance

Arroyo incision is a significant issue for land management, especially in arid and semi-arid regions (Graf, 1988). Incised channels damage agricultural production, as well as structures such as bridges and roads (Schuum, Harvey, & Watson, 1984). In addition, incised channels typically lower the water table, leading to loss of riparian and wetland areas, which are often valuable wildlife habitat in semi-arid regions (Patten, 1998). Gullying and stream erosion have been identified as problems in Eastern Washington since the 1930s (Rockie, 1942). The effects of erosion, though mitigated by conservation practices, remain as a land management issue in Douglas County (Pacific Groundwater Group, Montgomery Water Group Inc. & R2 Resource Consultants, 2003; “Soil and Water Conservation Supplement,” 1973; Thompson & Ressler, 1988). Understanding the extent, timing, and causes of past incision will help minimize future incision, and the resulting negative aspects of the incision on the surrounding environment.

# CHAPTER II

# STUDY AREA

## Location

The West Foster Creek watershed includes West and Middle Foster Creek and their tributaries (Figure 1). West Foster Creek and Middle Foster Creek are part of the larger Foster Creek watershed (Figure 1) in Douglas County in central Washington State. The Foster Creek watershed also includes East Foster Creek, which flows east to west through Foster Coulee to the Grand Coulee.

The study area (Figure 2) includes West Foster Creek from Dyer Hill Road to the confluence with East Foster Creek, the lower ~3.5 km of Fye Draw, and the lower 2 km of Middle Foster Creek. It is ~100 $km^2$ in area. The study area lies ~3 km south of the town of Bridgeport and Chief Joseph Dam on the Columbia River, and ~10 km north of the town of Mansfield. The study area was chosen because of presence of incision and public access. Road access to the study area is by way of US 2, SR 172, and the Bridgeport Hill Road.

## Geology, Geomorphology, and Topography

The West Foster Creek watershed (Figure 1) is on the Waterville Plateau, the portion of the Columbia Plateau bordering the Columbia River to the west and north, bisected by Moses Coulee, and extending eastward to the Grand Coulee. The Columbia Plateau is composed of Miocene Columbia River Basalts. This extensive series of flows erupted from linear vents in southeast Washington and adjacent areas in Oregon and Idaho. The flows spread north and west, burying pre-basin topography from 17.5 to

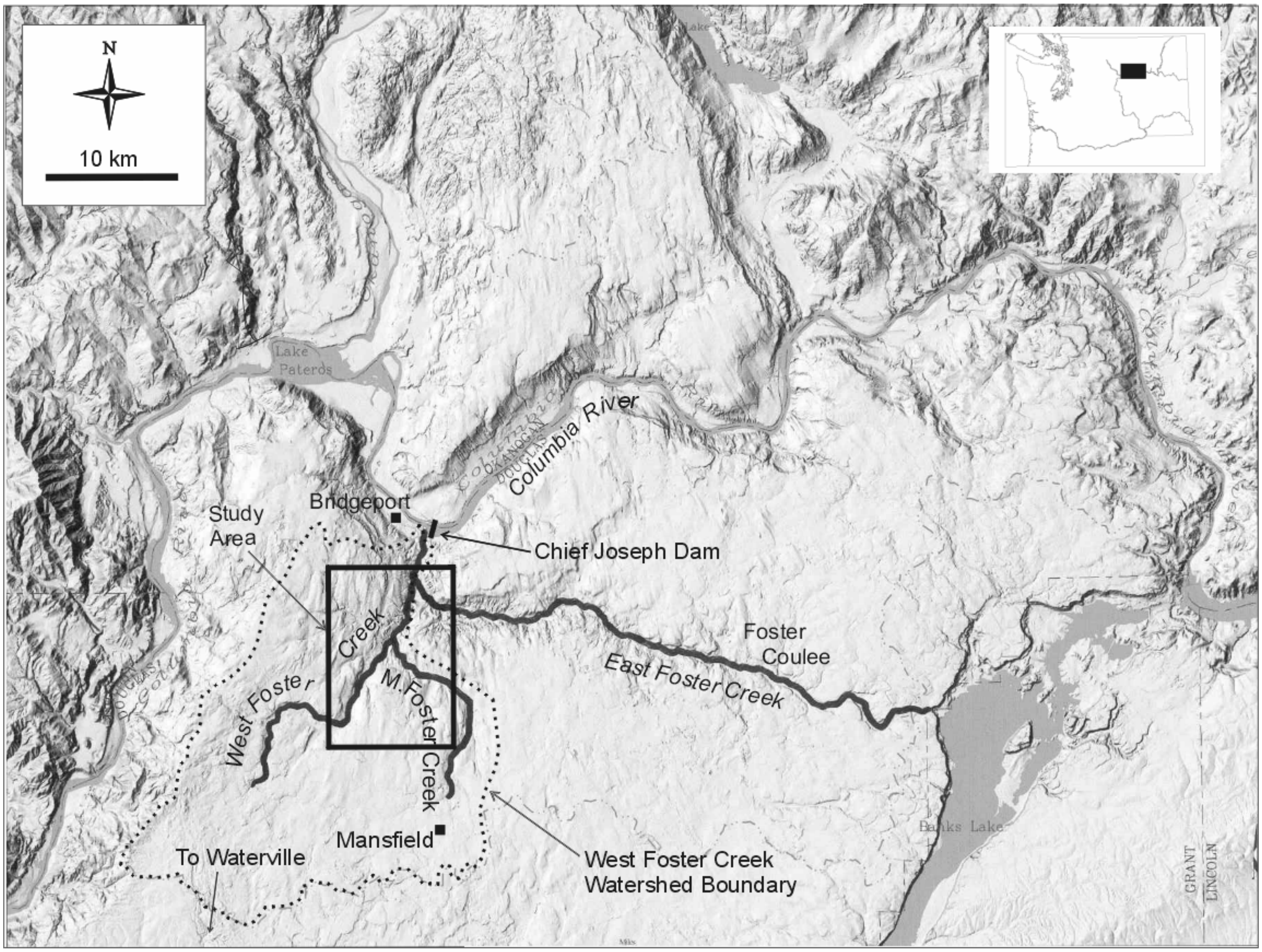


*Figure 1.* Foster Creek watershed, Washington. Source: Washington Department of Ecology (n.d.).

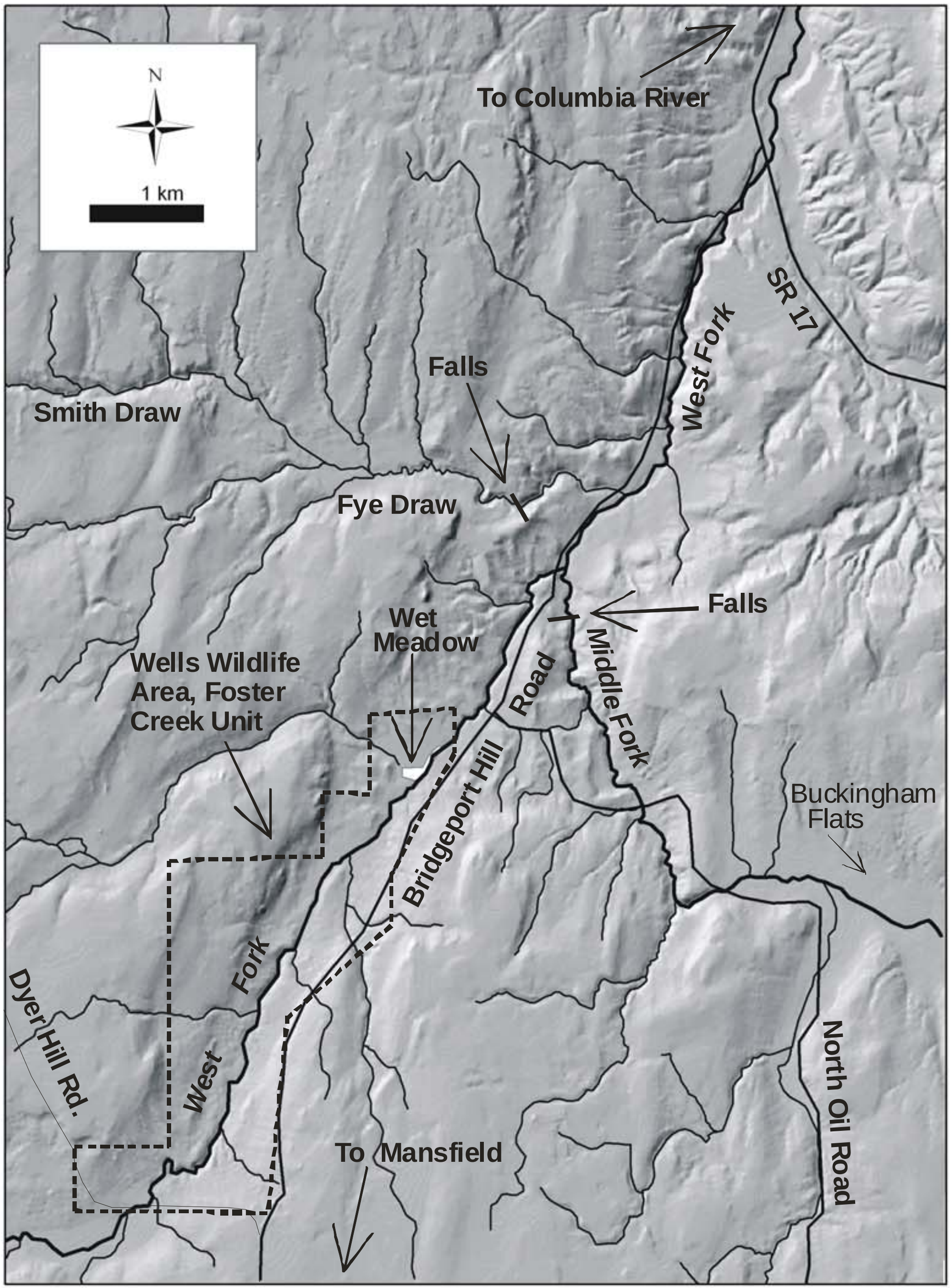


*Figure 2.* Study area, West Foster Creek, Washington.

14.5 million years ago, and creating a plain (Baker, Greeley, Komar, Swanson, & Waitt, 1987). The flows eventually reached a volume of greater than 200,000 $km^3$ and a surface area of 160,000 $km^2$, with the whole system 400 km in diameter, and 4 km or more thick at its center (Baker et al., 1987). Along the margin of the plateau, sedimentary deposits are interfingered with basalt. These include the Ellensburg Formation, a continental sedimentary rock that is quite erodible and distinguished by its reddish orange color (Stoffel et al., 1991).

The topography of the Waterville Plateau closely reflects the underlying structure, with synclinal valleys and anticlinal ridges. Stoffel et al. (1991) describe the regional structure of the Waterville Plateau as comprised of horizontal basalt flows at its center, with a rise of 200-800 ft in elevation to the north and west margins. To the south lies the Badger Mountain anticline. The area is also characterized by a lack of faulting compared to other areas on the Columbia Plateau (Stoffel et al., 1991).

The uplands in the study area are basalt bedrock covered with Late and pre-Late Wisconsin deposits of the Cordilleran Ice Sheet, including till, outwash and loess. Glacial drift in the form of the prominent Withrow terminal moraine, recessional moraines, eskers, and glacial lake fill terraces covers much of the study area (Hanson, 1970). The east-west trending Withrow moraine, ~20 km south of the study area, represents the maximum extent of continental glaciation in the region at ~15,000 years before present (Easterbrook, 1992). This moraine, along with the presence of large erratic boulders on the Waterville Plateau, was first noted by Russell (1893).

The valleys containing the three branches of Foster Creek were the location of late Pleistocene glacial lakes (Hanson, 1970; Stoffel et al., 1991). The sediments comprising these lake beds are thinly laminated clay, silt, and fine sand, locally including microbeds of stratified sand and gravel (Stoffel et al., 1991), and are quite erodible. In places, till is evident under the lake sediments.

Both the West and Middle Foster Creek valleys are steep and confined at their downstream ends. They are also incised in unconsolidated glacial lake sediments. The West Foster Creek valley was described by Russell (1893) as a basalt carved canyon with a wide bottom and well developed drainage. He also noted that the glacial lake sediments in this valley were eroded, leaving well-formed terraces above the stream channel. The Middle Foster Creek valley and Smith Draw contain basalt knickpoint waterfalls (Figure 2) that limit further upstream fluvial erosion.

The stepped nature of the West Foster Creek valley has led to the development of a large wet meadow (Figure 2). Wet meadows are emergent palustrine wetlands with primarily erect herbaceous plants, often appearing as grasslands or reed stands (Tiner, 1999). Wet meadows tend to form in topographic depressions (often of glacial origin in the northern U.S.), stratigraphic transitions, or breaks in slope (Tiner, 1999). Former glacial lakes, with their fine textured soils and gentle depressions often support extensive wetlands (Tiner, 1999).

## Climate

According to the Western Regional Climate Center (WRCC, 2004a, 2004b), the study area (represented by Waterville, Figure 3) has a mean January temperature of

23 ˚F. and a mean July temperature of 68 ˚F.  Prevailing winds come from the west to northwest, with the highest average windspeed in the spring at 9 miles per hour according to the United States Department of Agriculture (USDA, 1981).

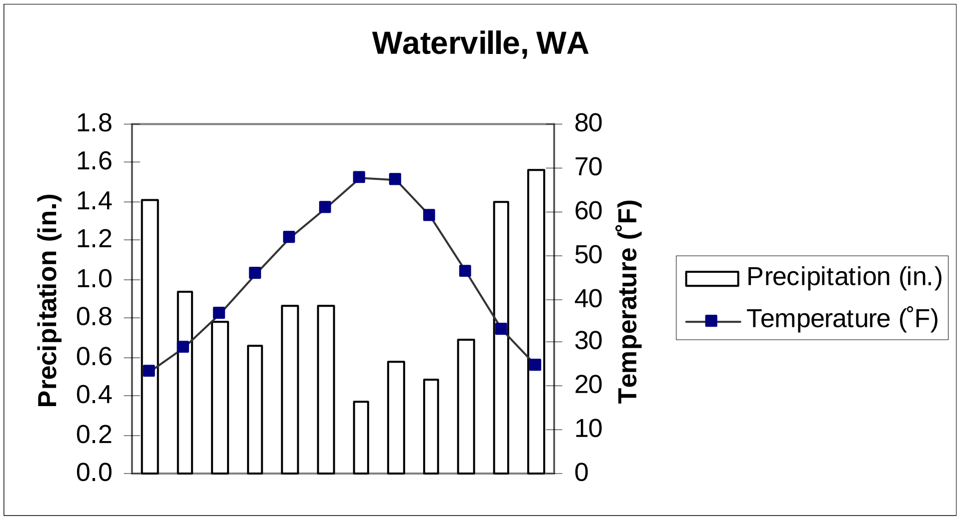


*Figure 3*.  Climograph, Waterville, Washington, 1900-2003.  Source: WRCC, (2004a, 2004b).

The West Foster Creek watershed is in a semi-arid environment, receiving ~11 in. of precipitation a year (WRCC 2004b).  Most precipitation is in the form of snow, but a secondary peak of precipitation occurs in the form of rain (sometimes accompanied by hail) in late May and early June (Figure 3).  This secondary peak is caused by cold fronts becoming increasingly unstable as they cross the Cascades (Quinn, 1984).  While this secondary pulse of precipitation can be beneficial to agriculture, it can also result in flash flooding.  Flash floods may also occur in this area as a result of late summer convective thunderstorms, such as the August 1976 storm and subsequent flash flood that washed out U.S. Highway 2 east of Waterville (Schuster, 1977).  Floods also result in this area from rapid snowmelt, often in conjunction with rain on snow events.

## Soils

Most soil in the West Foster Creek study area is Ellisford loam, 0% to 15% slopes on terraces. Ellisford loam forms on loess atop glacial lake sediment (USDA, 1981). This soil is deep, well drained, and susceptible to water erosion. The Ellisford series is classified as coarse-silty, mixed, mesic, Calciorthidic Haploxeroll. Ellisford soils are limited in terms of water management in many ways, including steep slope, erodibility, seepage, and piping (USDA, 1981).

Other soils present include Umapine variant loam, Haploxerolls, nearly level, Touhey loam, 0% to 15% on slopes, and Heytou very stony loam, 0% to 30% slopes (USDA, 1981). The Umapine Variant series, a moderately deep and well drained soil on low alluvium terraces that forms in long strips found immediately north of the wet meadow, are classified as coarse-silty, mixed, mesic Haploxerollic Durorthids. Embankments, dikes, and levees are limited by piping. Drainage is limited by the cemented pan. Irrigation of terraces and diversions are limited by wetness, the cemented pan, and erodibility (USDA, 1981).

Haploxerolls, nearly level, are deep, moderately drained soils that form on basalt plateaus, forming on a mix of alluvium and loess in areas with a slope of 0% to 2% (USDA, 1981). This unit is found in riparian environments, and depressions and potholes. In the study area, this mapping unit also includes the Aquolls of the wet meadow environment, and small areas of alkaline soils (USDA, 1981). As this soil unit forms on a variety of substrates, no typical pedon is given in the soil survey, and texture can vary greatly over a short distance (USDA, 1981). With vegetation loss, this soil unit is very susceptible to erosion.

Touhey loam, 0% to 15% on slopes, is a deep, well drained soil that forms on glacial till and loess. It is found in the south of the study area by the Dyer Hill Road. It is a gravelly loam with discontinuous cemented lenses of lime and silica at a depth of ~70 cm (USDA, 1981). It is easily erodible by water, and is susceptible to piping (USDA, 1981).

Heytou very stony loam, 0% to 30% on slopes, is another deep, well-drained soil that formed in glacial till and loess on the slopes of the West Foster Creek valley. This soil is only moderately susceptible to water erosion (USDA, 1981).

## Hydrology

Middle and West Foster Creek (Figure 2) are mapped as perennial streams on the United States Geologic Survey (USGS) Chief Joseph Dam 7.5 minute topographic map. The stream in Fye Draw is also mapped as perennial, while all other tributaries are mapped as intermittent. These streams are fed by upland springs. Middle and West Foster Creek converge roughly in the middle of the study area, and West and East Foster Creek converge at the north end of the study area. Foster Creek empties into the Columbia River just downstream of Chief Joseph Dam by Bridgeport.

Stream gradient on West Foster Creek is 2.57%, dropping from an elevation of 2,120 ft at the southern boundary of the study area to 1,017 ft at the confluence with East Foster Creek. The lower section of Middle Foster Creek, measured from the east edge of Buckingham Flats to the confluence with West Foster Creek is 3.12%. The stream in Fye Draw has a gradient of 3.27%. These are high gradients, especially compared to the 1% to 2% gradients found on East Foster Creek (Pacific Groundwater Group et al., 2003). Smaller, ephemeral or intermittent tributaries have even steeper gradients.

Current stream gaging data is lacking for the study area. Some gaging stations in the area were active from the 1950s to the 1970s. Stations applicable to the study area include USGS 12437950 East Fork Foster Creek tributary near Bridgeport, 1957-1977 and USGS 12437960 West Foster Creek near Bridgeport, 1957-1977. Discharge values at these stations were extremely variable, suggesting a flashy runoff regime. Discharge data for 2002-2003 were obtained from the Foster Creek Conservation District (FCCD) (Figure 4), representing discharge at an old irrigation dam below the junction of East and West Foster Creek.

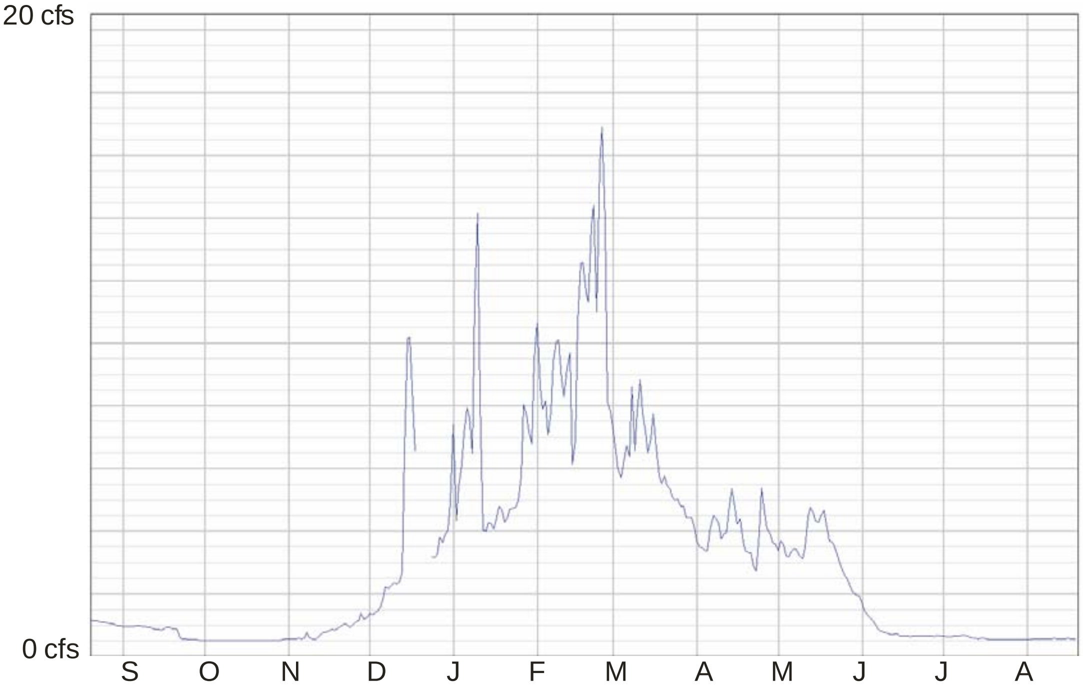


*Figure 4*. Mean daily discharge, Foster Creek, 2002-2003. Source: Tim Behne (written communication, 2003).

A typical current hydrograph for Foster Creek (Figure 4) shows the variability in discharge. High discharges from December to March are attributable to rain, snow melt and rain-on-snow events.  The intermediate level spikes from March to June correspond to the secondary peak of precipitation.  June to November discharges are low and stable.

### Plants

Native vegetation in the study area is mainly bunch grasses and shrubs.  Both the *Artemesia Tridentata/Agropyron* and *Artemesia Tripartia/Festuca* zonal associations are present.  Grasses include bluebunch wheatgrass (*Agropyron spicatum*), Sandberg bluegrass (*Poa sandbergii*), and big bluegrass (*Poa* spp.).  Shrubs include big sagebrush (*Artemesia tridentata*), three-tipped sagebrush (*Artemesia tripartita*), antelope brush (*Purushia tridentata*), and rabbitbrush (*Chrysothamnus* spp.) (Franklin & Dyrness, 1988; USDA, 1981).  In areas with moist saline soils, such as the upland next to the incised channel north of the gabion dam, greasewood (*Sarcobatus vermiculatus*) and saltgrass (*Distichlis stricta*) predominate.

Wetlands occur in the study area around springs and seeps, as riparian corridors along streams, and as small mesic meadows.  Meadows tend to be dominated by grasses, except along water bodies.  Springs, seeps, and streams support trees including red Ossier dogwood (*Cornus stolonifera*), willows (*Salix* spp.), and mock orange (*Philadelphus lewisii*).  Evergreens such as junipers and other exotics have been planted on the margins of wet meadows in the Wells Wildlife Area along with native plants to improve habitat.

### Animals

Wildlife species in the study area include mule deer (*Odocoileus hemionus*), various duck species, coyote (*Canis latrans*), and various raptor species.  This area also has a significant population of upland game birds, including the threatened populations of sage grouse (*Centrocercus urofasianus urophasianus*) and sharp-tailed grouse (*Tympanuchus phasianellus columbianus*) (Thompson & Ressler, 1988). The riparian areas along West Foster Creek are important winter refugia for grouse (Thompson & Ressler, 1988). Lower Foster Creek is accessible to anadromous fish, and is the furthest upstream tributary of the Columbia with fish access. Summer steelhead were observed below the irrigation dam in 2001 (Pacific Groundwater Group et al., 2003). Suspended sediment occurs at high levels in West Foster Creek, limiting the possibilities for fish habitat.

Thompson and Ressler (1988) found eight furbearing species that were trapped in the Foster Creek area. The most important were beaver (*Castor canadensis*) and muskrat (*Ondatra zibethica*). Others included mink, weasels, badgers, and bobcats. Beaver have both positive and negative impacts on the environment with resource management implications. Dams can facilitate floodplain development and improve riparian vegetaion structure, diversity, and productivity (Pritchard, 1998). Failed dams can cause more damage downstream, however. Muskrats affect riparian areas by undermining bank stability with their burrows (Thompson & Ressler, 1988).

## Human Use

At the time of Euroamerican contact, the inhabitants of this area were Native Americans of the Plateau culture (Walker, 1978). From approximately the East Fork north to Columbia River and beyond was Southern Okanogan (Sinkaietk) territory, while the majority of the study area was Columbia (Sinkiuse) territory (Walker, 1978). Primary resource use activities included salmon fishing, root gathering, and hunting ungulates

(Walker, 1978). These native groups did not cultivate crops, or range livestock, although they adopted the horse for transportation (Meinig, 1968; Walker, 1978).

In 1859, an Oregon pioneer named Joel Palmer drove a wagon train across the Columbia Plateau to take supplies to the Canadian mining districts to trade. He came north through Moses Coulee and then down Foster Creek, across the Columbia, and up the Okanogan to mining country (Anglin, 1995). The last part of this trail along Foster Creek before it reached the Columbia was also part of the Cariboo Trail, along which thousands of cattle were driven in the early 1860s (Anglin, 1995).

Lieutenant Symons, in his 1879-1880 survey of the area, described good quality ranching land along an unidentified branch of Foster Creek (Steele & Rose, 1904). He noted that Foster Creek had many branches, and fertile soil (Steele & Rose, 1904). Before 1883, no white settlers lived in Douglas County west of the Grand Coulee (Steele & Rose, 1904).

The General Land Office (GLO) surveyed the Foster Creek area in the 1880s. Neither the maps nor the written descriptions describe incised channels, or any other kind of erosion in any locations. Good farming and grazing land is commonly mentioned, with excellent bunch and ryegrass, and numerous creeks and springs. This area was hardly grazed before settlement (Meinig, 1968) although cattle were driven through the area on the Cariboo Trail. Local cattle were present in the study area from 1883 on and the early settlers raised stock rather than crops (Steele & Rose, 1904). The GLO notes indicate a healthy upland sagebrush/grassland association. In T. 28 N., R. 25 E., W.M. (including the wet meadow, the confluence of West and Middle Foster Creek, and much present-day incision), the surveyor noted plenty of level land along the creeks, indicating a lack of incision. Only the occasional settler in a cabin was noted.

In 1883, Douglas County was formed, and a garrison of 500 soldiers was placed at Bridgeport to "keep the hostile Indians in check" (Steele & Rose, 1904, p. 530). Two settlements were located around Badger Mountain to the southwest of the study area, including "Sourdough Flat" in the vicinity of Waterville (Steele & Rose, 1904) . In 1886, conflict between sheep men and settlers in the Badger Mountain area resulted in Western Douglas County ceasing to be an active sheep range (Steele & Rose, 1904). Also in 1886, Foster Creek was first settled, and the authors suggest that "at this period there was no thought that Foster Creek could possibly become the prosperous, thickly settled section that it is today" (Steele & Rose, 1904, p. 540). In 1889, the population of the Foster Creek area was 129, compared to Bridgeport's 1900 population of 110 (Steele & Rose, 1904). The Waterville Plateau was so rapidly settled at the turn of the 20th century that by 1904, the Douglas County Agricultural Society published an open letter in the Waterville Big Bend Empire discouraging potential homesteaders (Meinig, 1968), claiming a lack of suitable homestead land, or undeveloped land for sale from the railroads or individuals. However, improved land was available at $15-$25 an acre, and the resale of improved land was encouraged locally (Meinig, 1968).

In the study area's past, a large number of people farmed compared to the present. People often settled near streams and springs. The primary human land use in the study area historically was dryland wheat and other grain farming, with limited orchards and grazing (Meinig, 1968; USDA, 1981). Farming primarily took place on the loess covered uplands, and the larger stream terraces. Dryland wheat was first farmed in this area in

1884 (Steele & Rose, 1904). Grazing also took place in the uplands, but livestock were watered in springs and streams. An irrigation dam built by the Bridgeport Irrigation District in the early 20th century located 1.03 river miles south of the confluence with the Columbia River and north of the confluence of West and East Foster Creek was infilled with suspended sediments and bed load, and was abandoned later in the 20th century (Pacific Groundwater Group et al., 2003).

Drought conditions in the 1930s combined with the lingering economic effects of the Depression resulted in a large drop of population in the study area. By the end of the 20th century, the study area was mostly devoid of settlement. In the 1980s, much of the cropland in this area was placed in the Conservation Reserve Program, resulting in its being set aside from agricultural production and planted with grasses. The majority of the study area is now under the management of the Wells Wildlife Area. Cattle are still grazed on the uplands, but are prevented from entering riparian areas in the Wells Wildlife Area by fences.

The closest settlements to the study area are Mansfield and Waterville to the south and Bridgeport on the Columbia River to the north. Waterville, the county seat, was for the first half of the 20th century the dominant town in the region (Meinig, 1968). Mansfield, founded later than Waterville, became an important rail terminal for grain transport with the construction of the Great Northern line locally in 1909 (Meinig, 1968). With the mid-century construction of Chief Joseph Dam, Bridgeport became an important town in Douglas County (Meinig, 1968). Population figures are given below for Waterville, Bridgeport, and Douglas County as a whole (Table 1). Although Douglas County's population generally grew steadily over the 20th century, the trend was a decrease in rural population, and an increase in urban population, particularly in the East Wenatchee area.  An exception to this growth pattern (Table 1) was a decrease in population during the 1920s.

Table 1

*Selected Population Data, Douglas County*

| Year | Waterville | Bridgeport | Douglas County |
|---|---|---|---|
| 1890 | 293 | | 3,161 |
| 1910 | 950 | 431 | |
| 1920 | | | 9,392 |
| 1930 | | | 7,651 |
| 1960 | | | 14,890 |
| 2000 | 1,163 | 2,059 | 32,603 |

*Note.*  From Meinig (1968) and U.S. Census (2000).

## Wildlife Areas and the Gabion Dam

In 1974, the Wells Hydroelectric Project wildlife mitigation program was intitiated to compensate for wildlife habitat lost as a result of the construction of Wells Dam to east of the study area.  The Douglas County Public Utility District purchased 5,755 acres of land and gave it to the Washington State Department of Fish and Wildlife (WDFW).  Additional land is managed through leases or easements.  Total land in this project totals over 8,200 acres.  The West Foster Creek management unit, the portion of this land within the boundaries of the study area (Figure 2), totals 1,050 acres (Dan Petersen, personal communication, August 27, 2004).

Intially, this area was managed primarily for wildlife. Projects included riparian habitat restoration, including tree and shrub plantings, pond constructions, wetland construction, noxious weed management, and restoration of upland habitat, including bitterbrush. Problems encountered included beaver and deer damage to riparian plantings, noxious weeds, and lack of success in restablishing upland plant communities. Currently, the most pressing wildlife management issue in this area is the protection and enhancement of habitat for the area's threatened grouse species (Dan Petersen, personal communication, August 27, 2004).

In 1998, the West Foster Creek unit of the Sagebrush Flat Wildlife area was created in a similar fashion, with funding from the Bonneville Power Administration. This habitat area is mitigation for habitat lost as result of the Chief Joseph and Grand Coulee dams. This unit is over 2000 acres, and includes the area north of the gabion dam in the study area. It is also owned and managed by WDFW, and essentially is a continuation of the West Foster Creek unit of the Wells Wildlife Area (Dan Petersen, personal communication August 27, 2004).

In 1984, Brown and Caldwell Consulting Engineers, along with the FCCD and the Washington State Conservation Corps, constructed a gabion dam at the north end of the wet meadow to protect the meadow from a headcut advancing upstream. The project included a gabion drop structure and stilling basin with a training dike to prevent flood backwaters from circumventing the dam. Construction occurred during lowest flow conditions. Channel improvements included excavation of the channel downstream, channel reshaping, the addition of riprap to stop bank erosion, and seeding.  Gabions were built out of local rock, taken from a quarry approximately 1 mile north of the project site.  The Washington State Conservation Corps distributed seeds and brush mats on side slopes and dike faces, with help from WDFW.  Brush matting or wattling was constructed out of willow branches, and ground cover was a mix of fescue, clovers, lupines, and Scotch broom (Brown & Caldwell, 1984).

# CHAPTER III

# LITERATURE REVIEW

Glacial and glaciofluvial processes set the stage for arroyo incision in the study area. Glacial lake sediment is the key substrate in the study area in terms of managing incision. The substantial body of arroyo literature provides a context for analysis of incision in the West Foster Creek watershed.

## Glaciation

The late Pleistocene was characterized in Western North America by a rapid growth of the Cordilleran Ice Sheet between 18,000 and 14,000 years before present (B.P.), reaching a maximum extent around 14,000 years ago (Clague & James, 2002). The Cordilleran Ice Sheet (Figure 5) moved south from its source areas in British Columbia, terminating in the northwest United States between the Continental Divide and the Pacific Ocean (Waitt & Thorson, 1983). The sheet formed several lobes between mountain ranges and highlands, and extended the furthest south in north-south trending valleys. The Pend Oreille Lobe reached its maximum extent before 12,500 years B.P., when it blocked the Clark Fork River valley to induce a flood over the Channeled Scablands (Figure 5).

The Okanogan Lobe crossed the Columbia River channel and advanced across the northern part of the Waterville Plateau, covering the existing scabland networks (Hanson, 1970). Drastic climatic changes occurred at the end of the Pleistocene, and from 13,000 to 10,500 years B.P. glacial retreat and readvance occurred (Clague & James, 2002; Easterbrook, 1992). The Okanogan Lobe, which partially covered the Waterville Plateau, probably reached its maximum around 15,000 years B.P., but the extent of the Withrow

Moraine suggests that this lobe was stable and stagnated, melting in place, and was longer-lived than other lobes such as the Puget Lobe to the west (Easterbrook, 1992).

As the glacial ice retreated, it left ice stagnation features such as kettles, kames, and eskers behind, along with a series of at least 13 uniformly spaced and sized moraines and an outwash train of flood gravels from Moses Coulee (Hanson, 1970). The Okanogan Lobe apparently retreated to 15 to 20 km north of the mouth of the Okanogan River by the time of the Glacier Peak B eruption at ~11,200 years B.P. (Gough, 1995; Porter, 1978). While glacial processes certainly had a significant impact on the region, the most drastic regional geomorphic process was the series of floods caused by the ice damming of the Clark Fork River, the Lake Missoula Floods.

## Lake Missoula Floods

Bretz (1919, 1923, 1925a, 1925b, 1928a, 1928b, 1929a, 1929b, 1930, 1969) investigated the distinctive channeled scabland topography of eastern Washington. Through the course of his studies, he developed a theory of the Channeled Scablands' formation that was considered outrageous by his peers, and not generally accepted until much later. Bretz proposed that the only possible explanation for the region's unique and drastic landforms was massive flooding: that the scablands were cut by large, high gradient streams of glacial origin.

Bretz used many lines of evidence to support his theory, some of which were noted by his contemporaries but misinterpreted. By 1925, Bretz had assembled evidence of catastrophic flooding including slope denudation and erosion below the upper surface of flooding, deposition of giant gravel bars, and deltas on the Snake and Columbia rivers (Bretz, 1925a & 1925b). Bretz later added pieces of evidence such as ponded sediments

(1928b, 1929a, & 1929b), loessal scarps not of aeolian origin and erratic berg-floated boulders of foreign origin, absence of fossils in flood deposits, and giant ripples (1930). By the 1960s, the scientific community had, by and large, accepted his hypothesis. Bretz's hypothesis also provided an explanation for the presence of glacial lake sediments in the drainages of central Washington, including Foster Creek.

Just as the Purcell Lobe blocked the Clark Fork River, the Okanogan Lobe blocked the Columbia, forming Glacial Lake Columbia. Lake Columbia, to the north of the Columbia Plateau, was formed later than Lake Missoula and outlived it (Atwater, 1986). Lake Columbia also obstructed the path of subsequent flood waters, creating new channels by carving coulees (Atwater, 1986). Atwater (1987) used sediment as a proxy for the late glacial history of Glacial Lake Columbia. He concluded that first the Columbia River Lobe blocked the Columbia River near the mouth of the Spokane River, creating Lake Columbia. Then the Purcell Lobe blocked the Clark Fork River, creating Lake Missoula. Lastly, the Okanogan Lobe blocked the Columbia as it crossed south to cover the Waterville Plateau (Atwater, 1987), creating another phase of Lake Columbia. According to Waitt and Thorson (1983), Lake Columbia existed from about 15,500 to 12,700 years B.P. As the Okanogan Lobe decayed, ice marginal lakes coalesced to form drift-impounded Lake Brewster in the Columbia and Okanogan river valleys (Waitt & Thorson, 1983).

## Glacial Lake Sediments

Silt is deposited in the quiet waters of glacial lakes. If varves are present, they are very thick in the lower parts of the deposit, and progressively thin upwards. Maximum silt deposition occurred when ice receded from nearby uplands, eroding till with meltwater. The silt's source and its point of entry to the basin may not be obvious. Lake level or position of the lake outlet at time of deposition may be difficult to determine, as well (Fulton, 1965). Another key characteristic of silt is its tendency to form vertical jointing which leads to piping and dessication crack formation (Slaymaker, 1982), important factors for the development of incision, slope failure, and headcutting.

Glacial lake sediments are found in many locations marginal to the Columbia River. Lacustrine silt deposits in north central Washington are known as Nespelem Silts, a term coined by Pardee (1918) who undertook a survey of the geology and mineral deposits of the Colville Indian Reservation north of the Columbia River. He described terraces comprised of unconsolidated lake and stream sediments of glacial origin, with a maximum thickness of ~230 m at Nespelem Flat, lessening to a thickness of ~150 m to 180 m upstream by the north boundary of the reservation. Similar materials underlie terraces in the Columbia and Okanogan valleys. Nespelem Silt is smooth to the touch and Pardee describes it as "velvety." It is composed of microscopic quartz and undecomposed feldspar, mica, and other minerals. The silt is mostly very light colored, with localized thin bands of darker color. The beds exhibit poorly developed vertical jointing, and tend to form vertical bluffs that resist weathering fairly well. However, Nespelem Silt is quite erodible, and many terraces are extremely channeled by rain gullies and/or cut by steep walled ravines (Pardee, 1918).

Waitt and Thorson (1983) indicated that Lake Brewster, which formed the "Great Terrace" in the vicinity of Bridgeport, had a maximum altitude of ~400 m. Lake Brewster, centered at the confluence of the Okanogan and Columbia rivers and formed by drift impoundment was at an altitude ~100 m lower than the second Lake Columbia

(Atwater, 1987). Flint (1933) described another terrace between the mouths of the Sanpoil and Okanogan rivers. Although this terrace is contiguous with the Great Terrace, the Great Terrace is not primarily glacial lake sediments. Five miles upstream of Bridgeport, this terrace has an elevation of ~380 m (Flint, 1933). Flint and Irwin (1939) also distinguished between higher, ice marginal terraces made of sand, gravel, and boulders and exhibiting a kettled surface from lower stream terraces with non-paired benches. Atwater (1987) described patchy silt terraces in the Grand Coulee standing well above drainage divides on the coulee floor (elevation 465 m). Atwater (1987) suggested that lacustrine units at higher (~500 m and above) altitudes along the Columbia River downstream of the Grand Coulee may have been formed by the spread of the ~500 m deep Glacial Lake Columbia rather than Lake Brewster.

Russell (1893) was the first geologist to describe the Foster Creek area, and he noted the presence of glacial lake deposits in East and West Foster Creek valleys. He gave the highest elevation of these sediments as ~135 m above the elevation of the Columbia River, roughly corresponding with the elevation of the Great Terrace (Russell, 1893). He also noted that the glacial lake sediments in the Foster Creek drainage were incised, leaving multiple well-formed terraces (Russell, 1893). Hansen (1970) claimed that the glacial lake in the West Foster Creek valley was a southern extension of Lake Brewster. Glacial lake sediments in the study area either came from Lake Brewster or Lake Columbia.

## Arroyo Incision

Arroyos are incised channels in valley bottoms with vertical or near-vertical slopes in cohesive, fine sediments with flat and often sandy floors (Cooke & Reeves, 1976). They are frequently but not exclusively found in arid and semi-arid areas. Arroyos are either continuous or discontinuous. Continuous arroyos begin from many small rills, starting at a high elevation and migrating downhill deepening at a consistent level. Discontinuous arroyos are initiated by an abrupt head cut anywhere on a slope, and decrease rapidly in depth downhill, as the bottom aggrades. Discontinuous arroyos tend to evolve into continuous ones (Heede, 1974).

Interest in arroyos in the United States began to flourish in the early 20th century, although the phenomenon had been recorded in the late 19th century. Initial interest in arroyos was in the southwest U.S. (Cooke & Reeves, 1976) because of the intensive geological exploration and study in this region, the great size and number of arroyos there, and the obvious agricultural and economic effects of arroyo formation. Also, cut-and-fill evidence showing cycles of erosion and deposition suggested causal continuity from geologic to historic times, of interest to those studying environmental change.

Those who first studied arroyos generally promoted a single dominant cause for incision. Land use change was tied to European-American settlement in the Southwest, which generally coincided with a major period of arroyo incision from around 1865 to 1915. Incision was especially active in the 1880s (Cooke & Reeves, 1976). Land use changes cited included grazing and timber harvesting (Cooke & Reeves, 1976). Fur trappers and settlers in the semi-arid West in the early 1800s reported seeing large, well developed stands of riparian willows and expansive wet meadows along streams. By the early 20th century, however, many of these streams and their associated riparian areas were severely degraded as a result of improper livestock management (Elmore, 1992). Cattle and sheep congregate in riparian areas in semi-arid regions, especially in the hottest part of the summer (Elmore, 1992). Livestock destroy streambank vegetation and destablize banks both by plant removal and trampling, ultimately resulting in increased stream sediment loads (Elmore, 1992). Native wildlife can have the same effect in the absence of livestock, especially large game animals such as deer and elk (Patten, 1998). The problem with land use change as a single cause is the appearance of cut-and-fill sequences predating human settlement thus suggesting that some arroyo incision dates to prehistoric times (Denevan, 1967).

Another land use change that likely affects stream incision is the removal of beaver. Beaver dams and ponds reduce variablity in stream velocity and discharge, increasing stream stability. They also increase channel complexity, ecological production, and biological diversity (Gurnell, 1998). They also are efficient sediment traps (Swanston, 1991). Recent downcutting in North American low order streams has been attributed to beaver removal (Parker, Wood, Smith, & Elder, 1985).

Beaver can also have a negative impact on streams. Beaver can remove large quantities of riparian vegetation. If the riparian vegetation is affected by other stresses, this removal can result in bank and slope erosion (Swanston, 1991). If beaver dams are washed out by floods, they can cause more erosion downstream (Thompson & Ressler, 1988). Failed dams can cause stream degradation, channel widening, lowering, and channel movement (Prichard, 1998). Washed out dams also produce woody debris that can damage downstream structures such as bridges (Thompson & Ressler, 1988) and slugs of sediment that increase downstream turbidity (Swanston, 1991). Depending on local conditions, beaver may be a positive or negative factor on stream conditions.

Climate change was also proposed as a cause of arroyo incision (Cooke & Reeves, 1976). Both increased and decreased moisture were cited as factors, with increased moisture causing extreme runoff and decreased moisture as killing vegetation that would hold soils in place. Arroyo incision is associated with high magnitude, low frequency precipitation events (Graf, 1988; Leopold, 1951) with variation of rainfall intensity identified as a key variable (Leopold & Miller, 1956). High magnitude, low frequency events are more frequent in wetter years in semi-arid areas (Leopold, 1951). Climate hypotheses from the beginning were qualified by the suggestion that humans often acted as the "trigger" for arroyo incision given appropriate climate conditions (Cooke & Reeves, 1976). An intense precipitation event may initiate incision without related land use change if it follows a drier time with reduced frequency of light precipitation that results in vegetation loss (Leopold, 1951). However, semi-arid region plants are well adapted to drought stress, and it takes prolonged extreme drought for vegetation loss to become significant in terms of erosion (Whitford, 2002).

Balling and Wells (1990) studied the connection between historical rainfall patterns and arroyo incision in New Mexico. They correlated rainfall records with airphotos, cultural and radiometric dating, and tree ring dates to establish a chronology of climate and incision. They noted a long, severe drought in the region that occurred from 1898 to 1904 and ended with unusually extreme, frequent high-intensity summer rainfall. A 20- to 30-year cycle of downcutting began in 1905. During the period of initiation of incision, a high number of intense summer storms occurred with large rainfall totals.

Finlayson and Brizga (1993) investigated arroyos in Australia and proposed that the linking factors between Australia and the American Southwest incision are high variability in the annual flood series and variability in precipitation and runoff.

Gonzalez (2001) studied recent arroyo formation in the Little Badlands area of southwest North Dakota, using dendrochronology to date the ages of cottonwoods on the floodplain and terraces of arroyos. The time of incision is constrained by the age of the youngest tree on the terrace surface, and the oldest tree on the floodplain. Gonzalez (2001) described three sequences of local arroyo incision: the 1860s to 1870s (pre-settlement), the turn of the 20th century, and the last 20 years. He noted that there is evidence for many periods of drought without incision, and suggested that incision was caused by drought combined with intense thunderstorms and/or change in land use. He also emphasized scale, noting that smaller basins tend to be more sensitive to exterior factors.

While the work of researchers in the Southwest has established a connection between large scale climate patterns such as El Nino Southern Oscillation (ENSO) and geomorphology (Ely, 1997; Viles & Goudie, 2003), variation in these patterns between the Southwest and Northwest preclude direct comparison between these regions. The ENSO pattern, including La Nina, weakens from the Southwest to the Northwest, and is opposite in its climatic effects. The Northwest experiences cooler temperatures and more precipitation during a La Nina event. When evaluating arroyo landscapes outside the American Southwest, especially when considering the palaeoclimate record, one should look for correlation between local climatic conditions and arroyos, rather than extrapolating directly from Southwest chronologies.

The Pacific Decadal Oscillation (PDO) (Mantua, Hare, Zhang, Wallace, & Francis, 1997) may be an important influence on erosion in the Pacific Northwest. The "cool phase" PDO cycle in the Pacific Northwest corresponds with generally cooler and wetter conditions: a higher than average springtime snow pack, October-September streamflows, and a greater flood risk in the winter and spring. The "warm phase" PDO cycle has opposite effects (Mantua et al., 1997). Large scale ENSO events impact the Pacific Northwest most when the PDO and ENSO cycles are "in phase," i.e., a warm PDO with El Nino or cool PDO with La Nina (Mantua et al., 1997).

In the interior Northwest, precipitation variability tied to variation in sea surface temperatures (ENSO as well as PDO) is a winter phenomenon (Cayan, Dettinger, Diaz, & Graham, 1998) and likely has little effect on late spring and summer precipitation. Nigam, Barlow, and Berbery (1999) found a link between extreme positive sea surface temperature temperatures (a warm phase PDO cycle) and warm season drought in the United States. As the PDO events are much longer in duration than ENSO events (Mantua et al., 1997), it is possible that an extreme thunderstorm during a long, warm PDO cycle (and associated drought) could cause incision and other erosion, aided by the lack of supporting vegetation.

In all cases, substrate conditions are critical to incision development (Oostwald Wijdenes, Poesen, Vandekerckhove, Nachtergale, & de Baerdemaeker, 1999). Arroyos are incised in alluvium and valley fill, but less attention has been paid to substrate conditions than to the other variables (Graf, 1988). Substrate conditions may drive incision without drastic changes in external variables such as climate and land use (Schumm et al., 1984).

Researchers have generally recognized that the search for a single cause for arroyo incision is fruitless. Cooke and Reeves (1976) and others have noted that arroyos are a sort of “ink blot test,” with investigators finding the cause that fits their preconceived notions.  Arroyos have also been held up as an good example of equifinality, the geologic idea that a single result may have multiple possible causes. Champions of land use must deal with arid areas that were grazed for a long time without arroyo incision (such as areas of the American southwest used by Mexican pastoralists for hundreds of years) and places with little vegetation that do not exhibit arroyo formation (Denevan, 1967; Finlayson & Brizga, 1993). As the investigation of arroyos continued in the second half of the 20th century, researchers developed more complex and dynamic hypotheses.  Schumm and Hadley (1957) proposed that the factors of drought, steepening of gradient, decreased stability of valley fill, the size of the drainage basin, high intensity precipitation, floods, and depletion of vegetation all played a part.

Graf (1988) suggested a move from discussions of origin to discussions of process that recognize both spatial and temporal variation.  Such discussions of process must explain the depositional as well as the erosional phases of arroyo development (Antevs, 1952).  In the past, the depositional phases have been given short shrift.  Schumm and Hadley (1957) described arroyos as part of a cycle of erosion and deposition.

The impacts of arroyo incision can be assessed effectively through a combination of airphoto analysis and ground surveying (Gilvear & Bryant, 2003; Schumm et al., 1984).  In addition to road and other structural damage, incision extent, and downstream sediment deposition, damage to riparian vegetation may be assessed from airphotos (Prichard, 1999).

Relatively little work has been done on arroyos in the Pacific Northwest.  Pavish (1973) studied arroyo incision in canyons west of the Columbia River near Vantage, Washington.  Pavish (1973) studied stratigraphy in these arroyos to provide a history of aggradation and degradation in the area.  He only gave passing mention to human land use as a possible factor in the development of these arroyos, and was unable to sort out the causes of incision.  Cochran (1978) also worked in the Vantage area, in Johnson Canyon.  He found cycles of erosion, deposition, and soil formation throughout the Holocene.  Neither of these studies addresses incision in the historic period.

Sullivan (1994) also studied Johnson Creek, attributing erosion in small and ephemeral streams in central Washington to overgrazing of cattle and sheep. Vegetation critical to soil stabilization was negatively affected by soil compaction, selective removal, and physical damage by livestock in the form of trampling and rubbing. He also noted the effect of the loss of beavers on the riparian zone with a corresponding loss of ponds causing downcutting.

Buckley (1993) attempted to discover the root causes of arroyo incision in Oregon’s Camp Creek drainage from 1826 to 1905 through historic analysis, using primarily diaries and eyewitness accounts to reconstruct environmental conditions.  His conclusion was that during a period of prolonged drought, intense grazing and other settlement activities weakened the vegetative cover of the floodplain, and subsequently heavy rains eroded the stream channel.

## Summary

As glacial ice retreated from the study area, it left behind small ice marginal lakes. These lakes became wetlands, and then dried up, leaving large amounts of glacial lake sediments and much smaller riparian wetlands.  These wetlands lie atop erodible sediments, and are susceptible to erosion.

Earlier arroyo studies emphasize single explanations for the cause of incision, typically either a change in land use or climate.  Single cause explanations are problematic, and more recent research has emphasized multiple factors and more complex processes.  Substrate is also an important variable in arroyo incision, but has not received the same amount of attention as climate and land use.  Direct comparision of incision between watersheds in different regions such as the Southwest and Pacific Northwest is also problematic.  More local research is needed to understand arroyo incision in the Pacific Northwest.

# CHAPTER IV

# METHODS

The location and general nature of the arroyos in the West Foster Creek watershed were described and mapped through airphoto analysis and field checking. Timing of arroyo incision was assessed through the analysis of airphotos and historical sources. The literature establishes three primary factors in causing arroyo incision: climate change, land use, and substrate. These factors were assessed in terms of their contribution to arroyo incision in the study area over the last ~60 years. This assessment, along with the local impacts of arroyo incision and review of stream management literature was used to generate management recommendations. The time frame chosen for analysis reflects the availability of airphotos (1939 to present).

## Arroyo Mapping

Major streams in the study area were subdivided into reaches based on the positions of confluences, confinement, gradient, and substrate (Prichard, 1999; Rosgen, 1996). If incision was continuous through multiple reaches, these reaches were aggregated for purposes of analysis. A pocket stereoscope and airphotos from 1939, 1949, 1955, 1965, 1982, 1991, 1996, and 2002 (Table 2) were used to observe, describe and map the general location of arroyos in the study area. ArcMap™ was then used to digitize the location of arroyo incision on a digital raster graph of the Chief Joseph 7.5 minute quadrangle. Criteria for the presence of arroyo incision included exposure of light-colored sediments, the absence of riparian vegetation proximal to the stream channel, and visible depth of incision, often highlighted by shadows (Smith,

Table 2

*Airphoto Sources*

| Date | Format | Scale | Agency | Project number | County code, roll number |
|---|---|---|---|---|---|
| Jun-39 | B & W | 1:20,000 | USDA | 5218 | AAQ 211 |
| Jul-49 | B & W | 1:20,000 | USDA | | AAQ 3F, 4F |
| Jun-55 | B & W | 1:20,000 | USDA | | AAQ 4 |
| Jul-65 | B & W | 1:20,000 | USDA | 6809 | AAQ 3FF |
| Aug-82 | CIR | 1:40,000 | USGS | 471803 | HAP 265 |
| Jul-91 | B & W | 1:24,000 | USGS | 47119 | |
| Jul-96 | B & W | 1:80,000 | USGS | | 9298 |
| Jul-02 | Color | 1:20,000 | FCCD | | 96 S, 97 N |

*Note*. B & W = black and white; CIR = color infrared; USDA = United States Department of Agriculture; USGS = United States Geologic Survey; FCCD = Foster Creek Conservation District.

1943). If incised areas showed evidence of lateral stream migration, floodplain development, and renewal of riparian vegetation, they were no longer mapped as incised. Mapping error was estimated to be less than 10 m. Incision on the main stream channel and its major tributaries was also field checked in Fall 2003 and Spring 2004, using a handheld global positioning system receiver.

## Timing of Arroyo Incision

Timing of arroyo incision is commonly assessed using morphostratigraphic techniques. A crucial factor in this type of assessment is the availability of dateable materials in the arroyo walls to provide a chronology of geomorphic events. Initial reconnaissance of the study area suggested the presence of volcanic tephras at various depths along West and Middle Foster Creek, including Reaches WFC 5 (at a depth of ~5 m) and MFC 1 (at a depth of less than 1 m). However, these proved not to be tephras, thus precluding morphostratigraphic analysis.

To assess the timing of incision, maps showing the location of the arroyos for the time of each of the airphoto sets were created using ArcMap™ geographic information system (GIS) software and the abovementioned set of incision layers. This series of maps shows the development of arroyos in the study area between 1939 and 2002. Arroyo length was measured using ArcMap™. Total lengths of the arroyos were summed for each year with airphoto coverage and percentage change between years was calculated using Excel™.

Arroyo incision was statistically compared between West and Middle Foster Creek and Fye Draw over the time of study. The null hypothesis was that there existed no significant relationship between these three incised areas. The alternative hypothesis was that a significant relation existed. Spearman rank correlation was used to compare the three branches two at a time, and the significance level was set at $p = 0.05$, one-tailed.

## Causes of Arroyo Incision

### *Substrate*

Substrate was analyzed by creating a GIS layer of substrate using ArcMap™ and underlying it with the GIS incision layers created from the airphotos. Martin’s (2001) report, the Douglas County soil survey (USDA, 1981), and the geologic map of the area (Stoffel et al., 1991) were used to provisionally map substrate. Mapped units included glacial lake sediments, glacial outwash, and Ellensburg Formation sandstone. Airphotos were used to check the mapping of glacial lake sediments, using exposed light coloration and dissection of hillslopes as identification criteria (Smith, 1943). Outwash and Ellensburg Formation units were not identifiable from the airphotos; therefore, they were field checked. Mapping of all substrate was field checked by walking surveys of major streams in the study area.

### *Weather and Climate*

Precipitation data from February and March were examined to capture the effect of runoff from melting snow. Data from May through August were examined to capture the secondary precipitation peak, and late summer convective thunderstorms. Monthly precipitation data from the WRCC for Waterville (1939-2002) were examined to identify extreme monthly rainfall totals. Monthly precipitation data, particularly in semi-arid areas are not often normally distributed (Hereford, 1984), therefore the median was chosen as measure of central tendency and quartiles were chosen as measures of dispersion (McGrew & Monroe, 2000). Monthly values greater than the 3rd quartile were listed in tables. Daily precipitation values were examined for months with extreme totals.

Personal communication with local managers of the Wells Wildlife Area and FCCD, and with long time local residents provided information about large flooding events in the study area. Local newpaper archives including the *Big Bend Empire Press* and *Wenatchee Daily World*, accessed at the Central Washington University and Waterville libraries, were examined for mention of extreme precipitation, floods, and erosion. Events with extreme discharge and precipitation values that were recorded in archival materials and described by locals were checked with the timing of incision shown on the airphotos and described in archival materials and personal communication. Events were compared with the lists of extreme precipitation months and daily precipitation data.

The relationship between precipitation and incision was statistically analyzed. The null hypothesis was that there existed no significant relationship between preicipitation and amount of incision. The alternative hypothesis was that a significant relation existed. Spearman rank correlation was used, and the significance level was set at $p = 0.05$, one-tailed. Monthly precipitation amounts above the 3rd quartile were aggregated for the years between the airphotos, and compared to percent change in incision for the West and Middle Forks and Fye Draw.

Incision events were also compared with longer term climate cycles. A list of ENSO conditions from the WRCC from 1930 to present was compared with incision events for correspondance. PDO data available from the Joint Institute for the Study of the Atmosphere and Ocean website at the University of Washington was also analyzed to determine if flooding and erosional events in the study area are associated with PDO values.

### *Land Use*

Cause and effect relationships in environmental systems are often difficult to sort out (Schumm & Lichty, 1965), particularly the relationship between climate and land use in arroyo formation. Historical land use analysis is an effective tool in assessing the causes of stream degradation and designing and evaluating stream restoration efforts (Kondolf & Larson, 1995). A crucial land use change that affects erosion is the change from natural to cultivated vegetation (Hooke & Kain, 1982).

Land under cultivation was mapped on a digital raster graph of the Chief Joseph 7.5 minute quadrangle using ArcMap™ software, a pocket stereoscope, and the airphotos from 1939, 1949, 1955, 1965, 1982, 1991, 1996, and 2002. As erosion is the focus of this thesis, upland areas in the study area were included in addition to the channels and riparian areas. Maps were made showing cultivated land for each set of airphotos. Total cultivated area and cultivated area as a percentage of the study area were calculated using ArcMap™ and Excel™ software. Airphotos were also examined for evidence of grazing such as animal trails in or near floodplains. Land use layers were combined with incision and substrate layers to make one set of maps describing conditions between 1939 and 2002 in the study area.

The relationship between land use and incision was statistically analyzed. The null hypothesis was that there existed no significant relationship between percent change in land use and percent change of incision between airphoto sets for the West and Middle Forks and Fye Draw. The alternative hypothesis was that a significant relation existed. Spearman rank correlation was used, and the significance level was set at $p = 0.05$, one-tailed.

The influence of road crossings on streams in the study area was assessed by tallying the number of bridges and culverts for the West and Middle Forks and Fye Draw, using the eight airphoto sets available for the period of study.

### Impacts of Arroyo Incision and Management Recommendations

Impacts of incision were qualitatively assessed through airphoto analysis and field examination of the arroyos. These included floodplain degradation and loss of riparian vegetation (Graf, 1988; Prichard, 1999). Lessons learned from previous incision management efforts were used to develop recommendations. Key management issues and stresses were identified for the study area based on analysis of arroyo location, nature, timing, and causation, and personal communication with local managers.

General stream restoration principles were used to guide management recommendations. Stream management should not be limited to the confines of the channel, but should include the floodplain, valley slopes, and the immediate uplands as well (Federal Interagency Stream Restoration Working Group, 1998). Human activity in the floodplain has influences both up and downstream over long distances. Short term fixes to environmental issues may cause long term problems. A change in one stream variable results in a compensation in the others. A cautious approach to stream management is wise—the less modification the better, and management techniques should mimic natural processes and configurations as much as possible (Stern & Stern, 1980).

## Summary

Methods used in this project included airphoto analysis and mapping, archival research, and statistical analysis. These tools were used to analyze the distribution of arroyo incision in the study area, and the relationship between the variables of substrate, land use, and climate in causing incision. Results of this analysis provided the basis for management recommendations for the West Foster Creek watershed.

# CHAPTER V

# RESULTS AND DISCUSSION

The study area was divided into seven reach units, five of which were incised. These reaches were photographed, described and compared with each other. Timing and extent of arroyo incision were analyzed using airphotos from 1939 to 2002. Causation of incision was analyzed in terms of the factors substrate, weather and climate, and land use. In addition to historical analysis, statistical analysis was used to assess the relative importance of the abovementioned factors in causing incision. Impacts of incision in the study area were noted. These results provided the basis for generating management recommendations.

## Arroyo Description and Mapping

The West Foster Creek watershed was divided into reaches based on the location of confluences, gradient, confinement, and primary substrate (Table 3). These reaches were assigned reach codes to simplify subsequent description. Confinement was classified as unconfined, moderately confined, or confined. Confinement was defined as the ratio between bankfull and floodplain width (Watershed Professionals Network, 1999). Floodplain width greater than four times floodplain width indicated an unconfined reach and floodplain width less than two times floodplain width indicated a confined reach. Reaches with values in between these reaches were considered moderately confined. All reaches except WFC 1 and WFC 2 are confined and incised. Reach WFC 1 has a high (3%) gradient but no incision, suggesting that differences in substrate or land use explain the lack of incision in this reach. This reach, along with Reach WFC 2, is separated from the severe downstream incision by the gabion dam.

Table 3

*Reaches, West Foster Creek*

| Code | Description | Gradient | Confinement | Primary substrate |
|---|---|---|---|---|
| WFC 1 | West Fork: Dyer Hill Road to south end of meadow | 0.030 | MC | Alluvium, colluvium, drift |
| WFC 2 | West Fork: South end of meadow to gabion dam | 0.018 | UC | Glacial lake deposits |
| WFC 3 | West Fork: Gabion dam to Middle Fork confluence | 0.029 | C | Glacial lake deposits |
| WFC 4 | West Fork: Middle Fork to Fye Draw confluence | 0.016 | C | Drift |
| WFC 5 | West Fork: Fye Draw to East Fork confluence | 0.027 | C | Glacial lake deposits and sandstone |
| MFC 1 | Lower Middle Fork | 0.031 | C | Glacial lake deposits |
| FD 1 | Lower Fye Draw | 0.034 | C | Glacial lake deposits |

*Note*. MC = moderately confined; UC = unconfined; C = confined.

Figures 6-13 show the development of arroyo incision in the West Foster Creek watershed between 1939 and 2002. These maps also show the location of incision in relation to substrate type and areas under cultivation. Mapped substrate units include glacial lake sediments, glacial outwash, and Ellensburg Formation sandstone. Areas not indicated as one of these three units are covered with glacial drift, or modern alluvium in the stream channels. Reach WFC 1 has a large amount of colluvium that appears to be older drift from the uplands that has been deposited at lower elevations through mass wasting events. All of these substrate types are susceptible to incision, especially the lake sediments and sandstone.

Many of the arroyos in this area have a steep cutbank side wall that is actively eroding, with a lower angled wall on the opposite side of the arroyo. Lateral stream migration in these arroyos slowly renews the stream's floodplain, and creates a new, lower riparian zone. When the lateral movement of the stream overpowers the force of the vertical erosion, the arroyo incision may be thought of as no longer active. Airphoto evidence of this process is the presence of riparian vegetation proximal to the stream channel on the airphotos (Prichard, 1998) and when and if the channels reached this point they were no longer mapped as actively incising.

The lateral stream movement erodes the arroyo walls and creates a source of sediment. This is both a positive and negative development for the stream environment. Although the sediment provides material for the rebuilding of a floodplain, it also increases downstream turbidity. This process helps to explain why even in the absence of upstream land use that caused sheet erosion, downstream sediment levels may remain at relatively high levels.

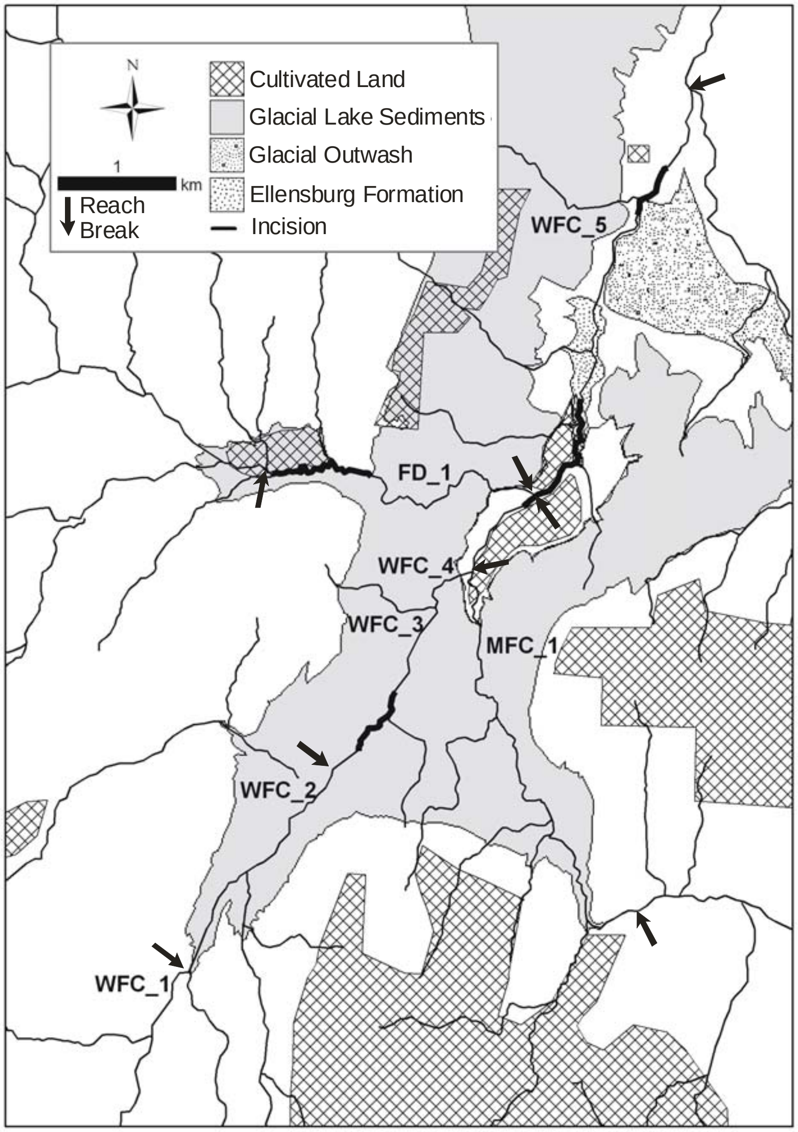


*Figure 6.* Incision, land use, and substrate, West Foster Creek, 1939.

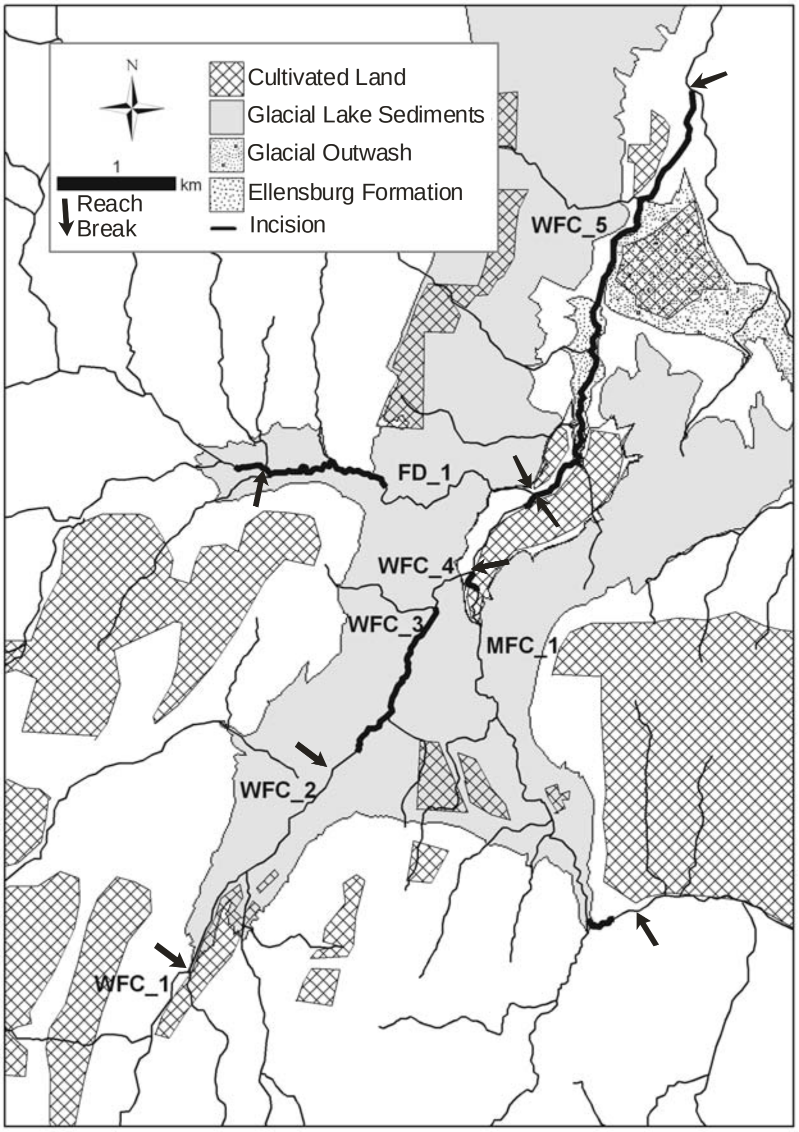


*Figure 7*. Incision, land use, and substrate, West Foster Creek, 1949.

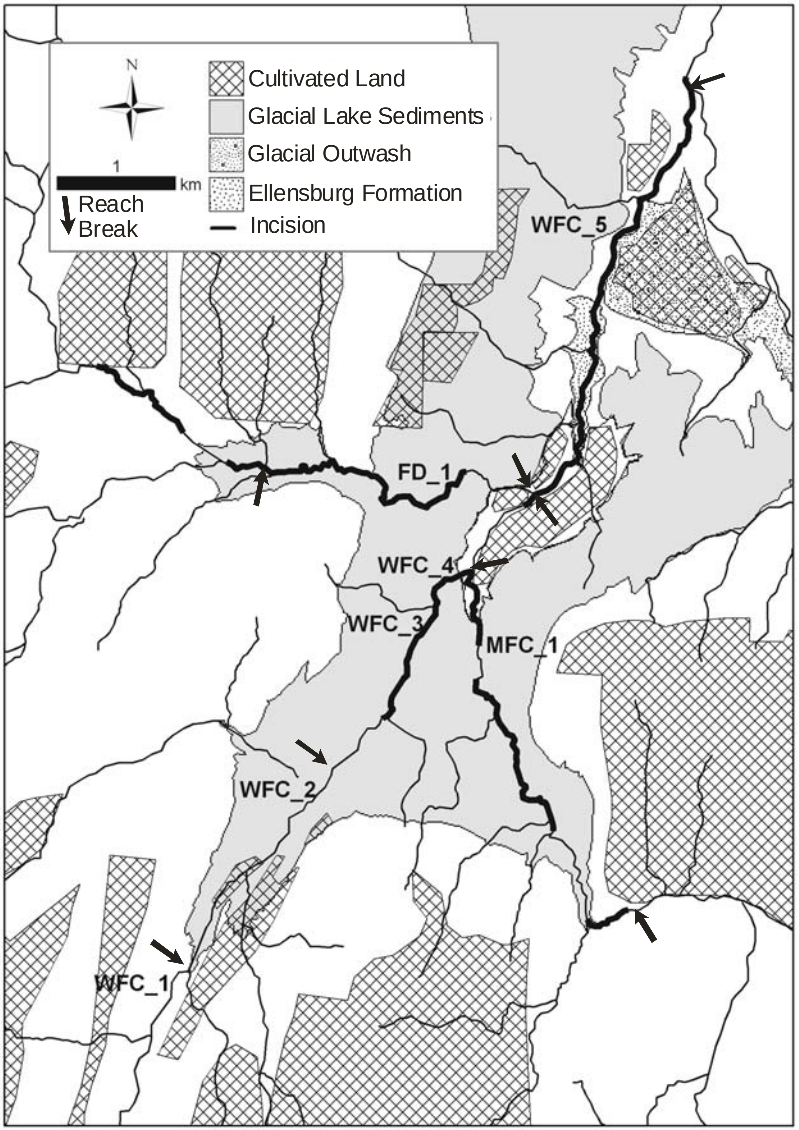


*Figure 8*. Incision, land use, and substrate, West Foster Creek, 1955.

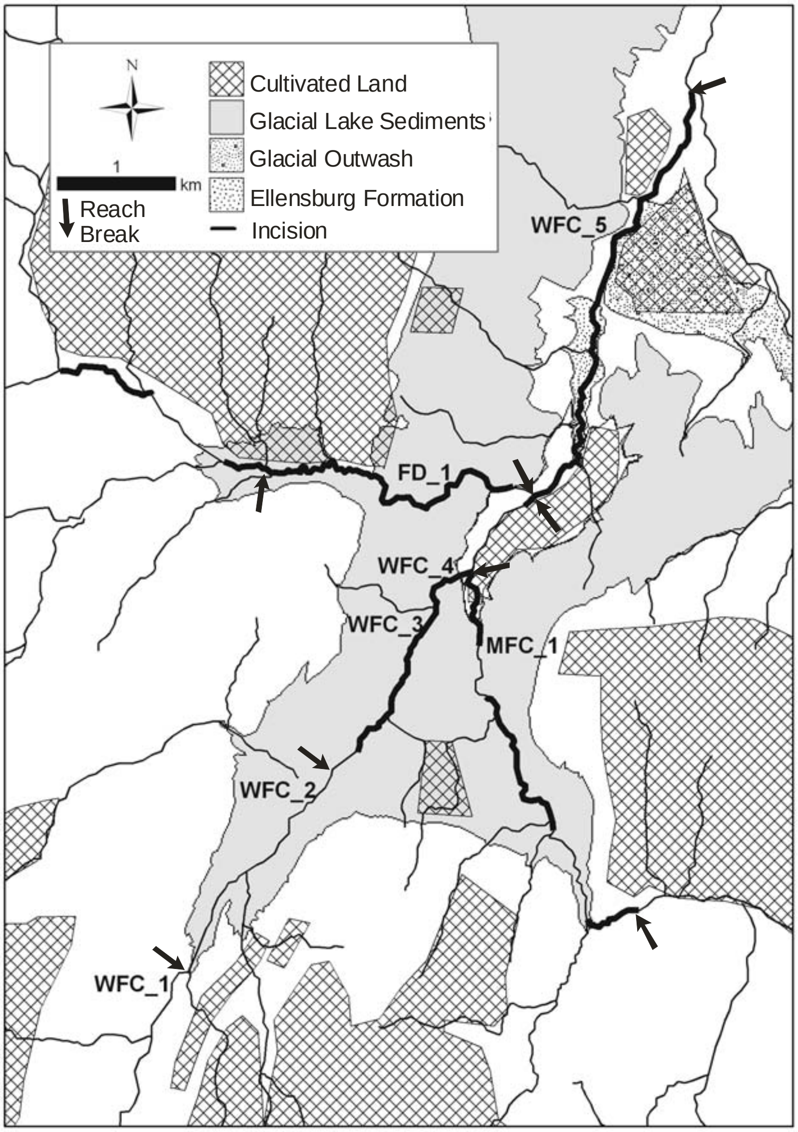


*Figure 9*. Incision, land use, and substrate, West Foster Creek, 1965.

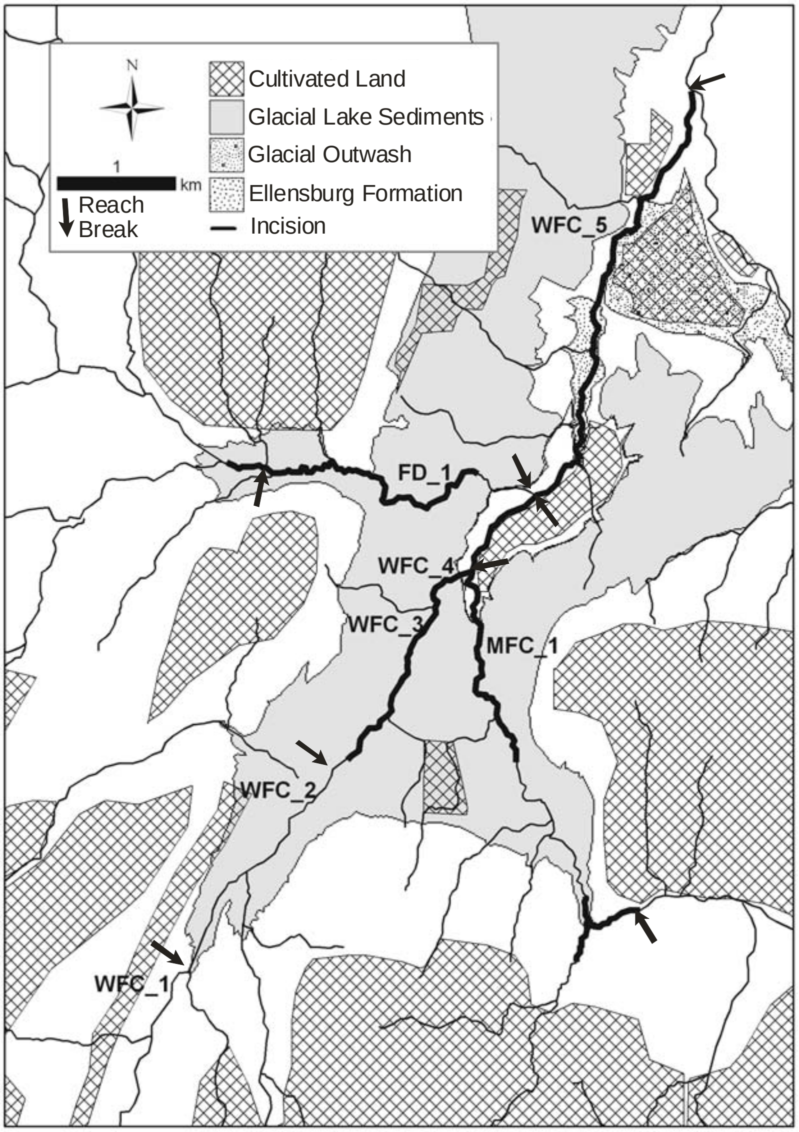
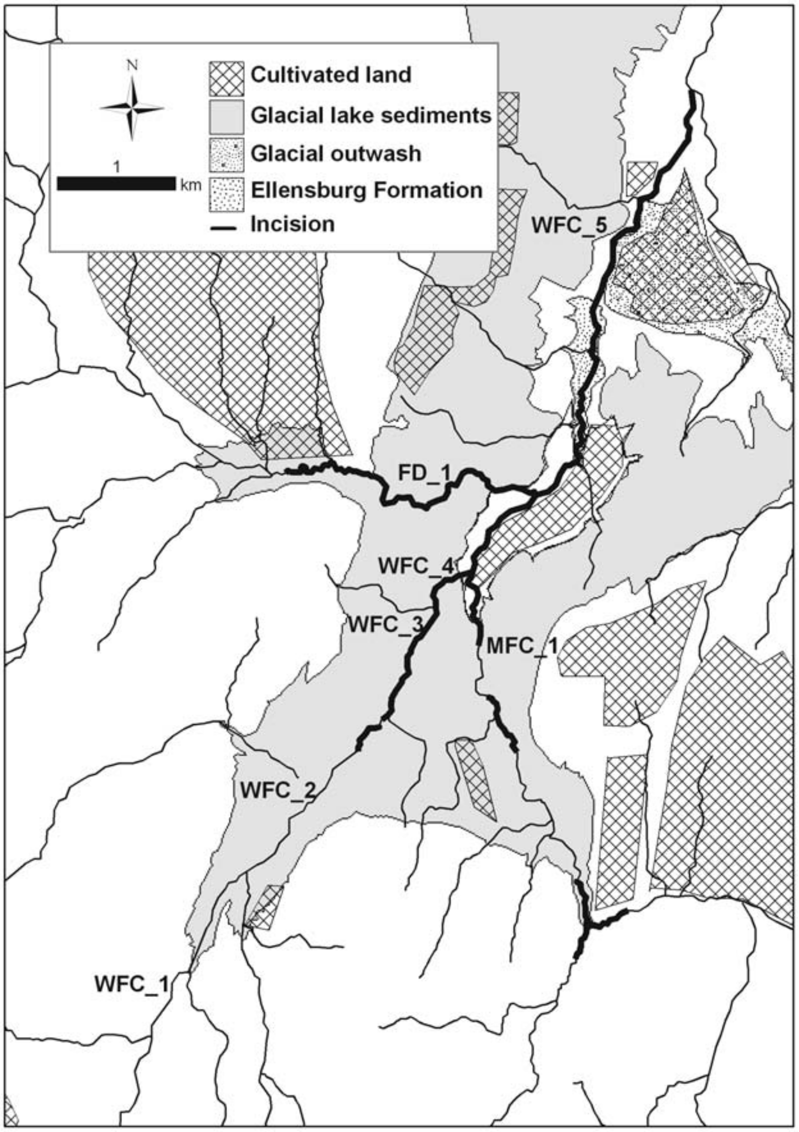


*Figure 10.* Incision, land use, and substrate, West Foster Creek, 1982.


N
1
km
Cultivated land
Glacial lake sediments
Glacial outwash
Ellensburg Formation
Incision
WFC_5
FD_1
WFC_4
WFC_3
MFC_1
WFC_2
WFC_1

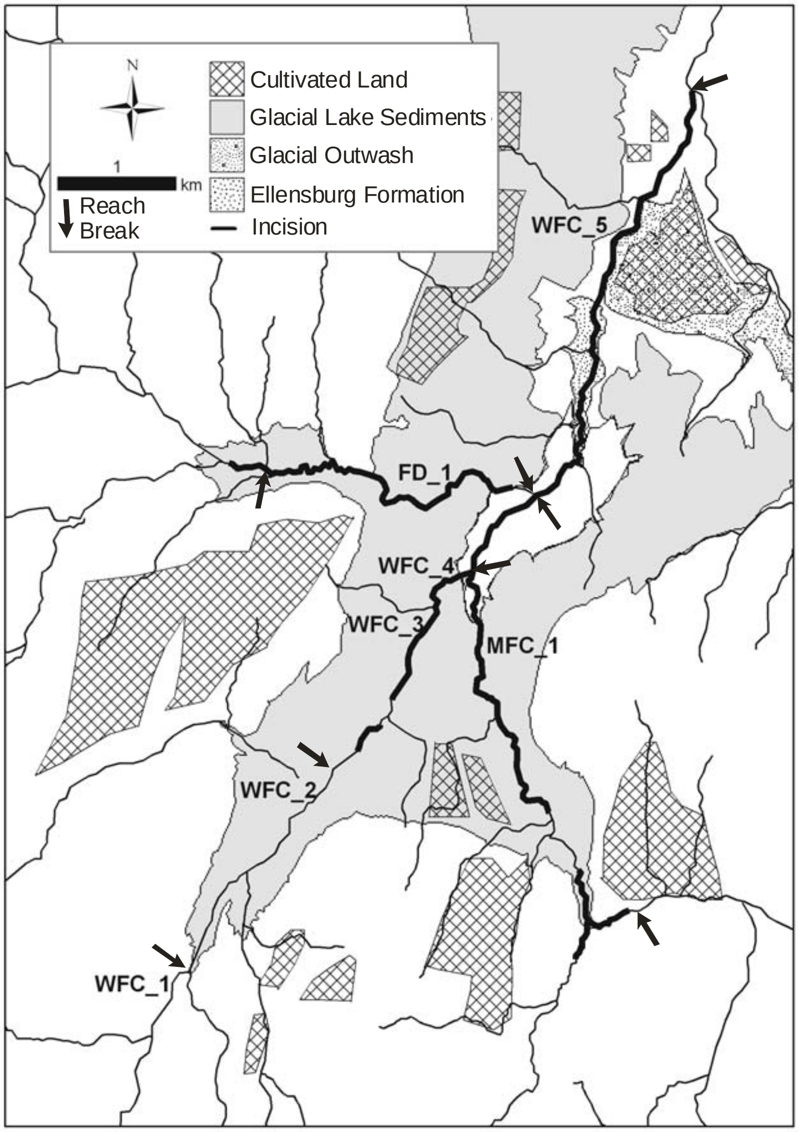


*Figure 12*. Incision, land use, and substrate, West Foster Creek, 1996.

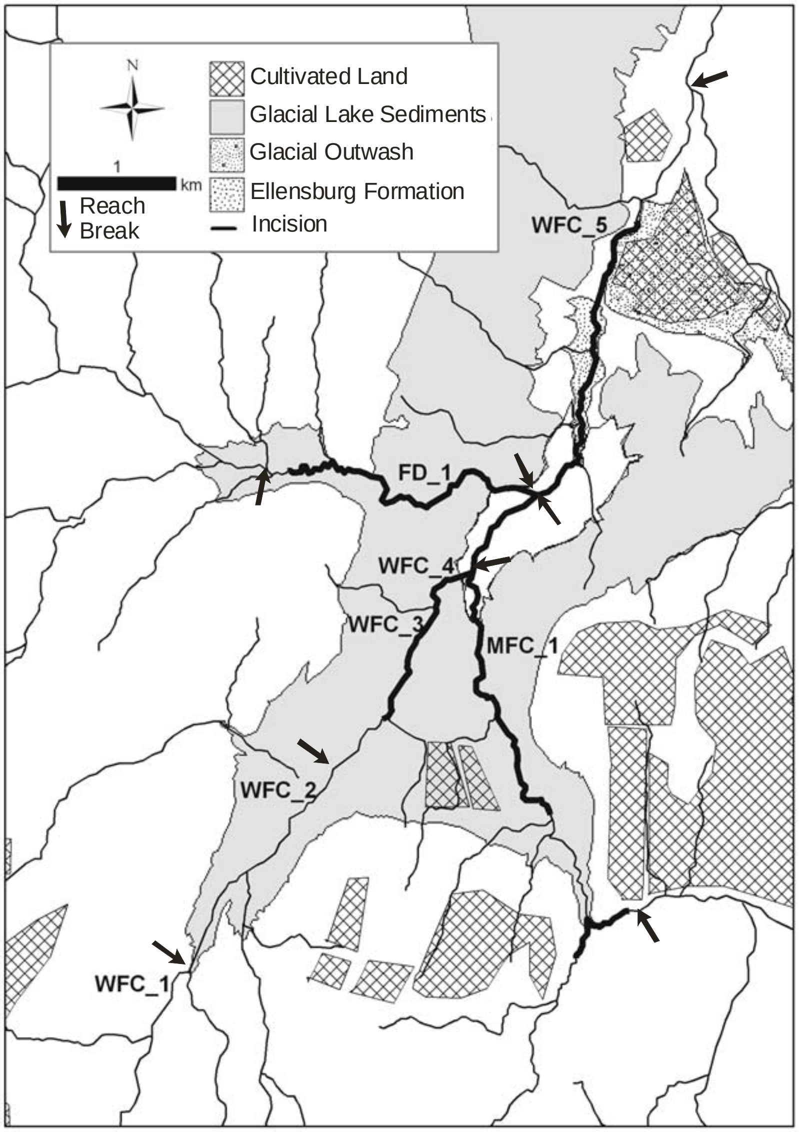


*Figure 13*. Incision, land use, and substrate, West Foster Creek, 2002.

Reach WFC 1 begins at the southern extremity of the study area, and ends at the wet meadow. West Foster Creek is less than 1 m wide in this reach, and its substrate is reworked till and colluvium. Soil in this reach is primarily Heytou very stony loam and Ellisford loam. The stream is not incised, although it forms cutbanks in erodible material (Figure 14). This cutbank is ~2 to 3 m high. Cutbank exposures along this reach include cobbles of all sizes, with the larger cobbles having a diameter of 60 to 120 cm. The cobbles are rounded, and are mostly basalt with some granitic erratics, some of which reach 120 cm.

*Figure 14.* Cutbank in colluvium and drift, Reach WFC 1.

Reach WFC 2 (Figure 15) begins at the south end of the meadow and ends at the gabion dam (Figure 2). Stream width is 1 to 1.5 m in this reach, and substrate is glacial lake sediment. Ellisforde loam is the primary soil type. This reach has a low (2%) gradient, which with the presence of the gabion dam helps to explain the lack of incision.

*Figure 15*. View west toward Dyer Hill from Bridgeport Hill Road, Reach WFC 2. Photo courtesy of Britt Dudek (2003).

Reach WFC 3 (Figure 16) begins at the gabion dam and ends at the Middle Foster Creek confluence. The stream is 1-2 m wide along this reach, with a gradient of 3%. The primary substrate is glacial lake sediment, and primary soil types include Ellisford loam and Umapine variant loam. This reach is incised along its entire length, as much as ~10 m deep in glacial lake sediments and ranges from 20-25 m wide. Glacial lake sediment colluvium extends up the arroyo wall ~5 m in places, and is vegetated by willows near the stream and sagebrush higher up. Beaver are active in this reach (Figure 17). At the confluence of West and Middle Foster Creek is a conspicous drift terrace, which grades into glaciolacustrine silt up Middle Foster Creek.

*Figure 16*. West arroyo wall incised in lake sediments, Reach WFC 3.

*Figure 17*. Beaver dam, Reach WFC 3.

Reach WFC 4 begins at the Middle Foster Creek confluence and ends at the Fye Draw confluence. West Foster Creek is 1-2 m wide in this reach. The primary substrate is glacial drift (Stoffel et al., 1991), and the primary soil type is Ellisford loam. The stream is incised in a terrace. Incision is 8-12 m deep and 20-30 m wide.

Reach WFC 5 begins at the Fye Draw confluence and ends at the East Foster Creek confluence. The stream is 1-3 m wide in this reach. The upper part in incised in glacial lake sediments (Figure 18), and the lower part is incised in Ellensburg Formation sandstone (Figure 19). Ellisford loam is the predominant soil. This reach includes the deepest incision in the study area, over 20 m in places. The arroyo is 20-35 m wide. A non-incised terrace composed of glacial outwash is between East and West Foster Creek south of their confluence. This outwash is made up of crudely to well stratified sand, gravel, pebbles, and cobbles deposited by glacial meltwater (Stoffel et al., 1991).

*Figure 18*. West arroyo wall incised in lake sediments, Reach WFC 5, upper section.

*Figure 19*.  Ellensburg Formation, east arroyo wall, lower section, Reach WFC 5.

Reach MFC 1 (Figure 20) begins on Middle Foster Creek at the North Oil Road bridge at the eastern edge of Buckingham Flats (Figure 2) and ends at the West Foster Creek confluence.  Middle Foster Creek is 1-2 m wide in this reach.  The primary substrate is glacial lake sediment, and Ellisford  loam is the predominant soil.  The lower ~1 km of Middle Foster Creek is incised to a depth of over 10m, and incision is 10-35 m wide.  Further deepening is limited by a basalt knickpoint waterfall (Figure 2).

Reach FD 1 (Figure 21) begins at the confluence of Smith and Fye Draws and ends at the confluence with West Foster Creek.  The stream is < 1 m wide in this reach. The primary substrate is glacial lake sediment, and Ellisforde loam is the predominant soil.  Lower Fye Draw is incised in glacial lake sediments to a depth ranging from 2 to 5 m, and width of 3 to 10 m.  Incision is limited by the presence of basalt knickpoint waterfalls, much as on Reach MFC 1.

*Figure 20*. View north from waterfall, incision in lake sediments, Reach MFC 1.

*Figure 21*. Incision to basalt in lake sediments, Reach FD 1.

## Timing and Extent of Arroyo Incision

West Foster Creek showed incision as of the 1939 airphotos, and the length of incision more than doubled by 1949 (Table 4, Figures 6-13). A steady increase occurred until 1982, and the overall rate of incision decreased since then. Currently, both the deepest and most active incision in the study area is found on Reaches WFC 3, WFC 4, and WFC 5 on West Foster Creek between the gabion dam and the East Foster Creek confluence. The stream channel between the Middle and East forks is a continuous arroyo with active headcut erosion.

Middle Foster Creek had no incision as of 1939, but showed incision on the 1949 photos. The largest increase in incision was between 1949 and 1955. As with the West fork, a decrease was noted since 1982.

Fye Draw was incised as of 1939, and showed the largest increase between 1949 and 1955. The largest decrease was between 1965 and 1982. In general, the largest increase in incision in the study area occurred in the mid 20th century (Table 4).

Headcuts tend to incise until they reach bedrock or a structure such as a gabion dam. The gabion dam on West Foster Creek and the basalt falls on Fye Draw and Middle Foster Creek have stopped headcuts in the study area, and the reaches immediately downstream from these barriers have started to aggrade. As Fye Draw was incised earlier than the other locations in the study area, it had already begun aggradation in the 1980s, before the introduction of the Conservation Reserve Program.

Spearman rank correlation was calculated for percent change of incision between the three main incised areas in the study area (Table 4). No significant relationship

Table 4

*Extent of Incision, West Foster Creek Watershed*

| Year | Incision (m) | Length (m) | Incision (%) | Change (%) |
|---|---|---|---|---|
| | | West Fork Foster Creek | | |
| 1939 | 2,209 | 12,350 | 18 | |
| 1949 | 5,420 | 12,350 | 44 | 59 |
| 1955 | 5,570 | 12,350 | 45 | 3 |
| 1965 | 5,965 | 12,350 | 48 | 7 |
| 1982 | 6,825 | 12,350 | 55 | 13 |
| 1991 | 6,607 | 12,350 | 53 | -3 |
| 1998 | 6,462 | 12,350 | 52 | -2 |
| 2002 | 5,036 | 12,350 | 41 | -28 |
| | | Middle Fork Foster Creek | | |
| 1939 | 0 | 4,864 | 0 | |
| 1949 | 402 | 4,864 | 8 | 100 |
| 1955 | 2,517 | 4,864 | 52 | 84 |
| 1965 | 2,372 | 4,864 | 49 | -6 |
| 1982 | 2,522 | 4,864 | 52 | 6 |
| 1991 | 2,030 | 4,864 | 42 | -24 |
| 1998 | 3,243 | 4,864 | 67 | 37 |

Table 4 (continued)

| Year | Incision (m) | Length (m) | Incision (%) | Change (%) |
|---|---|---|---|---|
| 2002 | 2,759 | 4,864 | 57 | -18 |
| Fye Draw | | | | |
| 1939 | 882 | 4,689 | 19 | |
| 1949 | 1,324 | 4,689 | 28 | 33 |
| 1955 | 3,423 | 4,689 | 73 | 61 |
| 1965 | 3,783 | 4,689 | 81 | 10 |
| 1982 | 2,478 | 4,689 | 53 | -53 |
| 1991 | 2,489 | 4,689 | 53 | 0 |
| 1998 | 2,502 | 4,689 | 53 | 1 |
| 2002 | 2,486 | 4,689 | 53 | -1 |

existed between West Foster Creek and Fye Draw ($p$ = 0.227) or Middle Foster Creek and Fye Draw ($p$ = 0.053). However, a significant relationship ($p$ = 0.04) was found between the West and Middle forks. Incision on the West and Middle forks was moderately correlated ($r$ = 0.679), as these areas incised at similar rates over the time of study.

## Causes of Arroyo Incision

### *Substrate*

Arroyos are incised in erodible glacial lake sediments, glacial drift, and Ellensburg Formation sandstone (Table 5, Figures 7-14). Lake sediments are more erodible than Ellensburg Formation, which is more erodible than drift. The soils found in all of these substrate types are very erodible by water, as well. Incision tends to deepen through these sediments until it reaches resistant bedrock such as knick point waterfalls (Figure 2). The deepest incision is in Reach WFC 5 in Ellensburg Formation (Figure 20) as the stream can erode down through the thick layered sandstone until it reaches basalt. This reach has the thickest amount of erodible substrate, and hence the deepest potential

Table 5

*Percent of Incision by Substrate*

| Year | Qgl | Qgd | Mc |
|---|---|---|---|
| 1939 | 55 | 25 | 20 |
| 1949 | 40 | 40 | 20 |
| 1955 | 57 | 29 | 14 |
| 1965 | 53 | 35 | 12 |
| 1982 | 51 | 37 | 12 |
| 1991 | 45 | 41 | 14 |
| 1996 | 51 | 37 | 12 |
| 2002 | 56 | 30 | 14 |

*Note*. Qgl = lake sediments; Qgd = drift; Mc = Ellensburg Formation.

for incision. Substrate clearly controls the distribution of arroyo incision in the study area.

### *Weather and Climate*

Climate data, accounts of floods and erosion in the *Waterville Empire Press*, *Wenatchee Daily World*, and the sporadic hydrologic data available for the region were used to construct a list of major storm events that most affected the Foster Creek watershed in the 20th century (Table 6).

Table 6

*Major Weather Events and Associated Effects in Study Area*

| Date | Weather event | Erosion |
|---|---|---|
| 8/31/1922 | Rain storm | Fye Draw incision, hillslope erosion |
| 6/10/1948 | Large storm over entire region | West Fork incision, flash flooding and associated erosion |
| 2/25/1973 | Flooding over frozen ground | Hillslope erosion |
| 8/06/1976 | Thunderstorm | Flash flooding, erosion |

Large storms affected the study area before 1939, creating incision that is still evident. In August, 1922, a heavy rainstorm covered the Waterville Plateau, breaking daily precipitation records and causing much damage. The storm was described as the heaviest of its kind experienced in many parts of north-central Washington. Rain came down in sheets, and caused hillslope erosion (“Precipitation Records,” 1922). This storm caused the incision in Fye Draw (Dan Peterson, personal communication, February 5, 2004). This event occurred during a cool phase PDO cycle between 1890 and 1924 (Mantua et al., 1997).

The most damaging flood historically in the region occurred in early June, 1948. This flood had the second largest flood peak in the time that records were kept in the Columbia River watershed. The June 1948 flood affected much of the Northwest, and destroyed the community of Vanport outside of Portland (USGS, 1949). The 1948 flood caused significant damage in Douglas County, with flooded fields, washed out roads, rills and gullies. landslides in canyons, and damage to railroads and bridges ("Flash Flood," 1948; "Railroads," 1948). May 1948 had the highest total precipitation on record for that month at Waterville (Appendix), and June 1948 was the second highest total.

Incision on West Foster Creek greatly increased between 1939 and 1949 (Figures 14 and 15) and the incision on the latter photograph set appeared fresh, based on the lack of vegetation and reflectivity of the sediments. This incision was catastrophically deepened by the June 1948 floods. The drier conditions associated with the immediately preceding warm PDO cycle (from 1925 to 1947) may have led to vegetation loss and increased erodibility that exacerbated the erosion caused by the May and June storms in the study area.

Floods occurred as a result of frozen ground and thaw in late February, 1973, causing hillslope erosion and road closure near Bridgeport ("Frozen ground," 1973). On August 6, 1976, a large rainstorm caused flash flooding and mudflows in the region, with much damage, including washed out roads, railroads and bridges, and gullying ("Local area digs out," 1976). August 1976 had the third highest total precipitation for that month at Waterville (Appendix). U.S. Highway 2 was washed out above Moses Coulee

(Schuster, 1977). These two events and the 1948 event happened during a cool PDO cycle between 1947 and 1976. The year 1948 was ENSO neutral (neither El Nino nor La Nina). The year 1973 was a strong El Nino year. The year 1976 was a strong La Nina year according to the WRCC, which may have enhanced the climatic impacts of the cool PDO cycle (Mantua et al., 1997).

The two weather events that have most affected incision in the study area (1922 and 1948) were high magnitude, low frequency events during cool PDO periods. Arroyo incision in the study area does not appear to be tied to winter precipitation or early spring runoff. The large flood event of 1948 was tied to melting snowpack across the Pacific Northwest, but local erosion in the study area was more related to May and June precipitation.

Few of the extreme months (Appendix) showed up as flooding and erosion events, implying that other factors are also responsible for erosion. In addition, the 1922 flood does not show up as a extreme month. Although the small number of erosional events precludes statistical analysis of events, the data suggest a lack of a direct cause and effect relationship between large monthly precipitation totals, flooding, and erosion in the study area. Flooding appears necessary to trigger erosion, but does not guarantee it. Other factors, such as land use, condition of bank stabilizing vegetation, and condition of substrate (e.g., soil moisture, piping, etc.) may be more critical in driving incision in the study area.

Spearman rank correlation showed no significant relationship between precipitation and incision for Middle Foster Crrek ($p = 0.251$) or Fye Draw ($p = 0.424$). However, a significant realtionship ($p = 0.04$) was found for West Foster Creek, with a moderate correlation of $r = 0.679$. The fact that correlation was restricted to West Foster Creek was most likely explained by the catastrophic 1948 flooding, which appeared to have less of an impact on Middle Foster Creek and Fye Draw. Also, if precipitation was the main factor in causing incision in the study area, and affected all three branches equally, incision on West and Middle Foster Creek and Fye Draw should have been significantly correlated.

### *Land Use*

The amount of cultivated land gradually increased over most of the 20th century in the study area until the 1980s (Figures 6-13, 22). Cultivated land affected incision in the study area by the removal of natural vegetation for crop land and by grazing, both of which increased runoff and erodibility (Dan Peterson, personal communication, May 23, 2004). Incision occurs in areas proximal to floodplain and terrace cultivation (Figures 6-13).

A steep decline in cultivated land occurred between 1982 and 1991, reflecting the post-1985 influence of the Conservation Reserve Program (Figure 22). Through this program, farmers were reimbursed for taking land out of active production, and having it replanted with native vegetation. This removal of land from active cultivation, combined with the development of the Wells Wildlife Area, resulted in the protection of West Foster Creek from human-caused erosive stresses.

Evidence of grazing in the study area was inconclusive. Trails might be evidence of grazing, but features such as trails can persist long after their period of use in semi-arid areas, making airphoto analysis difficult. It is also difficult to differentiate cattle trails

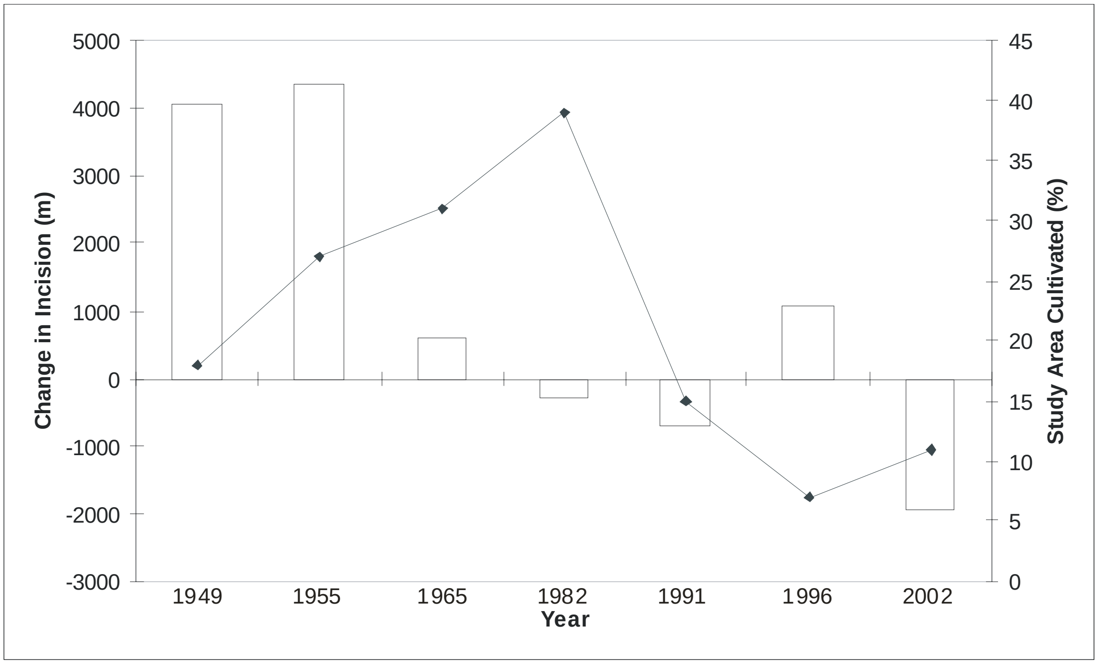


*Figure 22*. Change in incision relative to land use between years with airphoto coverage, 1939-2002, West Foster Creek watershed. Bars denote change in active incision, line denotes percent of study area under cultivation.

from deer trails on airphotos. Cattle were grazed in this area from the 1880s to the present (Dan Peterson, personal communication, May 23, 2004; Steele & Rose, 1904). The airphotos show no presence of cattle or extensive vegetation damage in the wet meadow or other non-incised riparian and wetland areas in the study area.

Land use likely played an important role in the Fye Draw incision (Figures 6-13) as incision is proximal to a cultivated area. This incision was formed in 1922 by a combination of flash flooding and poor land use (Dan Peterson, personal communication, February 5, 2004). Factors included removal of natural vegetation for wheat planting and overgrazing (Dan Peterson, personal communication, February 5, 2004). The 1939 airphotos show cultivated land proximal to the north side of Fye Draw (Figure 6). The 1949 airphotos show that cultivation was moved further to the north of Fye Draw (Figure 7).

The incision of the drift terrace at the confluence of West and Middle Foster Creek, and below the outwash terrace at the confluence of East and West Foster Creek is also through a cultivated area (Figures 6-13). By 1996, the only cultivated lands abutting incised streams were the two terraces (Figure 12). The drift terrace is being reseeded with native vegetation by the Wells Wildlife Area (Dan Peterson, personal communication May 23, 2004). The outwash terrace was still cultivated as of 2002 (Figure 13).

Spearman rank correlation showed no significant correlation between change in land use and change in incision on West Foster Creek ($p = 0.178$), Middle Foster Creek ($p = 0.424$), or Fye Draw ($p = 0.314$). This lack of significant correlation may be explained by the presence of a lag time between a change in land use (particularly a removal of land from cultivation) and a subsequent change in incision.

The number of bridge crossings and culverts did not vary much year to year (Table 7). West Foster Creek had many more culverts because of the presence of the Bridgeport Hill road. On West Foster Creek, runoff through culverts resulted in minor incision of tributary streams. Bridges did not appear to have a downstream influence on incision.

## Impacts of Arroyo Incision

Arroyo incision has had many negative impacts in the study area. Incision has resulted in the loss of floodplain and associated riparian vegetation. This vegetation is an important food source for sage and sharptail grouse in the winter months, especially

Table 7

*Bridge Crossings and Culverts, West Foster Creek Watershed, 1939-2002*

| | West Foster Creek | | Middle Foster Creek | | Fye Draw | |
|---|---|---|---|---|---|---|
| Year | Bridge crossings | Culverts | Bridge crossings | Culverts | Bridge crossings | Culverts |
| 1939 | 2 | 10 | 2 | 0 | 3 | 0 |
| 1949 | 2 | 10 | 2 | 0 | 3 | 0 |
| 1955 | 2 | 12 | 2 | 0 | 3 | 0 |
| 1965 | 3 | 7 | 2 | 0 | 3 | 0 |
| 1982 | 3 | 7 | 2 | 0 | 3 | 0 |
| 1991 | 3 | 7 | 2 | 0 | 3 | 0 |
| 1996 | 3 | 7 | 2 | 0 | 3 | 0 |
| 2002 | 3 | 7 | 2 | 0 | 3 | 0 |

on the West Fork in Reaches WFC 4 and WFC 5. Vegetation loss also results in higher water temperatures, impacting stream ecology (Pacific Groundwater Group, 2003). Incised areas contribute sediment to streams, increasing downstream turbidity (Pacific Groundwater Group, 2003). Incision also lowers the groundwater table, which, in turn, damages vegetation. Incision is also likely part of a positive feedback loop in which increased incision leads to deer and cattle going down the banks to the stream to find food and water, and in the process destroying vegetation and causing more erosion.

Between 1955 and 1965, the Bridgeport Hill road was undercut by expanding arroyo incision (Figure 23). The most drastic damage occurred between the wet meadow

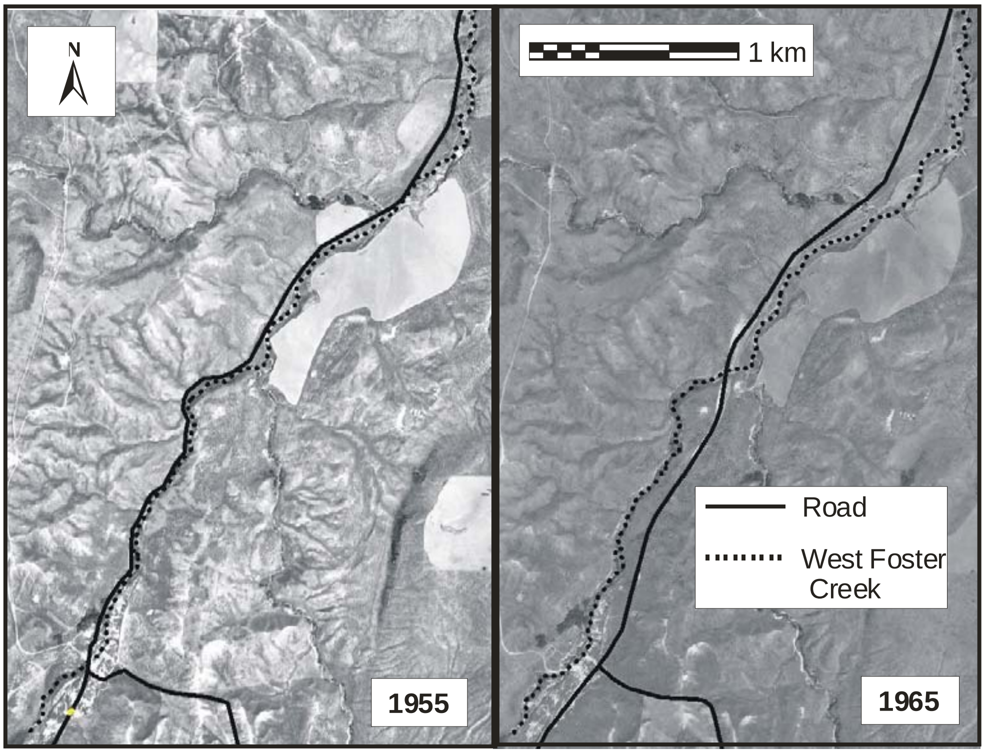


*Figure 23*. Bridgeport Hill Road relative to West Foster Creek, 1955 and 1965.

(at the southwest corner of the photographs) and the large terrace immediately north of the West Foster Creek–Middle Foster Creek confluence. The old road was built immediately above the stream on its west side. The rebuilt road was built higher above the stream on the east side, where it is today (Figure 23). It is likely that West Foster Creek entered into an erosional phase as a result of the floods of 1948 and more intensive land use, causing the undermining of the road roughly ten years later. Bridge and road damage from incision has occurred repeatedly over the 20th century in the study area (Dan Petersen, personal communication February 5, 2004).

# CHAPTER VI

# CONCLUSIONS AND MANAGEMENT RECOMMENDATIONS

## Timing and Extent of Arroyo Incision

The west fork of Foster Creek, including Reaches WFC 3, WFC 4, and WFC 5, had the most serious arroyo incision in the study area. These reaches demand the most management attention. One headcut on West Foster Creek has been stopped by the gabion dam, but in the northern part of Reaches WFC 3, and WFC 4 and WFC 5 the creek is incising. The Fye Draw and Middle Foster Creek arroyos have reached basalt and have stopped incising.

## Causes of Arroyo Incision

Substrate, climate and weather, and land use are the primary variables driving arroyo incision in the study area. Land use is the only variable that can be directly changed by management. However, the local implications of climate and substrate should be considered in the management of the study area. Given enough time and the absence of causal mechanisms, the incision will cease and aggradation will form a new floodplain. This time scale is not compatible with wildlife management needs in the area. Restoration of West Foster Creek to pre-incised conditions is also not realistic. It is more reasonable to stop severe headcutting with structures such as the gabion dam and smaller biodegredable instream structures, and to focus on protecting and restoring the riparian environment. Soil bioengineering methods are the most promising options for the latter. Deer and beaver both remove riparian vegetation. While beaver also provide environmental benefits, deer provide none. Moore (2003) described a boom and bust cycle in north central Washington deer populations, and the West Foster Creek deer population appears to be in a boom cycle.  The impacts of deer may be further exacerbated by the lack of  upland forage, which forces the deer to graze riparain and wetland vegetation.  It may be that the lack of upland habitat is more of an issue than the number of deer in the study area.

Beaver should be encouraged to build dams in the arroyos rather than be relocated.  If not enough woody material is available, it could be provided by managers. Restoration efforts should work with, rather than counter to, natural processes.

### *Substrate*

Arroyo incision in the study area is controlled by substrate.  The West Foster Creek valley's fill material, including glacial lake sediments, glacial outwash, till, and modern alluvium is all erodible.  Soils in the study area are moderately to extremely susceptible to erosion (USDA, 1981).  Areas with erodible Ellensburg Formation sandstone under the fill and soil will incise even deeper.  Incision continues until it reaches basalt bedrock or base level.  The wetland south of the gabion dam is an unstable environment, as the wetland soils are derived from glaciolacustrine silt and are very susceptible to incision.  The presence of the gabion dam, however, and the fact that land use at this site is now limited to game management, bodes well for the future of the wet meadow.  The riparian areas downstream of the dam are in considerably more jeopardy. Bank stability is an issue north of the gabion dam, as runoff and associated piping leads to slope failure and its associated stream sedimentation.

The literature establishes that erodible substrate can be stabilized by planting riparian vegetation and other slope and bank stabilization methods, known collectively as soil bioengineering (Federal Interagency Stream Restoration Working Group, 1998).

Erosion management should be based on understanding of local floodplain conditions, including lateral stream migration, flood regime, and stream morphology (Federal Interagency Stream Restoration Working Group, 1998; Rosgen, 1996).

Restoring riparian vegetation in the study area not only stabilizes the streambanks and reduces erosion, but also addresses a key management issue of the Wells Wildlife Area: the protection and development of riparian vegetation (specifically, trees) to provide winter refuge and food for the area's threatened grouse population (Dan Petersen, personal communication, May 23, 2004; Thompson & Ressler, 1988). Riparian vegetation in the study area is threatened by two stresses: stream incision and browsing animals. Stream incision cuts off the floodplain from groundwater, and ultimately results in loss of riparian vegetation. While riparian vegetation stabilizes substrate, loss of riparian vegetaion intiates a positive feedback cycle that results in more erosion. At the present, deer and beaver are more of a stress on riparian vegetation than cattle because upland fencing keeps cattle out of the riparian areas. The study area has a large deer population. The deer are especially hard on revegetation efforts.

Beaver were identified as potential positive and negative environmental factors in the Foster Creek watershed by Thompson and Ressler (1988) who recommended assessing beaver impacts at the site level and encouraging or discouraging beaver activity based on the assessment. In the West Foster Creek area, beaver have also been identified as a benefit and a detriment (Dan Petersen, personal communication, May 23, 2004). As mentioned earlier, beaver dams and ponds provide many geomorphological and ecological benefits. Beaver also eat riparian plantings and damage or remove trees in already stressed areas. However, the impact of beaver activity on riparian vegetation would be less noticeable if there wasn't the additional stress of deer in the study area.

Plantings may be protected from deer by using tree shelters or deer fences to protect seedlings (Federal Interagency Stream Restoration Working Group, 1998), but these methods are often too expensive. Replanting upland areas with plant associations that provide deer forage such as bitterbrush and needle-and-thread could help alleviate stress on the riparian and wetland vegetation.

Areas where beaver are removing riparian vegetation are also areas with unstable banks and erosion. Beaver may be trapped or transplanted, but another option is to provide the beaver with structurally sound building material (transplanted woody debris) in areas where wood supply is limited (U. S. Department of Agriculture Soil Conservation Service, 1989). Grazing must also continue to be limited in the recovering riparian area (U. S. Department of Agriculture Soil Conservation Service, 1989).

According to Rosgen (1996) entrenched streams with low width/depth ratio, and moderate sinuosity in erodible substrate such as West Foster Creek are extremely sensitive to disturbance with poor recovery potential and have a very high sediment supply and streambank erosion potential. The influence of riparian vegetation as a controlling influence on these channels' stability is high (Rosgen, 1996).

Other stream restoration methods appropriate for the study area include bank placed boulders, vortex rock weirs, and bank-placed root wads (Rosgen, 1996). The latter method also requires extensive revegetation efforts above bankful level to be effective, which is difficult in the study area because of deer interference. Instream structures such as ecology blocks will stop small headcuts, dam sediment and eventually beome buried in alluvium.

At best, the resulting stream environment will be somewhere in between the severely incised arroyos and the non-incised section of the west fork in the southern end of the study area. Given the flashy discharge regime of Foster Creek, adding loose material to the floodplain to fill in the arroyos is not advisable, as it would quicky erode or be transported downstream. Riprap may help stabilize eroding banks, however.

### *Weather and Climate*

The initiation and deepening of arroyos in the study area was triggered by high magnitude, low frequency precipitation events. Between 1939 and 2002, the storms and associated flooding of August 1922 and June 1948 were the most important events. The incision caused by these events occurred in or abutting cultivated land, making it difficult to isolate the effects of weather and climate from land use.

Analysis of precipitation data and climate patterns is inconclusive, primarily because of the small number of incision events to compare with the climate data. Also, the longer period of the PDO events means that a particular incision event is more likely to occur during a particular PDO cycle, suggesting a non-existent causal relationship. As incision in the study area does not appear to be driven by winter precipitation or early spring runoff, long term climate cycles that primarily affect winter conditions are not relevant to local arroyo incision. The exception may be extended periods of drought associated with a warm PDO cycle, followed by flooding at the beginning of a cool PDO cycle.

The primary management recommendation based on climate is that management practices in the study area, particularly efforts at stream and riparian restoration be based on a recognition of the natural range of variability in the watershed. West Foster Creek and its tributaries are extremely variable in their discharge, another factor making riparian revegetation difficult.

### *Land Use*

The intensity of land use in the early to mid 20th century, combined with the nature of the land use and flash flooding on an easily erodible substrate resulted in the formation of the incised channels of West Foster Creek. While new incision was limited in the last half of the 20th century by a land use change away from agriculture to the Conservation Reserve Program and wildlife management, preexisting arroyos continued to deepen and lengthen. The gabion dam on West Foster Creek has stopped the headcutting of the arroyo threatening the wet meadow in the Wells Wildlife Area. The meadow is also fenced to keep cattle out and is in no danger of further incision, unless head or side cutting results in the arroyo laterally bypassing the dam.

## Future Research

The relationship between climate and arroyo incision in the study area could be refined through an analysis of daily precipitation data for the 20th century. Further interviewing of long-time local residents could produce more accounts of erosive events.

Although interannual and decadal climate variation may not be an important factor in arroyo incision in the study area, climate change, particularly human-induced global warming may be. Climate modeling for the Columbia River basin projects future significant warming and increased winter precipitation, an earlier peak in the hydrograph, reduced groundwater recharge, and possibly lower summer flows (Cohen et al., 2000). The relation between climate change and geomorphology is actively studied, but not in eastern Washington State.

To better understand the future geomorphological effects of climate change in eastern Washington State, the Quaternary stratigraphic record of the study area could be investigated to examine the past cut and fill response to local and regional climate fluctuations. This information could then be used to refine predictions of the effects of climate change in the study area, as well as increase the knowledge of the effects of climate change on semi-arid regions in general.

This study also raises the issue of historic beaver removal and its effect on stream morphology across the West. Comparison of historic stream conditions with records of beaver trapping may shed light on this issue. Historical reconstructions of stream conditions across the West suffer from a lack of information about beaver. A combination of Quaternary stratigraphy (reconstructing stream conditions from the alluvial stratigraphic record, and buried evidence of beaver activity) with archival research of records of the Hudson’s Bay Company and similar sources could establish when and where beaver trapping was an important factor in altering stream morphology in the West.

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# APPENDIX

Extreme Monthly Precipitation Values (in.) for Waterville, Washington, 1939-2001

| Year | Feb | Mar | May | Jun | Jul | Aug |
|---|---|---|---|---|---|---|
| 1939 | 1.43 | | | | | |
| 1940 | 2.95 | 1.21 | | | | |
| 1941 | | | 1.45 | 1.58 | | 2.35 |
| 1942 | 1.61 | | 2.40 | | | |
| 1943 | | | | 1.48 | | |
| 1944 | 1.93 | | | 2.11 | | |
| 1945 | 1.76 | | 2.46 | | | |
| 1946 | 1.53 | | | 2.09 | | |
| 1947 | | | | 1.66 | | |
| 1948 | 1.60 | | 4.58 | 4.87 | 0.90 | 1.82 |
| 1949 | | 1.33 | | | | |
| 1950 | | 1.38 | | 2.15 | | |
| 1951 | | 1.43 | 1.96 | 1.47 | 0.62 | 1.55 |
| 1952 | | | | 1.78 | | |
| 1953 | | | 1.88 | 1.68 | | 0.67 |
| 1954 | | | | | | 2.12 |

| Year | Feb | Mar | May | Jun | Jul | Aug |
|---|---|---|---|---|---|---|
| 1955 | | | | 1.52 | | |
| 1956 | | | | 1.69 | | 1.59 |
| 1957 | | 2.04 | 1.90 | | | |
| 1959 | 1.82 | | | | | |
| 1960 | | | 1.65 | | | |
| 1961 | | | | | | |
| 1962 | | | 3.19 | | | |
| 1963 | | | | | | |
| 1964 | | | | | | |
| 1965 | | | | | 0.69 | 2.05 |
| 1966 | | 1.73 | | | 1.70 | |
| 1967 | | | 1.63 | | | |
| 1968 | | | | | | 4.02 |
| 1969 | | | | | | |
| 1970 | | | | | | |
| 1971 | | 1.50 | | | | |
| 1972 | | 1.25 | 1.75 | 1.48 | | 0.75 |
| 1973 | | | | | | |
| Year | Feb | Mar | May | Jun | Jul | Aug |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1974 | | | | | 0.59 | |
| 1975 | 2.11 | | | | 0.65 | 2.14 |
| 1976 | | | | | | 3.07 |
| 1977 | | | | | | 1.02 |
| 1978 | 1.53 | 1.17 | | | 0.97 | 0.65 |
| 1979 | | | | | | |
| 1980 | 2.28 | | 1.57 | | | |
| 1981 | 1.47 | | 2.58 | | 0.71 | |
| 1982 | | 1.56 | | | 0.63 | |
| 1983 | 2.03 | 2.76 | | | 1.24 | 3.22 |
| 1984 | | 1.76 | 1.27 | 2.98 | | |
| 1985 | | | | | | |
| 1986 | 1.79 | | | | | |
| 1987 | | | | | | |
| 1988 | | | | | | |
| 1989 | 1.67 | | | | | |
| 1990 | | | 2.78 | 1.93 | | 1.16 |
| 1991 | | | 2.48 | 1.47 | | |
| Year | Feb | Mar | May | Jun | Jul | Aug |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1992 | | | | 2.62 | 1.73 | |
| 1993 | | | | | 1.34 | |
| 1994 | | | | | | |
| 1995 | | 2.10 | | | | |
| 1996 | | | | | | |
| 1997 | | 1.23 | | 1.76 | 0.82 | |
| 1998 | 2.26 | 1.11 | 2.50 | | 0.87 | |
| 1999 | 1.68 | | | | | 0.72 |
| 2000 | | | | | | |
| 2001 | | | | | 0.97 | |
| Median | 1.01 | 0.70 | 0.73 | 0.86 | 0.15 | 0.20 |

*Note*. From Western Regional Climate Center (2004b).