

## *Vanishing riverscapes: A review of historical channel change on the western Great Plains*

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### ABSTRACT

The South Platte and Republican River basins provide examples of historical channel changes on the western Great Plains. Flow regulation and diversion caused substantial channel narrowing and vegetation encroachment along larger, perennial rivers that head in the Rocky Mountains. Intensive groundwater pumping has reduced the volume and longitudinal connectivity of refuge pools along smaller intermittent or ephemeral channels that head on the plains. A case study from the Pawnee National Grassland of Colorado illustrates the dynamics of intermittent streams, as well as measures that can be taken to protect and restore refuge pools along these streams. The implications of channel change, and the need to protect and rehabilitate rivers, are less widely recognized for smaller rivers of the western Great Plains than for the larger, perennial rivers. Our objectives in this chapter are to provide a regional context for understanding changes in smaller plains rivers during the past century by reviewing the diversity of channel types and historical changes in the western Great Plains, and to briefly explore the dynamics of smaller plains rivers and the challenges to preserving these riverscapes.

### INTRODUCTION

Increasing recognition of human-induced alterations in river ecosystems led to a dramatic rise in attempts to rehabilitate rivers during the last decades of the twentieth century. Rehabilitation measures vary in method from intensive engineering of channel form to modification of dam operation or land uses adjacent to the river channel (Kondolf, 1996; Bernhardt et al., 2005; Wohl et al., 2005), and in scope from short segments of

a few hundred meters of a stream channel to major rivers such as the Kissimmee, Colorado, and Mississippi (Toth et al., 1993; Gloss et al., 2005; O'Donnell and Galat, 2008). Rehabilitation projects have begun on some of the larger rivers of the western Great Plains, including the Missouri and the Platte (Graf et al., 2005; Adams et al., 2007). Smaller rivers of the western Great Plains have received less attention in terms of rehabilitation than smaller rivers in other regions of the United States, despite the fact that the shortgrass prairie of the western Great

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Plains is one of the most endangered ecosystems in the country (Manning, 1995).

This chapter briefly reviews the types of rivers present in the western Great Plains and the historical land uses that have altered these rivers, focusing on parts of the South Platte and Republican Rivers. We then use a case study of ephemeral streams on the Pawnee National Grassland in northeastern Colorado to illustrate the challenges of understanding and rehabilitating the ecosystems of smaller river systems in the western Great Plains. Our intent is to call attention to the importance of smaller, ephemeral and intermittent channels on the western Great Plains. These channels, which are more likely to be overlooked by those concerned with river protection, are an integral part of the riverscape of the western Great Plains. Fausch et al. (2002) introduced the term *riverscape* to emphasize the importance of viewing a river not as disjunct reaches but as an entire spatially heterogeneous ecosystem. Recent research compilations emphasize the importance of perennial headwater channels in the flow of water, sediment, nutrients, and organisms through riverscapes (Nadeau and Rains, 2007), but in drylands ephemeral and intermittent headwater channels can be equally important.

## RIVERS OF THE WESTERN GREAT PLAINS

The western Great Plains here refers to the portion of the United States from the 100th meridian west to the base of the Rocky Mountains or, in the south, the Basin and Range Province (Osterkamp et al., 1987). (We include all of the historical prairie lands, from the tallgrass prairie of Illinois to the shortgrass prairie along the eastern edge of the Rockies, within the Great Plains [Covich et al., 1997; Savage, 2004].) Shortgrass prairie vegetation of bunchgrasses, shrubs, and cacti dominate the semiarid western Great Plains (Savage, 2004). Much of the flat or gently rolling terrain is covered by fluvial and eolian sediments of Quaternary age (Osterkamp et al., 1987; Madole, 1994, 1995). These sediments are underlain by Mesozoic and Cenozoic sedimentary rocks deposited in shallow-marine and terrestrial environments, with the Rockies as the primary source area (Madole, 1995).

Rivers of the western Great Plains are of three basic types. The larger rivers originate in the Rockies and flow eastward toward the Missouri-Mississippi system. These rivers are perennial or in some cases intermittent at greater distances from the mountains. Peak flows are supplied by snowmelt from the Rockies, supplemented at lower elevations by groundwater recharge and rainfall runoff. Rivers draining the Rocky Mountains discharge >70% of their annual water budget during 2 to 3 months of snowmelt and have instantaneous discharges 10 to 100 times the mean low flow (Hauer et al., 1997). The primary larger rivers of the western plains, from south to north, are the Canadian, Arkansas, South Platte, North Platte, Niobrara, Cheyenne, Little Missouri, Yellowstone, Missouri, and Milk. Of these rivers, only the Yellowstone remains relatively unaffected by flow regulation and land uses within or adjacent to the river corridor. The Cimarron, Smokey Hill, and Republican are

exceptions in that they are large rivers that head on the plains, rather than in the mountains.

Smaller rivers that head on the plains can be intermittent systems fed by groundwater seeps or springs, or ephemeral channels that depend entirely on surface runoff from the adjacent plains. Many of the smaller rivers, which are tributary to the larger, perennial rivers, or end in playas, have also been substantially altered by land use patterns including pumping of groundwater, irrigated agriculture, road development, and grazing (Fausch and Bestgen, 1997; Falke and Gido, 2006; Ficke, 2006).

This chapter focuses on channels in parts of the South Platte and Republican catchments in eastern Colorado. Changes in the hydrologic regime and channel characteristics of these two catchments reflect changes occurring in other river systems of the western plains (Nadler and Schumm, 1981; Fausch and Bestgen, 1997; Strange et al., 1999; Peters and Schainost, 2005).

Prior to ca. 1860 the larger streams of the western Great Plains were braided, with relatively straight, shallow channels 1–2 km wide and perennial or intermittent flow (Williams, 1978). Historic descriptions of the South Platte, the Platte, and the Arkansas emphasized the character of these rivers with descriptive phrases such as “too thick to drink but too thin to plow” and “a mile wide and an inch deep.” Photographs from the 1860s to early 1900s depict channels so wide that it is sometimes difficult to detect the opposite bank, and banks largely bare of woody vegetation (Williams, 1978). Flow was highly seasonal, but even the large snowmelt peaks apparently did not go overbank (Eschner et al., 1983). These seasonal peaks were sufficient to rapidly erode the banks, causing the channel instability characteristic of braided rivers, and limiting the establishment of woody riparian vegetation. Rivers of the western plains have more fluctuating conditions of flow, temperature, and nutrients, as well as relatively simple habitat, in comparison with the more diverse and stable headwater mountain streams or with streams of the wetter eastern Great Plains. These conditions limited the diversity of fish species in rivers of the western plains but also led to the evolution of several endemic species with sensory and reproductive adaptations to turbidity and widely fluctuating flow. These adaptations include barbels and tactile sense organs that reduce the fish’s dependence on vision; smaller, thicker scales resistant to abrasion; a metabolism tolerant of high temperatures and low levels of dissolved oxygen; and buoyant eggs that float downstream to suitable habitats, even as the embryos inside develop and hatch in as little as 24 h into precocious larvae capable of swimming soon after hatching (Matthews, 1987; Fausch and Bestgen, 1997).

Intermittent streams had longitudinally continuous flow each spring, but by summer flow was limited to disconnected pools maintained by groundwater. Ephemeral streams might be incised arroyos or shallow, swale-shaped channels, but were characterized by extremely flashy hydrographs when summer convective storms created peak flows that commonly lasted less than an hour. Fish living in these smaller streams developed strategies to compress their reproduction and growth into short periods of high flow that occurred unpredictably, maximize their mobility

between suitable habitats that remained physically isolated for much of the time as a result of lack of flow, and survive physiologically stressful periods of high temperature and low dissolved-oxygen levels (Matthews, 1987; Fausch and Bestgen, 1997).

Although many of the intermittent and ephemeral streams were integrated into drainage networks that fed larger, perennial streams, some ended in playas. Playas of the western plains were widely scattered and typically small; the great majority covered <12 ha (Batt, 1996). These small, shallow, ephemeral lakes nonetheless formed a vital part of the riverscapes of the western plains. An estimated 25,000 playas spread from eastern Colorado and western Nebraska south to western Texas and Oklahoma. Only 10% to 20% of the playas contained water in an average year, but they supported invertebrates and plants adapted to long periods of dryness, as well as more than a million ducks, geese, cranes, and shorebirds that stopped to feed and rest in playas during their spring and fall migrations (Batt, 1996; Nickens, 2006).

### CONSUMPTIVE WATER USE AND CHANNEL CHANGES

Changes in land and water use altered river characteristics across the western Great Plains as people of European descent began to settle the region ca. 1860. The first settlers quickly constructed small ditches to divert water from the larger rivers and irrigate crops growing on floodplains. By the 1870s, larger canals were being built to irrigate terraces, and reservoirs were constructed to store snowmelt runoff (Eschner et al., 1983).

The establishment of prior appropriation as the rule governing water usage in Colorado facilitated these changes. Prior appropriation—often paraphrased as “first in time, first in right”—guarantees that the earliest legal claimants to water rights maintain priority over any subsequent claimants. Prior appropriation also facilitates commercial transfer of water rights through purchase, and physical transfer through diversion. More than one example in the history of the western United States indicates that during years of greater than average flow it was possible to allocate more water to consumptive uses than normally exists in the river (Hundley, 1975; Stockton and Jacoby, 1976). The earliest record of overappropriation on the western Great Plains in Colorado comes from the Cache la Poudre River, a tributary of the South Platte, in 1876 (Eschner et al., 1983). Faced with potential water shortages, the rapidly growing agricultural communities at the eastern base of the Rockies began to divert water from the western slope.

Transbasin water diversions, particularly from the Colorado River, and groundwater pumping were used to supplement surface-water supplies on the plains starting in the 1890s and 1880s, respectively (Eschner et al., 1983). Transbasin diversions in the South Platte basin culminated with completion of the Colorado–Big Thompson Project in 1953, in which water is diverted across the Continental Divide from the Colorado River into the Big Thompson River, a tributary of the South Platte. Out-of-basin sources now account for nearly a quarter of the South Platte’s total flow (Strange et al., 1999).

The net effect of diversions and storage on flow regime along the larger rivers was a decrease in peak flows, an increase in base flows, and a transition to more perennial flow farther away from the mountain front. Water tables rose locally as a result of infiltration from irrigated fields and more consistent streamflow. These changes facilitated the establishment of dense riparian forests of cottonwood and willow trees (Johnson, 1994) that stabilized channel banks and led to substantial reductions in channel width. Documented changes in channel width include sites on the South Platte (535 m wide in 1867; 80 m wide in 1952), the Arkansas (350 m wide in 1892; 34 m wide in 1977) (Nadler and Schumm, 1981), the North Platte (1280 m wide in 1865; 150 m wide in 1965), and the Platte (1405 m wide in 1865; 90 m wide in 1965) (Williams, 1978). Most of the larger rivers on the western Great Plains now have single-thread channels or an anastomosing planform.

Changes in flow along the smaller, intermittent and ephemeral rivers are more likely to reflect changes in the water table associated with groundwater pumping and agricultural irrigation. Although flood irrigation of crop fields can raise the water table locally, the most common effect of irrigation has been declining water tables because pumping rates exceed recharge. Much of the western Great Plains is underlain by the Ogallala aquifer, a heterogeneous sequence of clays, silts, sands, and gravels that extends beneath 372,000 km<sup>2</sup> of the plains (Gutentag et al., 1984). Declines in the water table in the Ogallala have been particularly extensive in the middle and southern portions of the western Great Plains (Gutentag et al., 1984). The Ogallala has dropped more than 8 m, for example, across ~5200 km<sup>2</sup> of eastern Colorado. In comparison with the extensive literature of historic channel changes induced by flow regulation on the larger rivers, few studies have documented the effects of groundwater declines on flow in smaller rivers. One of the better known case studies is that of the Arikaree River, an eastern Colorado tributary of the Republican River.

Although the Arikaree River drains 4,480 km<sup>2</sup>, most streamflow is derived from the underlying Ogallala aquifer. Areas contributing groundwater to the stream lie mostly within 5–10 km of the channel. The Ogallala aquifer as a whole has been described as being more like an egg crate than a bathtub, which implies that groundwater recharge and pumping from local areas can strongly influence local streamflow. High-capacity groundwater pumping in the region of the Arikaree drainage began during the mid-1960s, and farmers in the surrounding county now pump almost 370,000,000 m<sup>3</sup> (300,000 acre-feet) of groundwater annually (Durnford et al., 2007). Mean annual discharge on the Arikaree declined dramatically starting in the mid-1960s (Durnford et al., 2007). The river historically had long, dry segments from mid-late summer to the following spring, but the existence of pools that retained water throughout the year provided critical habitat for fish such as the brassy minnow (*Hybognathus hankinsoni*), which was once widely distributed in northeastern Colorado but is now almost entirely restricted to 10 km of the Arikaree River (Scheurer et al., 2003). Groundwater modeling of 10 fish refuge pools indicates that pool depths reflect long-term trends

associated with groundwater pumping, with shorter term fluctuations caused by precipitation and riparian evapotranspiration (Durnford et al., 2007). Along perennial segments of the river, flow drops rapidly once the irrigation season starts, and does not resume until about three weeks after pumping ceases in the autumn (Fardal, 2003).

The highly restricted range of the brassy minnow reflects the situation for many native fishes of the western Great Plains (Propst and Carlson, 1986; Peters and Schainost, 2005). Six of 38 native plains fish species in Colorado are known to have been lost since the first fish collections were made in the late nineteenth century, and an additional 13 species are listed by the state as endangered, threatened, or of special concern; in other words, half of the native plains fish species have either declined or gone extinct in eastern Colorado (Fausch and Bestgen, 1997). These fish are incredibly resilient, able to withstand unusually low levels of dissolved oxygen and high water temperatures, and possess unique strategies for surviving and reproducing in this harsh environment. Many of the fish grow to a maximum total length of <10 cm, probably because of the small size of potential habitats in many plains streams. Their small size, however, means that structures such as irrigation intakes, dams, and road or railroad culverts that create vertical barriers only a few centimeters high effectively preclude fish passage, fragment habitat, and restrict the ranging and migration behavior of plains fish that evolved to migrate in search of spawning, foraging, and refuge habitats. Ficke (2006) documented more than a hundred such structures in one 1,375 km<sup>2</sup> tributary basin of the 59,930 km<sup>2</sup> South Platte River basin.

#### A CASE STUDY: STREAMS OF THE PAWNEE NATIONAL GRASSLAND

It is within this context of historically changing riverscapes and declining and threatened populations of native aquatic species that we present a preliminary examination of potential controls on refuge pools. We use the term *refuge pools* to refer to depressions along stream channels that retain water throughout the year. Research along the Arikaree suggests that these features are highly vulnerable to groundwater pumping, but the western Great Plains are also in the midst of a relatively severe drought that began in 1999 and is presumably also lowering water tables. As a means of evaluating the relative influence of local consumptive water use versus regional climatic controls on water levels in refuge pools, we examined pools along channels tributary to the South Platte River in the Pawnee National Grassland, which lies ~100 km north of the Arikaree River basin. Unlike the situation in the Arikaree River basin, there is no center-pivot irrigation in the Pawnee study area.

Our primary objective was to conduct a preliminary examination of potential regional- and local-scale controls on the location and dynamics of refuge pools on the Pawnee National Grassland. Dynamics refers primarily to fluctuations in water volume through time, and to a lesser extent, fluctuations in fish

populations. Regional-scale controls include interannual variations in precipitation and position of the pools with respect to a prominent bedrock escarpment known as the Chalk Bluffs. (Because these bluffs are the most prominent bedrock exposure and topographic high point at the Grassland, we reasoned that increasing downstream distance might correlate with increasing depth of alluvium and thus decreasing runoff and surface flow in this region of limited precipitation.) Local-scale controls include drainage area, topography, lithology, depth to bedrock, and surrounding land use. The examination is preliminary because we have no data on subsurface flow paths, which are likely to influence the location and volume of the refuge pools. A secondary objective was to compare the dynamics of refuge pools on the Pawnee National Grassland to those along the Arikaree River, where center-pivot irrigation and intensive pumping of groundwater have been shown to strongly influence flow from springs that supply the intermittent river. The absence of center-pivot irrigation at the Pawnee sites provides an opportunity to evaluate the relative influence on flow along intermittent streams of regional drought, which has affected both the Arikaree and Pawnee sites since 1999, and groundwater withdrawal. An improved understanding of controls on the location and dynamics of refuge pools at the Pawnee Grassland can be used to develop more effective programs for conserving native plains fishes.

#### Field Area

The Pawnee National Grassland represents conditions common across large parts of the western Great Plains in terms of geologic, climatic, and land-use history. Covering 79,876 ha, the Grassland lies in northeastern Colorado between the South Platte River and the Wyoming state line (Fig. 1). The elevation decreases from 1935 m in the northwest to 1310 m in the southeast.

The Grassland lies within the Colorado Piedmont where it borders the High Plains to the east (Trimble, 1993; Madole, 1995). The High Plains, differentiated as a portion of the western Great Plains with minimal fluvial incision (Osterkamp et al., 1987), were formed during the Late Cretaceous–early Tertiary Laramide uplift of the Rockies. Silts, sands, and gravels carried eastward from the mountains were deposited across an extensive fluvial surface, forming a vast ramp tilting down to the east. The Fox Hills Sandstone and the Laramie Formation preserve Cretaceous sedimentation (Scott, 1978). Three main Paleogene and Neogene sedimentation cycles are preserved in the Oligocene White River Group (including the Brule and Chadron Formations), the Miocene Arikaree Formation, and the Pliocene Ogallala Formation. These Cretaceous, Paleogene, and Neogene sediments have undergone minimal subsequent erosion except in places such as the Colorado Piedmont. Streams tributary to the South Platte River have eroded progressively headward into an escarpment known as the Chalk Bluffs, which parallels the Colorado-Wyoming border. In the process, these tributaries have captured eastward-flowing channels. The Chalk Bluffs are capped by Miocene sandstones and conglomerates that are more resistant

to erosion than the underlying White River Group. The White River Group includes fluvial and eolian sandstones, siltstones, and shales. Most of these sediments are soft, densely fractured, and readily erodible (Trimble, 1993). Deeply incised ephemeral channels and badland topography commonly form where rocks of the White River Group are exposed or close to the surface.

In general, groundwater slopes toward the south to southeast, following the drainage network of the South Platte River. The water table varies throughout the Grassland as a result of differences in permeability and thickness of the water-bearing material or as a result of additions (isolated recharge areas associated with summer thunderstorms) or withdrawals of water. Specific water-bearing formations in the Grassland are the Cretaceous Fox Hills Sandstone and the Laramie Formation, the Paleogene White River Group, and the Neogene Arikaree and Ogallala Formations. The Cretaceous strata consist of interbedded sandstone, siltstone, and claystone units deposited in shallow-marine to nonmarine environments. Both the Cretaceous Fox Hills Sandstone and Laramie Formation yield moderate supplies of water to wells in the area and are under sufficient hydrostatic pressure to cause artesian wells (Babcock and Bjorklund, 1956). The Paleogene White River Group consists of interbedded sandstone and mudstone units. Within the Brule Formation, impermeable siltstones with fractures and joints lead to potential irrigation groundwater sources (Babcock and Bjorklund,

1956). The Neogene Arikaree Formation consists exclusively of sandstones, whereas the overlying Ogallala Formation shows a complete suite of grain sizes from conglomerates through sand- and siltstones to shales. In both units, water-bearing beds are relatively thin and yield water for stock and domestic uses in the area (Babcock and Bjorklund, 1956).

Soils in the Pawnee National Grassland are diverse, but are predominantly well-drained, shallow to deep loams, clay loams, and sandy loams of depths  $\ll 1$  m (Crabb, 1981; NRCS, 2008). Fluvial and eolian processes, along with underlying lithology, create substantial spatial variations in soils despite the relatively subdued topography of the region. Patches of exposed gravel and cobbles and barren siltstone badlands alternate with sandy soils along stream terraces and finer-textured soils in swales. Playas and riparian areas commonly have alkaline soils.

The area of the Pawnee National Grassland has a highland continental climate. Westerly winds dominate throughout much of the year. Most of the moisture that these winds carry inland from the Pacific Ocean is lost as air masses cross the Rocky Mountains, creating a rain shadow that keeps the western Great Plains semiarid. Annual precipitation averages 30–38 cm across the region. Cold, polar air masses travel southward into the region during autumn and winter, creating extremely low temperatures of  $-29$  to  $-34$  °C; the average winter temperature is  $-2$  °C (Crabb, 1981). Warm, moist air traveling inland from the Gulf of Mexico reaches the area during spring and summer. The heaviest rainfalls occur during spring, when air masses from the Pacific, the Arctic, and the Gulf of Mexico collide over the western plains. Seventy to eighty percent of the annual precipitation falls between April and August (Badaracco, 1971). Although an average of 100 cm of snow falls in northeastern Colorado, desiccating winds create high rates of sublimation, and relatively little of the snow actually melts and infiltrates except on the leeward sides of hills and around shrubs (Hazlett, 1998). Summer temperatures on the Grassland can exceed 38 °C; the average summer temperature is 21 °C (Crabb, 1981; WRCC, 2008). Precipitation during summer falls from localized convective storms that create flash floods. Relative humidity is typically low throughout the year (Badaracco, 1971).

Severe weather in the form of tornadoes, hailstorms, blizzards, and droughts are a regular part of the climate of the western Great Plains. Droughts, in particular, strongly influence regional vegetation and stream characteristics. A 400 yr climatic record from tree rings in western Nebraska indicates an average period of only 20.6 yr between droughts that persist for 5 yr or more; on average, droughts persist for 12.8 yr (Weakly, 1943).

The Grassland lies within the central shortgrass prairie ecoregion (The Nature Conservancy, 1997), also known as the shortgrass steppe. All of the available soil moisture is transpired before the end of the growing season, and less than half of the ground surface is covered by vegetation (Hazlett, 1998). Dominant plant species include blue grama grass (*Bouteloua gracilis*), buffalo grass (*Buchloe dactyloides*), threeawn grass (*Aristida purpurea*), fringed sage (*Artemisia frigida*), rabbitbrush

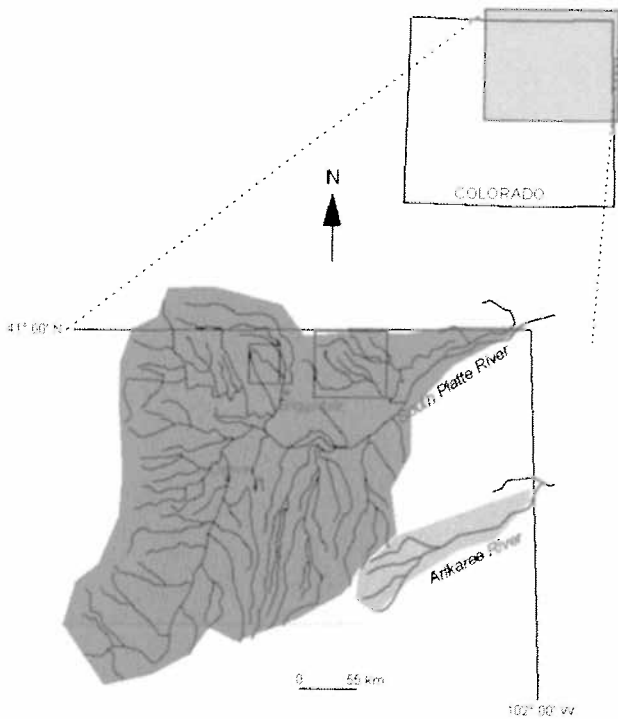


Figure 1. Location map of the South Platte basin (darker shading), Arikaree River basin (lighter shading), and the two main units of the Pawnee National Grassland (squares near Briggsdale), and Briggsdale. Inset shows location of the detailed map within the State of Colorado.

(*Chrysothamnus nauseosus*), snakeweed (*Gutierrezia sarothrae*), ring muhly (*Muhlenbergia torreyi*), prickly pear cactus (*Opuntia polyacantha*), western wheatgrass (*Pascopyron smithii*), scurf pea (*Psoralidium tenuiflorum*), and scarlet globemallow (*Sphaeralcea coccinea*) (Hazlett, 1998). Sand sage (*Artemisia filifolia*) and soapweed (*Yucca glauca*) are common on sandy soils, several species of aquatic plants are present in seasonal wetlands, and cottonwood trees (*Populus deltoides*) and sandbar willow (*Salix exigua*) occur along some riparian corridors (Hazlett, 1998).

The Pawnee National Grassland was established after the 1930s Dust Bowl in response to severe soil erosion from agricultural lands. An estimated 60% of the grassland in Weld County, which includes the Grassland, had been plowed by 1930 (Hazlett, 1998), mostly for dryland agriculture. At present, the area within the Grassland is a mosaic of lands owned by the federal government, the state government, and private individuals. Although some dryland cropping occurs, the most widespread land use is grazing of domestic cattle.

### Channels and Riparian Zones

Stream channels on the Pawnee National Grassland are intermittent or ephemeral. All of the channels drain south-southeast to the South Platte River. The degree of incision along individual

channels is highly longitudinally variable. Many channels begin downstream of broad, shallow, unchannelized grassy swales that have low (<1 m), arcuate scarps spaced irregularly downstream (Fig. 2). These characteristics, along with the presence of small pipes in channel cutbanks, suggest that subsurface piping strongly influences the surface expression of channels. The channelized portion of a network commonly shows indications of past incision, although the contemporary channel may now take the form of a grassy swale with a relatively broad, shallow, active channel (Fig. 3). Active headcuts and short (50–300 m) segments of deeply incised channel occur at irregular intervals downstream. Incised channel segments commonly begin at amphitheater-shaped headcuts and increase only slightly in width downstream, suggesting that piping exerts an important control on the location of headcuts and actively incising segments. Although little is known of the history of channel incision in the area, coring of junipers (*Juniperus scopulorum*) growing within stabilized incised channels suggests that incision occurred prior to 115–200 yr ago (Badaracco, 1971).

Ephemeral channels flow briefly, primarily during spring and summer in response to snowmelt and rainfall. Intermittent channels are supplied by groundwater recharge from shallow, perched aquifers. Most of the Grassland is underlain by the Ogallala Formation, and the Brule member of the White River Group also serves as an



Figure 2. Upstream view of a collapse feature along South Pawnee Creek on the Pawnee National Grassland. Photograph taken in October, when the channel is dry but for refuge pools (upstream edge of pool in lower right corner of photo). Notice the unchannelized swale upstream.

aquifer in some areas. Wells pumped by windmills and for residential use commonly tap into these units at depths  $>45$  m. Artesian springs that feed intermittent channels may be supplied by these deeper units, but may also be supplied by shallower, perched aquifers formed in Quaternary fluvial and eolian sediments where less porous and permeable bedrock rises to within a few meters of the surface along drainages. Many of these springs are identified and named on 1:24,000-scale topographic maps, suggesting that they are persistent features. Observations by residents and Forest Service employees indicate that some of these artesian springs commonly go dry during the later summer and autumn, whereas others typically persist throughout the year.

The only other form of surface water that persists throughout the year along the network of ephemeral channels occurs in depressions along the channels that appear to be piping-collapse features (Fig. 2). These depressions create pools that support resident populations of several native plains fishes, including plains topminnow (*Fundulus sciadicus*), plains killifish (*Fundulus zebrinus*), green sunfish (*Lepomis cyanellus*), fathead minnow (*Pimephales promelas*), Iowa darter (*Etheostoma exile*), northern creek chub (*Semotilus atromaculatus*), black bullhead (*Ameiurus melas*), and white sucker (*Catostomus commersoni*), as well as frogs, turtles, salamanders, and aquatic insects. Although the

depressions appear to be collapse features, scour and fill resulting from flash floods during summer thunderstorms probably also modify the depressions.

### Methods

Biologists with the Colorado Division of Wildlife and the U.S. Department of Agriculture Forest Service began monitoring the physical characteristics and organisms present in a series of refuge pools in the Pawnee National Grassland in 1988. Measurements have continued to the present but have been carried out by different individuals and have not consistently included the same parameters each year. Our first task therefore was to assemble the data collected from a variety of records kept at different agency offices. From these data we chose a subset of 13 refuge pools for which we could compile the most information (Fig. 4; Table 1). Because all of the stream channels containing refuge pools are ungauged, and the annual surveys were not referenced to benchmarks, we cannot evaluate the effects that scour and fill during brief, infrequent flash floods might have had on pool location or geometry.

Our analyses of pool locations were designed to evaluate whether average pool volume correlated with the physical



Figure 3. Downstream view of a now mostly stabilized incised channel network on the Pawnee National Grassland. Note the grassy bottom of the channel at the lower left of the photo and the presence of scattered juniper trees along the channel network; vegetation indicates contemporary stability of much of the incised valley bottom.



TABLE 1. CHARACTERISTICS OF REFUGE POOLS ON THE PAWNEE NATIONAL GRASSLAND, 1993-2007

Site	Drainage area (km <sup>2</sup> )	Elevation (m)	Relief (m)	Bedrock geology	Pool volume (m <sup>3</sup> )		Number of fish caught		Years of data collection
					Avg.	Std. dev.	Avg.	Std. dev.	
Coal Creek	106	1523	206	Laramie Fm	272	204	74	63	1993, 1999-2002
Geary Creek	201	1526	85	Laramie Fm	59	40	2	4	1993, 2001
Howard Creek	10	1532	70	Laramie Fm	353	185	295	321	1993, 1999-2007
Tributary to Little Crow Creek	2.8	1559	52	White River Group	228	185	148	144	1993, 1998-2001
Little Owl Creek	86	1556	304	Laramie Fm	132	0	66	66	1993, 1998-2001
Owl Creek	212	1578	346	Laramie Fm	540	283	245	230	1993, 1998-2005
South Pawnee Creek Box	290	1398	137	Pierre Shale	978	705	160	201	1998-2002
South Pawnee Fiscus	11	1404	131	Pierre Shale	184	117	88	147	1998-2006
South Pawnee Kibben	24	1438	97	Fox Hills Ss	421	273	255	312	1999-2007
South Pawnee Simmons	33	1406	129	White River	693	332	266	304	1998-2007
Two Mile Creek	3	1401	21	Alluvium	135	100	8	9	1998-2002
Wildhorse Creek	47	1517	140	Laramie Fm	301	256	18	16	1999-2002
Willow Creek	94	1550	228	Laramie Fm	743	546	193	176	1998-2007

Note: Cretaceous Laramie Formation is interbedded sandstone, siltstone and claystone units; Oligocene White River Group is interbedded sandstone and mudstone units; Cretaceous Pierre Shale is marine shale; Cretaceous Fox Hills Sandstone is shallow-marine sandstone; Pleistocene alluvium is coarse sand and gravel and lenses of silt, clay, cobbles, and boulders.

mechanism causing some of the refuge pools to go dry during certain years, it suggests that local controls may be exerting more influence on pool dynamics.

The multiple regression analyses did not produce a statistically significant model for the response variables of average pool volume and average number of fish caught in each pool. This indicates either that the sample size is too small to provide insight into the complexity of interacting controls on pool and fish characteristics or that the potential control variables analyzed in the test are not the best predictors of pool and fish characteristics.

The implication of these analyses is that the average volume and interannual variability in volume in refuge pools on the Pawnee National Grassland reflect local, site-specific controls rather than predictable criteria such as a minimum threshold of drainage area or relief. The numbers and diversity of fish present in a refuge pool partly reflect the size of that pool, as indicated by correlations between pool volume and average number of fish caught, and between standard deviation in pool volume and standard deviation in number of fish caught, respectively, that are significant at  $\alpha = 0.05$ . Fish abundance and diversity in a refuge pool also partly reflect the site-specific history of flow magnitude and duration, which control longitudinal connectivity between refuge pools and may influence pool geometry through scour and fill.

Summarizing the results of fish surveys on the western Great Plains of Colorado, Kehmeier and VanBuren (1990) noted that all fish species found in refuge pools were widely scattered and that the biggest limiting factor appeared to be the lack of water; even if fish could consistently reach a pool during higher flows of springtime, biologists interpreted the variability between annual samples to indicate that refuge pools go dry or undergo die-offs as a result of freezing or lack of dissolved oxygen. Observations at the Pawnee National Grassland sites of complete drying of some pools that had been present for several years and then were present again in subsequent years support this interpretation.

Concerned about the status of several endemic plains fish species, the Colorado Division of Wildlife has in the past actively stocked some of the refuge pools on the Pawnee National Grassland, only to have these pools subsequently go dry. The lack of correlation between pool location and dynamics and regional-scale controls suggests that the best strategy for maintaining endemic fish populations may be to concentrate on those pools that annual samples indicate have consistently large volume. Such pools can be targeted for protection by restricting consumptive water use or drilling for oil and gas in the vicinity, and by limiting construction of structures such as road culverts that could limit longitudinal connectivity in the drainage system during periods of high flow. Owl Creek, Willow Creek, and South Pawnee Creek, which have numerous large refuge pools that are only a few river kilometers apart, are particularly good candidates for this type of targeted protection.

The refuge pools at the Pawnee National Grassland sites also provide an interesting contrast to those along the Arikaree River. Measurements of pool dynamics throughout the spring, summer, and autumn indicate that seasonal groundwater

pumping along the Arikaree reduces local water tables and volume of refuge pools, with a very short lag time between the start and cessation of pumping and the response of pool volumes. Pools at the Pawnee Grassland are not subject to local water withdrawals and drawdowns but still exhibit tremendous interannual variability in volume and ability to support aquatic life. Although we were not able to statistically demonstrate the controls on this variability, further examination of subsurface parameters that influence the water table locally might improve the ability to predict which pools most reliably contain sufficient water to support fish populations.

### PROTECTING AND RESTORING RIVERSCAPES OF THE WESTERN PLAINS

The Great Plains as a whole is an exceptionally endangered ecosystem. An estimated 1% of grasslands with native plant communities remain across the spectrum of tallgrass prairie in the eastern plains, mixed-grass prairie in the central plains, and shortgrass prairie in the western plains (Manning, 1995). Alterations of plant

communities, soils, and topography have resulted primarily from agricultural land use, and to a lesser extent from transportation corridors and urbanization. Plains rivers of varying size have also been substantially altered during the past 150–200 yr. Channelization, flow regulation, levees, and increased sediment yields are the most important land-use changes to alter rivers in the eastern plains, whereas groundwater pumping and flow regulation have created the greatest effect on rivers of the western plains.

Several studies have documented the historical metamorphosis of channel form and function along larger rivers of the western Great Plains that originate in the Rocky Mountains (Williams, 1978; Nadler and Schumm, 1981; Eschner et al., 1983; Johnson, 1994), as well as the effects of this metamorphosis on native fishes, migratory birds, and other species of plants and animals (Propst and Carlson, 1986; Graf et al., 2005). Public awareness of the negative aspects of these historical changes has led to efforts to restore some of the form and function present along these rivers prior to 1850. These efforts range from national-scale studies and coordinated programs (e.g., Graf et al., 2005) to groups of local stakeholders who organize public information

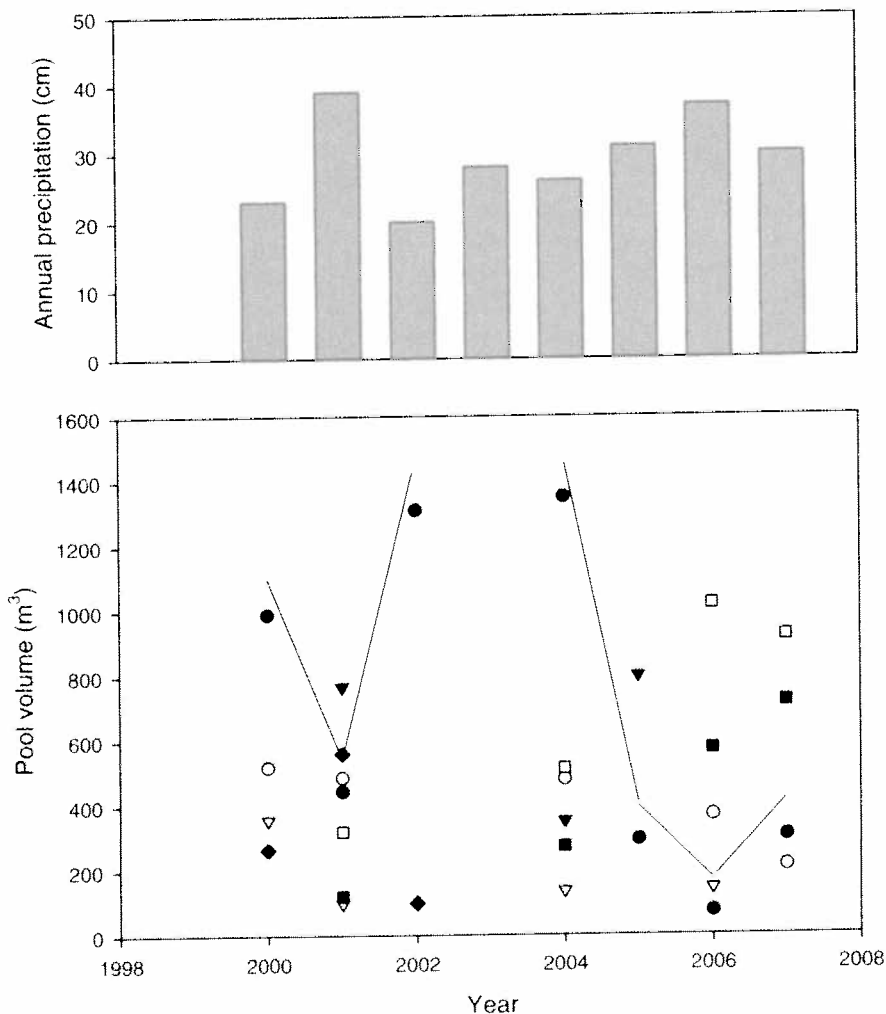


Figure 5. Plots of interannual variations in pool volume and annual precipitation at Briggsdale, Colorado, for 2000–2007. Each symbol in the lower plot represents a different pool. The symbols for the Willow Creek refuge pool are connected to illustrate more clearly interannual variability; the gap represents the absence of a sample in 2003.

fora and commission studies and restoration projects (e.g., Big Thompson Watershed Forum, Annual South Platte Forum).

Public awareness of analogous historical changes along smaller, intermittent and ephemeral rivers of the western plains is much lower, perhaps in part because of fewer and more recent scientific studies of these changes and their effects on biotic communities, and perhaps in part because many people do not think of ephemeral or intermittent channels as supporting riverine ecosystems. Loss of refuge pools and longitudinal connectivity along these smaller channels is likely to have the greatest impact on aquatic communities, although riparian grazing may create an equally significant impact on riparian communities. Loss of pools and longitudinal connectivity may reflect changes in the rainfall-runoff regime as a result of land use, but fluctuations in regional and local, perched water tables are likely to be the most important control at many sites, including the Arikaree River catchment and Pawnee National Grassland sites discussed in this paper. Understanding the relative importance of variables that influence fluctuations in water tables thus becomes critical for effectively managing populations of native plants and animals that are at risk because of loss of riparian and aquatic habitat along ephemeral and intermittent streams.

Research to date on smaller rivers of the western plains has been undertaken primarily by fish biologists who, as Labbe and Fausch (2000) note, "... typically assumed that abundance within habitats was primarily controlled by local environmental factors and that, once established, most populations would persist indefinitely" (p. 1774). Research by Fausch and others suggests that ecosystem-scale processes exert an important control by creating a context within which smaller-scale physical and biotic processes influence the distribution and abundance of plains fishes. Consequently, effective conservation of plains biodiversity requires a landscape-scale approach that considers the controls on movement of fishes between isolated habitat refugia.

Labbe and Fausch's (2000) study of the distribution of Arkansas darters (*Etheostoma cragini*) in two pools in small, headwater subwatersheds within the 8412-km<sup>2</sup> watershed of Big Sandy Creek in southeastern Colorado provides an example of how processes operating at different scales interact to influence fish populations. Darters persisted in the deeper pools that were most permanent during summer droughts, dying only when the pools dried out. Flow variation among seasons and years controlled habitat connectivity and thus dispersal, reproduction, and distribution and age composition of darters. Juvenile darters, for example, were more abundant and hatched earlier and grew faster in the warmer downstream pool that can freeze during winter and have harsh, variable thermal regimes during summer. Older fish dominated populations in the spring-fed pool upstream. Adult darters were more mobile, dispersing out of the upstream pool in early spring and returning upstream before the onset of summer drying. Large summer floods along the two channels scoured new spring-fed pools that provided darter refugia, and filled other pools, continually altering the distribution, abundance, and quality of habitat available to darters. Labbe and Fausch (2000) con-

sequently concluded that "To be effective, recovery efforts for species inhabiting variable environments must consider multiple scales, from landscape-level processes that create and maintain refugia to fine-scale factors that regulate the abundance and persistence of local populations" (p. 1774).

The case study summarized here examines the relative importance of regional- and local-scale controls on the dynamics of refuge pools at the Pawnee National Grassland. Unlike previously studied field areas on the plains of Colorado, scour and fill during flash floods (Labbe and Fausch, 2000) and intensive groundwater pumping (Durnford et al., 2007) do not appear to be the most significant influences on longitudinal connectivity and water-level fluctuations in refuge pools at the Pawnee sites. Instead, nonhuman, local-scale controls dominate connectivity and pool volume through their influence on local water tables. Our results imply that protecting and restoring riverscapes and ecological communities in the Pawnee drainages require identifying the most consistently suitable refuge pools and then limiting patterns of land use that could affect either water tables or longitudinal stream connectivity in these drainages. This is likely to be easier to implement than restoration strategies in catchments such as the Arikaree River, where the existence of irrigated agriculture implies that refuge pools can be most effectively protected if consumptive water use on adjacent lands is reduced or eliminated. The recognition that many endemic, endangered fish species of the western Great Plains depend on refuge pools, and that adjacent land uses can alter the ability of these pools to sustain fish populations, can guide efforts to manage scarce water resources in the region.

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