Part 645 – National Range and Pasture Handbook

Subpart G – Rangeland Ecohydrology

645.0701 Introduction

A. Rangeland hydrology is founded on basic biological and physical principles and is a specialized branch of science, which studies land use effects on infiltration, runoff, and sedimentation (hydrologic assessments) in natural and reconstructed rangeland ecosystems. Water is the main driving and limiting factor on rangelands. Hydrology is an important element of consideration and discussion with rangeland producers and landowners during planning and implementation of rangeland management practices. The term “Ecohydrology” is a relatively new term, which integrates ecology with hydrology and focuses on the water cycle as influenced by biotic and other environmental factors (Hannah et al. 2004). Ecohydrology considers the complex interactions between climate, soils, vegetation, disturbance, and management.

B. About 35 percent of the land area in the world is grasslands and woodlands, 21 percent sparse and barren lands, 28 percent forest and woodlands, and 12 percent cultivated, and the remainder settlement and infrastructure and inland water (Part 645, Subpart A). Estimates of rangeland throughout the world vary. Heitschmidt and Stuth (1991) estimated that rangelands occupy 47 percent of the world’s land area; Mannetje (2003) estimated 50 percent. About 26 percent of the global land surface is grazed and is the most prevalent land use throughout the world (FAO 2012). Managed grazing systems have increased more than 600 percent during the last three centuries, amounting to about 1.5 billion animal units (AU) in 1990 (Asner et al. 2004). In the United States, rangeland comprises about 50 percent of the land area (770 million acres (FAO 2011)). Privately owned rangeland comprises over half of the rangeland in the United States (~406–409 million acres) and pastureland (~119–121 million acres). These lands are over 27 percent (528 million acres) of the total combined acreage of the contiguous 48 states.

C. Rangeland comprises over two-thirds of the Nation's watershed area (FAO 1989) and provides a significant part of its water. The increasing importance of water has added a new dimension in range management strategies. In the southwestern and western United States, rangeland watersheds are the source of most surface water flow and aquifer recharge. Management on these lands can have a positive or negative effect on plant cover and compositional change, which ultimately influences water quality and quantity. Since the need for clean water is critical, and rangelands comprise a vast watershed area in the United States, policies and activities must be formulated and implemented to arrest resource degradation.

D. Watershed management on rangeland not only focuses on the protection and conservation of water resources, but also considers that vegetation resources are managed for many other goods and services [food and fiber production, wildlife habitat, mining, petroleum products, and recreation (Brooks et al. 1991)]. The most significant factor facing resource managers and conservation planners is that no uniform set of management guidelines fits all rangeland community types, pastures, or other units of grazing land. Plant communities and associated environmental factors are multivariate in nature, and interactions between plants, soils, environment, and management are complex and unique among rangeland community types (Gifford 1985). Resource managers are challenged with synthesizing an overwhelming amount of scientific information relative to ecology, soils, hydrology, plant science, and grazing management. ecological site descriptions (ESD) can provide a conceptual view of the rangeland landscape. Carefully crafted narratives, examples, and descriptions of hydrologic function and erosion dynamics are important aspects of managing lands (example in appendix G-A).

E. Conservation strategies on rangeland can be classified as preventive or restorative. Scientifically based strategies and sound management plans can prevent rangeland degradation and are more economically viable than restorative actions. Depending on the severity of resource and watershed degradation (which includes water, soil, plant, animal, air, and human resources), restoration to some desired ecological state may not be feasible from an ecological and/or economic perspective. The results of rangeland degradation can be serious and irreversible at the site and watershed scale. The principles and tools of assessing rangeland hydrology related to conservation planning and management on rangelands are articulated in this chapter. By developing a basic understanding of how hydrologic processes are affected by vegetation, soil properties, climatic events, management practices, and disturbances such as grazing and fire, one can integrate biophysical processes in discussions on rangeland conservation issues with land users and address key environmental and management questions. For example:

(1) How can a rangeland producer maximize available water for plant growth (i.e., increase the effectiveness of precipitation, reduce runoff, and limit evaporative soil surface moisture)?
(2) In discussions on grazing systems (e.g., continuous, rotational, mob) what are the effects of grazing intensity and timing of grazing on site hydrologic processes and erosion?
(3) What are the effects of plant compositional change on hydrology and erosion?
(4) How do invasive shrubs and trees such as mesquite and juniper affect hydrology and erosion?
(5) Fire is an integral and natural disturbance factor in many rangeland plant communities. What are the risks and vulnerabilities from burning, due to generation of excessive runoff and accelerated erosion?
(6) What tools are available to access hydrology and erosion on rangeland?
(7) What role can the Rangeland Hydrology and Erosion Model (RHEM) have in conservation planning and assessment?

F. Common problems and issues regarding rangeland watersheds can be categorized as ecological, management oriented, water quality and quantity, erosion, and economic. Table G-1 summarizes the most common problems and issues on rangeland and pastureland watersheds.

Table G-1. Common related problems and issues regarding hydrology on rangeland watersheds (Spaeth 2020).

Category	Situation
Ecological	Understanding interrelationships: plant/soil complexes, ecology, environmental, and hydrology
	Climatic shifts, vegetation response, and the hydrologic cycle
Management oriented	Trampling impacts and effect of grazing treatments on watersheds
	Range improvement practices and their effect on hydrology
	Riparian management and hydrologic implications
Water quantity, quality, and erosion	Enhancement of surface water, ground water, and aquifer recharge in response to vegetation manipulation
	Deficient and unpredictable availability of water supplies
	Flooding
	Polluted surface water and reduced aquatic, fish, and wildlife habitat
	Erosion and sedimentation
	Sludge and animal waste applications
Economic	Economics of watershed restoration

645.0702 Hydrologic Definitions

A. Hydrology

(1) Hydrology is the science dealing with the occurrence of water on the earth and its physical and chemical properties, transformation, combinations, and movements, especially with the course of water movement from the time of precipitation on land and movement to the sea or atmosphere.

(2) Ecohydrology is "the study of the functional interrelationships between hydrology and biota at the catchment scale, is a new approach to achieving sustainable management of water." (Zalewski 2000).

(3) Ecohydrology is the sub-discipline shared by ecological and hydrological sciences that is concerned with the effects of hydrological processes on the distribution, structure, and function of ecosystems, and on the effects of biotic processes on elements of the water cycle (Nuttle 2002).

B. Rangeland Hydrology

Rangeland hydrology is founded on basic biological and physical principles and is a specialized branch of science, which studies land use effects on infiltration, runoff, sedimentation, and nutrient cycling (hydrologic assessments) in natural and reconstructed ecosystems.

C. Watershed Management

Watershed management is the management of land for optimum production of high-quality water, regulation of water yields, and for maximum soil stability, along with other goods and services from the land.

645.0703 Hydrologic Cycle

A. The hydrologic cycle is a continuous process by which water is transported from the oceans to the atmosphere, to the land, through the environment, and back to the sea (figure G-1). Many sub-cycles exist such as the evaporation of inland water, evaporation of water from the soil, sublimation of snow from plants or soil, transpiration of water from plants, and the eventual return of this water to the atmosphere. The sun provides the energy required for evaporation, which drives the global water transport system.

B. Hydrologic Budget

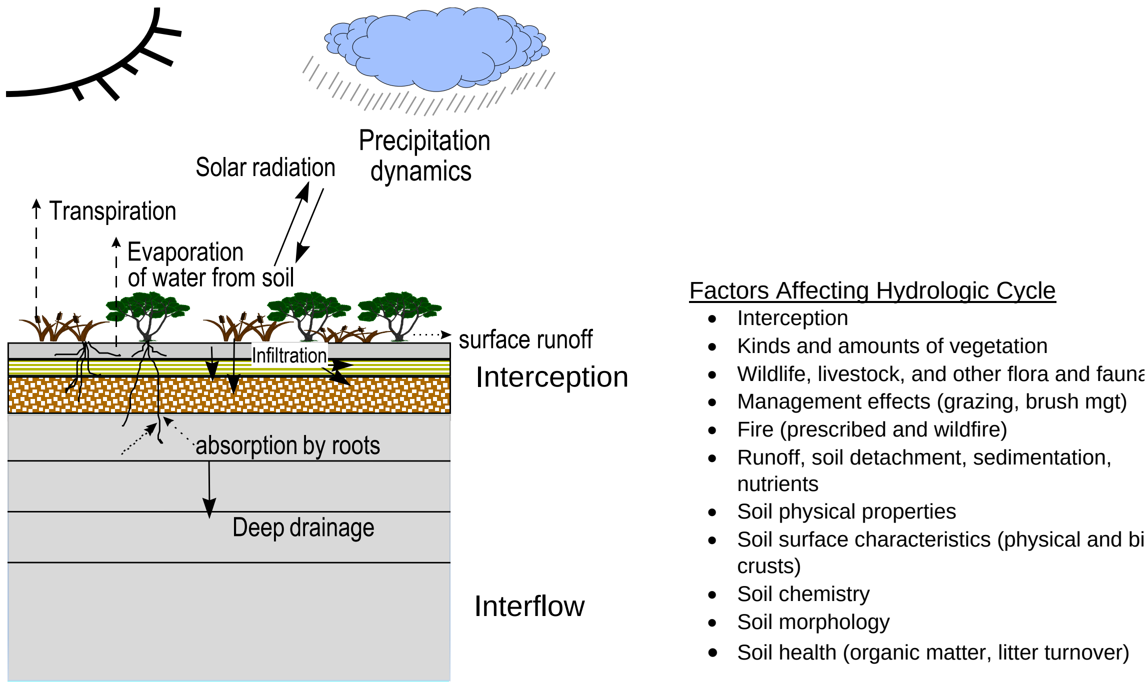
(1) The hydrologic budget can be expressed as:

$$P - R + Rg - G - E - T - I = S$$

where:

P = total precipitation
R = surface runoff
Rg = ground water flow that is effluent to a surface stream
G = ground water flow
E = evaporation
T = transpiration
I = interception
S = storage

Figure G-1. The hydrologic cycle with factors that affect hydrologic processes.



(2) There are many interacting factors related to soils, plants, environmental conditions, and management that affect the hydrologic cycle in rangeland watersheds. A comprehensive list appears in Table G-2.

645.0704 Hydrologic Cycle Components

A. Precipitation

(1) Precipitation is the primary input of the hydrologic cycle. The three major categories of precipitation are convective, orographic, and cyclonic:

(i) Convective precipitation occurs in the form of light showers and heavy cloudbursts or thunderstorms of extremely high intensity. Often, precipitation intensity varies throughout the storm. Most convective storms are random and last less than one hour and usually contribute little to overall moisture storage in the soil.

(ii) Orographic precipitation results when moist air is lifted over mountains or other natural barriers. Important factors in the orographic process include elevation, slope, aspect or orientation of slope, and distance from the moisture source.

(iii) Cyclonic precipitation may be classified as frontal and non-frontal and is related to the movement of air masses from high pressure to low pressure regions.

(2) Water originating from other sources may have an effect on a site. Shallow ground water or baseflow reserves may be utilized by deep-rooted shrubs and trees on the uplands and phreatophytes (riparian vegetation) along rivers and lakes.

Table G-2. Interacting factors that affect the hydrologic cycle in rangeland watersheds (Spaeth 2020).

Soils	Plants	Environmental	Management
Soil morphology	Types of plants	Climate	Grazing intensity
Soil texture (particle size)	Rooting morphology	Types of storms	Timing of grazing
Bulk density	Plant growth form bunch, sod)	Precipitation type	Continuous vs. rotational systems
Compaction	Plant life form (grass, shrub, forb, tree)	Duration of storm	Pitting
Organic matter	Plant biomass, cover, density	Intensity of storm	Chiseling
Aggregate stability	Biological soil crust (mosses, lichens, algae)	Topography	Herbicides
Nutrient levels	Plant canopy layers	Geology	Seeding
Soil structure	Plant architecture	Aspect	Brush management
Infiltration rates	Successional dynamics (State-and-transition model dynamics)	Slope	Wildfire
Percolation rates	Native vs. introduced plants	Microtopography (soil roughness)	Prescribed burning
Saturated hydraulic conductivity	Plant competition		Past management history
Runoff characteristics	Physiological characteristics of plant species		Fencing
Rills and gullies	Physiological response to grazing		Hoof impact
Porosity	Biodiversity		Class of livestock
Erosion dynamics	Phenological stages		Disturbance
Salinity			Stockwater location
Alkalinity			Water Harvesting
Biotic components			Past disturbance from farm implements
Parent material			Recreation
Pedogenic processes			Kinds and types of wildlife
Soil chemistry			
Soil health attributes			

B. Raindrop Dynamics

(1) Raindrop sizes vary with storm intensity, which affects soil surface stability and infiltrability. Average drop sizes for various storm intensities range from 1.25 mm in diameter at 1.27 mm hr^{-1} (0.05 in hr^{-1}), 1.80 mm diameter at 12.7 mm hr^{-1} (0.5 in hr^{-1}), and 2.80 mm diameter at 101.6 mm hr^{-1} (4.0 in hr^{-1}).

(2) Falling raindrops at terminal velocity are hemispheric or oblate in shape. Raindrop velocity (2.5 mm diameter) is about 2 m sec^{-1}, but terminal velocities can vary with storm intensity and raindrop size (table G-3).
Recent studies indicate that raindrops can reach speeds faster than terminal velocity (Montero-Martinez et al. 2009, Thurai et al. 2013, Larsen et al. 2014). Hypotheses related to “super terminal drops” moving 30 percent faster than normal drop velocity suggest that larger faster moving raindrops break up and generate fragments from “parent raindrops” (Spaeth 2020). Kinetic energy associated with large rainstorms can splash more than 220 tons of soil per acre into the air, and bare and loose soil particles can be splashed more than 1.64 ft. in height and 4.9 ft. horizontally (Ffolliott et al. 2013).

Table G-3. Raindrop size and terminal velocity (Gunn and Kinzer 1949, Byers 1959, Rogers 1979, and Pruppacher 1981, Spaeth 2020).

Storm Type		Raindrop size (mm)	Raindrop Terminal Velocity ($m\ sec^{-1}$)	Raindrop Terminal Velocity ($ft\ sec^{-1}$)
Light Storm Intensity	Small droplets	0.5	2.1	6.9
	Large droplets	2.5	6.5	21.3
Moderate Storm Intensity	Small droplets	1.0	4.0	13.1
	Large droplets	2.6	7.6	24.9
Heavy Storm Intensity	Small droplets	1.2	4.6	15.1
	Large droplets	4.0	8.8	28.9
	Maximum droplet	5.0	9.1	29.9
	Hailstone	10.0	10.0	32.8

C. Design Storm Frequencies

(1) Hydrologists and climatologists categorize storm events as “design storm events” to estimate risks of failure when addressing infrastructure (physical structures) and above-average soil erosion. The design storm event is used for estimating runoff volumes and durations and range from recurrence intervals of 2, 5, 10, 25, 50, 75, to 100 years. A 10-year design storm event is the storm intensity and amount that would occur at least once in 10 years or 10 times in a hundred years. Several storms of equal intensity may occur during the 10-year period or during a single year.

(2) The National Oceanic and Atmospheric Administration (NOAA) publishes precipitation and storm frequency data (NOAA Atlas 14 Point Precipitation Frequency Estimates). NOAA data tables show average recurrence of storm (1 to 1,000 years) and storm duration (5 minutes to 60-day intervals). Using Oklahoma City, Oklahoma as an example, a 5-year design storm could generate 2.13 inches in 60 minutes and 4.59 inches in 24 hours (table G-4).

(3) As the design storm increases, so does precipitation and runoff. A 50-year storm can be expected to yield 7.89 inches in 24 hours, 1.7 times the precipitation from a 5-year storm. Design storm information is useful in evaluating runoff and erosion risks on rangeland. The Rangeland Hydrology and Erosion Model (RHEM) (Nearing et al. 2011 and Hernandez et al. 2017) uses the Climate Generator (CLIGEN) (Nicks et al. 1995) stochastic weather generator to estimate precipitation intensity, duration, and frequency. The user locates the nearest weather station location, and the CLIGEN model provides 300 years of daily stochastically derived precipitation records that represent historical records. CLIGEN is used by RHEM to estimate average runoff and annual soil loss during a 300-year time span. The RHEM model also estimates 2, 5, 10, 50, and 100-year return runoff events to provide an assessment of heavy storm event impacts on a site. The impacts of design storms (2, 5, 10, 25, 50, 75, and 100 years) on rangeland are more critical for evaluating site vulnerability from raindrop splash and sheet flow soil-erosion processes than long-term.

D. Interception

(1) Vegetation intercepts raindrops, dissipating their kinetic energy. Interception is variable and is affected by plant height, leaf area, plant canopy cover, plant architecture, rainfall frequency, rainfall duration, amount of precipitation, type of precipitation, and time of precipitation (figure G-2).

(2) During small storms, water intercepted and evaporated without reaching the soil surface may be substantial, especially in shrub, tall grass, mixed grass, and bunchgrass communities. Rainfall interception loss during heavy storms is often a small proportion of the storm’s total volume (<10 percent) (Corbett and Crouse 1968).

Table G-4. National Oceanic and Atmospheric Administration Atlas 14 precipitation frequency estimates for Oklahoma City, Oklahoma. Average recurrence interval (years).

NOAA Atlas 14 Point Precipitation Frequency Estimates Location Information:
Name: Oklahoma City, OK, US, **Latitude:** 35.4909°, **Longitude:** -97.5101°, **Elevation:** 1209 ft.
PDS-based precipitation frequency estimates with 90% confidence intervals (in inches)[1]

	Average Recurrence Interval (years)									
Duration	**1**	**2**	**5**	**10**	**25**	**50**	**100**	**200**	**500**	**1000**
5-min	**0.422** (0.331–0.544)	**0.493** (0.386–0.635)	**0.612** (0.478–0.791)	**0.714** (0.554–0.926)	**0.860** (0.647–1.15)	**0.977** (0.717–1.32)	**1.10** (0.778–1.51)	**1.22** (0.831–1.72)	**1.40** (0.912–2.00)	**1.53** (0.972–2.22)
10-min	**0.618** (0.485–0.797)	**0.722** (0.565–0.930)	**0.896** (0.699–1.16)	**1.05** (0.812–1.36)	**1.26** (0.947–1.68)	**1.43** (1.05–1.93)	**1.61** (1.14–2.21)	**1.79** (1.22–2.51)	**2.05** (1.34–2.93)	**2.24** (1.42–3.25)
15-min	**0.754** (0.591–0.972)	**0.880** (0.689–1.14)	**1.09** (0.853–1.41)	**1.28** (0.990–1.65)	**1.54** (1.16–2.05)	**1.75** (1.28–2.35)	**1.96** (1.39–2.69)	**2.19** (1.48–3.07)	**2.49** (1.63–3.57)	**2.74** (1.74–3.96)
30-min	**1.10** (0.863–1.42)	**1.29** (1.01–1.66)	**1.61** (1.25–2.08)	**1.88** (1.46–2.44)	**2.27** (1.71–3.03)	**2.58** (1.89–3.48)	**2.90** (2.06–3.99)	**3.24** (2.20–4.54)	**3.70** (2.41–5.30)	**4.06** (2.58–5.87)
60-min	**1.45** (1.14–1.87)	**1.70** (1.33–2.19)	**2.13** (1.66–2.76)	**2.51** (1.95–3.25)	**3.06** (2.30–4.10)	**3.50** (2.57–4.73)	**3.97** (2.81–5.46)	**4.46** (3.03–6.27)	**5.14** (3.36–7.38)	**5.68** (3.60–8.22)
2-hr	**1.80** (1.42–2.29)	**2.11** (1.67–2.69)	**2.66** (2.10–3.40)	**3.14** (2.46–4.03)	**3.85** (2.93–5.11)	**4.42** (3.29–5.93)	**5.03** (3.61–6.88)	**5.68** (3.90–7.93)	**6.58** (4.35–9.39)	**7.30** (4.68–10.5)
3-hr	**2.01** (1.60–2.55)	**2.36** (1.88–2.99)	**2.97** (2.36–3.77)	**3.52** (2.78–4.49)	**4.34** (3.34–5.75)	**5.02** (3.76–6.71)	**5.75** (4.15–7.83)	**6.52** (4.51–9.08)	**7.62** (5.06–10.8)	**8.49** (5.48–12.2)
6-hr	**2.40** (1.93–3.00)	**2.79** (2.25–3.50)	**3.50** (2.81–4.40)	**4.16** (3.32–5.25)	**5.16** (4.02–6.80)	**6.01** (4.56–7.98)	**6.93** (5.07–9.39)	**7.93** (5.55–11.0)	**9.36** (6.29–13.2)	**10.5** (6.85–15.0)
12-hr	**2.82** (2.30–3.49)	**3.24** (2.64–4.02)	**4.03** (3.27–5.00)	**4.77** (3.85–5.95)	**5.93** (4.69–7.77)	**6.93** (5.32–9.14)	**8.03** (5.94–10.8)	**9.23** (6.54–12.7)	**11.0** (7.46–15.4)	**12.4** (8.16–17.5)
24-hr	**3.24** (2.67–3.97)	**3.71** (3.05–4.55)	**4.59** (3.77–5.64)	**5.43** (4.43–6.70)	**6.75** (5.39–8.75)	**7.89** (6.13–10.3)	**9.15** (6.84–12.2)	**10.5** (7.55–14.4)	**12.5** (8.62–17.5)	**14.2** (9.44–19.9)
2-day	**3.68** (3.07–4.45)	**4.23** (3.52–5.12)	**5.24** (4.34–6.36)	**6.19** (5.11–7.55)	**7.68** (6.20–9.84)	**8.96** (7.02–11.6)	**10.4** (7.82–13.7)	**11.9** (8.60–16.1)	**14.1** (9.79–19.5)	**15.9** (10.7–22.2)
3-day	**4.00** (3.36–4.81)	**4.59** (3.84–5.52)	**5.67** (4.73–6.83)	**6.68** (5.54–8.09)	**8.24** (6.68–10.5)	**9.57** (7.55–12.3)	**11.0** (8.38–14.5)	**12.6** (9.18–17.0)	**14.9** (10.4–20.5)	**16.8** (11.3–23.2)
4-day	**4.27** (3.60–5.11)	**4.90** (4.12–5.86)	**6.03** (5.06–7.24)	**7.08** (5.90–8.53)	**8.69** (7.07–11.0)	**10.0** (7.95–12.8)	**11.5** (8.80–15.0)	**13.1** (9.60–17.6)	**15.4** (10.8–21.2)	**17.3** (11.8–23.9)
7-day	**4.96** (4.22–5.88)	**5.69** (4.83–6.75)	**6.97** (5.90–8.28)	**8.11** (6.82–9.68)	**9.81** (8.02–12.2)	**11.2** (8.93–14.1)	**12.7** (9.76–16.4)	**14.3** (10.5–18.9)	**16.5** (11.7–22.5)	**18.3** (12.6–25.2)
10-day	**5.57** (4.77–6.56)	**6.37** (5.44–7.51)	**7.74** (6.59–9.15)	**8.94** (7.57–10.6)	**10.7** (8.77–13.2)	**12.1** (9.68–15.1)	**13.6** (10.5–17.4)	**15.1** (11.2–19.9)	**17.3** (12.3–23.4)	**19.0** (13.1–26.1)
20-day	**7.31** (6.32–8.50)	**8.23** (7.12–9.59)	**9.78** (8.42–11.4)	**11.1** (9.49–13.0)	**12.9** (10.7–15.7)	**14.4** (11.6–17.7)	**15.8** (12.3–20.0)	**17.4** (12.9–22.5)	**19.4** (13.9–26.0)	**21.0** (14.6–28.5)
30-day	**8.70** (7.58–10.1)	**9.76** (8.49–11.3)	**11.5** (9.96–13.3)	**12.9** (11.1–15.0)	**14.9** (12.4–17.9)	**16.4** (13.3–20.0)	**18.0** (14.1–22.5)	**19.5** (14.6–25.2)	**21.6** (15.5–28.7)	**23.1** (16.2–31.3)
45-day	**10.4** (9.14–11.9)	**11.7** (10.2–13.4)	**13.7** (12.0–15.8)	**15.4** (13.4–17.8)	**17.7** (14.8–21.0)	**19.4** (15.8–23.5)	**21.1** (16.6–26.2)	**22.8** (17.2–29.2)	**24.9** (18.1–33.0)	**26.6** (18.7–35.8)
60-day	**11.8** (10.4–13.5)	**13.3** (11.7–15.2)	**15.7** (13.8–18.0)	**17.7** (15.4–20.3)	**20.2** (17.0–24.0)	**22.2** (18.2–26.7)	**24.1** (19.0–29.8)	**25.9** (19.6–33.0)	**28.3** (20.5–37.2)	**30.0** (21.3–40.3)

(3) The form of precipitation (rain versus snow) has a significant influence on interception, with snow having higher rates of interception. As precipitation falls, it may be intercepted by vegetation (trees, shrubs, forbs and/or grasses) and stored in the canopy until it evaporates. It may slowly drip off vegetation as droplets, intercepted by secondary branches and leaves, and later falling from the canopy of shrubs and trees can form an erosive drip line under the plant. It may land directly on bare soil as splash erosion, or it may collect in the plant canopy and may run down plant stems. This water is redistributed in a concentrated way and can either infiltrate depending on the volume of water and soil surface conditions, or it can run off. It may also be intercepted by soil surface mulch or litter. In a watershed, interception must be considered as a factor in the total water balance and budget (loss of water). Interception of precipitation by vegetation and surface plant litter also plays an important role in protecting mineral soil from sheet and splash erosion. Table G-5 shows canopy interception, interill erosion, surface runoff, and infiltration for four vegetative conditions. Table G-6 shows average annual interception rates for forest, woodland, and grassland vegetation types.

Figure G-2. Interception rates for various rangeland species and plant growth forms. POPR–*Poa pratensis*–Kentucky bluegrass; PSSP6–*Pseudoroegneria spicata*–bluebunch wheatgrass; KOCR–*Koeleria cristata*–prairie junegrass; ARTR–*Artemisia tridentata*–big sagebrush, QUVI–*Quercus virginiana*–live oak (Spaeth 2020).

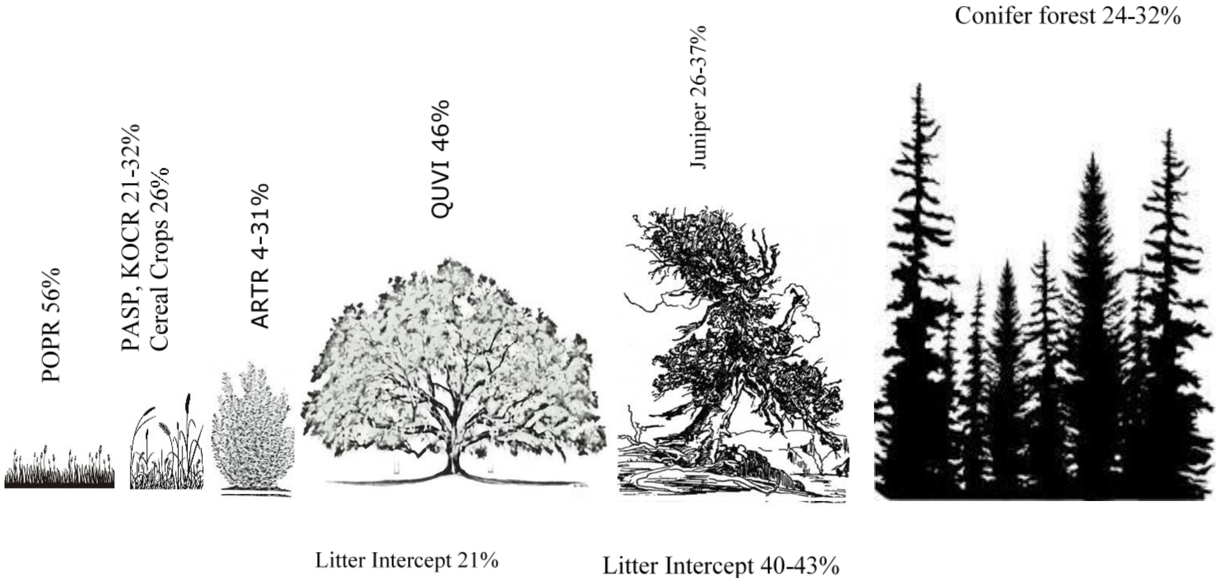


Table G-5. Canopy interception, interill erosion, surface runoff, and infiltration from oak mottes, bunchgrass, sodgrass, and bare ground-dominated areas. From rainfall simulation based on 10 cm rainfall rate over 30 minutes rainfall event (Blackburn et al. 1986).

Hydrologic Component	Oak Motte	Bunchgrass	Sodgrass	Bare Ground
Canopy Interception (%)	7.0	-	-	-
Grass and Litter Interception (%)	-	0.5	0.4	0.0
Litter Interception (%)	12.0	-	-	-
Interill Erosion (kg/ha)	0.0	200.0	1,400.0	6,000.0
Surface Runoff (%)	0.0	24.0	45.0	75.0
Infiltration (%)	81.0	75.5	54.6	25.0

(4) On an annual basis, tree interception is greater than grass interception. However, at maximum growth, some grasses have as much leaf area per unit area of ground as some trees (Dunne and Leopold 1978). Alfalfa can intercept as much rainfall during the growing season as a forest (Dunne and Leopold 1978). Water storage of grasses is proportional to the product of average height and ground cover (Crouse et al. 1966).

(5) Canopy interception can substantially decrease the amount of water reaching the ground in forest and prairie ecosystems (Clark 1940, Parker 1983, Gilliam et al. 1987), which ultimately evaporates and reduces available water. Studies of interception rates between trees, shrubs, and grasses on Texas rangeland show that live oak (*Quercus belangeri*), ashe juniper (*Juniperus ashei*), and honey mesquite (*Prosopis glandulosa*) canopies intercepted about 2.4 and 1.4 times more rainfall than curly mesquite (*Hilaria belangeri*), a shortgrass species, and sideoats grama (*Bouteloua curtipendula*), a midgrass species, respectively (Blackburn et al. 1986, Thurow et al. 1987). Shifts in the kind and amount of vegetation on the Edwards Plateau in Texas have the potential for greatly influencing the hydrologic water balance, and to a large extent, determining the amount of rainfall retained, lost, or yielded from a watershed (Blackburn et al. 1986).

E. Surface Detention/Storage

Excess surface water tends to accumulate in depressions, forming puddles. See figure G-3. The total volume per unit area is the surface storage capacity. Surface water storage or detention is a function of soil surface microtopography, slope, and soil physical properties such as texture, bulk density, porosity, and soil structure. Soil surface microtopography is affected by vegetation structure and life-form characteristics, and surface litter. As slope increases, initial runoff usually occurs sooner and at an increased rate because of a decrease in the size of detention storage sites. Water ponded on the soil surface is lost through evaporation or infiltrates into the soil.

Table G-6. Average annual rainfall interception rates for forest, woodland, and grassland vegetation types.

Vegetation	interception (%)	Interception by litter layer after passing through canopy (%)
Alfalfa field (Clark 1940)	7–36	
Ashe Juniper (Thurow and Hester 1997)	36.7	43
Aspen forest (Dunford and Niederhof 1944)	16	
Big sagebrush (Hull and Klomp 1974, West and Gifford 1976)	4–31	
Bluestem prairie (Clark 1940)	57–84	
Brazilian tropical rain forest (Lloyd et al. 1988, Dykes 1997)	8.9–18	
Buffalo grass (Clark 1940)	17–74	
California annual grassland (Kittredge 1948, Tate 1995)	26	
Chaparral (Rowe and Colman 1951, Tate 1995)	8–11	
Conifer forest (Tate 1995)	30	
Conifer litter (Tate 1995)	5	
Curly mesquite (sod–type shortgrass) (Thurow et al. 1987)	10.8	
Hardwood forest (Beall 1934)	21	
Kentucky bluegrass (Haynes 1940)	56	
Live oak (Texas) (Thurow et al. 1987)	46.1	20.7
Lodgepole pine (Miner and Trappe 1957)	24	
Mixed prairie (Couturier and Ripley 1973)	14–24	
Pinyon–Juniper (Eddleman and Miller 1991, Niemeyer et al. 2016, Stringham et al. 2018)	44–79	
Ponderosa pine (Connoughton 1936)	32	
Redberry Juniper (Thurow and Hester 1997)	25.9	40.1
Shadscale saltbush (West and Gifford 1976)	4	
Sideoats grama (bunch–type midgrass) (Thurow et al. 1987)	18.1	
Utah Juniper (Skau 1964)	17	
Western Juniper (Young et al. 1984)	2–27	
Wheat field (Leuning et al. 1994)	33	
Wheatgrass and Junegrass prairie (Couturier and Ripley 1973)	21–32	

F. Infiltration

Infiltration (figure G-4) is the process by which water enters the soil surface and is affected by the combined forces of capillarity and gravity (Hillel 1982, Brooks et al. 1991). Soil physical and chemical properties, vegetation characteristics, and soil fauna and flora interact and affect the process of infiltration. Under dry soil conditions, a higher initial infiltration rate is caused by the physical attraction of soil particles to water, which is called the matric potential gradient or matric suction gradient. Infiltration of water into the soil starts to decrease over time until a relatively constant rate is achieved (a curvilinear relationship). The cause of decreased infiltration over time is caused by one or more of the following factors: gradual decreases in the matric suction gradient; deterioration of soil structure, the breakdown of soil aggregate stability, and consequential partial sealing of the profile by detachment and migration of pore-blocking particles; and the presence of a restricting layer in the soil profile. As a precipitation event progresses and the soil surface becomes saturated, infiltration rate stabilizes according to a combination of soil and vegetation characteristics.

Figure G-3. Small detention ponds on the soil surface as a result of livestock hoof action near Price, Utah on a silty soil.

(i) Infiltration Dynamics

Main broad factors include soil surface conditions, subsurface conditions, flow influences, physical and biological factors, and hydrophobicity (adapted from Elliot and Ward 1995).

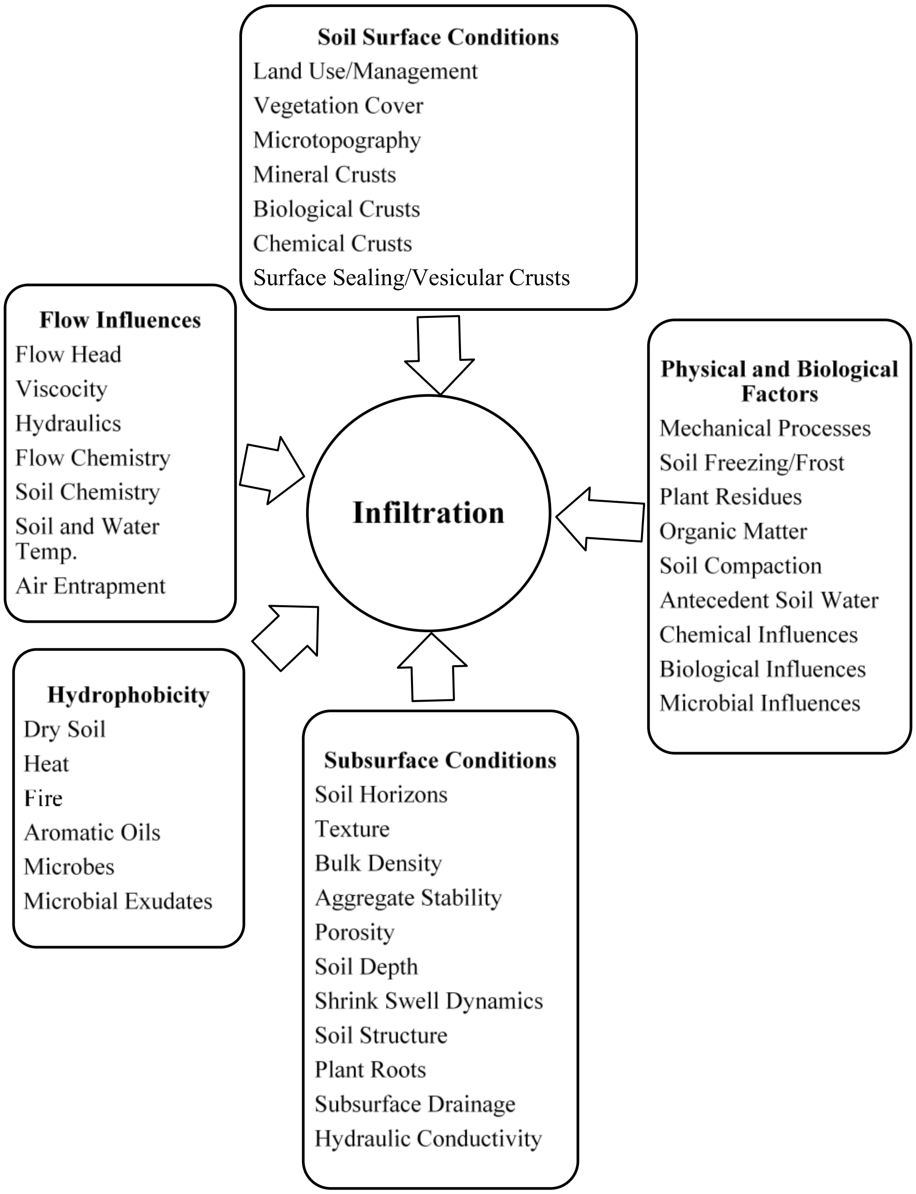
(ii) Infiltration Capacity

When rainfall rates during a storm exceed infiltration paucity of the soil, surface runoff or ponding on the soil surface occurs. Infiltration capacity of the soil is dependent on soil texture, porosity of the soil, soil structure, soil surface conditions, the physical nature of soil colloids, organic matter content, soil depth or the presence of impervious layers, macropores and biopores, antecedent soil water content, and temperature of the soil (at or near frozen conditions).

(iii) Infiltration Rate

Infiltration rate is related to the volume of water moving into the soil profile per unit area of surface area.

Figure G-4. Interrelated factors associated with infiltration.

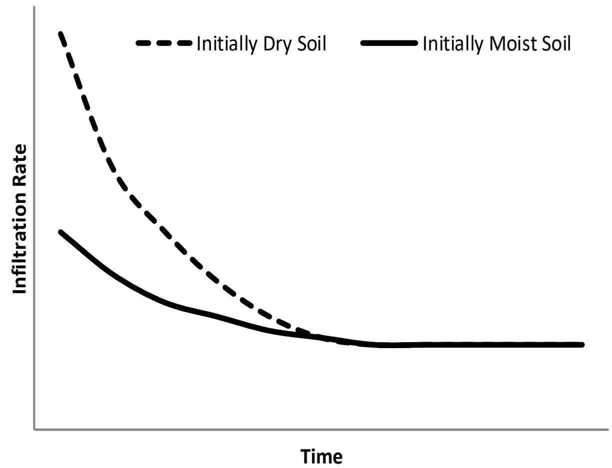


(iv) Infiltration Curve

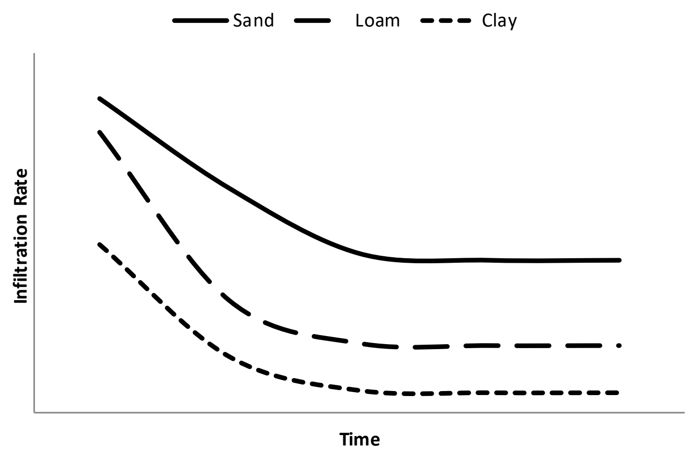
Infiltration curves are diagrammatic representations of infiltration over time. Figure G-5 shows infiltration over time for dry and wet soils. Soils that are initially dry infiltrate water more readily than moist or wet soil. In wet or moist soils, suction gradients are small at the onset of a rainfall event and become negligible as time progresses. Figure G-5 shows infiltration curves for sand, loam, and clay.

Figure G-5. Infiltration as a function of time for an initially dry **(a)** and wet soil **(b)**. Respective infiltration curves for sand, loam, and clay (Spaeth 2020).

(a)



(b)



(v) Infiltrability

Infiltrability denotes the infiltration flux resulting when water, at atmospheric pressure, is freely available at the soil surface (Hillel 1982) and depends upon initial wetness, suction, texture, structure, soil layering and its uniformity, aggregate stability, and bulk density. In soils with high clay content, infiltrability may initially be high due to macropores and cracks in the soil surface. However, as these cracks swell, infiltrability decreases. As clay particles expand, air pockets become entrapped, and the bulk compression of soil air is prevented from escaping as it is displaced by water.

G. Hydraulic Conductivity

Hydraulic conductivity is the ratio of the volume of water passing through a cross-sectional unit area per unit time (flux) to the hydraulic gradient (the driving force acting on the liquid) (Spaeth 2020). Hydraulic saturated conductivity is often symbolized as Ks and differs between unsaturated and saturated soil conditions. See figure G-6 and table G-7. In a saturated soil, there is a positive pressure potential. However, in unsaturated soil, there is subatmospheric pressure, or suction, which is analogous to a negative pressure potential (Spaeth 2020). The higher the saturated hydraulic conductivity of the soil, the higher its infiltrability.

Figure G-6. Comparison rates for saturated hydraulic conductivity (Ks) for various soil textural classes (data from Rawls et al. 1998).

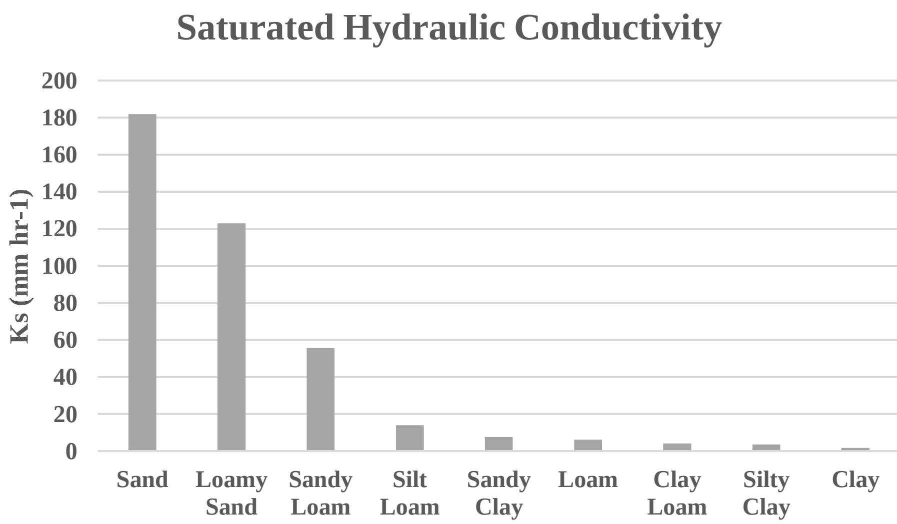


Table G-7. Approximate relationships between soil texture, water storage, and water intake rates under irrigation conditions (Spaeth 2020).

Texture	Water mm @ 0.3 m (in ft. of soil)	Max. rate of water intake in hr^{-1} ($mm\ hr^{-1}$) (bare soil conditions)
Sand	12.7–17.8 (0.5–0.7)	0.75 (19)
Fine sand	17.8–22.9 (0.7–0.9)	0.60 (15.2)
Loamy sand	17.8–27.9 (0.7–1.1)	0.50 (12.7)
Loamy fine sand	20.3–30.5 (0.8–1.2)	0.45 (11.4)
Sandy loam	20.3–35.6 (0.8–1.4)	0.40 (10.2)
Loam	25.4–45.7 (1.0–1.8)	0.35 (8.9)
Silt loam	30.5–45.7 (1.2–1.8)	0.30 (7.6)
Clay loam	33.0–53.3 (1.3–2.1)	0.25 (6.4)
Silty clay	35.6–63.5 (1.4–2.5)	0.20 (5.1)
Clay	35.6–63.5 (1.4–2.5)	0.15 (3.8)

H. Percolation

Percolation is the downward movement of water through the soil profile. Deep drainage is the downward movement of soil water past plant roots. The amount of water lost to deep drainage depends upon soil infiltrability, evapotranspirational demands, substrate and geological conditions, and rooting dynamics of plants (Spaeth 2020).

I. Soil Water Characteristics

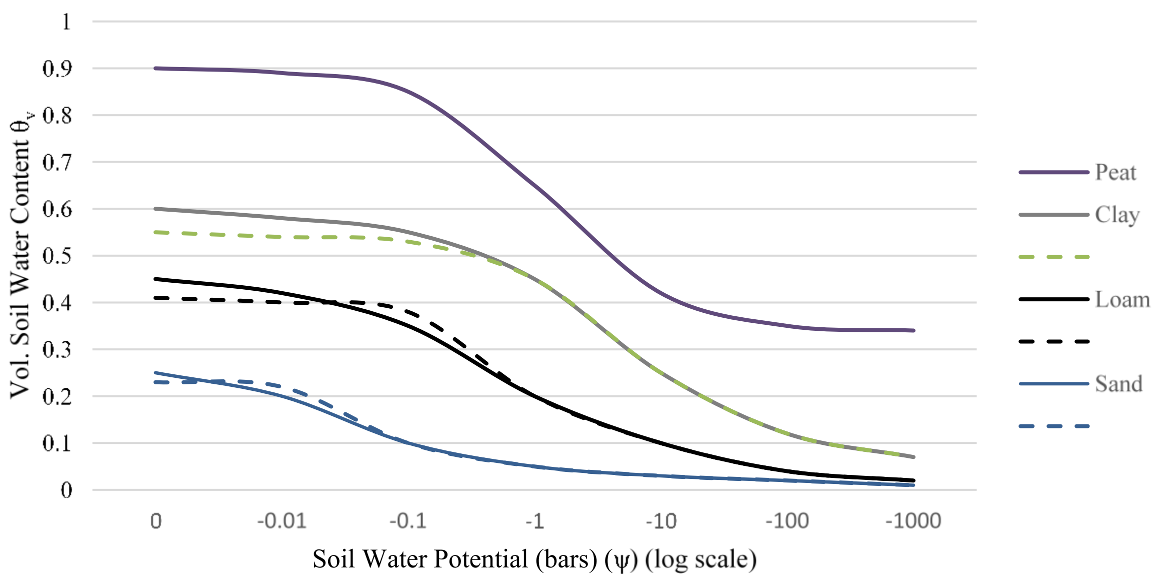
(1) Water loss in soils occurs by surface runoff, evaporation, transpiration, leaching, ratios of air and water in soil pores, and soil temperature dynamics. Soil water dynamics affect soil physical and chemical characteristics, soil biotic components, and plant growth, which are related to overall rangeland ad pastureland health. Total soil water potential (Ψ_t) is affected by various forces: gravitational (Ψ_g), matric (Ψ_m), hydrostatic (Ψ_h), and osmotic (Ψ_o)—all having singular potentials.

$$\Psi_t = \Psi_g + \Psi_m + \Psi_h + \Psi_o + \ldots \text{(other possible potentials)}$$

(2) The physics of soil water potentials and dynamics are quite complex and are ultimately related to how water moves in the soil, between wet and dry soils. Regardless of the complexity of soil water dynamics, there is one important point to remember about the behavior of water in soils: water moves from areas with high water potential to areas with lower water potential. In farming and ranching enterprises, soil water content and storage capacity are of primary importance to growing a crop or forage plants. There is a curvilinear relationship between soil water potential (Ψ_t) and moisture content in the soil (θ) (figure G-7). Several soil physical properties influence soil water content: soil texture, soil structure, soil aggregate stability, and bulk density. The latter two may change as a function of compaction from tillage implements or grazing animals.

(3) Soil water potential curves represent saturated soil condition and progressive drying. Dashed lines are effects of soil compaction or poor soil aggregate stability for soil textures, respectively. Units for volume soil water content = m^3 H_2O/m^3 soil (data from Rawls et al. 1982, 2004; Schwarzel et al. 2002; Weil and Brady 2017). The volume of soil water content is affected by pore sizes and decreases with soil water potential. Clays sustain more water at given potentials than loam and sand. Clay content in the soil determines the amount of soil micropores. As soil water potential increases, water is held more tightly in the micropores.

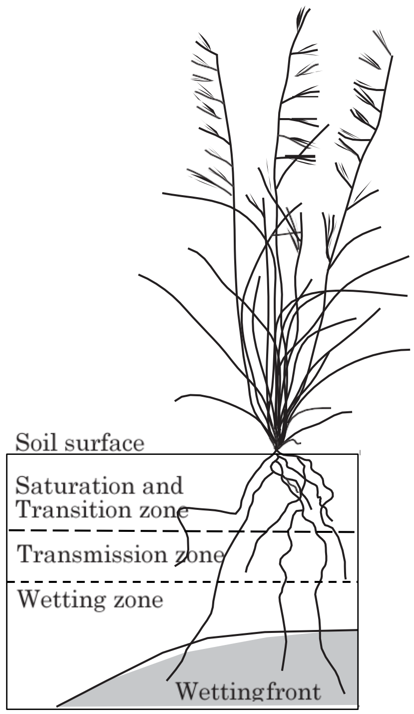
Figure G-7. Soil water potential curves for peat and three mineral soil textures.



J. Soil Moisture

Figure G-8 shows a moisture profile with the saturation and transition zone, transmission zone, wetting zone, and wetting front. The saturation and transition zones are fully saturated. The transmission zone is the ever-lengthening unsaturated zone of uniform water content. The wetting zone is the area where the transmission zone joins the wetting front. The wetting front is the line of delineation where the soil changes from wet to dry. Depth of the wetting front is an important factor for sustained plant growth. Grasses with laterally extending fibrous roots as well as a deep tap root are adapted to utilize precipitation from low precipitation events as well as subsurface water.

Figure G-8. Moisture profile during infiltration (Spaeth 2020).



K. Plant Available Water

(1) Wilting point, field capacity, and plant available water are important concepts that vary significantly with soil texture (figure G-9). These concepts are especially important in determining irrigation schedules for crops. Plant growth and yield are reduced at 40–60 percent of the plant available water (PAW) content (figure G-10) (Elliot and Ward 1995).

(2) For example, to determine the water needed to increase a loam soil from a critical water deficit (~50 percent) to field capacity, obtain upper and lower bounds for loam (English units, wilting point = 1.1 in, and field capacity = 3.2 in).

$$\theta \text{ paw} = (3.2 \text{ in} – 1.1 \text{ in}) = 2.1 \text{ in}$$

(i) The crop root zone is 2 ft. and PAW = (2.1) (2) = 4.2 in (106.6 mm)

(ii) If the critical deficit is 50 percent of PAW, then (0.5) (4.2) = 2.1 in of water is needed to raise the soil water content from the critical value to field capacity.

(iii) Wilting point is the moisture content of the soil (oven-dry basis) where plants wilt and fail to recover a turgid state in a dark environment. Wilting point is typically at 10–15 bars for crops. In rangelands, wilting point may exceed 30 bars for specific desert and semi-arid plants.

(iv) Field capacity is the percentage of water remaining in the soil two to three days after saturation and drainage has stopped.

(3) If significant erosion has occurred and topsoil with inherent levels of organic matter is lost, soil moisture holding capacity is compromised. Soil water retention is a function of soil physical properties and organic matter (Rawls et al. 1991; Wösten et al. 1988). The effects of organic matter on soil water retention cannot be overemphasized. Rawls et al. (2003) provide a detailed review the literature on the effects of organic matter on soil water retention. Some research using organic matter in regression models is contradictory, but there is agreement that organic matter "is an important factor when water contents at field capacity and wilting

point are measured directly" (Rawls et al. 2003). (See Section 645.0707(B), and Subpart F, Soil Health for discussions and information on organic matter and carbon dynamics on grazing lands).

Figure G-9. Plant available water capacities of different soil textural groups.

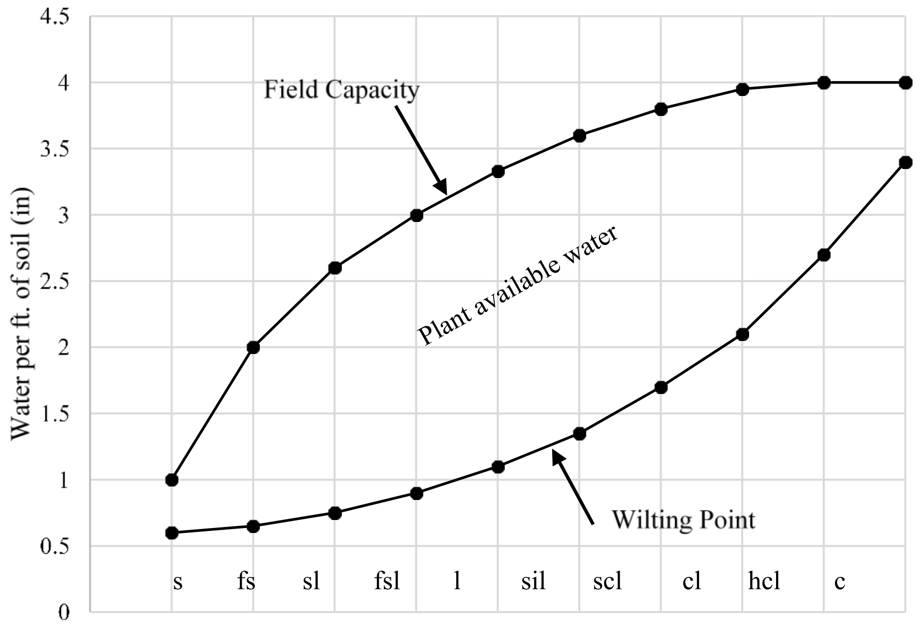
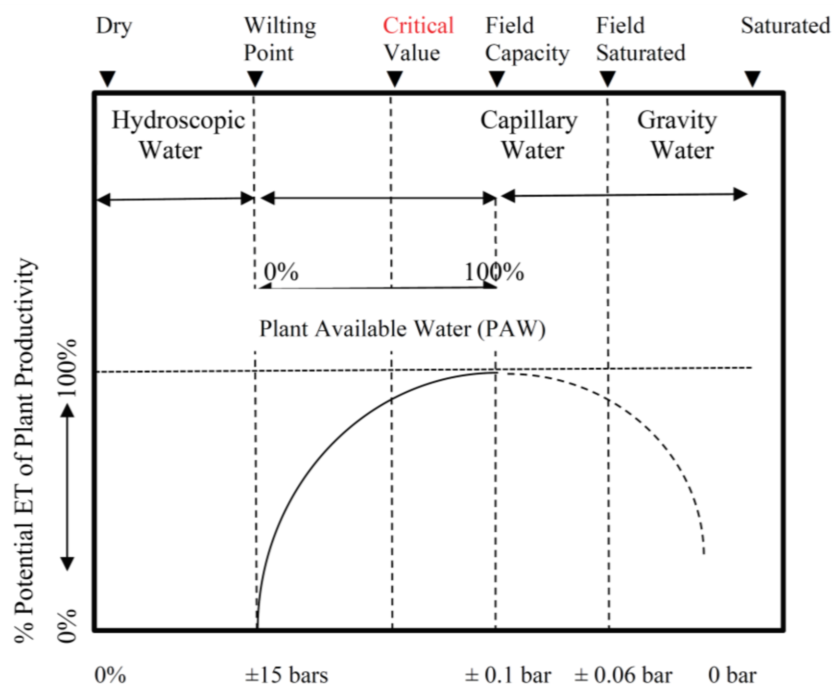


Figure G-10. Expected plant yield response with soil water content at 0 to 15 bars (wilting point). The critical value (40–60 percent) where plant production falls off due to waning available plant water (adapted from Ward and Elliot 1995).



L. Direct Surface Runoff

(1) Surface runoff or overland flow occurs when rainfall rate exceeds infiltration capacity, and the soil becomes saturated. The rate and distribution of runoff from a watershed are determined by a combination of physiographic, land use, and climatic factors. Runoff is closely linked to nutrient cycling, erosion, and contaminant transport. Runoff can be a sensitive indicator of ecosystem change, especially rangeland health determinations (hydrologic function and soil and site stability). Factors influencing runoff include:
(i) Form of precipitation (rain, snow, hail)
(ii) Type of precipitation (convective, orographic, cyclonic)
(iii) Seasonal distribution of precipitation
(iv) Intensity, duration, and distribution of precipitation
(v) Plant cover and biomass
(vi) Plant community types and the character of vegetative cover
(vii) Kind of vegetation as well as quantity of vegetation
(viii) Watershed topography and geology
(ix) Physical and chemical soil characteristics
(x) Evapotranspiration
(xi) Antecedent soil moisture
(xii) Degree of compaction i.e., land use practices

(2) High intensity convective storms are typically associated with runoff, as rainfall intensity and amount are greater than infiltration capacity. The dynamics of high intensity convective storms vary considerably across states and rangeland environments (Consult National Oceanic and Atmospheric Administration Atlas 14, precipitation frequency estimates, for local information). High return period storms > 5, 10, 25, 50, 75, 100-year frequency can initiate rills, gullies, and irreparable soil loss, especially when low cover and production, and soil compaction are present. On stable rangelands with adequate cover and proper management, long-term average soil loss is usually not a concern. However, erosion risk and potential during high intensity design storms that generate high runoff can be associated with significant erosion. Lower intensity frontal storms, where rainfall occurs at a low rainfall intensity (< 1 in/hr) rate, are conducive to higher amounts of water infiltrating and percolating through the soil.

M. Watershed Hydrograph

Various environmental processes and pathways determine streamflow. Hydrographs are used for analyzing the dynamics of surface runoff. A hydrograph shows the properties of streamflow with respect to time and has four component elements: channel precipitation, direct surface runoff, subsurface flow, and baseflow (figure G-11).

(i) Baseflow

Baseflow is that portion of precipitation which percolates into the soil profile and is released slowly and sustains streamflow between periods of rainfall and snowmelt. Baseflow does not respond quickly to rainfall (Spaeth 2020).

(ii) Subsurface Flow

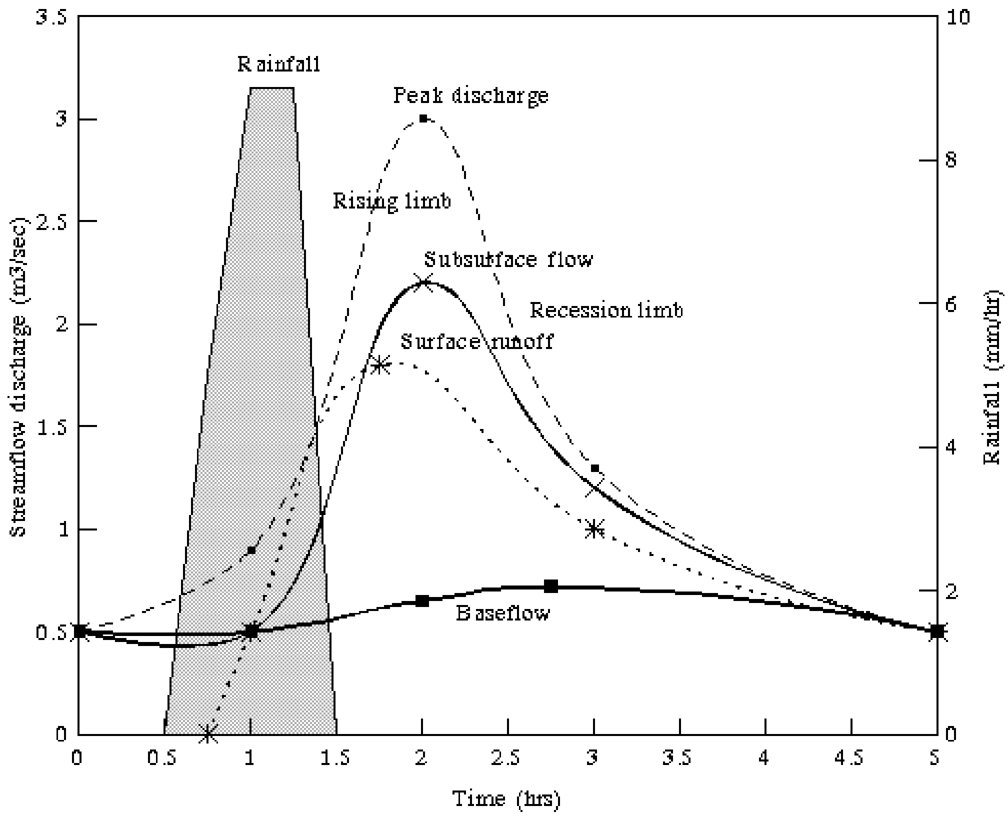
Subsurface flow is infiltrated water that is impeded by a restrictive layer in the soil (e.g., hardpan, caliche layer, bedrock). Subsurface water is diverted laterally and flows through the soil until it arrives at a stream channel over a short time period, where it is considered part of the storm hydrograph (Spaeth 2020).

(iii) Evaporation

Evaporation is the physical process where water transitions from a liquid to a gaseous state. Wherever water exists in a liquid state, evaporation occurs. The majority of water evaporation occurs from oceans, lakes, and other water bodies (>90 percent);

the remainder of evaporated water is from soil surfaces. Water evaporating from the soil surface is dependent upon energy associated with atmospheric conditions and vapor pressure gradients. As solar energy inputs to the soil surface layer increase, the vapor pressure of water and the gradient increase. The upper boundary layer of soil (0.5–1.0 inches) represents the evaporation layer.

Figure G-11. Example hydrograph of a watershed showing the relationship of water flow pathways (Spaeth 2020).

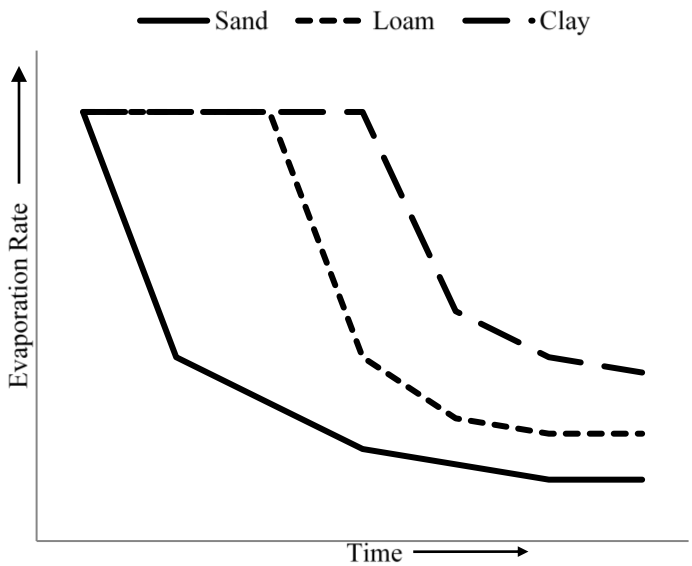


- Water evaporating from the soil surface is replaced by water moving upward in the soil profile by connecting water films around soil particles and through soil capillary pores. Water moves from zones of high potential (lower soil layers) to areas of lower potential (the upper soil surface). Soil hydraulic conductivity decreases as soil dries, and upward water migration decreases as soils become drier. In summary, as soil dries over time, water flow to the surface slows and cannot keep pace with atmospheric energy gradients at the soil surface. As subsoil water is lost during drying, evaporation is limited, regardless of surface atmospheric energy inputs. Water deficits occur sooner in lighter textured soils (sandy) compared to heavier textured soils (clayey) (figure G-12).
- The ionic effects of salts in soil lowers the vapor pressure of water, thereby reducing the vapor pressure gradient between the atmosphere and the soil solution. The result is lower evaporation potential. As salts precipitate in soils, pore-clogging can occur, which reduces the evaporative surface area and soil permeability.
- Managing vegetation cover and height is important in minimizing soil water evaporation losses. As soil surface temperatures rise, so does the vapor pressure

gradient. Soil surface evaporation is a factor that can be managed by prescribed grazing and maintaining minimum plant heights. Maintaining minimum plant stubble height (see state standards for Prescribed Grazing (528) and Forage and Biomass Planting (Code 512) standards) is not only important for insuring plant recovery and initiation of photosynthesis, but adequate plant cover and height also help buffer soil surface temperature, soil water evaporation, and soil erosion. Where these conservation practices cannot restore proper function and plant recovery, range and pasture seeding can be implemented.

- Evaporation rates vary with soil texture. Evaporation is highest with sand textures, lower for clay, over time. See section 645.0705 Hydrologic Water Budgets.

Figure G-12. Soil water evaporation with soil texture (Spaeth 2020).



(iv) Transpiration

- The process of water loss in plants is transpiration. When a plant is turgid, and water balance is sufficient (saturated), water vapor is transpired to the atmosphere. Most of the water adsorbed by the plant is transpired or lost as water vapor via stomata. More than 90 percent of the water in plant uptake is transpired and is lost to the atmosphere. If humans perspired as much, we would have to drink 20 gallons or more of water per day. Water is the basis of metabolic processes in the plant and is used in photosynthesis and synthesis of hormones, chlorophyll, and other plant pigments. The exchange of gases in photosynthesis requires moist cell surfaces. When the balance of water absorption by roots falls below transpiration rates, leaves may wilt and stomata close. Stomata remain closed at night when plants are restoring water balance.
- Transpiration rate is dependent upon water vapor pressure gradients between plant intercellular spaces and the atmosphere. As water vapor fills plant intercellular spaces, it then diffuses out to the atmosphere through stomata, lenticels (horizontal slit-like areas in the bark of woody stems or roots), or other plant openings that may be present. Any part of the plant anatomy can transpire water. High temperatures, bright sunlight, low humidity, high air pressure, and wind are associated with increased transpiration rates. Leaf size is an indication of transpiration potential because large leaves transpire more water compared to smaller leaves. Transpiration

increases about 20–30 percent for every 18° F rise in temperature. In rangeland plant environments, transpiration is generally a factor beyond control of land management.

(v) Evapotranspiration

Evapotranspiration (ET) is the process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants. Transpiration from plants is the major component of water loss in semiarid and arid rangelands. Table G-8 gives estimated ET rates for various vegetation types. Evapotranspiration affects water yield and largely determines what proportion of precipitation input to a watershed becomes streamflow. Changes in vegetation composition that reduce ET result in an increase in streamflow and/or ground water recharge, whereas increases in ET have the opposite effect. Vegetation cover can reduce soil evaporation rates by shading and reducing wind velocity. The greater the vegetation cover, the greater the interception and transpiration loss, which usually offsets the benefits of reduced evaporation.

Table G-8. Average evapotranspiration rates for various vegetation types (from various sources).

Plant Species or Plant Community	Evapotranspiration (% of total or inches per day)
Pinyon-Juniper	63–97% of annual precipitation
Honey mesquite, Texas	95% of annual precipitation
Chaparral, California, 23 in/yr ppt.	80–83% of annual precipitation
Rio Grande Plains, S. Texas, Honey-mesquite Shrub clusters (shrub cluster)	0.09 in/day
Low sagebrush community, springtime	0.05–0.12 in/day under differing soil moisture and sunlight conditions (6-day average)
Wyoming big sagebrush/bluebunch wheatgrass, spring, Idaho, 12 in/yr ppt.	0.07 in/day
Wyoming big sagebrush/bluebunch wheatgrass, summer, Idaho, 12 in/yr ppt.	0.04 in/day
Low sagebrush/Idaho fescue, spring, Idaho, 13 in/yr ppt.	0.09 in/day
Low sagebrush/Idaho fescue, summer, Idaho, 13 in/yr ppt.	0.06 in/day
Mountain big sagebrush/grass, spring, Idaho, 19 in/yr ppt.	0.10 in/day
Mountain big sagebrush/grass, summer, Idaho, 19 in/yr ppt.	0.02 in/day
Mountain big sagebrush/grass, summer, Idaho, 30 in/yr ppt.	0.12 in/day
Mountain big sagebrush/grass, fall, Idaho, 30 in/yr ppt.	0.03 in/day
Forest, summer	0.12–0.2 in/day
Open desert vegetation	0.001–0.02 in/day

645.0705 Hydrologic Water Budgets and Interaction with Precipitation, Runoff, Evaporation, Transpiration, Erosion, and Sediment Yield

A. The hydrologic cycle is the foundation for developing water budgets for various rangeland plant communities. Water is regarded as the limiting factor in forage production in rangelands. Discussing water budgets with land users is an excellent way to show how total rainfall is partitioned due to site vegetative status and management. In addition, a water budget can be an effective way to show land users the benefits of various rangeland conservation practices. A simplified equation for evaluating available water for plant growth is as follows:

$$\text{Available Water for Plant Growth} = P - R - G - E - T$$

where:

P = total precipitation
R = surface runoff
G = deep percolation and/or ground water flow
E = evaporation
T = transpiration

(B) Table G-9 is an example of a water budget for various stands of grass in Major Land Resource Area (MLRA) 106, Nebraska and Kansas Loess-Drift Hills.

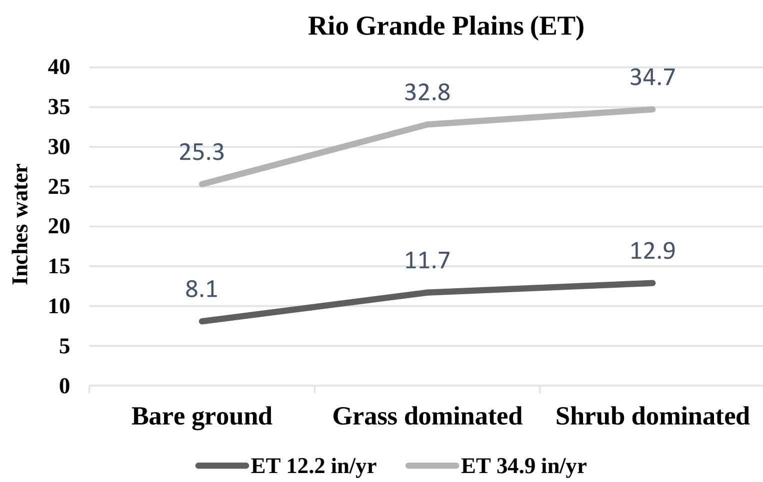
Table G-9. Water budget examples for MLRA 106, Nebraska and Kansas Loess-Drift Hills. Loamy site, 25 inches average annual precipitation for stands I, II, and III with different species composition (%). (Data from Rangeland Hydrology and Erosion Model, and Evapotranspiration Equations).

Plant Species	Stand I (%)	Stand II (%)	Stand III (%)
Little bluestem	30–50		
Big bluestem	15–30		
Prairie dropseed	10		
Porcupine grass	40		
Sideoats grama	5		
Grasses (Subdominants: Blue grama, Sedges, Prairie junegrass, Buffalograss)	5		
Kentucky bluegrass	0	75	25
Smooth bromegrass	0	25	75
Hydrologic Data	**Stand I inches (%)**	**Stand II inches (%)**	**Stand III inches (%)**
Precipitation (in)	25	25	25
Infiltration	19.3 (77)	13 (52)	17 (68)
Runoff	5 (20)	11.2 (45)	7.5 (30)
Grass and litter interception	0.13 (0.05)	0.10 (0.04)	0.15 (0.06)
Evapotranspiration (ET)	18.1 (94)	18.3 (95)	18.3 (95)
Soil evaporation	11.5 (60)	11.5 (60)	11.5 (60)
Plant transpiration	6.5 (34)	6.7 (35)	6.7 (34)
Deep percolation	0.6 (2.5)	1 (4)	2 (0.05)
Change in soil water (affected by antecedent soil moisture)	0	-1.4	-0.6

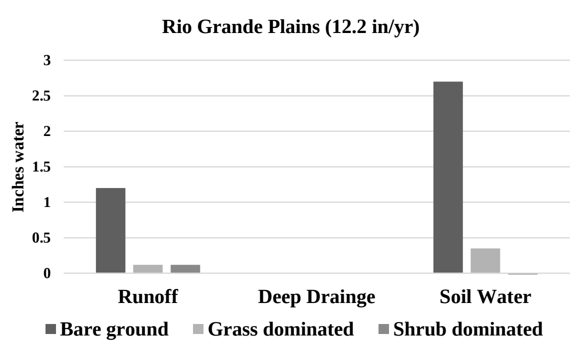
Stand I represents a tallgrass prairie reference state (historic plant community) dominated by native bunchgrasses. Stand II is dominated by Kentucky bluegrass (*Poa pratensis*), a sod forming species. Stand III is dominated by smooth bromegrass (*Bromus inermis*) with subdominant Kentucky bluegrass. Note the difference between native bunchgrasses and invasive sod forming grasses. Twenty percent of the total precipitation was runoff in Stand I (tall grasses), 45 percent (Stand II), and 30 percent (Stand III) dominated by Kentucky bluegrass and smooth bromegrass, respectively. C. In figure G-13, the pattern of evapotranspiration between the shrub clusters and grass interspaces were similar. However, ET rates were about three times higher the second year with increased rainfall rate (34.9 in yr^{-1}) (Weltz and Blackburn 1995). Surface water runoff and deep drainage from bare soil treatments were significantly greater than the shrub clusters and grass interspaces. Figure G-14 shows ET rates, water budgets, and sediment production for three cover conditions in the Texas Rolling Plains.

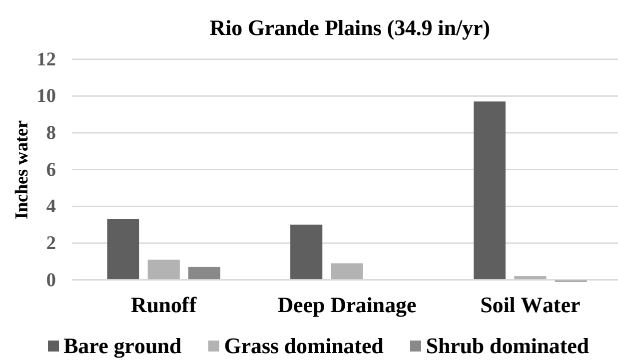
Figure G-13. (a) Evapotranspiration rates and **(b)** water budgets for bare soil areas, grass interspaces, and shrub clusters. Rio Grande Plain of Texas on a Miguel fine sandy loam soil with 1–3% slope for two years with significantly different annual precipitation rates (Weltz and Blackburn 1995).

(a) Evapotranspiration rates



(b) Water budgets



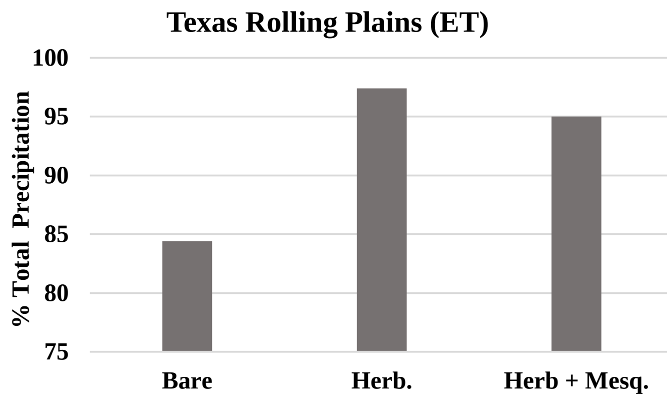


Notes:
Miguel fine sandy loam (1–3 percent)
Soil water was calculated as Precipitation–Runoff–ET–Deep Drainage.
Shrub clusters are honey mesquite (*Prosopis glandulosa*), brasil (*Condalia hookeri*), spiny hackberry (*Celtis pallida*), lime prickly ash (*Zanthoxylum fagara*), Agarito (*Berberis trifoliota*), Texas persimmon (*Diospyros texana*), Texas colubrina (*Colubrina texensis*), and wolfberry (*Lycium berlandieri*).

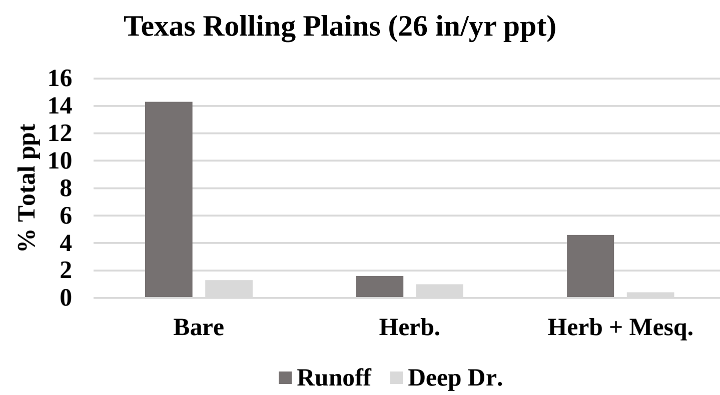
Grass clusters: thin paspalum (*Paspalum setaceum*), knotroot bristlegrass (*Setaria geniculate*), and windmillgrass (*Chloris verticillata*), red lovegrass (*Eragrostis secundifola*), red grama (*Bouteloua trifida*), threeawn (*Aristida* spp.), and southern sandbur (*Cenchrus echinatus*).

Figure G-14. (a) Evapotranspiration percent, **(b)** annual water balance differences between bare ground, herbaceous, and herbaceous plus mesquite vegetation composition from 1986 to 1988 on the Texas Rolling Plains, and **(c)** sediment losses for the same treatments (Carlson et al. 1990).

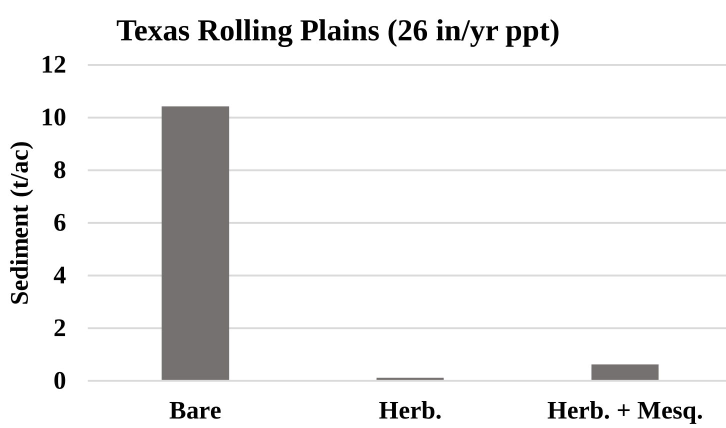
(a) Evapotranspiration as percent of total precipitation



(b) Water balances



(c) Sediment production



D. Runoff, interill erosion, and sediment losses were linked with rainfall amount, peak short-term storm intensity, and amount of bare ground (Carlson et al. 1990). On the bare and herbaceous treatments, mesquite trees were removed by cutting and stump treatment with diesel oil.

E. Evapotranspiration accounted for over 95 percent of water loss from vegetated sites. Runoff was lowest on herbaceous plots, followed by the herbaceous + mesquite plots. There was essentially no net change in deep drainage or evapotranspiration on sites where the herbaceous component increased in response to shrub removal.

645.0706 Water-Use Efficiency

A. The water requirement for a plant is the amount of water required to produce a given weight of above-ground dry matter. See Table G-10. An average value of water use efficiency for arid-land plants is 1,428 g of H_2O lost per gram of biomass produced. Given that plant tissue is 50 percent C content, 0.042g C is released as CO_2 per gram of C fixed in plant biomass (Fischer and Turner 1978). For every pound of arid-land biomass, 171.12 gal of water is required; or for 1,000 lbs. of arid-land biomass produced, 171,121.2 gal of water is required. Water requirements for plants are affected by many factors such as available water, physiologic characteristics of the plant, ecotypic variations of plants, environmental demands, phenology, plant rooting depth, length of growing season, temperature, and nutrient availability. In some rangeland community types, the benefits of converting shrub lands to grass can be shown by comparing water-use efficiencies. There is considerable variability among studies to determine water use efficiencies; however, grasses tend to be more efficient in terms of water use compared to forage, legumes, and shrubs. Water use efficiency of productivity is defined as:

$$Wp = \frac{\text{Dry matter production (lbs.)}}{\text{Water consumption (gal)}}$$

Table G-10. Water requirements of specific plant species.

Plant Species	Gallons of water needed for 1 lb dry weight.
Plant Species in the Pinyon/Juniper type	
Crested wheatgrass (*Agropyron cristatum*)	68–85
Western wheatgrass (*Pascopyrum smithii*)	52–84
Blue grama (*Bouteloua gracilis*)	72
Black grama (*Bouteloua eriopoda*)	69
Tobosa grass (*Pleuraphis mutica*)	110–136
Russian thistle (*Salsola australis*)	12–32
Fourwing saltbush (*Atriplex canescens*)	185–234
Broom snakeweed (*Gutierrezia sarothrae*)	310–716
Water use efficiencies at Tifton, Georgia	
Coastal bermudagrass (*Cynodon dactylon*)	85
Common bermudagrass (*Cynodon dactylon*)	190

Controlled field conditions at Cheyenne, Wyoming. Water availability was maintained at 0.3 to 0.8 bars at 12-inch depth; soil was a fine, sandy, clay loam; organic matter ranged from 2–4 percent; (July 20 and Aug 29 harvest dates) (Fairbourn 1982).

Range Grasses	July 20	Aug. 29
Blue grama *(Bouteloua gracilis)*	245	180
Slender wheat grass (*Agropyron trachycaulum*)	520	262
Western wheatgrass *(Pascopyrum smithii)*	493	191
Green needle grass (*Stipa viridula*)	361	293
Pasture Grasses	**July 20**	**Aug. 29**
Fawn tall fescue (*Festuca arundinacea*)	493	219

Garrison creeping foxtail (*Alopecurus arundinaceus*)	580	249
Latar orchardgrass (*Dactylis glomerata*)	361	253
Regar bromegrass (*Bromus bieebersteinii*)	493	267
Thickspike wheatgrass (*Agropyron dasystachyum*)	538	177
Legumes		
Alsike clover (*Trifolium hybridum*)	366	233
Dawson alfalfa (*Medicago sativa*)	548	385
Ladak alfalfa	519	332
Vernal alfalfa	529	332

B. Studies at the Northern Great Plains Research Center in Mandan, North Dakota, showed that water use efficiencies of fertilized grasses generally increased. Comparisons among crested wheatgrass, smooth bromegrass, and native mixed grass prairie show that water use efficiency in response to nitrogen (N) fertilization was greatest for smooth bromegrass and least on mixed grass prairie. Under semiarid conditions, grass growth processes are controlled primarily by soil water availability and secondarily by N availability. Studies in the eastern United States (Pennsylvania) with cool and warm season grasses have shown that during years of evenly distributed precipitation, N was the main factor controlling yields, and water use efficiency accounted for 80 percent of the variation in yields of the species. When most precipitation occurred as large storm events or when precipitation was low or poorly distributed, soil water holding capacity was the major factor controlling yield, and water use efficiency accounted for about 40 percent of the variation in yields.

645.0707 Runoff and Erosion Dynamics

A. Runoff

(1) Overland flow or runoff begins when infiltration capacity is surpassed and when storage capacity of surface depressions is filled. In general, runoff varies with scale on the landscape. Runoff decreases as the size of the contributing area increases and provides more opportunities for infiltration. Runoff is closely tied to soil moisture content, compaction, condition or existence of soil aggregates, soil frost conditions, soil texture, porosity, as well as plant species, plant cover and root dynamics.

(2) Soil erodibility follows an annual cycle. It is highest at the end of a freeze-thaw period of late winter and lowest at the end of the summer rainy season when soils have been compacted by repeated rainfall.

(i) The Rangeland Hydrologic and Erosion Model (RHEM) (Nearing et al. 2011, Hernandez et al. 2017) is now available and has been proven effective for estimating surface runoff and soil erosion on rangeland uplands (Weltz and Spaeth 2012; Belnap et al. 2013; Hernandez et al. 2013, 2017; Al-Hamdan et al. 2015; Williams et al. 2016).

(ii) In arid and semiarid rangeland ecosystems, runoff is sporadic and interannual variations in runoff are quite high. Runoff is closely linked to chemical and nutrient cycling, erosion, salts, and contaminant transport. Runoff is a sensitive indicator of ecosystem change from one ecological state to another ecological state and response to disturbance (Pierson et al. 2011, Pierson and Williams 2016).

B. Erosion

(1) Soil erosion is the detachment of soil by wind and water. Variations in landscape, soil type, and available energy cause a continuum of detachment and deposition on rangeland, resulting in most soil particles moving only a few feet. Sediment production is related to runoff, which is the principle means of soil detachment and transport. Climate, vegetation, soil, and topography are the major variables affecting soil erosion from rangelands. In the western

United States, rangeland watersheds yield most of the sediment load, and forested watersheds produce the majority of streamflow.

(2) The key to developing more effective management systems requires an understanding that certain kinds of plants, vegetative growth forms, and vegetation clusters are more effective at stabilizing a site than others and provide early warning signals to rangeland degradation. In semi-arid and arid environments, alterations of the natural plant community—caused either by a natural event or anthropogenic causes—can lead to depletion of the original native plant species and replacement by exotic weedy species. Reduction of vegetative cover causes increased surface runoff and often leads to accelerated erosion. Rills and gullies develop, followed by larger flow concentrations. Further dissection of the land surface results in lower ground water tables, decreased infiltration of snowmelt and rainfall, and lower streamflows. Perennial streams can become ephemeral due to depletion of ground water storage, which has a deleterious effect on riparian vegetation.

(3) For every watershed and site within the watershed, there exists a critical point of deterioration due to surface erosion. Beyond this critical point, erosion continues at an accelerated rate, which cannot be overcome by the natural vegetation and soil stabilizing forces. Areas that have deteriorated beyond this critical point continue to erode even when human-caused disturbance is removed.

(4) What does 1mm of soil loss amount to in tons ac^{-1}, or Mg ha^{-1}? Several publications have provided estimates of average soil loss.

(i) How much is 1 mm of soil loss?

- 0.1 mm yr^{-1} for our most recent geologic epoch (Wilkinson and McElroy 2007)
- 0.021 mm yr^{-1} (the average erosion rate at 21 meters per million years (m/m.y.) (Summerfield and Hulton 1994).
- Loess and glacial till areas of Iowa, USA ~ 0.8–1.9 Mg ha^{-1} yr^{-1} (Ruhe and Daniels 1965, Walker 1966).
- On cultivated United States croplands, average estimated erosion rates are about 600 m/m.y. (0.6 mm yr^{-1}) (USDA NRCS 2000).

(ii) If 1 mm of soil erodes on a silt loam with a bulk density of 1.33 Mg m^3, what is the equivalent soil loss in Mg ha^{-1} and United States tons ac^{-1}?

- For 1 mm soil depth = (1m)(1m)(0.001m) = 0.001 m^3
- Weight of soil 1 m^2 at 1 mm depth = (0.001 m^3)(Bulk density 1.33 Mg m^3) = 0.0013 Mg m3
- Weight of soil for 1 hectare at 1mm depth = (100m)(100m)(0.0013 Mg m^3) = 12.97 Mg ha^{-1} (5.79 t ac^{-1})

(5) Increases in erosion will occur on rangeland sites and in watersheds not protected by vegetation. Fine surface particles and organic matter are removed. Organic matter is rapidly decomposed on exposed soils, and raindrop impact further causes surface sealing, resulting in a more impermeable soil crust. The first stage of erosion is interrill erosion. Interill erosion (sheet erosion) combines detachment of soil from raindrop splash and transport by a thin flow of water across the surface. Minute rills form concurrently with the detachment of soil particles. As runoff becomes more concentrated in rills and small channels, the velocity, mass of the suspended soil, and intensity of turbulence increases. As kinetic energy of the runoff event occurs, the ability of the water flow to dislodge larger soil particles increases. In more arid areas with sparse vegetation cover and poor land use management, sheet and rill erosion is common. Rill erosion begins when water movement causing interrill erosion concentrates in discrete flow paths. Rill erosion produces the greatest amount of soil loss worldwide. Where soils are more resistant to sheet and splash erosion, erosion occurs mostly by rills and gullies. Sheet erosion is a more erosive process on sandy textured soils. Velocities of

6 in sec^{-1} are required to erode soil particles 0.3 mm diameter. Velocities as low as 0.7 in sec^{-1} will carry the particle in suspension.

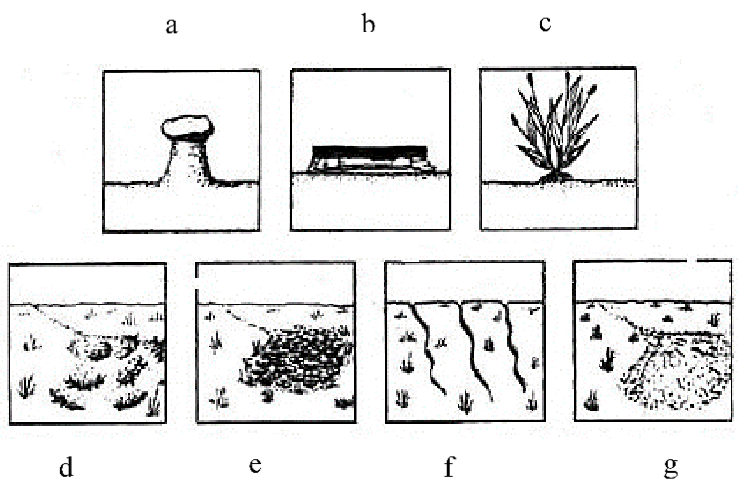
(6) Gully erosion occurs when runoff is concentrated at a nickpoint, where there is an abrupt change of elevation, slope gradient, and a lack of protective vegetation. See figure G-15. Gullies are recently channelized drainage features that transmit ephemeral flow, usually have steep sides and a head scarp (leading upslope area of exposed soil and rock), and are more than 30 cm wide and 60 cm deep (Selby 1982, Toy et al. 2002). These erosional features commonly form when a master rill deepens and widens its channel, especially where changes in slope or vegetation patterns occur on unconsolidated materials (Neary et al. 2012). Gullies may also form where debris and mud flows exit unstable drainage basins or where large subsurface drainage features collapse. The most common cause of gully formation is a loss in surface protection associated with a change in the overlying vegetation or soil disturbance on the hillslope. Headcuts are caused as water falls over the nickpoint and undermines this point and migrates upslope.

Figure G-15. Initiation nickpoints and headcuts associated with gully erosion on rangeland.

(7) Often, under normal climate and average precipitation regimes and intensities, erosion on rangeland can be difficult to detect. Long-term average erosion rates on rangeland are usually not informative as a measure of site erosion dynamics because they mask the accelerated erosion rates that occur during intense rainfall events. Attention to the effects of design storm dynamics is more important and relevant on rangelands, where 5 to 100-year storm frequencies with intense high-capacity short-term storms can initiate erosive events, especially rills and gullies. Pedestalling of plants, an indicator in the rangeland health matrix,

can be a warning sign of active erosion, where wind erosion, rills and gullies may not be readily apparent (figure G-16).

Figure G-16. Visual indicators of accelerated erosion on rangeland. **(a)** soil pedestal; **(b)** differential charring of woody litter is an indication of amount of soil eroded after fire; **(c)** pedestalled plant; **(d)** debris dams caused by accelerated runoff; **(e)** puddled depressions on soil surface where fine clays are deposited and form crusts, which have a cracked appearance during drying; **(f)** rill and gully formation; and **(g)** small alluvial fans deposited at slope transitions (adapted from Thurow 1991).



(8) Erosion can reduce productivity of the plant community so slowly that the reduction may not be recognized until the site has reached a threshold level. Increased runoff reduces available soil water which affects plant growth. Less plant growth means less residue. Less vegetation and residue provide less cover, which increases erosion. Because water erosion strongly relates to runoff, increased runoff also leads to increased erosion. Thus, the process advances exponentially, and reversing it may become physically and economically impossible, if it is not detected and controlled by proper management practices.

(9) Water erosion on range and pastureland can be determined in the field by a variety of indicators. Some of these factors are accounted for in Interpreting Indicators of the Rangeland Health (IIRH), Determining Indictors of Pasture Health (DIPH), and pasture condition scoring models. Examples of the indicators include:

(i) Pedestalled soil, plants, rocks
(ii) Base of plants discolored by soil movement from raindrop splash or overland flow
(iii) Exposed root crowns
(iv) Formation of miniature debris dams and terraces
(v) Puddled spots on soil surface with fine clays forming a crust in minor depressions which crack as the soil surface dries and the clay shrinks
(vi) Rill and gully formation
(vii) Accumulation of soil in small alluvial fans where there are minor changes in slope
(viii) Surface litter, rock or fragments exhibit some movement and accumulation of smaller fragments behind obstacles
(ix) Eroded interspace areas between plants with unnatural gravel pavements
(x) Flow patterns contain silt or sand deposits and are well defined or numerous
(xi) Streambank erosion

(10) Soil surface characteristics, the dynamics of plant growth life and growth forms, individual plant species, and plant community type (ecological sites) have dynamic properties and

impacts on runoff and erosion (table G-11). Soil surface characteristics such as organic matter, bulk density, texture, structure, aggregate stability, porosity, and moisture conditions influence soil runoff and erosion by controlling the amount of infiltration and runoff from a site. Litter and vegetation reduce the soil's susceptibility to erosion by protecting the soil surface from raindrop impact, decreasing the velocity of runoff, encouraging soil aggregation, binding the soil with roots, and reducing soil compaction.

Table G-11. Measurements of Soil Loss from Various Land Uses and Types.

Land Use	Location	Soil Loss (Tons/Ac)	Reference
Prairie dog towns	High Plains TX	0.80	Spaeth 1990
Three awn grass/Texas tumblegrass	High Plains TX	0.78	Spaeth 1990
Broom Snakeweed	High Plains TX	0.47	Spaeth 1990
Buffalograss	High Plains TX	0.07	Spaeth 1990
Blue grama	High Plains TX	0.10	Spaeth 1990
Blue Grama/Buffalo	High Plains TX	0.10	Spaeth 1990
Honey Mesquite/Sideoats grama/ Texas wintergrass	Rolling Plains TX	0.62	Carlson et al. 1990
Mesquite removed/Sideoats grama/ Texas wintergrass	Rolling Plains TX	0.11	Carlson et al. 1990
Denuded Honey Mesquite/Sideoats grama/Texas wintergrass	Rolling Plains TX	10.4	Carlson et al. 1990
Natural ungrazed rangeland, Semi-arid to sub-humid	Avg. 17 data sources	0.32	van Oudenhoven et al. 2015
Pastureland	Avg. 7 data sources	1.89	van Oudenhoven et al. 2015
Abandoned rangeland, Semi-arid to sub-humid	Avg. 2 data sources	1.20	van Oudenhoven et al. 2015
Silvo-pasture	Avg. 14 data sources	1.49	van Oudenhoven et al. 2015
Restoration rangeland Semi-arid to sub-humid	Avg. 16 data sources	0.06	van Oudenhoven et al. 2015
Sparse grassland	Alberta. Canada	7.7	Campbell 1970
Grass and scrub	India	1.60	United Nations 1951
Dry Woodland and Rangeland	Southern CA	2.70	Krammes 1960
Dry Woodland and Rangeland after fire	Southern CA	24.7	Krammes 1960
Woodland Protected	Texas	0.05	Smith and Stamey 1965
Pinyon-juniper woodland Undisturbed	New Mexico	0.14	Ludwig et al. 2005
Pinyon-juniper woodland	New Mexico	0.45	Disturbed, Ludwig et al. 2005
Eucalypt savanna Undisturbed	NE Australia	0.55	Ludwig et al. 2005
Eucalypt savanna	NE Australia	0.79	Disturbed, Ludwig et al. 2005
Vegetation eliminated by Smelter fumes	Ontario	26.1	Pearce 1973
Rural Roads Forest Roads	Idaho	7.90	Copeland 1965
Forest Roads in a jammer unit	Idaho	29.7	Megahan and Kidd 1972
Grazing Systems			
Low intensity grazed rangeland	Avg. 9 data sources	0.61	van Oudenhoven et al. 2015
High intensity grazed rangeland	Avg. 22 data sources	1.80	van Oudenhoven et al. 2015
Overgrazed degraded rangeland	Avg. 2 data sources	4.41	van Oudenhoven et al. 2015

645.0708 Soil Properties Affecting Hydraulic Processes

A. Soil Particle Size (Texture)

(1) Rangeland plant communities are multivariate in nature. No single variable acts alone—many variables interact and affect hydrologic dynamics. Soil texture is probably the most dominant physical property that is correlated with infiltration capacity. Soil texture provides a way to identify the contribution of sand, silt, and clay (soil test results may describe texture as soil particle size). In general terms, fine textured soils have more clay, whereas coarse-textured soils contain more sand. Technically, the United States Department of Agriculture has classified sand particles as being between 0.05 mm to 2 mm in size. Sand particles are visible to the naked eye. Silt particles are not visible to the naked eye, ranging from 0.002 mm to 0.05 mm. Clay particles are the smallest class of particles, < 0.002 mm. Surface area increases inversely to particle size. Clay particles have a large surface area per unit weight and have a tremendous capacity to absorb and store water. Very fine clay particles act as colloids, and if suspended in water do not settle out. Soil hydraulic properties for soil textural classes are shown in table G-12 and figure G-6 (Rawls et al. 1998). Infiltration rates can be higher, particularly in the initial stages of the process, where soils are well aggregated, and surface mineral crusting is minimal. Table G-12 shows approximate relationships between soil texture, water storage, and water intake rates under irrigation conditions.

(2) Infiltration rates that are slower than expected for certain soil textures are usually an indication of several causal factors. Soil structure, the arrangement of soil particles and pore spaces, may be altered by previous cultivation or other disturbances (grazing, compaction by machinery). Heavier-textured soils typically form aggregates, which are formed by biotic components such as roots, fungal hyphae, mycorrhizae, compounds formed by fungi and algae, and adhesive byproducts of organic matter decay, humic components, and microbial synthesis of mucilaginous compounds. Porosity (pore volume) is a physical soil attribute and is correlated with soil texture and the degree of soil aggregation. Some soil hydraulic properties are shown by soil texture in table G-12. Porosity and pore size, in addition to other soil physical attributes (texture, bulk density, structure), determine infiltrability of water into the soil.

B. Soil Organic Matter

(1) The global soil pool contains about as much of the carbon reservoir as plants and the atmosphere combined. See figure G-16. Carbon imbalance occurs from burning fossil fuels and open burning (fire). The largest carbon reserve is in carbonate rocks (75 million Pg). More carbon is emitted from the soil (62 Pg) than entering the soil (59–60 Pg) due to erosion and loss of organic matter. Land use changes have been estimated to produce 1.6–2 Pg C yr^{-1}. Throughout the world, grazing lands contain 10 to 30 percent of the world's organic carbon stores (Kimble et al. 2001); about 5 percent is contained in U.S. soils (Waltman and Bliss 1997). Significant losses of soil organic matter on rangeland have occurred over time and are attributed to cultivation and abandonment, overgrazing, introduction of exotic plant and animal species, invasive native species, and lack of proper rangeland management practices. Following cultivation, soil organic carbon losses of 20 to 40 percent occur over a 5 to 20-year period (Davidson and Ackerman 1993). Figure G-17 shows the decline in organic matter after cultivation on tallgrass prairie. The active soil organic matter (SOM) pool of organic matter is rapidly mineralized when cultivation begins. After 100 years of cultivation, about 56 percent of the total soil organic matter has been lost. Reseeding back to permanent native plants would slowly and continually begin to build organic matter content over time.

Table G-12. Estimation guides for soil hydraulic properties based on sample data (Rawls et al. 1998). The geometric mean of the K_S sorted according to soil texture and bulk density classes along with the 25 and 75th percentile.

USDA Soil Class Texture	Sand (%)	Clay (%)	Porosity (m^3 m^{-3})	Geometric Mean K_S (mm h^{-1})	K_S 25th percentile (mm h^{-1})	K_S 75th percentile (mm h^{-1})	Mean Capillary Drive C_d (mm)	Sample Size
Sand	92 91	4 4	0.44 0.39	181.9 91.4	96.5 64.0	266.8 218.5	50	39 30
Loamy Sand	82 82	6 7	0.45 0.37	123.0 41.4	83.8 30.5	195.5 77.6	70	19 28
Sandy Loam	65 68	11 13	0.47 0.37	55.8 12.8	30.5 5.1	129.6 31.3	130	75 112
Loam	38 43	23 22	0.47 0.39	3.9 6.2	1.6 2.8	28.4 16.5	110	44 65
Silt Loam	18 21	19 20	0.49 0.39	14.4 3.4	7.6 1.0	37.1 9.9	200	61 46
Sandy Clay Loam	56 58	26 26	0.44 0.37	7.7 2.8	2.0 1.0	50.5 10.9	260	20 53
Clay Loam	29 35	35 35	0.48 0.40	4.2 0.7	2.2 0.2	13.1 3.8	260	20 53
Silty Clay Loam	10 10	34 32	0.50 0.43	3.7 4.9	2.3 2.3	10.4 14.0	350	26 33
Sandy Clay	51	36	0.39	0.9	0.3	2.5	300	14
Silty Clay	4	49	0.53	1.8	0.5	7.5	380	10
Clay	18 26	53 50	0.48 0.40	2.0 1.8	0.9 0.3	6.0 6.9	410	20 21

(2) Estimates are slightly different among authors (adaptations and data from Berner 1990, Schimel 1995, Batjes 1996, Falkowski et al. 2000, Pacala and Socolow 2004, Houghton 2007, Solomon 2007, Battin et al. 2009, Haddix et al. 2011, Pan et al. 2011, Lal 2018). Note: 10^6 g=Mg=megagram (tonne); 10^{12} g=Tg=teragram; 10^{15} g=Pg=petagram (Adapted from Spaeth 2020).

(3) Carbon gains in rangeland soils occur early in soil formation and development, but eventually reach equilibrium or a steady state (Schlesinger et al. 1990, Chadwick et al. 1994, Li et al. 1994, Larcher 2003). In terrestrial ecosystems, once soil organic matter has reached equilibrium, during some years there is a positive buildup of organic matter. During other years a loss of organic matter may occur. However, the long-term average is constant or zero (Larcher 2003, Wolf and Snyder 2003). Development of soil organic matter in rangeland soils is dependent on the soil forming processes:

soil formation = function of (climate, potential biota—plants and animals, relief, soil parent material, and time)

Figure G-16. The global carbon cycle with representative carbon pools and reservoirs that interact with earth's atmosphere (units next to reservoir names are Pg C; Pg = 10^{15} g).

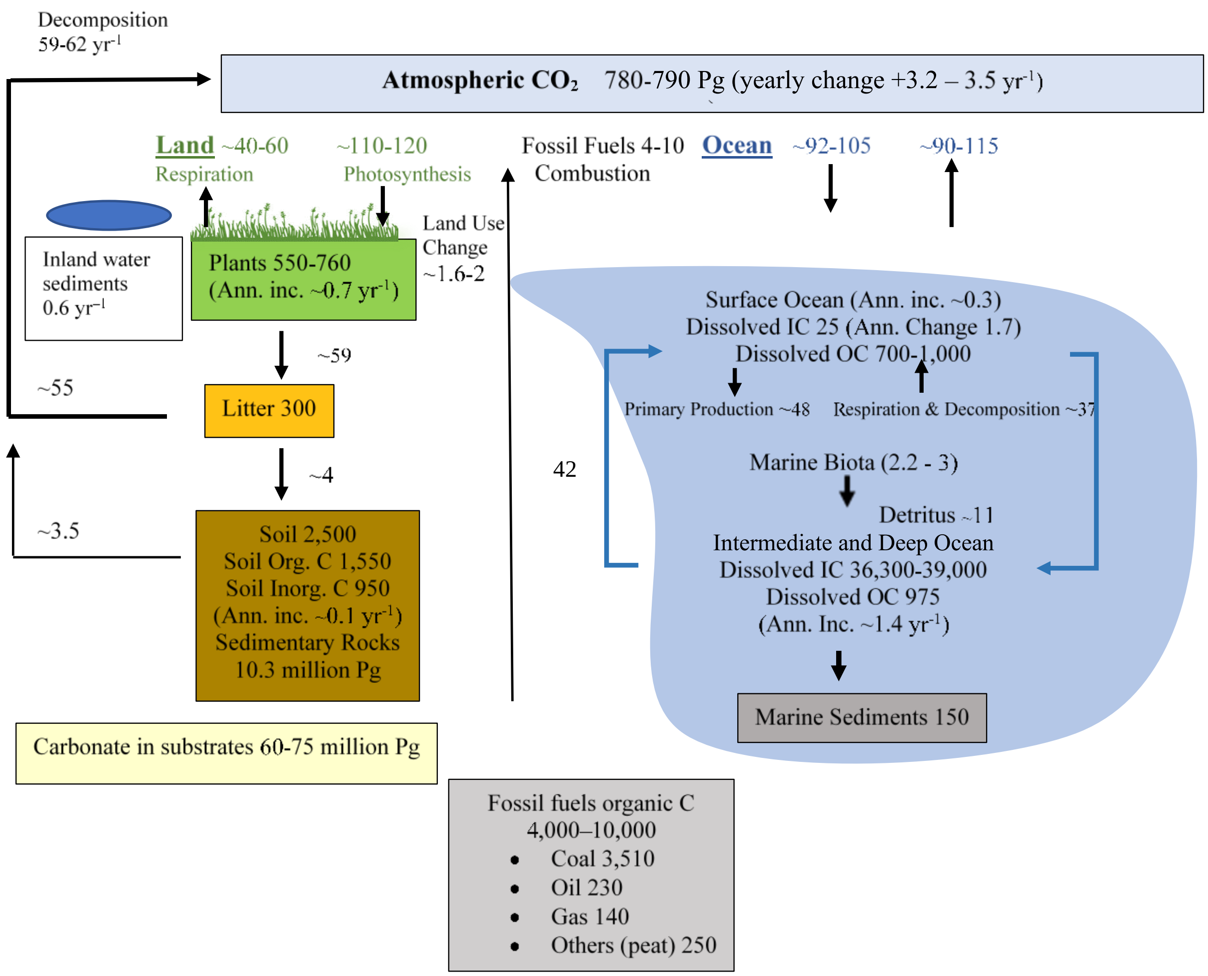
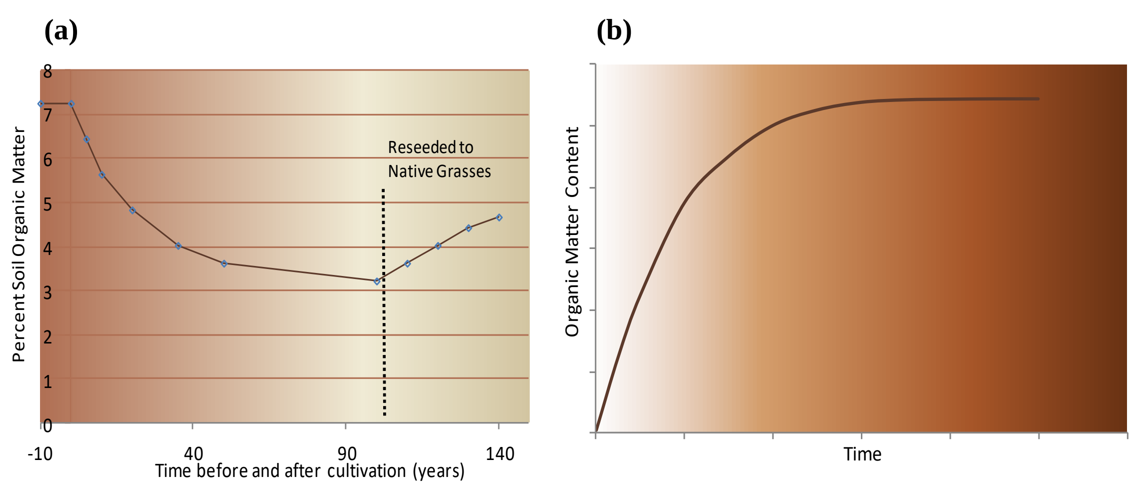


Figure G-17. **(a)** Tallgrass prairie converted to cropland with high historic organic matter content (7.5 percent). **(b)** Development of organic matter over time



Graph **(a)** shows progressive loss of organic matter in the upper 10 inches after cultivation. If field is seeded back to native grasses after 100 years, organic matter would slowly increase. Graph **(b)** With development of organic matter over time, the rate of accumulation is progressive until a constant level is reached—in equilibrium with climate, soil properties, plant community, and decomposition processes.

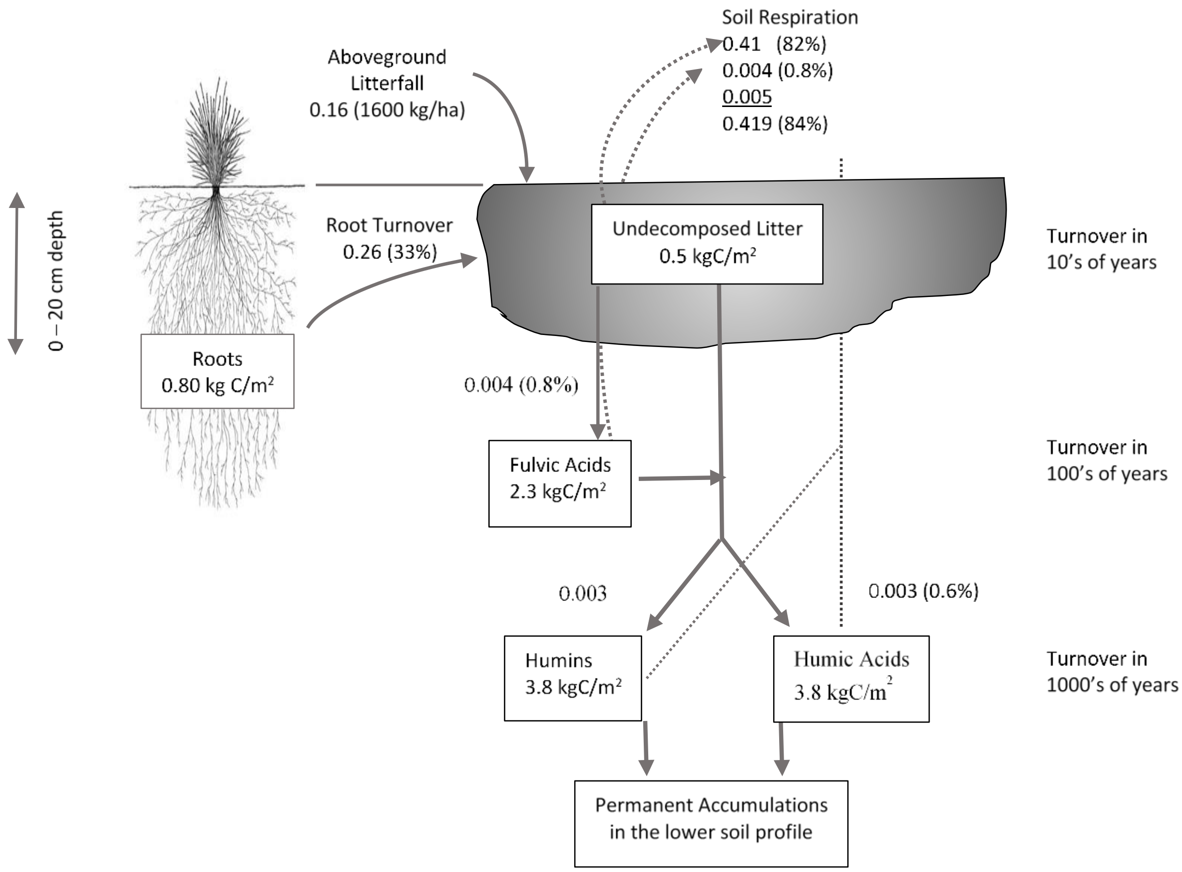
(4) Organic matter is an important and dynamic soil component in natural rangeland ecosystems. It is the foundation of a productive soil and is a principle underlying component of soil and site stability, hydrologic function, biotic integrity, and overall soil health. Soil organic matter provides important soil functions related to energy, nutrients, and biological diversity, which affect soil aggregation and subsequent infiltrability. The stratification and inherent amounts of organic matter with soil depth is an indication of proper function of soil and site stability, hydrologic function, and biotic integrity because of improved infiltrability, resistance to erosion, and a source of plant nutrients. The ramifications of organic carbon in soils and soil health are immense (Schnitzer and Khan 1989, Sylvia et al. 1998, Wolf and Snyder 2003, Paul 2007, Motuzova et al. 2011, Bj'orklund and Mello 2012, Wall et al. 2012).

(5) Soil organic matter consists of plant or animal products in various stages of breakdown (decomposition). Decomposition of plant material includes physical, chemical, and biological processes. Mineralization is a biological process in which organic substances are converted to inorganic substances by soil microorganisms. The common outputs are carbon dioxide (CO_2), energy, water, plant nutrients, and resynthesized organic carbon compounds. The rate of decomposition is determined by three major factors: soil organisms, the physical environment, and the quality of the organic matter. Bacteria and fungi are primarily responsible for mineralization of organic matter in soils. Microorganisms release enzymes that oxidize organic compounds in organic matter. The final end-products are nutrients in the mineral form.

(6) The rate of mineralization is influenced by biotic and abiotic factors, and nutrients released vary significantly among the different fractions of soil organic matter. On average, after one year, about 17 to 35 percent of the C in plant residue was incorporated into SOM (65 to 83 percent is lost to the atmosphere) (Schlesinger 1995, Himes 1998, Stewart et al. 2017). Schlesinger's 1995 model of detrital carbon dynamics at 0–20 cm soil depth on a grassland soil shows that about 84 percent of the above-ground litterfall and root turnover is lost through soil respiration (figure G-18). In grasslands, the vegetation grows rapidly; and at the same time, parts of the shoots and roots die off or are eaten. The annual increase in organic matter fluctuates between large positive and negative values, but the long-term average is approximately a zero gain (figure G-19 data from Kucera et al. 1967). Recovery of soil organic carbon in soil depends upon the soil type, initial carbon inventories, climate, field cultivation practices, and field management. Management practices capable of minimizing erosion and maximizing return of residue biomass are fundamental to the maintenance of organic matter in cultivated soils.

(7) Organic matter has a profound effect on soil physical and chemical properties, which subsequently affect hydrology. The interrelationships among all the related factors create a complex web that is dynamic with the environment. For example, from a physical point of view, soil organic matter influences and enhances soil structure, granulation, aggregate stability, and porosity, which are related to hydrologic factors such as infiltration capacity. Organic matter is highly correlated with infiltration, water holding capacity, and subsequent available water for plant growth, reduced runoff and erosion, deep percolation into the soil profile (which can recharge ground water and eventually aquifers), and subsurface lateral flow to streams and springs.

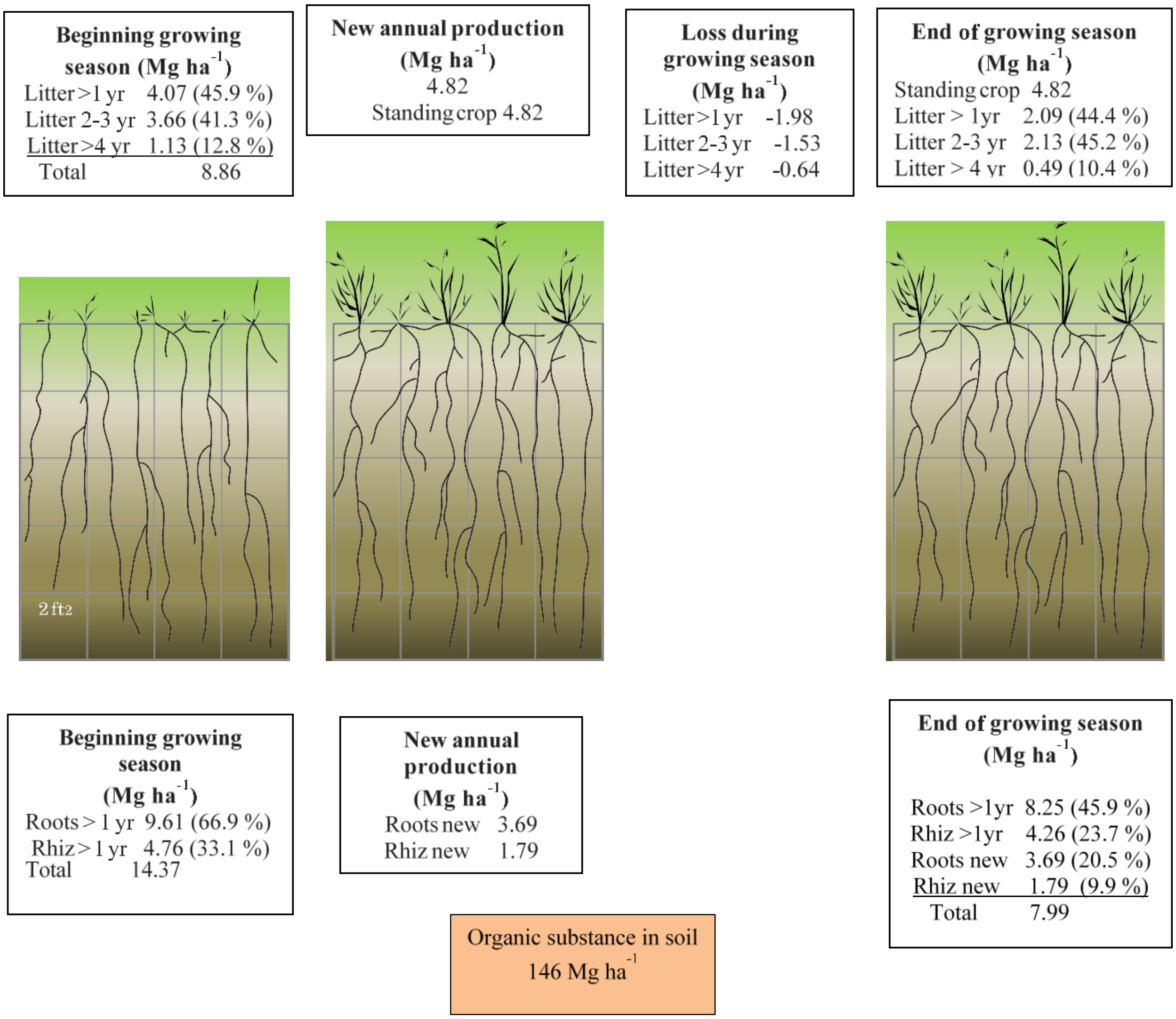
Figure G-18. Carbon dynamics (carbon pools and annual transfer) on a grassland (mollisols). (Adapted from Schlesinger 1995).



C. Soil Aggregate Stability

(1) Soil aggregation facilitates water infiltration, providing pore space (oxygen) and habitat niches for soil microorganisms, stabilization, and a buffer of soils to erosion. Soils that lack adequate residue cover are compacted by grazing or other means and have high amounts of bare ground. Such soils are more apt to have poor aggregations, soil crusting, lower water holding capacity, and higher runoff and erosion (Franzleubbers 2002a, Franzleubbers and Stuedeman 2002b). The stability of soil aggregates is often used as an index of soil and site stability and hydrologic function, as it represents the culmination of processes that bind the soil into discrete particles that resist deterioration upon wetting. Soil aggregate stability is an important concept to recognize because it is related to organic matter content and biological activity in the soil. Aggregate stability refers to how well soil aggregates hold together. Soil aggregates are soil particles that are bound together into larger particles as a result of biological activity in the soil, soil physical characteristics and chemistry.

Figure G-19. Content and turnover of organic dry matter in the Tallgrass Prairie. No grazing of large herbivores, only from insects and rodents (Data from Kucera et al. 1967).



(2) Soil microorganisms secrete compounds, fungi form hyphae (thread-like structures), and earthworms secrete a mucus (coelomic fluid that enables them to move more easily in the soil and lines their burrow paths to keep them from collapsing) that stabilizes and aggregates soil particles, essentially organic glues. Generally, soil aggregates < 0.25 mm are held together by older, more stable organic compounds, whereas larger aggregates (>0.25 mm) form from more recent biological activity and organic material. The larger aggregates are more fragile and less stable but are good indicators of soil health. Aggregate stability can be measured in the lab or in the field with test kits (Herrick et al. 2005). Tillage practices, hoof impact by livestock, and foot traffic can degrade aggregate stability.

D. Soil Structure

(1) Soil structure is a physical property of soil and is characterized by how the individual particles (sand, silt, and clay) and organic matter are arranged into larger aggregates called peds. See figure G-20. The peds break apart along natural weak points which have low tensile

strength. Soils covered by natural vegetation and undisturbed by previous tillage exemplify the inherent structure of the soil. Soil structure is identified by shape and appearance. The easiest structure to identify is single-grained where the soil particles consist of non-aggregated sand or loose windblown loess. Granular structure appears as small, rounded aggregates that are easily separated from the mass.

(i) Granular soil structure is characteristic of soil surfaces (A horizons) high in organic matter with earthworm activity.

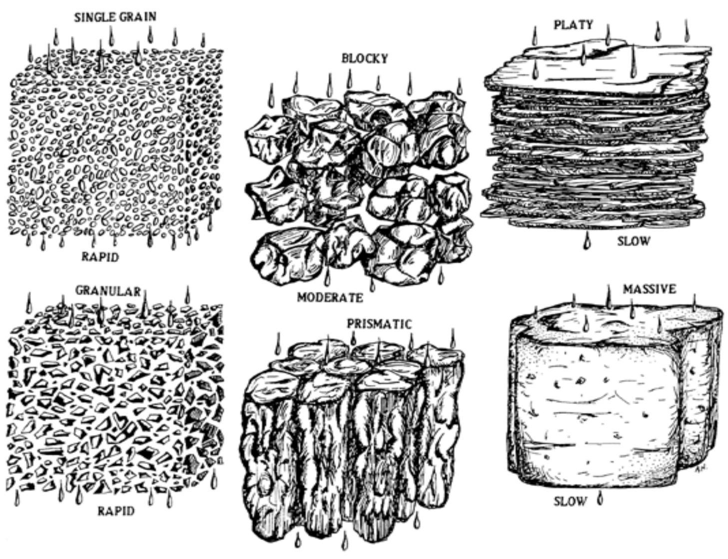
(ii) Platy structure has particles which are arranged in flattened planes and are usually arranged horizontally. During the soil forming processes, soil parent materials deposited by water and ice can develop a platy structure. Clay soils that are compacted by machinery can also develop a platy structure.

(iii) If soil peds are blocky, irregular, or cube like, the structure is blocky. There are two types of blocky structure: angular, block edges are sharp and distinct; and subangular, planes are rounded in appearance. Blocky structure is usually seen in B horizons but may also occur in the A horizon.

(iv) Columnar and prismatic structures appear as vertically oriented columns, which vary in height (subsurface horizons in arid and semiarid regions; poorly drained areas in humid regions). Columnar is differentiated from prismatic in that the top of the peds are more rounded. Prismatic or columnar structure is often associated with swelling clays and in some subsoils where sodium is present.

(v) The last structural type, massive, represents a soil condition where there is no evidence of the above structural types. The soil particles appear as a mass with no apparent pattern.

Figure G-20. Soil structural types found in mineral soils and associated infiltration rate.



(2) What happens to soil structure when rangeland has been previously cultivated or compacted by various disturbances such as machinery and heavy grazing? Several things begin to occur: reduction and damage to soil structure, soil aggregates are broken up and dispersed, and soil pores are aerated above the norm, which exposes, oxidizes, and accelerates the breakdown of soil organic matter. Farming operations that use heavy machinery (deep plows, heavy discs, chisels) can penetrate the subsoil, disturb, and alter soil structure. Rangelands with a cultivation history have undergone mixing of the surface and subsoil, which lead to a loss of organic matter, possibly bringing heavier clay particles and sodium (if in the subsoil horizon) to the surface, and development of plowpans (dense layers of soil caused by compaction

during mechanical disturbance, especially plowing). Soil surfaces of frequent and heavily disturbed soils tend to crust over after wet and dry cycles because of altered soil texture, soil physical properties, and loss of organic matter.

E. Bulk Density

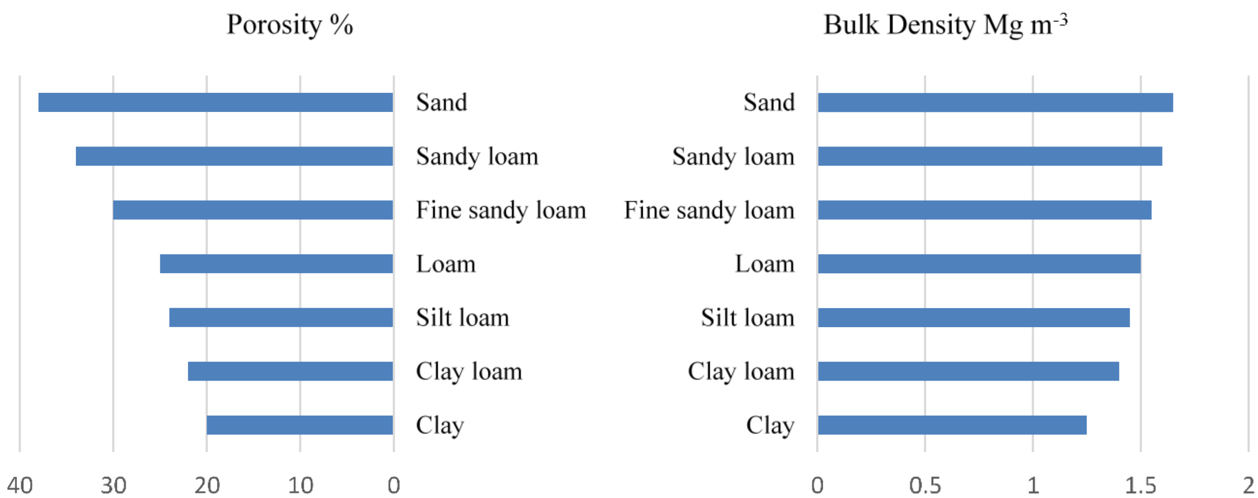
(1) Particle density and bulk density are two important factors that are inherently associated with particle size (texture) and degree of compaction (table G-13). Particle density (same as specific gravity) is the mass per unit volume of the individual particles. Particle density for coarse sand=2.65 Mg m^{-3}, silt = 2.79 Mg m^{-3}, and clay = 1.25 Mg m^{-3}. Particle density of soils with high organic matter is reduced (0.9 to 1.4 Mg m^{-3}). The SI unit for density is megagrams per cubic meter (Mg m^{-3}), which is numerically equivalent to grams per cubic centimeter (gm cm^{-2}). Bulk density can be a measure of soil compaction, although soils have predictable bulk density ranges with textural classes. Bulk density decreases as soils become finer textured (silt loams and clays). Bulk density tends to increase with soil depth due to a variety of factors such as textural changes from the original soil-forming materials, downward movement of clay, and gravity and weight of the soil compacting the material.

(2) There is a relationship between porosity, bulk density, and texture: pore space and bulk density in fine-textured soils (clays) is lower compared to coarse-textured sandy soils (figure G-21). As soils become compacted (machinery, grazing, foot traffic), there is less pore space and higher bulk density. Compaction is deleterious and negatively impacts crop and rangeland plant growth and production because it results in less water storage in the soil horizon.

Table G-13. Average bulk density values for soil textural groups (USDA-NRCS 2018a) https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/office/ssr10/tr/?cid=nrcs144p2_074844

Texture Terms:	Moist Bulk Density Mg m^{-3}
COS (coarse sand)	1.70–1.80
S (sand)	1.60–1.70
FS (fine sand)	1.60–1.70
VFS (very fine sand)	1.55–1.65
LCOS (loamy coarse sand)	1.60–1.70
LS (loamy sand)	1.55–1.65
LFS (loamy fine sand)	1.55–1.65
LVFS (loamy very fine sand)	1.55–1.60
COSL (coarse sandy loam)	1.55–1.60
SL (sandy loam)	1.50–1.60
FSL (fine sandy loam)	1.50–1.60
VFSL (very fine sandy loam)	1.45–1.55
L (loam)	1.45–1.55
SIL (silt loam)	1.45–1.55
SI (silt)	1.40–1.50
SCL (sandy clay loam)	1.45–1.55
CL (clay loam)	1.40–1.50
SICL (silty clay loam)	1.45–1.55
SC (sandy clay)	1.35–1.45
C (clay (35–50%)	1.35–1.45
C (clay) (50–65%)	1.25–1.35
SIC (silty clay)	1.40–1.50

Figure G-21. Comparison of average porosity and bulk density values with soil texture (Spaeth 2020).



645.0709 Vegetation Effects on Hydrologic Processes

A. Infiltration and runoff are regulated by the kind and amount of vegetation, edaphic, climatic, and topographic influences (Wood and Blackburn 1981). Vegetation is the primary factor that influences the spatial and temporal variability of soil surface processes which affect infiltration, runoff, and interrill erosion rates on arid and semiarid rangelands (Blackburn et al. 1992). As plant cover declines, infiltration decreases (Holechek et al. 2004). Each plant-soil complex exhibits a characteristic infiltration pattern (Gifford 1985). Hydrologic processes such as infiltration are not constant from one range or soil complex to another. Factors such as soil physical and chemical attributes, plant life growth forms, and storm dynamics can significantly change hydrologic dynamics among different ecological sites and within an ecological site.

B. Each plant community type must be evaluated in terms of what variables affect hydrology on the site. No single factor ever varies alone, especially with regard to hydrologic processes. Variables that affect site hydrology include:

(1) above- and below-ground plant morphology
(2) total production
(3) production of individual plant species
(4) total canopy cover
(5) canopy cover of individual plant species
(6) plant architecture
(7) grass growth form or habitat (sod vs. bunch caespitose)
(8) interspace
(9) shrub coppice
(10) soil physical properties
(11) soil chemical properties

C. Semiarid rangelands throughout the western United States have significant spatial and temporal variations in hydrologic and erosion processes. The spatial distribution of the amount and type of vegetation has been shown to be an important factor in modifying infiltration and interrill erosion rates on rangeland grass (Thurow et al. 1986, 1988; Spaeth et al. 1996a). In comparisons between permanent grass, cropland, and denuded forest, grass stands can have twice the infiltration capacity. See table G-14.

Table G-14. Infiltration capacity for various plant covers (Bonde and Subramanyam 1968).

Cover Type	Infiltration Capacity
Established Grass	5.1 in hr^{-1}
Wheat	3.6 in hr^{-1}
Peas	3.6 in hr^{-1}
Fallow Land	2.8 in hr^{-1}
Denuded Forest	2.4 in hr^{-1}

D. Plant life form, such as tall grasses, mid grasses, short grasses, forbs, shrubs, half shrubs, and trees and their compositional differences on a site greatly influence infiltration and runoff dynamics. Infiltration is usually highest under trees and shrubs and decreases progressively in the following order: bunchgrass, sodgrass, and bare ground (figure G-22) (Thurow et al. 1986). On the Edwards Plateau, Texas, shrub coppice zones showed highest interception and infiltration, followed by bunchgrass, then sodgrass (table G-15, figure G-23) (Blackburn et al. 1986). Infiltration rate was correlated to total organic cover and bulk density characteristics on the site. The amount of cover in the individual vegetation stands provided protection of soil structure from direct raindrop impact. Sediment production was related to the total aboveground biomass and bunchgrass cover of the site (Blackburn et al. 1986).

Table G-15. Summary of canopy interception, interrill erosion, runoff, and erosion from oak, bunchgrass, sodgrass, and bare ground dominated areas, Edwards Plateau, Texas. Based on 4 inches rainfall rate in 50 minutes (data from Blackburn et al. 1986). Tarrent silty clays overlying an undulating fractured caliche, slope (l–2 percent).

Condition	Oak Motte	Bunchgrass	Sodgrass	Bare Ground
% Canopy Interception	7	-	-	-
% Grass and Litter Interception	-	0.5	0.4	0.0
% Litter Interception	12	-	-	-
Interill Erosion (lbs/ac)	0.0	179	1,250	5,358
% Surface Runoff	0.0	24	45	75
% Infiltration	81	75.5	54.6	25

Figure G-22. Average infiltration rates for three vegetation types, Edwards Plateau, Texas (adapted from Thurow et al. 1986).

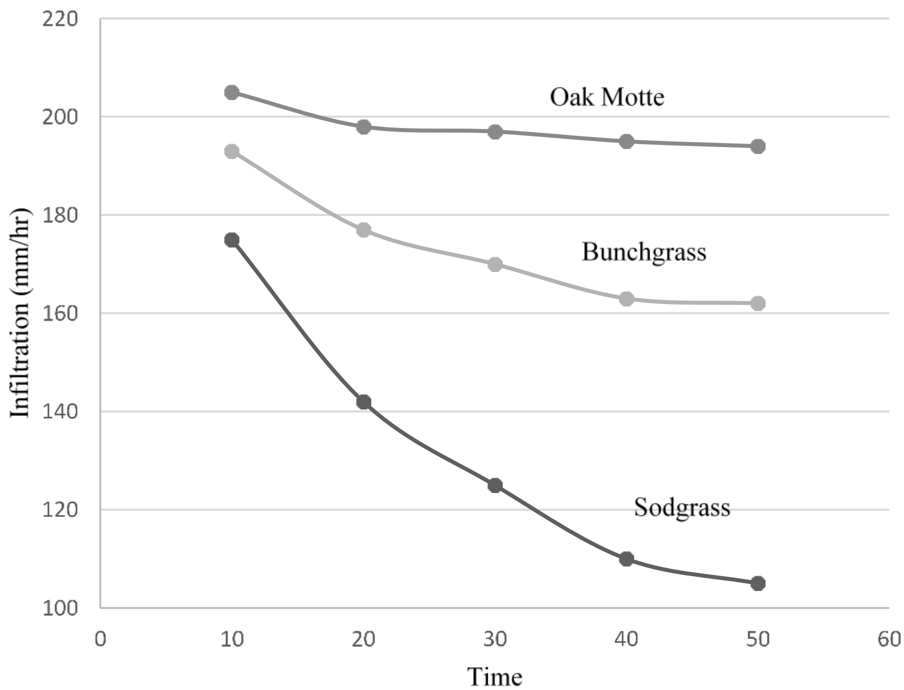
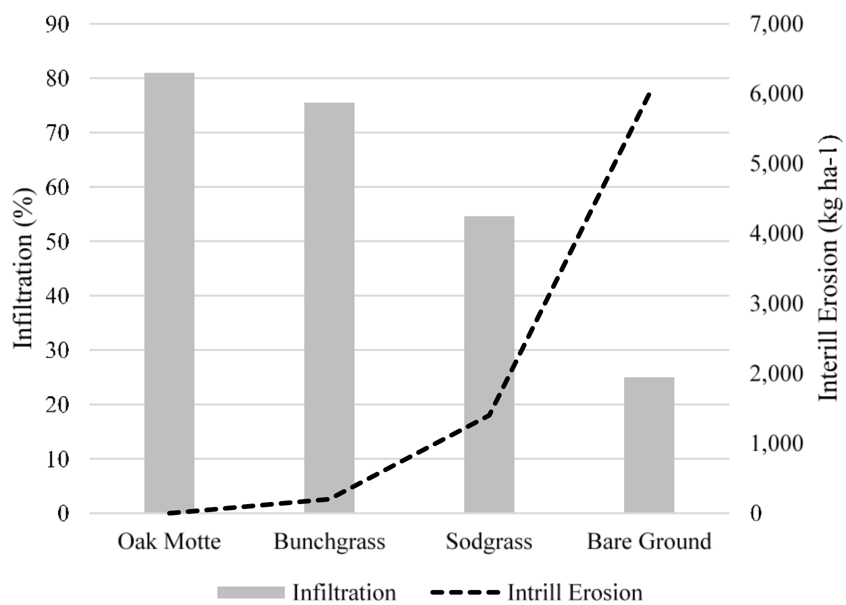


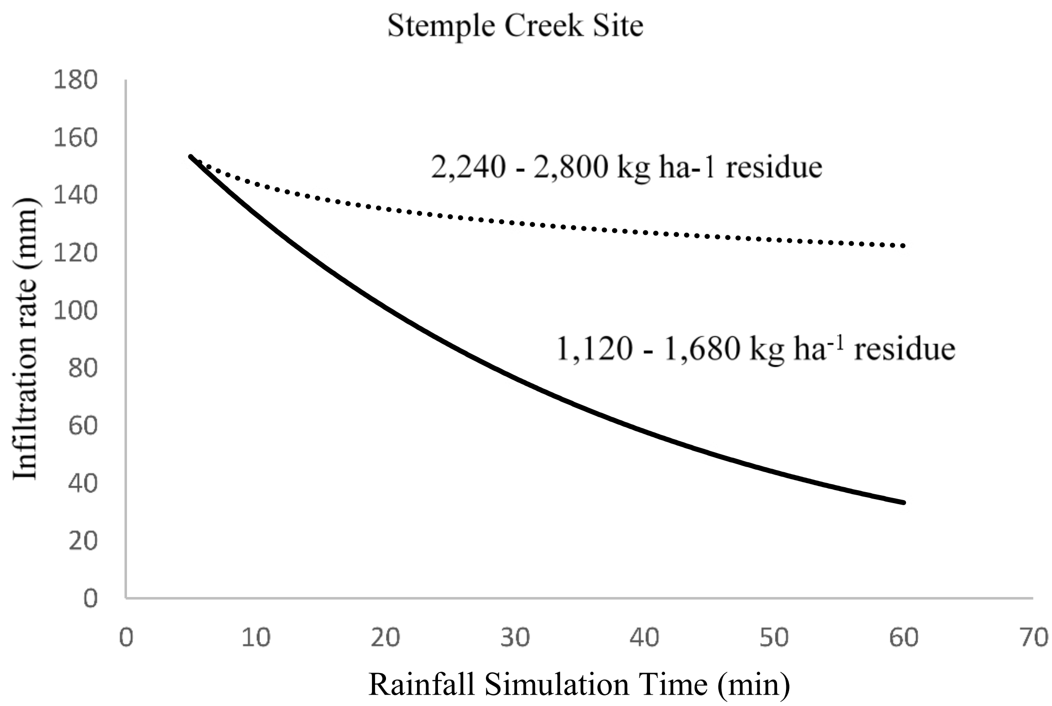
Figure G-23. Amount of infiltration and interrill erosion from oak, bunchgrass, sodgrass, and bare ground dominated areas on Edwards Plateau, Texas. Rainfall Simulation applied 4 in rain in 50 minutes. Tarrent silty clays overlying an undulating fractured caliche, slope (l–2 percent) (data from Blackburn et al. 1986).



E. Annual grasses can provide sufficient cover to protect the soil surface, but are vulnerable to wildfire, which usually denudes the site, causing high risk for accelerated runoff and high erosion rates. In California annual grass communities, foliar cover of grass species may be high. However, rainfall simulation experiments showed that the amount of biomass on the site (with high cover) was more closely correlated with higher infiltration and lower runoff than foliar cover (figure G-24) (Spaeth 2020).

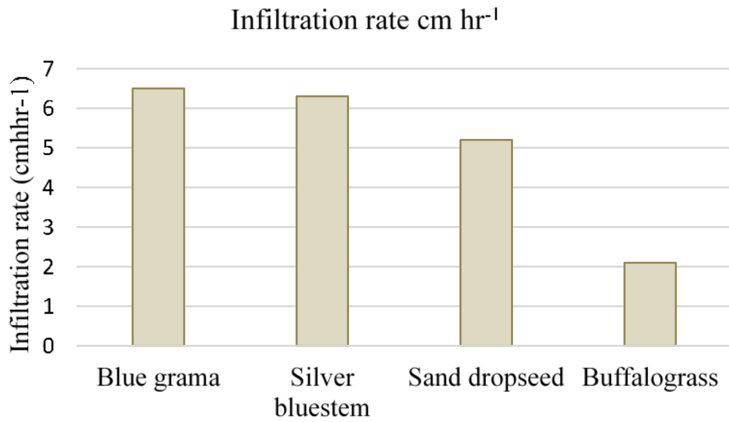
F. Levels of foliar cover necessary for site protection against accelerated soil erosion on rangelands vary from 20 percent in Kenya (Moore et al. 1979) to 100 percent for some Australian conditions (Costin 1959). Most studies indicate that cover of 50 to 75 percent is probably sufficient to prevent degradation from accelerated soil erosion processes (Wood and Blackburn 1981, Gifford 1985,Weltz et al. 1998, Pierson et al. 2011, 2016, Williams et al. 2014, and Cadaret et al. 2016 a, b).

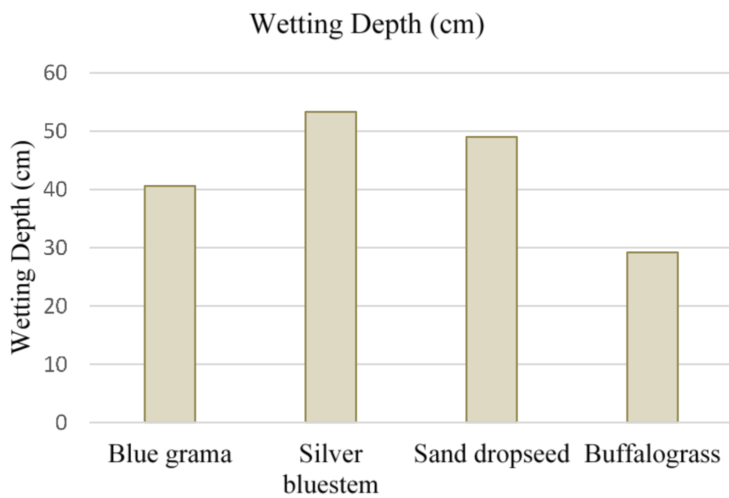
Figure G-24. Rainfall simulation infiltration rate vs. time at Stemple Creek site, California. Soil type identical, with two residue levels (Spaeth 2020). Foliar cover was near 100 percent on all plots.



G. Individual plant species, such as different grasses, forbs, and shrubs, also have a profound effect on hydrology and erosion dynamics (Spaeth 1996a, b). Field studies have documented infiltration capacity with individual species composition. Dee et al. (1966) found that water infiltrated three times faster in blue grama and silver bluestem (*Bothriochloa saccharoides*) stands than areas dominated by annual weeds such as summer cypress (*Kochia scoparia*) and windmill grass (*Chloris verticillata*) (figure G-25). Blue grama terminal infiltration capacity was also about three times higher than buffalograss stands, holding soil type constant. Wetting front was greatest under silver bluestem, most likely because of deeper rooting depth and macropores from root decay.

Figure G-25. Infiltration and wetting front experiments in shortgrass prairie, west Texas (Dee et al. 1966).





H. Mazurak and Conard (1959) evaluated infiltration capacity of different grass species as three locations in Nebraska (table G-16). Infiltration on western wheatgrass plots was highest at two locations. Big bluestem was associated with greater infiltration rates at two locations, and smooth bromegrass and buffalograss (sod forming species) were associated with low infiltration.

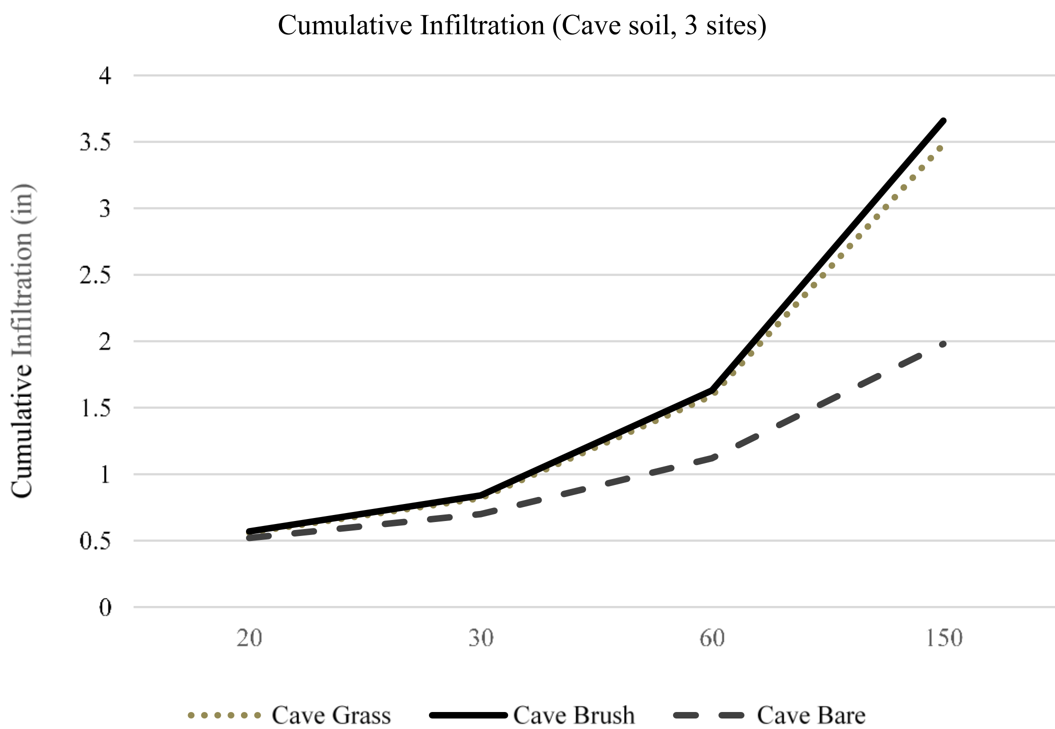
I. On the Walnut Gulch Experimental watershed in southeastern Arizona, Tromble et al. (1974) conducted a study of infiltration rates for three vegetation states on Cave and Hathaway gravelly loam soils: grass, brush, and bare ground. Dominant vegetation on the Cave site was whitethorn acacia (*Acacia constricta*), creosotebush (*Larrea divaricata*), sandpaper bush (*Mortonia scabrella*), tarbush (*Flourensia cernua*), yucca (*Yucca* spp.), common sotal (*Dasylirion wheeleri*), Mexican bluewood (*Condalia mexicana*), squawbush (*Condalia spathulata*), burroweed (*Haplopappus tenuisectus*), and various cacti. The grasses included black grama (*Bouteloua eriopoda*), fluffgrass (*Tridens pulchellus*), sideoats grama (*Bouteloua curtipendula*), wolftail (*Lycurus phleoides*), threeawn (*Aristida* spp.), and annuals. Dominant vegetation on the Hathaway soil was black grama, fluffgrass, curly mesquite (*Hilaria belangeri*), and a limited number of annuals. Shrubs encountered were burroweed, whitethorn, creosotebush, bear-grass (*Nolina microcarpa*), yucca, common sotol, and ocotillo (*Fouquieria splendens*). On the Cave gravelly loam, cumulative infiltration was very similar for the brush and grass states, compared to significantly lower cumulative infiltration for bare ground (figure G-26a). The Hathaway gravelly loam site exhibited the same trend for grass ungrazed and brush. Cumulative infiltration was significantly lower for the grazed grass site (figure G-26b).

Table G-16. Field experiments comparing infiltration rates of different grass species at three locations in Nebraska using ring infiltrometer at 60 min, values are cm hr^{-1} averaged for 7 years (Mazurak and Conard 1959).

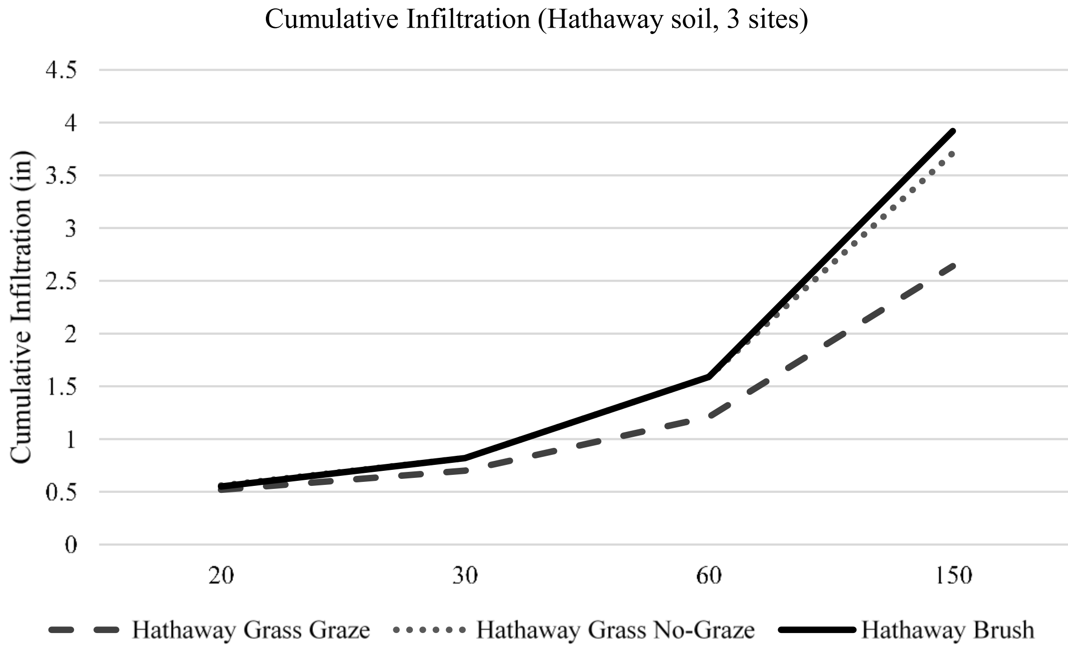
Sharpsburg scl l (Lincoln, NE)	Holdrege vfsl (North Platte, NE)	Rosebud vfsl (Alliance, NE)
Western wheatgrass (12.2)	Big bluestem (5.7)	Western wheatgrass (6.9)
Crested wheatgrass (10.8)	Russian wildrye (5.0)	Desert wheatgrass (4.7)
Big bluestem (9.7)	Western wheatgrass (4.8)	Crested wheatgrass (4.1)
Desert wheatgrass (8.7)	Blue grama (4.7)	Russian wildrye (3.4)
Intermediate wheatgrass (8.6)	Sideoats grama (4.7)	Smooth bromegrass (3.8)
Buffalograss (8.2)	Desert wheatgrass (4.0)	Intermediate wheatgrass (2.9)
Smooth bromegrass (7.8)	Smooth bromegrass (2.8)	
Blue grama (7.4)	Buffalograss (2.4)	
Sideoats grama (7.0)		

Figure G-26. Average infiltration rates on two soil-vegetation complexes at the Walnut Gulch Experimental Watershed in southeastern Arizona. **(a)** cumulative infiltration (Cave soil, three sites) and **(b)** cumulative infiltration (Hathaway soil, three sites) (Tromble et al. 1974).

(a)



(b)



J. Some shrubs and half-shrubs are associated with coppice dunes or mounds composed of litter and wind-transported soil. Field experiments show that surface soil organic carbon, bulk density, percentage silt, and infiltration and interrill erosion rates are higher for shrub-coppice dunes and shrub-interspace areas compared to interspace (figures G-27 and G-28) (Blackburn 1975, Johnson and Gordon 1988, Blackburn et al. 1990, 1992; Pierson et al. 2001, 2002a, 2008).

Figure G-27. Infiltration curves for the big sagebrush community, Duckwater Watershed, Nevada. (data from Blackburn 1975).

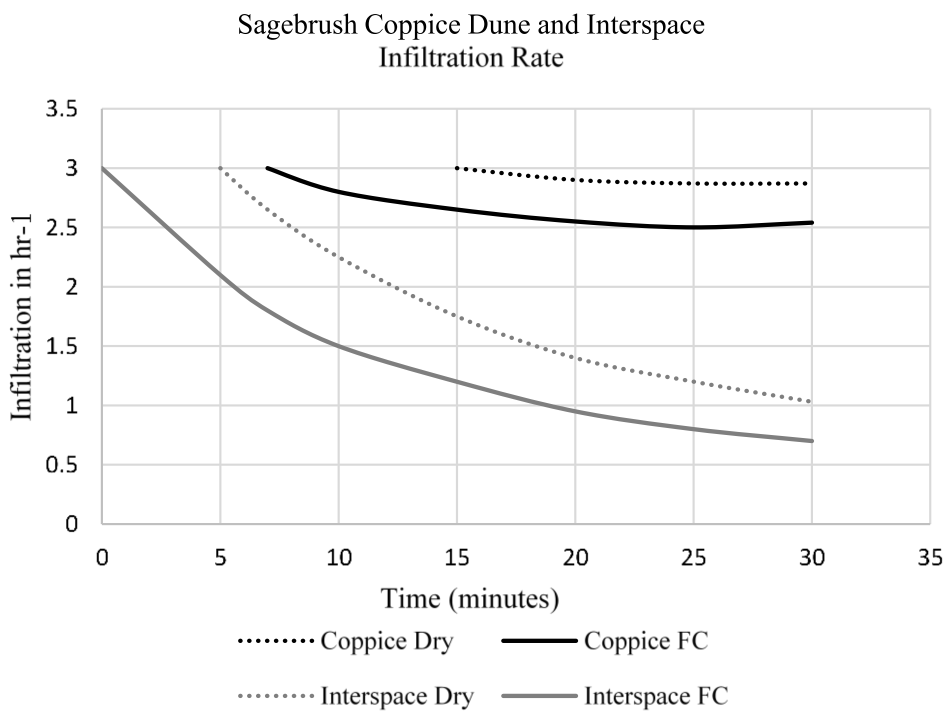
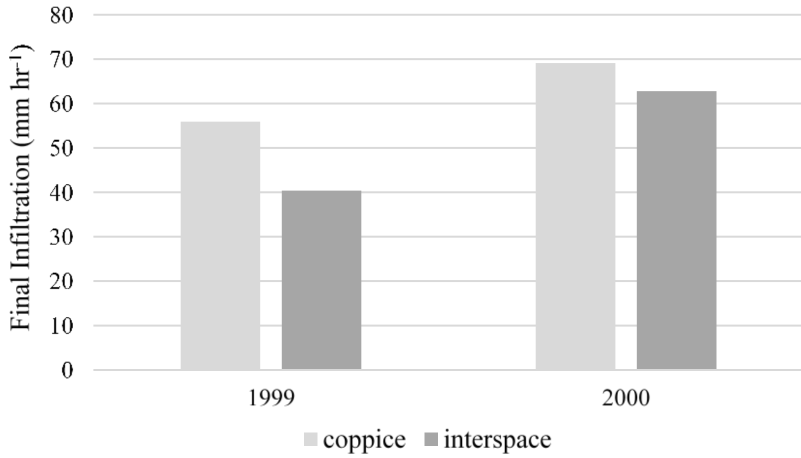
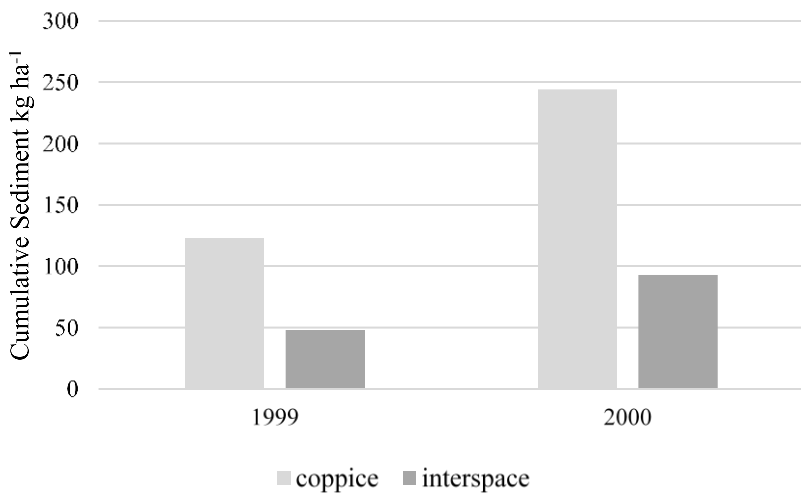


Figure G-28. **(a)** Average final infiltration rates on sagebrush coppice and interspace. **(b)** Cumulative sediment losses on sagebrush coppice and interspace. Mountain big sagebrush site, Denio, Nevada. (Pierson et al. 2001).

(a)



(b)



K. Vegetation patches (small clumps of grasses 0.5–2 m^2 to large tree groves 100–1,000 m^2) and other obstructions such as logs, rocks, and ant mounds on the landscape act as barriers and impediments that slow and trap runoff water, sediments, and nutrients from open interspace areas (Wilcox and Breshears 1995, Ludwig et al. 2005). In addition, when vegetation patch growth is enhanced, capturing water and nutrients, new biomass and woody growth further increases the capacity of the patch to intercept overland flow from subsequent rainstorm events (Ludwig et al. 2005). When grazing or other disturbances reduce vegetative cover in patches, not only is forage production reduced, but runoff and sediment losses can increase.

645.0710 Case Studies: Review of Vegetation Effects on Hydrology and Erosion

A. Tall grass prairie

Soils and vegetation data were collected along a line transect extending eight-tenths of a mile across a chalk flat range site in Gove County, Kansas (Linnell 1961). Infiltration was collected along the transect, using a ring infiltrometer. Soils were friable silt loams and light silty clay loams. Clay content was higher in the lower horizons. The dominant plant species were sideoats grama, buffalograss, salt grass, little bluestem, sand dropseed, and big bluestem. Average basal cover and above ground biomass were 16.4 percent and 2,348 lbs acre^{-1} respectively. Infiltration rates varied considerably depending on the soil properties and vegetation. Infiltration was higher when little bluestem was dominant, compared to sideoats grama-dominated sites.

B. Short grass prairie

Water infiltrated three times faster in blue grama and silver bluestem (*Bothriochloa saccharoides*) stands than areas dominated by annual weeds such as summer cypress (*Kochia scoparia*) and windmill grass (*Chloris verticillata*) (Dee et al. 1966). Wetting front was greatest under silver bluestem, most likely because of deeper rooting depth. Infiltration rates were three times greater for blue grama (bunch grass growth form), compared to buffalograss (sodgrass growth form) (Spaeth 1990).

C. Short grass prairie, weedy species

Some weedy species such as broom snakeweed (*Gutierrezia sarothrae*) are associated with similar infiltration rates found in native grass stands (historic plant reference communities) in west Texas short grass prairie (Spaeth 1990). On a loamy ecological site in west Texas, infiltration rates in broom snakeweed stands were equal to reference state blue grama stands. The implication is that vegetation states within an ecological site or successional stage are not always correlated with hydrologic condition. Some half-shrub and shrub species develop coppice dunes beneath the plant, which capture additional organic matter and windblown silt.

D. Mixed grass prairie, clubmoss vs. mid grasses

In rainfall simulation studies near Killdeer North Dakota, runoff on soils at antecedent moisture with 17 to 25 percent composition by weight of clubmoss (*Lycopodium dendroideum*) had 0.28 in hr^{-1} of runoff compared to near zero runoff on sites with native mid-grasses.

E. Mixed grass prairie

(1) Aase and Wight (1973) measured and compared infiltration rates between undisturbed mixed grass prairie and adjacent prairie sandreed (*Calamovilfa longifolia*) colonies. The predominant species in the mixed grass component were western wheatgrass (*Agropyron smithii*), fringed sagebrush (*Artemisia frigida*), blue grama (*Bouteloua gracilis*), sedges (*Carex* spp.), prairie junegrass (*Koeleria cristata*), and needle and thread grass (*Stipa comata*).

(2) Prairie sandreed colonies were interspersed in the mixed grass vegetation and measured 20 ft in diameter. According to the profile descriptions, sand content in the A horizon and clay content in the B horizon were higher under the prairie sandreed colonies. Statistically, only the clay content in the upper one to two inches was significantly different. Infiltration was almost four times higher (9.0 in hr^{-1}) in the prairie sandreed colonies than the surrounding vegetation mixed grass vegetation (2.4 in hr^{-1}). The authors attributed the higher infiltration rate to the vigorous growth form of prairie sandreed. Less raindrop impact on the soil surface caused less sealing of the soil surface. Soil texture may have been a secondary influencing

factor which influenced infiltration rates, as indicated from the small textural differences between the two plant communities.

F. Tap rooted and fibrous rooted plants

In the Boise river watershed, Pearse and Wooley (1936) compared the absorption rates of water between bare soil plots and vegetated plots. In general, plots with a single plant absorbed water 71 percent faster than bare soil plots. Compared to bare soil, a fibrous-rooted plant was associated with a 127 percent increase in infiltration, while a 51 percent increase in infiltration was noted for tap-rooted species.

G. Soil loss in relation to bare soil conditions

(1) On reclaimed grassland sites in South Dakota, a marked increase in soil loss was recorded when bare soil increased from 28 to 45 percent (Ries and Hoffmann 1986).
(2) Lane et al. (1987) conducted large plot rainfall simulation studies on five sites in semiarid and desert rangeland areas in Arizona and Nevada. Three treatments were evaluated: natural vegetation, vegetation removed, and bare soil conditions. Sites differed in plant communities, soils, and locations. When all data from both states were pooled, a 39 percent decrease in average infiltration rates was observed by removing the vegetative canopy cover. Also, when rock and gravel cover was removed from the clipped sites, an additional decrease of 34 percent in infiltration rate occurred. A 60 percent decrease in average infiltration rates occurred between the vegetated and bare soil areas. “Vegetative canopy cover and surface cover of rock and gravel exhibited comparable influences on final infiltration rates. Final infiltration rates decreased significantly as vegetative canopy cover and soil surface rock and gravel cover decreased" (Lane et al. 1987).
(3) Branson and Owen (1970) found that runoff on salt desert shrub watersheds in western Colorado were directly related to the percentage of bare soil within a watershed. As bare soil surfaces increased, runoff increased (r = 0.81); and as plant cover plus mulch increased, runoff decreased (r = -0.80).
(4) Lysimeter Study, Grass vs. Bare Soil: Hino et al. (1987) investigated the role of grass on infiltration processes and subsurface flow (table G-17). Lysimeter I, grass was planted (species not given, mean height was 24 inches); lysimeter II was bare soil. Soil was a loamy clay. The dimensions of the lysimeter were 7.4 ft. in length x 1.3 ft. in width x 2.3 ft. in depth. The lysimeters were inclined at a slope of 10 percent.

Table G-17. Water use by grass and bare soil.

Treatment	Bare Soil	Grass Cover
Total water applied (mm)	500	500
Infiltration (mm)	372	496
Surface runoff (mm)	128	4
Evaporation/Transpiration (mm)	194	354
Ground water flow (mm)	176	140

H. Impacts of plant cover, rock cover, slope, and soil Depth on infiltration on semiarid rangeland in New Mexico: On semiarid rangeland (slopes 16 –70 percent) in the Guadalupe Mountains of southeastern New Mexico, infiltrability was strongly influenced by vegetal cover and biomass. Plant cover was generally better correlated with infiltrability than plant biomass. Aerial cover was a better indicator of infiltrability than basal cover. "The relative importance of grasses, shrubs or litter was dependent on their respective abundance, especially grass" (Wilcox et al. 1988). On shallow soils, the impacts of soil depth became more acute as infiltration progressed. Rock cover was negatively associated with infiltrability because of low vegetal cover. A positive correlation was found between slope gradient and infiltrability, which may be due to increased interflow rates with increases in slope (Wilcox et al. 1988).

I. The importance of soil and vegetation and their influence on rangeland hydrology: Grazing management treatments have been investigated more extensively than any other issue in rangeland hydrology research (Blackburn 1984). Treatments such as grazing intensity and systems are often compared with respect to infiltration and sediment yield. Studies of this nature are often of limited value since the "real issue is not the practice itself, but how the practice alters the soil and vegetation components that influence the hydrologic relationships" (Blackburn et al. 1986).

J. Infiltration in various plant communities in Nevada: Infiltration rates of 29 plant communities and soils on five rangeland watersheds in Nevada varied considerably within and between watersheds. "Highest infiltration rates and lowest sediment production occurred on sites with well-aggregated soils free of vesicular porosity" (Blackburn and Skau 1974).

(1) On five watersheds in Nevada, Blackburn (1975) found that soil surface horizon morphology had the greatest influence on infiltration. On a scale of 1 to 5, 1 = sandy texture or well aggregated granular structure without vesicular pores, and 5 = strong platy structure having many vesicular pores, or clayey and massive. More sediment was produced from moist soils at field capacity than for dry conditions because soil surface instability was enhanced when it was saturated. Sediment production decreased on sites where organic matter, sand-sized particles, coppice dunes, and litter increased. Sediment production was usually greater as bulk density increased in the surface four inches.

(2) Invasive plants have contributed to rapid desertification and loss of ecosystem services in the last century. Extensive woody plant encroachment altered runoff and soil erosion across much of the drylands and significantly contributed to desertification. An example is the Great Basin region in western North America, where over 20 percent of Great Basin ecosystems have been significantly altered by invasive plants, especially exotic annual grasses and native conifers, resulting in loss of biodiversity. This land conversion has resulted in desertification and reductions in forage availability, wildlife habitat, and biodiversity (Pierson et al. 2011, 2013; Miller et al. 2013).

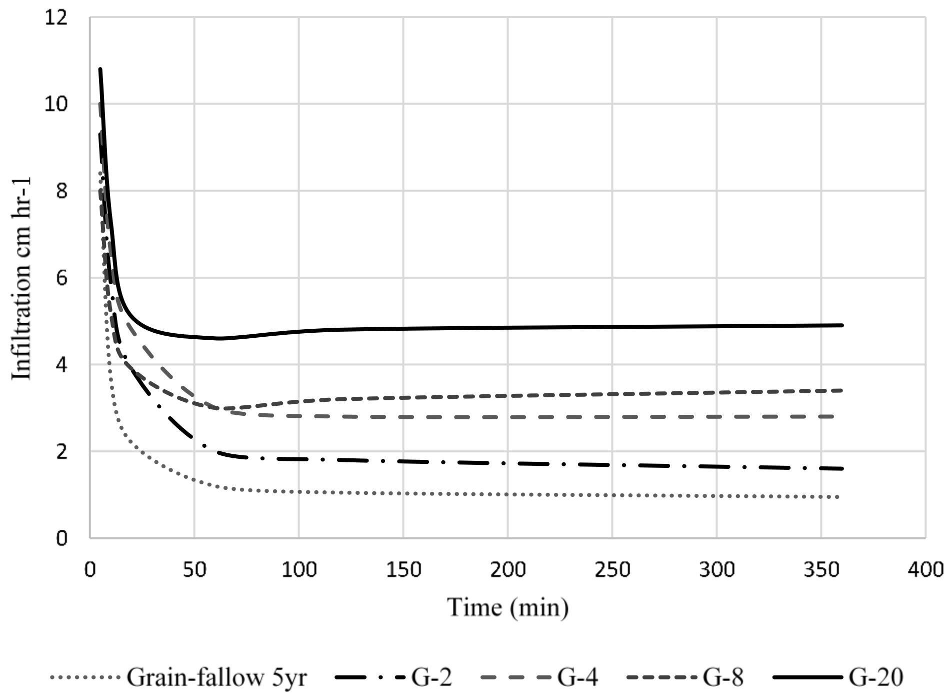
K. Mazurak et al. (1960) compared grain crop infiltration with various age-seeded perennial grass stands of intermediate wheatgrass (Agropyron intermedium) and smooth bromegrass (Bromus inermis). See figure G-29. Infiltration rates of grass seedings starting at age four years were significantly different from a grain-fallow system. Infiltration increased with age of grass stands, and the authors discussed possible effects that may be due to more developed root systems.

L. Water intake and plant cover on rangelands: "The more plant cover on rangeland soils, the more rainfall will be absorbed" (Rauzi 1960). Comparisons of infiltration rates on a silty soil near Newell, South Dakota showed that higher plant cover and good range condition (2,600 lbs ac^{-1} biomass production) absorbed 1.43 in hr^{-1} during a rainfall simulation test. In comparison, a low-cover condition (1,200 lbs ac^{-1} biomass production) absorbed only 0.61 in hr^{-1} of artificial rain.

(1) The amount of plant material on the soil surface is important in absorbing the impact of raindrops. Erosion and soil surface sealing are also reduced (Rauzi 1960). "Regardless of soil type, water-intake rates depend on the type of plant cover, the amount of standing vegetation, and the amount of mulch material on the ground" (Rauzi 1960).

(2) Infiltration is usually highest under trees and shrubs and decreases progressively by bunchgrass, sodgrass, and bare ground (Blackburn 1975, Wood and Blackburn 1981, Knight et al. 1984, Thurow et al.1986).

Figure G-29. Comparison of infiltration of grain crop with different age intermediate wheatgrass and smooth bromegrass pastures. Notes: plots hayed with 40 lbs ac^{-1} ammonium nitrate in spring, not grazed. (Age of stand in years: G-2 = 2 yr. per. Grass; G-20 = 20 yr. per. grass).

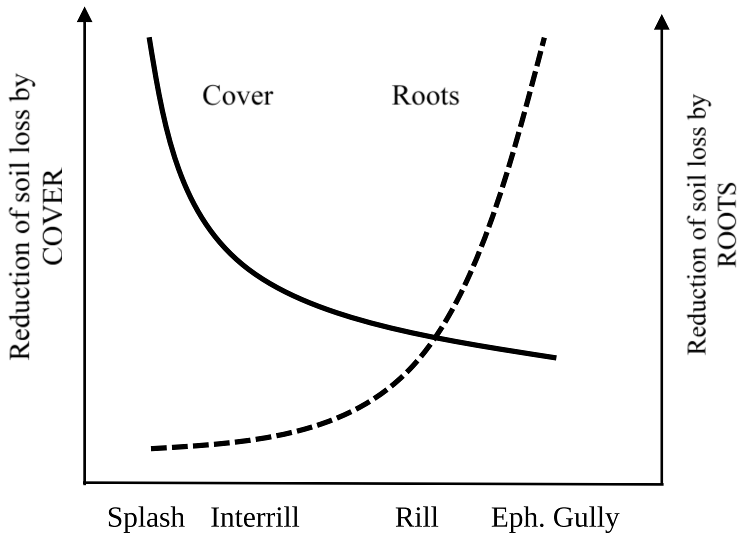


M. Runoff and vegetation relationships: "Runoff varies with the kind of vegetation as well as the quantity of vegetation" (Branson et al. 1981). Runoff quantities from different vegetation types are related to environmental complexes with major influential variables such as vegetation, soil, temperature, altitude, and precipitation zones (Branson et al. 1981). Rainfall events ranging from 1.5 to 3 in hr^{-1} have 4 to 9 times more runoff on bare soil compared to areas with adequate plant cover (Branson et al. 1981).

N. Effect of roots on rangeland hydrology and erosion: In addition, biotic factors such as roots and soil flora can enhance infiltration rates and capacity (Pearse and Wooley 1936, Lipiec et al. 2006). It was found that infiltration rates in grass-covered soil can be higher (van Noordwijk et al. 1991, Mitchell et al. 1995) or lower (Gish and Jury 1983, Huat et al. 2006, Ng and Menzies 2014, Ng et al. 2016) than those in bare soil. Infiltration rates in grass-covered soil were lower when roots were actively growing, but they were higher when mature roots were decaying.

Based on the structural model (figure G-30) indicating the relative importance of vegetation cover and plant root density on the different water erosion processes (splash, interrill, rill, and ephemeral gully erosion), vegetation cover is the most important parameter for reducing splash and interrill erosion. In contrast, plant roots have greater influence of reduction of rill and ephemeral gully erosion.

Figure G-30. Structural model indicating the relative importance of vegetation cover and plant root density on different water erosion processes, i.e., splash, interrill, rill, and ephemeral gully erosion.

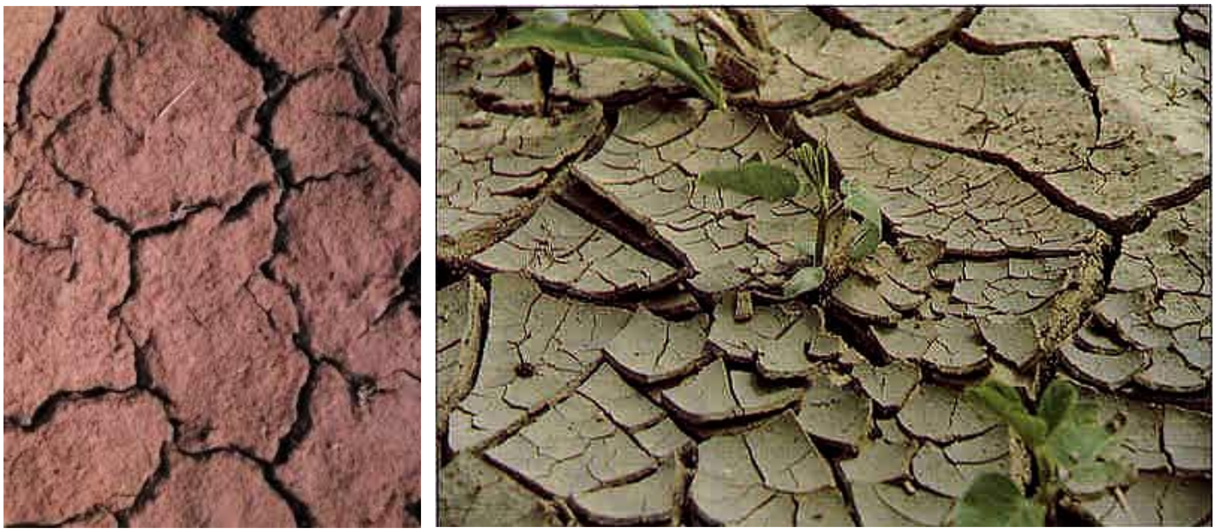


645.0711 Physical, Chemical, and Biological Crusts affect Infiltration (Spaeth 2020).

A. Physical and chemical crusts can be problematic in cropland soils and rangelands where these crusts alter ecosystem functions related to soil health. These crusts can form on the soil surface by raindrop impact on bare soil, evaporative processes forming chemical crusts, and compaction from various sources such as grazing and other related vehicular traffic. Vesicular crusts are common where aggregate stability breaks down, and gas bubbles form a crusty layer 1–10 mm thick. As raindrops impact bare ground, whatever remnant of aggregate stability remains is further dispersed to the inherent soil particles. The smaller soil particles wash into and block any existing soil pores and form a crust as the soil dries. As drying occurs, soil surface tension contracts the soil particles into a dense layer. This clogging action can reduce pore continuity and infiltration capacity by 90 percent (Belnap et al. 2001). The outcome results in low saturated hydraulic conductivity and increased runoff and soil erosion. As this process continues, poor soil structure, reduced pore space, consistently less and unstable soil aggregates, decreases in organic matter, and less microbial function become more pronounced. In contrast to physical soil crusts reducing hydrologic function, these crusts may have a positive influence on reducing wind erosion—at least temporarily. The presence and perpetuation of soil physical crusts creates an environment that is associated with low plant reproductive capacity, negligible seed germination; and on rangelands, this condition is highly conducive to the beginning of desertification.

B. Physical crusts can commonly form on silt, clay, and loam soils; and in some cases, salts either in the soil or irrigation water can promote clay dispersion. As aggregates are dispersed, clay particles permeate soil pores; and when soil begins to dry out, the soil surface forms a thin cemented layer, often with cracks, which inhibits water infiltration, exacerbating runoff and potential erosion (figure G-31). Soils with low organic matter are also more prone to developing physical crusts and soil sealing on tilled cropland. The formation of physical soil crusts is common after a rain event on freshly tilled and planted fields and often results in poor seedling emergence and the need to reseed.

Figure G-31. Physical soil crusts on cropland have reduced infiltration capacity and porosity, have higher density, and are an indication of high evaporation rates in the presence of sunlight (Belnap et al. 2009) (Courtesy of USDA-NRCS, Soil Health Division).



C. Biological Soil Crusts (Spaeth 2020)

(1) Biological crusts (also referred to as microphytic, microbiotic, crytogamic, and cryptobiotic), where prevalent, are comprised of various microorganism complexes (green algae, cyanobacteria, lichens, mosses, microfungi, and bacteria) (figure G-32). The impact of biological soil crusts on infiltration rates and soil erosion is poorly understood and often contradictory.

(2) Biological soil crusts can reduce infiltration rates and increase soil erosion by blocking flow through macropores, or they may enhance porosity and infiltration rates by increasing water-stable aggregates and surface roughness (Loope and Gifford 1972, West 1991, Eldridge 1993). Disturbance of the soil surface can disrupt biological soil crusts and result in enhanced wind erosion–and may or may not affect water erosion processes (Belnap and Gillette 1998, Eldridge and Koen 1998, Barger et al. 2006, Li et al. 2008, Belnap et al. 2009).
Li et al. (2008) evaluated the interactions between biological soil crusts and runoff on a hillslope with patchy shrub vegetation. They reported that in undisturbed areas 53 percent of the simulated rainfall became runoff from the crust patches, and 55 percent of this was redistributed and absorbed by the shrub patches. In addition, approximately 75 percent of the sediments, 63 percent of the soil carbon, 74 percent of the nitrogen, and 45 percent to 73 percent of the dissolved nutrients transported in runoff from the crust patches were transported to shrub patches. The disturbance of crust patches tended to result in the uniform distribution of water over the whole slope, with a corresponding reduction in the transport of runoff and nutrients from the crust patches to the shrub patches. The exact response on runoff and soil erosion is a function of site disturbance and level of development of the biological soil crusts (Belnap et al. 2013).

(3) When studies are evaluated based on biological crust type, the results indicate that biological crusts in hyper-arid regions reduce infiltration and increase runoff. Biological soil crusts have mixed effects in arid regions, and infiltration is increased and runoff reduced in semi-arid cool regions. Most research has shown that intact biological soil crusts are effective in reducing soil erosion and transport of sediment and associated contaminants (Belnap 2006).

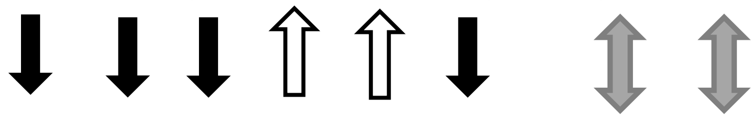
Figure G-32. Biological soil crusts comprised of algae, cyanobacteria, and nonvascular plants (mosses, lichens) have evolved in many rangeland ecosystems. Canyonlands and Arches National Parks are hosts to good examples of biological soil crusts that help stabilize soil interspaces around vegetation patches. (Courtesy of USGS Canyonlands Research Station).

645.0712 Grazing Effects on Hydrology and Erosion

A. A considerable number of studies and reviews concern grazing impacts on hydrologic processes on rangeland (Gifford and Hawkings 1978; Branson et al. 1981; Blackburn et al. 1981; Blackburn 1984; Warren et al. 1986a, b, c; Warren 1987; Savory 1988; Thurow 1991; Spaeth et al. 1996a, b; Weltz et al. 1998; Asner et al. 2004; Holechek et al. 2004). From a conservation-management perspective, the grazing management specialist should consider how grazing is affecting the soil surface, plant species composition, and ultimately hydrologic dynamics of the site, field, and watershed. Available water in the soil and ET regulate soil moisture, which ultimately determines the dynamics and function of the plant community (Stephenson 1990). Three elements in the hydrologic cycle are responsible for water loss, evaporation, transpiration, and runoff. Evaporation of water from the soil and runoff can be managed somewhat with vegetation management—including grazing intensity and timing. Figure G-33 shows how components of the hydrologic cycle change with managed grazing.

Figure G-33. Grazing and effects on the hydrologic cycle. Processes are divided into aboveground (AG) and belowground (BG) components. PPT=precipitation, Ps = spring snow melt, F = fog or cloud condensation, I = canopy interception, R = runoff, E = evaporation from soil surface, T = transpiration from plants, S = the change in soil moisture, and D = subsurface flow of water vertically and horizontally from plant roots. Note: Ps and F are not applicable in all rangeland environments (Adapted from Asner et al. 2004).

$$PPT + P_s + F = (I + R + E + T)_{AG} + (\Delta S + D)_{BG}$$



Direction of change with managed grazing

B. The amount of disturbance from hoof action by livestock on a site depends on soil type, soil water content, seasonal climatic conditions, and vegetation type. Repetitive and continuous high intensity trampling results in a cascading effect: bulk density increases (compaction), and soil aggregates degrade, especially on lighter textured soils. This results in lower infiltration, higher runoff, and greater potential for erosion. If intensive grazing occurs on wet soil, soil aggregate stability is further damaged, resulting in an impermeable surface layer and possible development of a physical crust. On some soils, a physical vesicular crust can occur, which impedes infiltration.

C. Grazing at any level triggers an immediate vegetation response and imposes either subtle or drastic changes in soil physical, chemical, and biological factors (figure G-34). Depending on the level of grazing (light to heavy), there are numerous implications that managers should be aware of (figure G-35). These changes may be entirely natural, as many rangeland plant communities evolved with ungulate grazing (Mack and Thompson 1982); or they may be disruptive, depending on the severity of the perturbation.

Figure G-34. Model depicting effect of grazing practices on soil surface and subsequent results on plant communities, hydrology, energy and nutrient cycles, and erosion and sedimentation dynamics.

Short- and Long-Term Effect of Grazing Practices and
Potential for Modification of
⇓
Soil Surface Properties
⇓
Plant Species Structure and Composition
⇓
Hydrology (Infiltration and Runoff)
⇓
Energy and Nutrient Cycles
⇓
Erosion and Sedimentation Dynamics

D. Heavy use by livestock can compact the soil, have a negative impact on soil structure, mechanically disrupt soil aggregates, reduce soil aggregate stability, and destroy biological soil crusts which may be essential to erosional stability. Infiltration capacity is generally reduced with increased grazing intensity, mainly through vegetation removal and composition change, changes to soil structure, bulk density, and aggregate stability.

Figure G-35. Diagrammatic representation of grazing and the relationship to soil surface.

Increase	Decrease
plant cover	runoff
soil organic matter	soil bulk density
infiltration rate	soil detachment and erosion
soil water content	erosion and sedimentation
subsurface flow	site entropy
aquifer recharge potential	soil water evaporation
ET potential	
litter	
soil microorganisms and/or biological crust response where present on ecological site	
rangeland health	
plant community integrity	
enhances soil structure	
soil aggregate stability	
balanced nutrient and energy cycle	
enhances wildlife habitat	
livestock thriftiness and health	

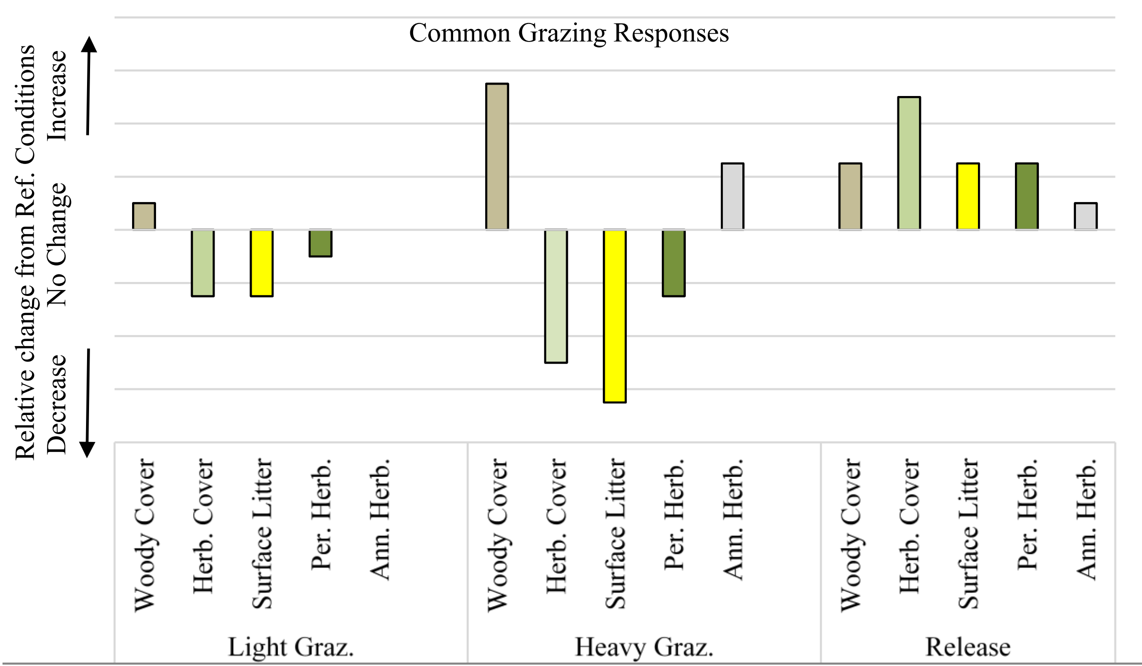
Proper Grazing Management and Expected Plant Community Response

Excessive Grazing and Expected Plant Community Response

Increase	Decrease
runoff	plant cover
soil bulk density (compaction)	soil organic matter
soil detachment and erosion	infiltration rate
erosion and sedimentation	soil water content
site entropy	litter
risk of a non-recoverable situation	soil microorganisms and/or biological crust response where present on ecological site
soil water evaporation	rangeland health
	plant community integrity
	soil structure
	soil aggregate stability
	subsurface flow and aquifer recharge potential
	soil surface stability
	balanced nutrient and energy cycle
	ET potential

E. On rangelands, increases of woody plant cover have been associated with overgrazing, especially where the trend of increasing woody cover and biomass is already advancing (Archer 1994) (figure G-36). The main causal agents of woody encroachment are associated with fire suppression that enhances native woody plant densities, invasion and survival, atmospheric CO_2 enrichment that favors C3 (woody) plant growth, climatic pulses that favor shrub establishment, and overgrazing (Archer et al. 1995, van Auken 2000). Studies show that light grazing intensity results in slight increases in woody plant cover (Tobler et al. 2004) and a decrease in herbaceous biomass or cover and surface litter cover and biomass (Harris et al. 2003, Oba et al. 2003). In addition, perennial grasses can slightly decrease in production, although there is no clear and consistent trend (Mapfumo et al. 1999). Decreases of perennial grasses are more pronounced in settings with long-term heavy grazing (Asner et al. 2004) (figure G-36). The key to limiting loss of production of key forage species lies in proper management and consistent monitoring of vegetation composition.

Figure G-36. Responses of vegetation to light grazing, heavy grazing, and release from grazing. Bar graph shows relative responses from literature (Hendricks 1942, Archer 1994, Fuhlendorf et al. 2001, Pettit and Froend 2001, Asner et al. 2003, Cingolani et al. 2003, Friedel et al. 2003) (adapted from Asner et al. 2004).



645.0713 Influence of Livestock Grazing and Trampling on Hydrologic Characteristics

A. Many grasslands and rangeland plant communities evolved with ungulates, some more intensively grazed than others (table G-18) (Mack and Thompson 1982). Mack and Thompson (1982) characterized two grassland provinces dominated by perennial grasses, the *Agropyron* province (dominated by bunch or caespitose grasses) west of the Rocky Mountains and the *Bouteloua* province (dominated by rhizomatous/stoloniferous species) east of the Rocky Mountains. Before and after the Wisconsin glaciation, *Bison bison* were prolific and numerous throughout the *Bouteloua* province (may have exceeded 40 million animals at the time of European contact). In contrast, there is not much evidence of large herds of bison west of the Rockies (Durant 1970). Few prehistoric records of bison existed on the Columbia Plateau of Washington and Oregon, with a regional decline to extinction by 2500 BP.

Table G-18. Physiological characteristics and grazing tolerance of dominant species in the *Agropyron* and *Bouteloua* provinces in the United States.

Species	Sensitivity to grazing	Growth Habit	Photosynthetic pathway	Flowering/veg. culm ratio	Meristem position
***Agropyron* province**					
Pseudoroegneria spicata	very sensitive in late spring	caespitose, rhizomatous at higher elev.	C3	high	elevates early
Festuca idahoensis	sensitive to light grazing	caespitose			
Poa sandbergii	sensitive to light grazing	caespitose	C3	high	
Poa pratensis	delayed response if any	rhizomatous	C3	low	at ground level throughout season
***Bouteloua* province**					
Bouteloua gracilis	delayed response if any	tufted, but forming a sod	C4	low	at ground level throughout season
Pascopyrum smithii	less sensitive than PSSP	rhizomatous	C3	low	elevated early
Bulbilis dactyloides	delayed response if any	stoloniferous, extensive stolon-forming dense sod	C4	low	at ground level throughout season

B. With the introduction of livestock on United States grasslands and ranges came the irrevocable impact on plant composition change in more arid rangelands, especially the *Agropyron* province. These endemic grass species did not evolve with heavy grazing and therefore are sensitive to grazing pressure (Mack and Thompson 1982).

(1) In the *Bouteloua* province, one bovid essentially replaced the other. The main change that occurred with cattle herds is frequency of disturbance rather than the type of disturbance. In more recent times, fire frequency has also changed dramatically. In some locations it has been essentially eliminated, excepting the inescapable wildfires that occur.

(2) In the *Agropyron* province, dramatic changes occurred compared to the *Bouteloua* province, where the introduction of domestic cattle herds and changes in frequency of grazing rapidly changed the composition of many grazed native ranges with the introduction of Eurasian exotic annual grasses and forbs.

(3) The fragile arid rangelands were more susceptible to exotic annuals, as many of them are winter annuals. Cheatgrass (*Bromus tectorum*) was first collected in Pennsylvania, 1861;

Washington, 1893; Utah, 1894; Colorado, 1895; and Wyoming, 1900 (Yensen 1981). Field bromegrass (*Bromus arvensis)*, another common exotic annual C3 brome species, is also native to Eurasia and is also characterized as a winter annual that germinates in fall and survives throughout the winter as "rosettes" (Baskin and Baskin 1981). It is found in all states within the United States, with the exception of Hawaii and Alaska and in the Canadian provinces of British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and Prince Edward Island (USDA-NRCS Plants Database 2020). Medusahead wildrye (*Taeniatherum caput-medusae*), is a Eurasian C3 introduction (Hungary through Ukraine to Tadzhikistan), and made its début in the United States in the 1880s near Roseburg, Oregon. The spread of medusahead has been slower than cheatgrass (Pyke 2000) but is now becoming increasingly prominent on western United States rangelands (Turner et al. 1963, Hilken and Miller 1980, USDA-NRCS 2018b). Unlike cheatgrass and field brome, medusahead has a high ash and silica content (72–89 percent), which makes it less palatable as the plant matures (Swenson et al. 1964).

C. By the turn of the century, irreversible changes to the ecological and biological structure of the *Agropyron* province was well underway. Native grass species could no longer recolonize disturbed areas, once the exotic annual grasses were present. With the advent of heavy grazing, the transformation from perennial bunchgrass was rapid; and when annual grass dominance occurs, ecosystem function can be compromised (Vitousek et al. 1997). On United States rangelands, non-native exotic plants can negatively impact biotic integrity, ecosystem resilience and stability, composition and structure, natural fire cycles, diversity, soil biota, vegetation production, forage quality, wildlife habitat, soil physical properties, organic matter dynamics, carbon balance, nutrient and energy cycles, and hydrology and erosion dynamics in many unique ways (Chapin et al. 2000, Evans et al. 2001, Pierson et al. 2002b, 2008; Ehrenfeld 2003; Ogle et al. 2004; Brooks et al. 2004; Norton et al. 2004; Belnap et al. 2005; Hooper et al. 2005; Boxell and Drohan 2009; Herrick et al. 2010; Davies 2011).

D. Modification of plant composition, cover, and biomass on a site can singularly or collectively affect infiltration dynamics and may accelerate erosion. Stocking rates that continuously exceed moderate stocking (continuous, season long, and intensive systems) will ultimately decrease infiltration and increase runoff, erosion, and sediment loss (Rhoades et al. 1964; Rauzi and Hanson 1966; Rauzi and Smith 1973; Gifford and Hawkins 1978; Owens et al. 1982; Blackburn 1984; Wood and Blackburn 1984; Warren et al. 1986 a, b, c; Warren 1987; Thurow et al. 1988; Naeth et al. 1990; Thurow 1991).

E. In general, the effects of livestock grazing on hydrologic resilience are associated with the degree to which grazing pressure affects surface soil conditions by altering the spatial and temporal variations in canopy and ground cover (Gifford and Hawkins 1978; Wood and Blackburn 1981;Thurow et al. 1986, 1988; Thurow 1991; Trimble and Mendel 1995; Spaeth et al. 1996a, b; Asner et al. 2004). Grazing pressure that substantially reduces vegetation and ground cover or compacts and disturbs surface soils will likely increase losses of water and soil resources through water and wind erosion processes (Greene et al. 1994, Trimble and Mendel 1995, Field et al. 2011). High intensity grazing, particularly over multiple years, can alter plant composition such that the biotic structure triggers long-term site degradation through abiotic-driven losses of water and soil resources (Warren et al. 1986 b, c; Schlesinger et al. 1990; Greene et al. 1994; Rietkerk and Van de Koppel 1997; Van de Koppel et al. 1997; Ludwig et al. 2007; Turnbull et al. 2008, 2012).

F. Grazing systems such as intensive rotation grazing (IRG), short-duration grazing methods, high intensity-short duration, or other forms of heavy stocking rotation systems ("mob grazing," ultra-high stocking densities) have been purported in the popular literature to be advantageous to hydrology, animal performance, litter decomposition and organic matter dynamics, lessening carbon footprints, and cattle production profits. Weltz and Wood (1986) found that even short duration grazing had adverse impacts on both surface runoff and sediment yield. The intensive removal of standing biomass leaves the site at an elevated risk of erosion if intensive rainfall events occur before vegetation can regrow. Continuous intensive grazing systems over time can increase risk of deteriorating plant production, changes in native plant composition and loss of species diversity, which have ramifications beyond livestock production, such as pollinating species' dependence on preferred nectar plants. Intensive grazing systems can be especially damaging during drought periods because plants don't have the resources to regrow (Thurow et al. 1986 and Warren et al. 1986b). Before initiating intensive grazing, consideration should be given to the physiological response of the species to grazing (See Mack and Thompson, 1982; Briske and Richards, 1995; Dahl, 1995; and Dahl and Hyder, 1977).

G. In any agricultural endeavor where the manager is unequivocally convinced of a particular practice using anecdotal evidence, and the rangeland is in healthy condition, caution needs to be exercised with monitoring of the practice. Some intensive grazing systems as proposed by Goodloe 1969, Savory 1978, 1979; Savory and Parsons 1980, including those mentioned above, have been the subject to controversy with regards to effects on species composition and hydrology. Managers claim purported benefits supported by anecdotal evidence; however, under scrutiny of scientific experimental evidence, are the benefits sustainable and beneficial in the long term? With most intensive short duration grazing systems, livestock are concentrated in small paddocks for short periods of time, creating a concentrated herd effect with intensive trampling of the soil and plants. Proponents claim that the "hoof action" disturbs the soil surface and helps incorporate litter for microbial breakdown, enhancing soil surface organic matter and infiltration of rainfall. Hoof action may quicken contact of standing litter with the soil, but subsequent decomposition and overall soil organic matter would be about equal, with standing dead litter naturally collapsing and eventually falling to the soil surface. Different gases such as CH_4, NH_4^+, NO_3^-, SO_4^{-2}, H_2S, and HPO_4^{-2}, and especially CO_2 are emitted when organic materials begin to decompose as residues come in contact with the soil, and mineralization by soil microbes begins, coupled with adequate soil moisture and complementary temperatures, (Al-Kasi and Lal 2017). The rate of mineralization is influenced by biotic and abiotic factors, and nutrients released vary significantly among the different fractions of soil organic matter. On average, after one year, about 17 to 35 percent of the carbon added as plant residue is incorporated into SOM (Himes 1997 and Stewart et al. 2017).

H. Trampling intensity is correlated with compaction and changes in bulk density. Warren et al. (1986a) demonstrated experimentally that repeated high intensity trampling decreased soil aggregate stability and increased bulk density, which reduced infiltration rates and increased surface runoff and interrill erosion (table G-19). Trampling dry soil disturbed the soil surface and resulted in reducing the size of naturally occurring soil aggregates and increasing bulk density. When moist silty clay soils were trampled, soil aggregates were largely destroyed by compaction into the impermeable surface layer. In summary, Warren et al. 1986a found that infiltration rate decreased, and sediment production increased significantly on a silty clay soil, following trampling that typifies intensive rotation grazing systems. Warren et al. 1986a also found that 30 days' deferment from grazing was insufficient to allow for hydrologic recovery.

I. The amount of damage to a site from "hoof action" by livestock depends on soil texture, soil water content, seasonal climatic conditions, and vegetation type. In summary, repetitive and continuous high intensity trampling increases bulk density (compaction) and breaks down soil aggregates, resulting in lower infiltration, higher runoff, and a potential for erosion (Gifford and Hawkins 1978; Branson and Miller 1981; Warren et al. 1986 a, b, c; Greenwood and McKenzie 2001; Daniel et al. 2002; Teague et al. 2011; Asner et al. 2004). If this action occurs on wet soils, soil aggregate stability is damaged even more, resulting in an impermeable surface layer. Freeze-thaw cycles and wet-dry cycles can ameliorate surface soil compaction from livestock, depending on time since disturbance and soil texture (Weltz et al. 1989).

645.0714 Case Studies Livestock Grazing and Hydrologic Effects

A. Infiltration and erosion response to trampling intensity (Warren et al. 1986a)

(1) Warren et al. (1986a) state: "the idea that benefit can be derived from short-term, high intensity physical impact of livestock is the principal foundation upon which many proponents of intensive, rotational grazing systems base their support. The physical impact is believed to chip or churn the soil surface and break up surface crusting without compacting the soil, thus improving water infiltration and reducing erosion (Goodloe 1969, Savory and Parsons 1980). This study showed that repeated high intensity trampling, at levels typical of intensive rotational grazing systems, was detrimental to soil properties which are normally well correlated to infiltration rate and sediment production. The detrimental impact generally increased as stocking rate increased. Trampling on a dry soil did indeed, chip and churn the soil surface. However, the 'hoof action' reduced the size of naturally occurring soil aggregates and increased the density of the surface soil layer. Trampling on moist paddocks destroyed existing soil aggregates and led to the creation of a flat, comparatively impermeable surface layer composed of dense, unstable clods. Both of these conditions were detrimental to infiltration rate and sediment production."

(2) In summary, trampling activity by grazing animal hooves reduces infiltration by altering soil surface physical factors: bulk density or compaction, breakdown of soil aggregates, and reduction of porosity. Intense trampling as a result of doubled or tripled stock intensities in smaller paddocks for short periods of time (creating a herd effect) has been hypothesized as enhancing infiltration and reducing erosion. Research to date by rangeland hydrologists has not supported the idea that increased intensity of trampling enhances infiltration capacity (table G-19).

Table G-19. Mean infiltration rate and interrill erosion in relation to trampling intensity and water content on the Edwards Plateau, Texas. Simulated rainfall =15 cm in 45 minutes (Warren et al. 1986c). Symbols IX indicates moderate stocking intensity, 2X double the moderate intensity, 3X triple the moderate intensity, soil texture was silty clay.

Infiltration Rate x				
Stocking Intensity	**Before Trampling ($mm\ hr^{-1}$)**	**Trampled Dry ($mm\ hr^{-1}$)**	**Before Trampling ($mm\ hr^{-1}$)**	**Trampled Moist ($mm\ hr^{-1}$)**
0	166	166	160	160
1X	147	132	133	130
2X	137	106	115	83
3X	134	101	109	82
Interrill Erosion				
Stocking Intensity	**Before Trampling ($kg\ ha^{-1}$)**	**Trampled Dry ($kg\ ha^{-1}$)**	**Before Trampling ($kg\ ha^{-1}$)**	**Trampled Moist ($kg\ ha^{-1}$)**
0	976	976	2,007	2,007
1X	1,892	3,824	2,998	2,752
2X	2,272	4,605	3,542	5,048
3X	2,211	7,078	4,057	7,465

B. Comparison of grazing treatments on infiltration and interrill erosion, Sonora, Texas.

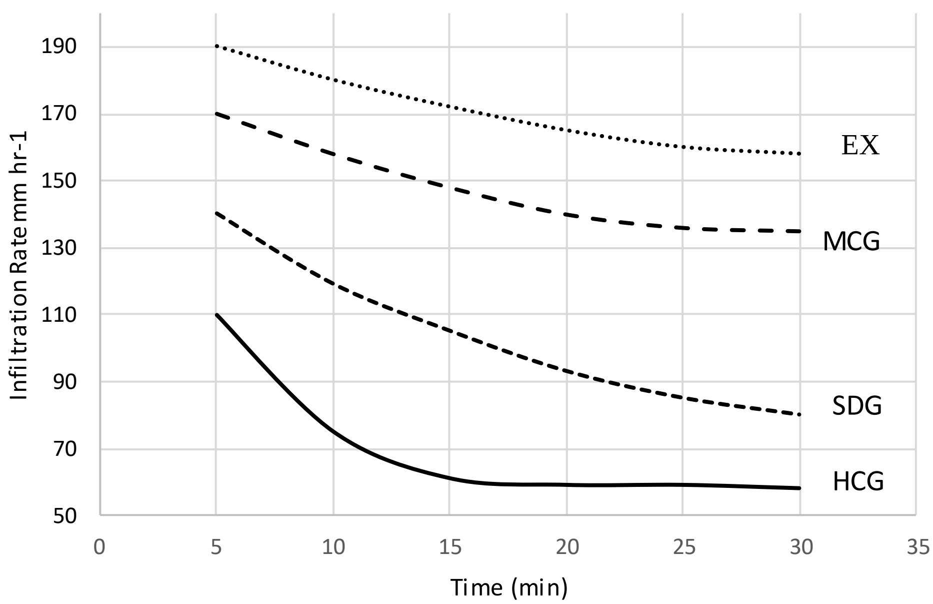
(1) The key components affecting infiltration rate – such as aggregate stability, bulk density, standing crop, litter biomass, and litter cover – are sensitive to grazing management systems (Thurow et al. 1988). It is imperative for the land manager and conservationists assisting in planning grazing systems to recognize temporal responses of infiltration and interrill erosion to the planned grazing system as unwanted shifts to alternate states (consult state-and-transition model in ecological site description).

(2) Thurow et al. (1988) reported that the infiltration rates and erosion for continuously grazed at moderate intensity (MCG) and at high intensity low frequency (HILF) were maintained at acceptable levels; however, infiltration rates decreased and interrill erosion increased on heavy continuous (HCG) and heavily stocked short duration grazing (SDG) pastures. Infiltration and erosion on HCG and SDG were not gradual but occurred in a more dramatic stair step pattern. See figure G-37. Infiltration and interrill erosion rates did not recover after drought conditions when normal precipitation patterns returned. Heavy stocking rates and climatic factors were the primary factors in reducing infiltration and increasing erosion.

C. Impacts of grazing in Utah.

West et al. (1984) reported, after 13 years of livestock deferment, desirable native perennial vegetation had not reestablished, despite a trend of increased precipitation over the length of the study. They concluded that the site had transitioned to a stable shrub-dominated site. The concept that removing livestock would return the plant community to the original sagebrush-native shrub-grass assemblage is unlikely. Therefore, direct manipulation of the site is mandatory if rapid return to the desired plant community is desired. Belnap et al. (2009) reported that grazed watersheds in southeast Utah had significantly more soil loss from wind than ungrazed watersheds. When comparing soil losses among the sites, they determined that biological soil crusts were the most important factor in predicting site stability, followed by perennial plant cover.

Figure G-37. Mean infiltration rates from four grazing treatments on Edwards Plateau, Texas (6-yr study). HCG = continuous grazed and heavily stocked at 1.75 x the moderate intensity; SDG = short duration rotation (14-pasture, 1-herd; 4 days on, 50 days rest); MCG = continuously grazed at moderate intensity; EX = livestock enclosure, no grazing (Thurow et al. 1988).



D. Infiltration rates and interrill erosion responses to selected livestock grazing strategies, Edwards Plateau, Texas.

During the hydrology grazing study, infiltration rates decreased and interrill erosion increased in the heavily stocked short duration rotation (SDG) and continuously grazed and heavily stocked (HCG) pastures. Decreases and deterioration of infiltration and interrill erosion rates in these heavily stocked pastures tended to follow a stair-step pattern typified by decreasing grass basal cover, litter, and midgrass cover during drought, and an inability to recover to predrought levels during periods of above normal precipitation. In comparison, infiltration and interrill erosion rates in the moderately stocked pastures were able to recover from droughts and maintain initial or improved rates during periods of above-normal precipitation.

E. Infiltration rates and sediment production as influenced by grazing systems in the Texas Rolling Plains.

(1) Two production scale grazing treatments were sampled at Throckmorton, Texas to evaluate their impact on hydrologic processes. Treatments were yearlong continuous grazing, stocked at a moderate rate (MC); 16-paddock rotational grazing treatment, stocked at a heavy rate (RG-16); moderately stocked pasture three-herd deferred rotation treatment (DR-3); and ungrazed exclosure (EX). Sediment production was lowest in the exclosure. Compared to the RG-16 treatment (sediment = 63 kg ha^{-1} and infiltration 82 mm hr^{-1}), sediment production was least (33 kg ha^{-1}) and infiltration rate greatest (89 mm hr^{-1}) in the MC treatment. As above-ground biomass and cover increased, infiltration rates increased, and sediment production decreased. The RG-16 treatment had higher sediment production and lower infiltration rates than MC treatment (Pluhar et al. 1987).

(2) Before grazing treatments, infiltration rates and sediment production in the RG-16 and DR-3 treatments were not significantly different from those in the MC treatment. However, subsequent grazing caused a significant decline in infiltration rates and a significant increase in sediment production in both treatments (as a function of removal of above-ground biomass, cover, and proportion of the area in midgrasses). Midgrasses had higher infiltration rates and lower sediment production than shortgrasses. This study is similar to the Weltz and Wood (1986) study: high intensity rotational grazing removes excessive amounts of above-ground biomass and increases the vulnerability of the site to accelerated soil erosion.

F. Grazing effects on plant cover, soil and microclimate in fragmented woodlands in south-western Australia.

(1) This study evaluated the impacts of livestock grazing on native plant species cover, litter cover, soil surface condition, surface soil physical and chemical properties, surface soil hydrology, and near ground and soil microclimate in remnant *Eucalyptus salmonophloia* woodlands in western Australia (loamy sand over clay) (Yates et al. 2000).

(2) Heavy grazing by sheep was "associated with a decline in native perennial cover and an increase in exotic annual cover, reduced litter cover, reduced soil cryptogam cover, loss of surface soil microtopography, increased erosion, changes in the concentrations of soil nutrients, degradation of surface soil structure, reduced soil water infiltration rates and changes in near ground and soil microclimate. The results suggest that livestock grazing changes woodland conditions and disrupts the resource regulatory processes that maintain the natural biological array in E. salmonophloia woodlands" (Yates et al. 2000).

(3) Intensive livestock trampling typical of multi-pasture rotational grazing systems had a negative impact on soil physical properties. The deleterious effects tended to increase as stocking rate increased. Trampling on dry soil caused disruption of naturally occurring aggregates and compaction of the surface soil layer. Trampling on moist soil disturbed existing aggregates and led to the creation of a flat, comparatively impermeable surface layer composed of dense, unstable clods. Bulk density was higher in heavily grazed woodlands, thus increasing soil penetration resistance and soil pore volume, a result associated with loss of perennial vegetation cover, biological soil crusts, and the impact of sheep trampling. Perennial vegetation provides a feedback mechanism where organic litter provides protection against raindrop splash and surface sealing effects.

G. Yearlong grazing on pastures in Coshocton, Ohio

On pastureland in Ohio, the highest annual soil loss values (1.12 t ac^{-1}) occurred on unimproved pastures grazed yearlong where cattle had direct access to riparian areas. Rotational summer grazing with >90 percent grass cover had trace amounts of soil loss (Owens et al. 1996).

H. Impact of cattle treading on hill land and soil damage patterns

"Animal treading (or trampling) in grassland ecosystems is known to affect the condition of both soil and vegetation. Much of this knowledge centers on dry and/or rangeland conditions where soils and vegetation are considered to be very fragile. Treading action can result in reduced soil water infiltration and increased water runoff" (Sheath and Carlson 1998). Soil surface damage was greatest on animal tracks and easy contoured areas. For rapid recovery of damaged paddocks, continued grazing of cattle during spring should be avoided (Sheath and Carlson 1998).

I. MOB grazing and effects on compaction, forage quality, and hydrology

Unfortunately, few scientific studies exist on mob grazing (MOBG). Most of the positive or negative claims about MOBG grazing are anecdotal and from the popular literature. Mob grazing is a more intensive type of rotational grazing and is characterized by ultra-high stocking densities, short durations (one day or less between rotations), and long rest periods (usually at least 45 days of growth). Highly intensive grazing treatments have more flexibility of management options in humid climates where there is adequate precipitation to regenerate forage species. Semiarid and arid rangelands are not conducive to long-term success from MOBG grazing. The scientific literature on intensive stocking systems on rangeland do not support the claims of increased infiltration, organic matter, and plant response. Many native perennial rangeland grasses are not as resilient to continual heavy grazing as introduced exotic forage grasses; therefore, careful monitoring is needed to assess the results.

J. Water and hydrologic processes are the main drivers in plant ecosystems. If hydrologic function is compromised, reducing infiltration and increasing runoff, all other systems will be altered, including nutrient, energy, and organic carbon cycles. Ignorance of these effects in high intensity grazing treatments is a "recipe for disaster" with sometimes unrecoverable consequences, including vegetation state change and impacts on livestock health.

K. Grazing affects vegetation stature and composition and soil surface factors, which can subsequently affect the hydrologic cycle (figure G-33). On a watershed scale at intensified levels, livestock grazing can initially decrease plant cover, cryptogamic crusts, soil aggregate stability, and soil organic matter, and increase compaction and soil crusting. Improper grazing intensities, over longer periods, can and often alters plant composition, which may seriously affect the hydrology of a watershed. With continuous heavy stocking, plant composition will ultimately change over time, perhaps subtlety at first where the manager does not notice immediate changes. Rangeland grazing and hydrology studies show that soil physical factors consistently change in many high intensity grazing treatment studies. Increases in bulk density and compaction and decreased soil aggregate stability are common with high intensity grazing treatments. If erosion is occurring at a higher than sustainable rate, the dynamics of the organic matter cycle may change, resulting in altering the stability of soil aggregates and soil microbial populations and activity associated with organic matter and soil health.

L. The literature is clear with respect to high intensity grazing: infiltration rates and capacity are reduced, water runoff is increased, and interrill erosion increases. The main factors associated with hydrologic decline on rangeland are due to changes in:

(1) Plant cover
(2) Plant species composition

(3) Accelerated erosion leading to decline in surface soil horizon dynamics
(4) Increased incidence of invasive species
(5) Decline in grazing intolerant perennial grasses (Mack and Thompson 1982)
(6) Reduced biomass production
(7) Deterioration of soil aggregates and soil biological crusts
(8) Increased bulk density
(9) Increased soil surface water evaporation
(10) Decreasing water holding capacity and available moisture
(11) Soil microorganism populations may change the balance between soil fungi and bacteria.
(12) Bacterial populations in the soil can be depressed by dry conditions, soil acidity, soil compaction, and lack of organic matter.

(i) Soil surface disturbance, especially tillage, has an adverse effect on fungi as it physically severs the hyphae, breaking up the mycelium. Soil microorganism populations are important indicators of soil health as they respond rapidly to environmental changes and site conditions because of their direct relationship with conditions of the site. Changes in microbial populations can occur and precede detectible changes of soil physical and chemical properties – an early warning system to soil degradation and decreasing soil health (Nielsen and Winding 2002).

(ii) Soil organisms are inherent to many soil processes such as organic matter and nutrient cycles, which are prominent aspects of range and pasture health. Plant vigor, productivity, and reproductive capability are "first responders" – factors associated with soil health, which are immediate indicators for identifying imbalances, an aspect that cannot be determined by soil physical and chemical measures alone.

M. Summarized findings of hydrology studies on range and pastureland:

(1) Species composition changes can have a positive or negative effect on hydrology, depending on the individual species involved.
(2) Hydrology studies consistently show that ungrazed areas and study exclosures have the lowest runoff rates compared to the grazing systems in the respective study areas and are often similar to light grazing.
(3) The reaction to the impact of trampling varies with stocking rate, soil type, soil water content, time of grazing and seasonal climatic conditions, and vegetation type.
(4) On heavier textured soils, trampling impact on wet soils can break down soil aggregates, and impermeable surface layers can develop (e.g., vesicular crusts and rainfall induced crusts).
(5) "Deferred Rotation Systems" with adequate rest periods generally maintain hydrologic parameters similar to ungrazed areas. Adequate rest periods vary with soil type and vegetation types. Soil surface conditions should be monitored on a site-specific basis.
(6) Watershed research data suggest that watershed conditions can be maintained and improved with light and moderate continuous grazing. On lighter textured soils, there is little hydrologic response between light and moderate continuous grazing on rangeland hydrology.
(7) Short duration high intensity grazing is associated with higher sediment production, compared to moderate continuous grazing. The reduced standing vegetation and plant cover, compaction, decreasing soil aggregate stability and porosity, and development of soil crusts associated with this system are the major causes of increased runoff and sediment production. No definite hydrologic advantage has been documented in the scientific literature for increased stocking density via manipulation of pasture size and numbers.

N. Caution needs to be exercised concerning short duration high intensity systems. The rangeland community type and the physiological response of species inherent species to defoliations needs to be carefully considered (See Mack and Thompson, 1982; Briske and Richards, 1995; Dahl, 1995; and Dahl and Hyder, 1977). Soil surface physical properties, mineral and microbiotic crusts, and plant species composition must be monitored carefully. Rangeland plant communities are unique, and plant/soil interactions are complex and are not consistent from one vegetation and soil type to the next. This makes it difficult for the land manager, since consistency in hydrologic response is not well documented for many plant/soil complexes. Frequent on-site monitoring is essential.

O. In Midwestern pasturelands, the majority of soil loss occurs when the vegetation is dormant. Large runoff events (usually a small percentage of the total number of rainfall events) produce most of the runoff volume and erosion; however, these events are usually the impetus for the initiation of rills and gullies and subsequent decline in hydrologic function.

P. Because grazing systems and hydrologic impacts vary, management specialists should consult references for particular grazing trials (Gifford and Hawkins 1978; Blackburn et al. 1980, 1981; Blackburn 1984; Wood and Blackburn 1981; Warren et al. 1986 a, b, c; Weltz and Wood 1986; Warren 1987; Holechek et al. 2004).

645.0715 Monitoring Prerequisites for Grazing Systems

The following factors should be observed or evaluated regularly to determine the effectiveness of grazing systems:

(1) Monitor forage quality
(2) Watch animal activity, signs of stress
(3) Monitor and evaluate species composition shifts, especially in native grass stands. Watch for the establishment or increase of invasive or less desirable species
(4) Consumption vs. trampling. High density stocking may be impacting desired consumption
(5) Evaluate impacts on soil surface dynamics
  (i) Soil temperature changes
  (ii) Soil moisture, accelerated drying of soil surface
  (iii) Excess litter
  (iv) Soil compaction
  (v) Physical changes in soil surface (structure, porosity, aggregate stability)
  (vi) Crust formation, especially in clayey soils
  (vii) Significant soil stability (aggregate stability) changes
  (viii) Soil organic matter depletion
(6) Noticeable decrease in infiltration capacity and increase in runoff.
(7) Changes in rangeland health assessments (soil and surface stability, hydrologic function, and biotic integrity).

645.0716 Soil Erosion and Sediment Production on Watersheds

A. A serious recurring problem in the United States and throughout the world is the loss of soil resources on productive and functioning watersheds as well as dysfunctional watersheds. Soil loss impacts both on-site and off-site watershed functions. On-site effects include the changes in soil structure, decline in organic matter and nutrients in the soil, and a reduction of available soil moisture (Morgan 1995, Gregersen et al. 2007, Brooks et al. 2013), with overall negative impacts on productivity and decline in value of natural resources within watershed landscapes (Ffolliott et al. 2013). Loss of the soil resources from otherwise productive and well-functioning watersheds is often a recurring problem confronting hydrologists and watershed managers. Sediment is the product of soil erosion, and its source can be from upland sheet and rill erosion, gully erosion, soil mass movement, or channel erosion. Sediment yield is the amount of eroded soil that moves from a source to a downstream control point, such as a reservoir, per unit time.

B. Sediment yield from watersheds depends on inherent watershed characteristics: geology, topography, vegetation, land use and management, condition of vegetation, conservation measures, and storm dynamics and streamflow which produce and transport sediment (Anderson 1957). Sediment that is deposited in a stream channel is dependent on:

(1) The proximity of the source of the erosion to the channel
(2) Shear forces acting on soil and rock
(3) Size and distribution of sediment particles
(4) Transport of sediment from one part of the watershed to another and eventually into a major stream channel

C. Not all of the eroded soil that accumulates as sediment in water courses is transported through and out of the given watershed in response to storm events. Eroded soil can be deposited at the base of hillslopes, on stream terraces, or buffered in riparian zones before deposition to a stream channel (Neary et al. 2012, Brooks et al. 2013). Off-site effects commonly include increases in sediment loads and loss of nutrients such as nitrogen and phosphorous that are transported with sediment to stream channels (Dunne and Leopold 1978, Morgan 1995, Brooks et al. 2013). The consequences of sediment and nutrient loads from upland watersheds are reductions in river flow capacity, thus increasing risk of flooding in river basins and pollution that impacts water quality. The consequent increases of sediment in streamflow from upland watersheds often reduces the capacity of rivers to deliver high-quality water to downstream users, increases the risk of flooding, reduces or blocks the flow of water through irrigation systems, and shortens the expected operational life of downstream reservoirs. Increased soil erosion and sedimentation rates can also impact a variety of ecosystem services from watersheds, such as water supply quality, ground water and aquifer recharge, effective nutrient cycling, and biodiversity of plants and animals.

D. The NRCS plays an important role in assisting landowners with preventing accelerated and unacceptable rates of soil erosion, resulting in decreased sedimentation to water courses. Many conservation practices are implemented to prevent or reduce detrimental impacts to the environment and watershed.

E. Sediment delivered to rivers from agricultural watersheds, including cropland and pastureland, ranges from 1 to 30 percent of the estimated erosion (Robinson 1988). It is estimated that about eight percent of all erosion from cropland is deposited in estuaries and the ocean; however, cropland soil erosion is highly variable from site to site (Office of Technology and Assessment 1982). Smaller watersheds generally have higher sediment delivery ratios than larger watersheds. In the United States, estimates suggest that between 5 and 10 percent of water eroded soil ends up in the Gulf of Mexico or oceans (Robinson 1988).

F. Average sediment delivery ratios (SDR) for various sized watersheds are:

(1) 25-acre watershed: 30–90 percent (SDR)
(2) 2,400-acre watershed: 10–50 percent (SDR)
(3) 10,000 mi^2: 5 percent (SDR)

G. Examples of watershed and sedimentation case studies are given below:

(1) Nichols and Renard (2006)
   (i) Walnut Gulch Experimental Watershed is located in the transition zone between the Sonoran and Chihuahuan Deserts in southeastern Arizona. The experimental watersheds ranged in size from 35 ha to 92 ha and are underlain by a coarse-grained Quaternary and Tertiary alluvium shed from the Dragoon Mountains. See table G-20.
   (ii) Sediment yield from semiarid grazed watersheds (cattle) can be erratic due to variability of precipitation and runoff (table G-21).

(iii) Soil textures were not listed in their paper; however, to derive an estimate in tons ac^{-1} sediment: Watershed I with a soil bulk density of 1.7 Mg m^3

$$(1.7 \text{ Mg m}^3) \times (0.4 \text{ m}^3 \text{ ha yr}^{-1}) = 0.68 \text{ Mg ha yr}^{-1} (0.4047) = 0.275 \text{ tons ac yr}^{-1}$$

Table G-20. Walnut Gulch Experimental Watershed, southeastern Arizona, USA. (Lane et al. 1998).

Watershed Features	Area (km^2) (acres)	Runoff (mm) 1973–76	Sediment yield (t km^2 yr^{-1})	Sediment concentration (%)
Hillslope, brush, Tombstone Pediment, ungullied	0.0018 (0.4)	12.7	151.0	1.19
Grass, Tombstone Pediment, ungullied	0.0186 (4.6)	19.7	51.2	0.26

Table G-21. Sediment yield from desert watershed in southern Arizona.

Drainage area (ha)	Dominant Vegetation Type	Period of Record	Years of Records	Volume of Accum. Sediment (m^3) for Years of Record	Sediment Yield (m^3 yr^{-1})	Sediment Yield per Hectare (m^3 ha yr^{-1})
92.2	Black Grama, Curly Mesquite	1973–1984	29	1,057	36	0.4
35.2	Whitethorn Acacia, Creosote Bush, Tarbush	1966–1984	35.9	2,936	82	2.3
84.2	Black Grama, Curly Mesquite	1962–1996	39.9	5,667	142	1.7
43.8	Whitethorn Acacia, Creosote Bush, Tarbush	1956–2002	45.6	5,658	124	2.8

(2) Trimble (1997)

San Diego Creek, which drains a 288 km^2 basin in Orange County, California supplies sediment to Newport Bay, which is considered to be one of the primary estuarine wildlife habitats in the state. An initial channel study indicated that from the late 1930s to the early 1980s channel erosion supplied more than one-fourth of all sediment yield. From 1983 to 1993, stream channel erosion comprised about two-thirds of the total sediment yield.

(3) Spomer et al. (1986) working in
- (i) Dry Creek Basin in south central Nebraska
- (ii) 20 mi^2 watershed area; 65 percent of land area is steep; 35 percent is relatively level
- (iii) 33 percent cropland, 66 percent rangeland
- (iv) High gully erosion rates
- (v) Approximately 60 percent of eroded soil reached the watershed outlet

(4) Coote (1984) working in
- (i) Prairie landscape in Manitoba and Saskatchewan, Canada
- (ii) Delivery of eroded soil to streams was estimated to be about 5 percent

(5) Lowrance et al. (1986) working in
- (i) Forest, Crop Watershed in Turner County, Georgia
- (ii) 34 percent of the watershed area was row crops, 59 percent forested
- (iii) About one percent of eroded soil was delivered to streams

H. Estimates of sediment delivery should be tempered by judgment and consideration of other influencing factors such as soil texture, relief, type of erosion, sediment transport system, and deposition areas and precipitation intensity and duration.

645.0717 Hydrologic Effects of Range Improvement Practices

A. Rangeland management practices that promote increased production usually increase transpiration, while surface runoff and water yields are reduced (Boughton 1970). Many researchers have reported increases in infiltration following mechanical range improvement practices, such as root plowing, vibratilling, and pitting by creating a macroporous surface which is able to store more water (Branson et al. 1966, Wight 1976, Tromble 1976, Neff and Wight 1977, Gonzales and Dodd 1979, Bedunah 1982, Bedunah and Sosebee 1985).

B. Bedunah and Sosebee (1985) studied the results of site manipulation on infiltration on a mesquite/buffalograss community in west Texas. Seven treatments were applied: foliar spray, shred, control, grub between trees, grub trees, Kleingrass (*Panicum coloratum*) planting, and vibratill. Vibratilling resulted in the highest infiltration rates. Shredding trees was ranked second for increasing infiltration rates. The shredding treatment was associated with increases of litter and standing crop. Removal of mesquite trees by foliar spraying, mechanical grubbing, or planting to Kleingrass did not increase water infiltration rates, compared to the control treatment.

C. In the last 150 years, proliferation of trees and shrubs on rangelands worldwide has had a significant impact on land cover at the expense of perennial grasses (Archer et al. 2011). With shrub encroachment, estimates suggest that for every millimeter of precipitation above 300 mm, aboveground net primary production increases by 0.6 g C m^{-2} yr^{-1} (Barger et al. 2011). Research from the Walnut Gulch Experimental Watershed and the Jornada Experimental Range have demonstrated significant differences in hydrology and water erosion between grasslands and shrublands (Wainwright et al. 2000). In general, splash detachment and inter-rill erosion rates are higher in shrublands compared to grassland sites (Abrahams et al. 1988, Parsons et al. 1991). However, there are interesting dynamics in shrub coppice zones with significant litter accumulations under the canopy. Higher infiltration rates, greater organic matter and nutrient accumulation, greater aggregate stability, lower bulk density, and greater biological activity are associated with coppice mounds (Pierson and Williams 2016).

D. When grass production is lost due to woody plant encroachment, grass cover often declines rapidly. Above and belowground productivity, litter inputs, rooting depth, distribution, biomass changes, hydrology, microclimate, and energy balance are altered as woody plant encroachment progresses (Archer et al. 2011).

E. Brush management on rangeland can be accomplished by one or more means such as mechanical removal, prescribed burning, herbicides, and selecting the proper class of grazing animal. Brush control on watersheds increases available water to other usually more desirable forage plants, which can include seeding as part of the management action; and increase runoff water for off-site use by replacing deep-rooted shrubs with more shallow-rooted grasses or forbs which consume less water. Overall broad sweeping conclusions about the hydrologic impacts of brush control are difficult because of the interactions of climate, weather, vegetation composition before and after treatment, soil type, shrub control methods, density of and type of shrubs, understory vegetation, timing of shrub control, and management after treatment. Brush control impacts will vary over time and from one rangeland plant community type to another because of these natural variations. Improvements in hydrologic response following brush control depends upon the factors listed above.

645.0718 Riparian Vegetation and Grazing

A. Riparian zones occur along the interface between aquatic and terrestrial ecosystems. Riparian ecosystems generally make up a minor portion of the landscape in terms of land area but are extremely important components in the planning and management of the rangeland or pastureland unit. It is important to recognize that management and condition of the transitional zone (inactive floodplains, terraces, meadows, etc.) and upland sites are critical to the health of riparian ecosystems because these are areas of runoff and recharge. Excessive runoff and gully erosion on uplands ultimately has a profound impact on the riparian zone and stream corridor.

B. A well-planned grazing system that provides periodic rest can alleviate many of the problems associated with livestock in riparian areas. Continuous season-long grazing is the most damaging grazing regime to riparian sites because livestock congregate and spend most of their time in riparian zones. Riparian zones, compared to more rugged, steep upland sites in the western United States, provide available and easily accessible water, forage, and shade. Excessive livestock impacts, such as heavy grazing and trampling, affect riparian-stream habitats by reducing or eliminating riparian vegetation, changing streambank and channel morphology, increasing stream sediment transport, and lowering of the surrounding ground water tables.

C. Livestock are perceived as a major cause of riparian degradation in the West, which has resulted in increased concerns from resource users. In addition to forage for livestock, riparian areas are generally one to two percent of the summer range land area but produce about 20 percent of the summer forage. Riparian areas have high value for fisheries habitat, wildlife habitat, recreation, transportation routes, precious metals, water quality, and timing of water flows.

D. Rehabilitation of riparian zones can include rotational grazing schemes, complete exclusion of livestock, changes in type or class of animal, and techniques to improve livestock distribution (salt placement, development of watering areas away from the riparian zone, fencing, herding, alternate turnout dates, etc.). Rest-rotation is one of the most practical means of restoring and maintaining riparian zones. Under moderate stocking, rest-rotation can improve riparian vegetation and physical stability. Where livestock grazing is compatible in a particular riparian area, grazing management practices must allow for regrowth of riparian plants and should leave sufficient vegetation cover for maintenance of plant vigor and streambank protection.

E. Streamside use of herbaceous forage in riparian areas in summer-grazed pastures should be used judiciously (not more than 50 percent by weight). In the intermountain region, riparian plant communities have limited regrowth potential after mid-summer. In riparian zones, “Rule of thumb” stubble heights proposed by some grazing guides (e.g., 4.0 inches) may or may not be adequate for certain species. State technical guides should be consulted for the dominant species on the site. Fall grazing should be monitored carefully because little or no regrowth potential remains. Utilization should be monitored on a per weight basis for native species or by height of stubble (as per state technical guides).

645.0719 Fire Dynamics on Hydrology and Erosion

A. Periodic fire is a natural disturbance that has formed and been part of the evolution of many rangeland plant communities and has been part of their evolution (Fuhlendorf et al. 2012) (Table G-22). Interruption and alteration of natural fire regimes since European settlement has resulted in altered rangeland ecosystems. In many rangeland ecosystems, the historic plant community was maintained by fire, and subsequent removal of fire has resulted in community threshold transitions, often with the consequence of woody plant invasion and loss of plant cover, resulting in increased erosion and loss of production for livestock and wildlife. In many rangeland ecosystems, most herbaceous plant species recover within 2–3 years postfire, irrespective of season of burn. However, there are always exceptions in rangeland ecosystems where fire is inherently infrequent (Fuhlendorf et al. 2012). There is always associated risk of excessive runoff and erosion is always associated with either prescribed fire or wildfires. Landowners and producers must weigh out the benefits versus the risk. However, risk of soil erosion is less on prescribed burns because current climate forecasts can be evaluated, plant root systems remain intact, and plants resprout quickly, and affected land areas are usually much less than when wildfires consume large areas of land.

B. Wildfire frequency intervals can be more frequent than natural fire frequencies in some rangeland plant communities and have a significant effect on runoff and hydrology. Wildfire, especially on rangelands where fire has been previously repressed, can have devastating effects on the environment. If high intensity rainfall events occur after severe burn events, there is high risk of accelerated runoff and flooding, debris-flow events, high erosion rates and sedimentation in water courses, damage to property, and loss of life. Pierson and Williams (2016) state: “the degree to which fire increases runoff and erosion rates and the associated risks is highly variable and depends on many factors.” The dynamics and effects of runoff and erosion in response to fire is highly dependent on the intensity of the burn, fuel type, soil, climate, time of burn, topography, and vegetation. Fire has a dramatic effect on vegetative and ground cover and may also physically and chemically affect soils as fire intensity and temperatures increase.

- (1) Fire effects on hydrology:
  - (i) Reduced infiltration, increased runoff, and soil surface protection
  - (ii) Alteration of physical, chemical, and biological factors
  - (iii) Exacerbation, alteration, and formation of soil water repellence (hydrophobicity)
- (2) Fire and erosion effects:
  - (i) Increased rain splash and soil erosion
  - (ii) Altered concentrated flow processes

C. For example, fire temperatures have varying effects on organic matter. Humic acids and organic compounds (long-chain aliphatic hydrocarbons) are lost at temperatures below 212^{o}F. At temperatures between 212^{o}F and 390^{o}F, nondestructive distillation of volatile organic substances occurs, and at temperatures between 390^{o}F and 570^{o}F about 85 percent of the organic substances are destroyed by destructive distillation. The duration and temperature of the fire can distill organic material and other substances downward into the soil and form a non-wettable hydrophobic layer. Fuels that burn quickly (e.g., grass) or very hot (brush piles) generally do not form a hydrophobic layer in the soil. Water repellent layers in the soil are most common in shrub communities where fires burn from five to 25 minutes. This situation is inherent in chaparral communities where 90 percent of the decomposed organic matter is usually lost as smoke and ash, and the remaining material is distilled downward and condensed in the soil.

Table G-22. Fire frequency comparisons and fire regime characteristics in range and forest plant communities. LANDFIRE Rapid Assessment Vegetation Models. Courtesy U.S. Forest Service. https://www.fs.fed.us/database/feis/fire_regime_table/fire_regime_table.html

Vegetation Community	Fire Severity*	% of Fires	Mean Interval (yrs)	Minimum Interval (yrs)	Maximum Interval (yrs)
Pacific NW Grassland					
Bluebunch wheatgrass	Replacement	47%	18	5	20
	Mixed	53%	16	5	20
Pacific NW Shrubland					
Mountain big sagebrush (high elev)	Replacement	100%	20	10	40
Wyoming big sagebrush steppe	Replacement	89%	92	30	120
California Shrubland					

Vegetation Community	Fire Severity*	% of Fires	Mean Interval (yrs)	Minimum Interval (yrs)	Maximum Interval (yrs)
California grassland	Replacement	100%	2	1	3
Chaparral	Replacement	100%	50	30	125
California forested					
Coast redwood	Replacement	2%	≥1,000		
	Surface or low	98%	20		
Southwest grassland					
Desert grassland with shrubs and trees	Replacement	85%	12		
	Mixed	15%	70		
Plains mesa grassland	Replacement	81%	20	3	30
	Mixed	19%	85	3	150
Northern and Central Rockies Forested					
Douglas-fir (cold)	Replacement	31%	145	75	250
	Mixed	69%	65	35	150
Grand fir-Douglas-fir-western larch mix	Replacement	29%	150	100	200
	Mixed	71%	60	3	75
Ponderosa pine (Black Hills, low elevation)	Replacement	7%	300	200	400
	Mixed	21%	100	50	400
	Surface or low	71%	30	5	50
Plains Grassland					
Central Tallgrass prairie	Replacement	75%	5	3	5
	Mixed	11%	34	1	100
	Surface or low	13%	28	1	50
Northern mixed-grass prairie	Replacement	67%	15	8	25
	Mixed	33%	30	15	35
Southern shortgrass or mixed-grass prairie	Replacement	100%	8	1	10
Northeast Woodland					
Pine barrens	Replacement	10%	78		
	Mixed	25%	32		
	Surface or low	65%	12		
Eastern woodland mosaic	Replacement	2%	200	100	300
	Mixed	9%	40	20	60
	Surface or low	89%	4	1	7

*Fire Severities

Replacement: Any fire that causes greater than 75% top removal of a vegetation-fuel type, resulting in general replacement of existing vegetation; may or may not cause a lethal effect on the plants.

Mixed: Any fire burning more than 5% of an area that does not qualify as a replacement, surface, or low-severity fire; includes mosaic and other fires that are intermediate in effects.

Surface or low: Any fire that causes less than 25% upper layer replacement and/or removal in a vegetation-fuel class but burns 5% or more of the area.

The thickness and depth of a hydrophobic layer depends on the intensity and duration of the fire, soil water content, and soil physical properties. Hydrophobic layers form in dry soils more than in wet soils, and coarse-textured soils are more likely to become water repellent than fine-textured soils (Pierson et al. 2001, 2002a, 2008). In sagebrush ecosystems, water repellency was generally greater on unburned hillslopes and had a greater impact on infiltration capacity than fire effects (Pierson et al. 2008). Fire-induced reduction on infiltration was the result from the combined effect of canopy and ground cover removal and the presence of naturally occurring water repellent soils. Pierson et al. (2008) summarized: “removal of ground cover likely increased the spatial connectivity of runoff areas from strongly water repellent soils. The results indicate that for coarse-textured sagebrush landscapes with high pre-fire soil water repellency, post-fire increases in runoff are more influenced by fire removal of ground and canopy cover than fire effects on soil water repellency, and that the degree of these impacts may be significantly influenced by short-term fluctuations in water repellent soil conditions."

D. Fire-induced hydrologic vulnerability is generally low where canopy and ground vegetative cover is minimal. In high intensity burns, the risk of accelerated runoff, sheet-rill and gully erosion risks increase exponentially, especially with land slope increases. Hydrologic studies on plots and hillslopes show that runoff and erosion can increase after fire from 2 to 40 times greater on small simulation plots and more than 100-fold on large plots to hillslope scales, compared to unburned treatments (Pierson and Williams 2016).

645.0720 Rangeland Models Associated with Hydrology and Erosion

A. The Rangeland Health Model is based on the qualitative assessment of 17 indicators that determine the preponderance of evidence for Hydrologic Function, Site Stability, and Biotic Integrity. All three of these rangeland health attributes relate to watershed management and should be considered in planning and monitoring rangeland. The Rangeland Health Model can be used in conjunction with quantitative assessments of rangeland (production, foliar cover, bare ground, invasive species). The model is useful in detecting subtle changes, which may indicate if a site is near or has passed a threshold to an alternative state. Once a resource manager has been properly trained, a high degree of repeatability and reliability can be achieved.

B. Interpreting Indicators of Rangeland Health V5 (Pellant et al. 2020) is available for use by NRCS for estimating historical surface runoff, soil erosion, and sediment yield, or future risks at the hillslope scale for conservation planning and assessing the sustainability of rangelands. Specific classes are offered by NRCS to provide training on this tool.

C. Rangeland Hydrology and Erosion Model (RHEM)

(1) RHEM was developed as a coordinated project between three USDA agencies: Agricultural Research Service (ARS), NRCS, and the United States Forest Service (USFS) (Wei et al. 2009, Hernandez et al. 2017, Nearing et al. 2011, Hernandez et al. 2017). The RHEM model is designed for government agencies, land managers, and conservationists who need sound, science-based technology to model and predict runoff and erosion rates on rangelands and to assist in assessing rangeland conservation practice effects. RHEM is a process-based erosion prediction tool specific for rangeland application and is based on fundamentals of infiltration, hydrology, plant science, hydraulics and erosion mechanics. RHEM can be used to evaluate runoff and erosion as a consequence of plant species and growth form changes from disturbances such as fire, brush management, and climate change. RHEM will also evaluate the statistical risk from various storm events (2, 5, 10, 25, 50, 75, and 100-yr). Outputs of RHEM include average precipitation, number of storms producing runoff, runoff, soil loss, and hydrology and erosion risks for the design storm events. The RHEM model can be accessed at the USDA-ARS Southwest Watershed Research Station web site: https://apps.tucson.ars.ag.gov/rhem/login.

(2) Model Functionality:

(i) Model and evaluate conservation practice and systems benefits
(ii) Evaluate conservation program benefits
(iii) Assist in developing conservation system guides
(iv) Conservation planning, check site parameters with planned management practices
(v) Assist in developing hydrologic function sections for ecological site descriptions
(vi) Watershed planning
(vii) National Resource Inventories—assessment of rangeland hydrology and erosion
(viii) Training tool to teach interactions between climate-soils-plants-management
(ix) Use in "Market-based approaches"

(3) Importance: benefits for NRCS customer
- (i) Provide a quantitative tool for evaluating the effectiveness of conservation practices.
- (ii) Model and predict rangeland hydrology and erosion for current and future conditions.
- (iii) Identify ecological site thresholds and identify critical site issues that may still be rectified.
- (iv) Provide data and tools to support market-based approaches.

(4) Benefits for field staff

RHEM outputs can be linked with other NRCS web-based technologies. This information can be used in many NRCS programs and planning activities (i.e., predict rangeland hydrology and erosion at the field and watershed level scale).

(5) Benefits for area and state offices

All items above, and for use in developing Conservation guidance sheets, Ecological Site Descriptions, and Rangeland Health Reference Sheets.

(6) National benefits

NRCS program evaluation, evaluating conservation priorities, NRI, and conservation benefits analysis. RHEM can be used to support activities across all missions in the agency strategic plan and carrying out Farm Bill initiatives.

(7) Several publications, handbooks, and RHEM ESD guide documents have been produced to assist in using the RHEM model and writing ecohydrology sections for ecological site descriptions or evaluating benefits of conservation.
- (i) NRCS Handbook: Title 190, Rangeland Processes Handbook, Part 646, “Hydrology and Soil Erosion.
- (ii) NRCS Handbook: Title 190, Rangeland Hydrology and Erosion Model Handbook, Part 647, “RHEM Guide.”
- (iii) Rangeland Hydrology and Erosion Model Guide and Discussion for: Short Grass Prairie Ecological Site, West Texas. Discusses the Deep Hardland Loamy 16–21" PZ (R077CY022TX) Major land resource area (MLRA): 077C-Southern High Plains, Southern Part Ecological Site, Texas.
- (iv) Rangeland Hydrology and Erosion Model Guide and Discussion for: Post Oak Savanna Ecological Site with Ash Juniper Encroachment, Central Texas. Discusses Deep Redlands 29–35” PZ (R081CY358TX). Major land resource area (MLRA): 081C eastern part of the Edwards Plateau region of central Texas.
- (v) Rangeland Hydrology and Erosion Model Guide and Discussion for: Mountain Big Sagebrush and Bluebunch Wheatgrass, with western Juniper Encroachment and cheatgrass Invasion, Southeast Oregon. Discussion for South Slopes 12–16 in PZ (R023XY302OR); Major Land Resource Area (MLRA): 23 Malheur High Plateau, Southeast Oregon.
- (vi) Rangeland Hydrology and Erosion Model Guide and Discussion for: Desert Grassland Ecological Site with Invasive Grass and Shrub Encroachment, Southeastern Arizona. Discusses the Limy Slopes 12–16” PZ ecological site (Site ID: R041XC308AZ) Major land resource area (MLRA): 041-Southeastern Arizona Basin and Range.

645.0721 Appendix G-A.

A. Ecological Site Development: Ecohydrology

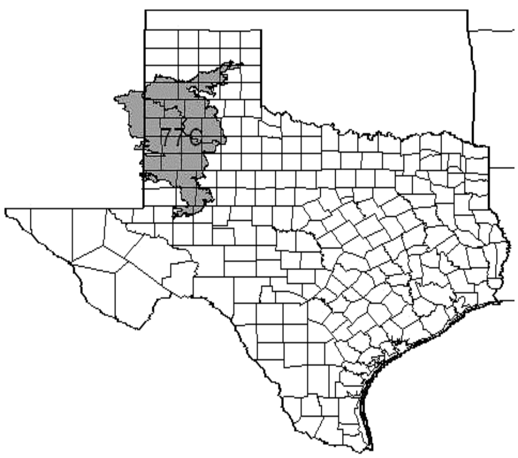
Ecological site descriptions (ESD) support discussions on ecohydrology. The following fact sheet guide “Rangeland Hydrology and Erosion Model (RHEM) guide and Discussion for: Short Grass Prairie Ecological Site, west Texas” is an example of a detailed ecohydrology narrative and discussion with RHEM outputs to illustrate hydrology and erosion dynamics with state-and-transition model changes.

B. Rangeland Hydrology and Erosion Model guide and Discussion for: Short Grass Prairie Ecological Site, west Texas

(1) General Background

(i) The Ecological Site for this example is a Deep Hardland Loamy 16–21" PZ (R077CY022TX); Major land resource area (MLRA): 077C-Southern High Plains, Southern Part Ecological Site (ES). See figure G-A-1.

Figure G-A-1. Location of Major Land Resource Area and example of Reference plant community.



(ii) MLRA 77C is characterized by nearly level plains with numerous playa depressions, moderately sloping breaks along drainageways, and a steep escarpment along the eastern margin. This site occurs on the large nearly level to moderately sloping, well drained, moderately permeable soils formed in calcareous, loamy colluvium and slope alluvium derived from the Ogallala Formation of Miocene-Pliocene age. A few ancient drainage ways dissect this plateau, and relatively shallow closed depressions are scattered throughout the area. The elevation ranges from 2,800 feet to 4,500 feet above sea level. Slopes range from 0 to 5 percent. The site is extensively used for cultivated cropland, as well as rangeland. The climate is semi-arid dry steppe. Mean annual precipitation is 21 inches. This site consists of very deep, well drained, moderately permeable soils that formed in loam and clay loam loess deposits. These are very well-developed soils on old stable landforms and are moderately alkaline throughout. The soils have dark colored loam subsurface layers. Parent material is Eolian deposits from limestone origin. There are no surface fragments greater or less than three inches on the soil surface.

(2) Ecological Site Description

(i) The reference plant community (figure G-A-2) is shortgrass prairie grassland dominated by blue grama (*Bouteloua gracilis*, Bogr, 60–70 percent composition by weight) and buffalograss (*Bulbilis dactyloides*, Buda, 15–25 percent composition by weight). Other shortgrass species and a variety of forbs comprise the remaining plant composition. Typically, forbs contribute around five to eight percent of the total production. A few woody species, cholla cactus (*Cylindropuntia imbricata*, prickly pear (*Opuntia* spp.), broom snakeweed (*Gutierrezia sarothrae,* Gusa) or occasional yucca (*Yucca* spp.) will be present, usually only one to two percent of the total plant community. Although honey mesquite (*Prosopis glandulosa*) is not a native component species on this ecological site, it can be invasive. The Deep Hardland ecological site can exhibit high plant species richness and diversity (Spaeth 1990).

(ii) With continued heavy grazing pressure, the plant community shifts to a more equal distribution of blue grama (25–50 percent) and buffalograss (15–30 percent) (figure G-A-2, phase 1.2). In community phase 1.2 the soil can become more compacted, and subsequently rainfall infiltration capacity is reduced and runoff increases. Further long-term grazing pressure can result in a transition to State 2.1 where buffalograss dominates the stand. Once buffalograss dominates the stand, transition to State 1 can be long-term (decades) because of the ecohydrologic dynamics of buffalograss (see RHEM modeling results and discussion, this appendix). The dominant buffalograss, state 2.1, also occurs as a transition from State 4.1, which results from prairie dog colonization and abandonment. This transition may take decades and depends on climate and management of the site.

(iv) Combinations of long-term heavy grazing pressure and drought can facilitate the increase of the native half shrub broom snakeweed. Sandier soil pockets and components within the ecological site are also more conducive to broom snakeweed invasion (Spaeth 1990). This low-growing (less than 0.5 m tall) suffrutescent plant is poisonous and is considered undesirable by many landowners because it suppresses growth of other native grasses and forbs. Allelopathy may be a factor, as it is correlated with reduced grass and forb production, which enhances its own life cycle (Lowell 1980). Plant diversity is low in stands with dominance of broom snakeweed (Spaeth 1990).

(v) Mesquite and cholla cactus can be invasive on this ecological site (State 5.1). Once this state becomes established, gains momentum, and woody densities increase, more stringent applications of conservation practices will be necessary (Brush Management, Prescribed Burning and Grazing). The economic inputs to convert State 5.1 to 2.1 can be high.

(vi) Black-tailed prairie dogs (*Cynomys ludovicianus*), often referred to as “ecosystem engineers” and “keystone species” (Lawton and Jones 1995, Power et al. 1996) in shortgrass prairie can have a profound effect on grassland structure, composition, and ecosystem dynamics (Winter et al. 2002, Fahnestock et al. 2003). Where prairie dogs are abundant, grassland vegetation can be altered dramatically with extensive and persistent burrow systems. Prairie dogs have intrinsic biological value in grasslands. Colonies can provide refugia for subdominant grasses, forbs, and shrubs (Coppock et al. 1983). Soil structure and chemistry can be modified. Nutrients can be altered (Whicker and Detling 1988), and modifications in habitat can benefit other grassland animals (Clark et al. 1982, Lomolino and Smith 2003). Although the disturbance regime can be extreme in active prairie dog colonies, floristic richness can be high, even greater than State 1.1 (Bonham and Lerwick 1976, Klatt and Hein 1978, Coppock et al. 1983, Martinsen et al. 1990, Spaeth 1990, Fahnestock and Detling 2002). Soil surface physical and chemical condition changes created by prairie dog colonization also have a significant effect to decrease infiltration capacity, soil water storage, and increase runoff and erosion (see RHEM modeling results and discussion, this appendix).

(3) Soils

Existing soil texture components in the Deep Hardland Loamy Ecological Site include loam, silty clay loam, and clay loam.

(4) Climate

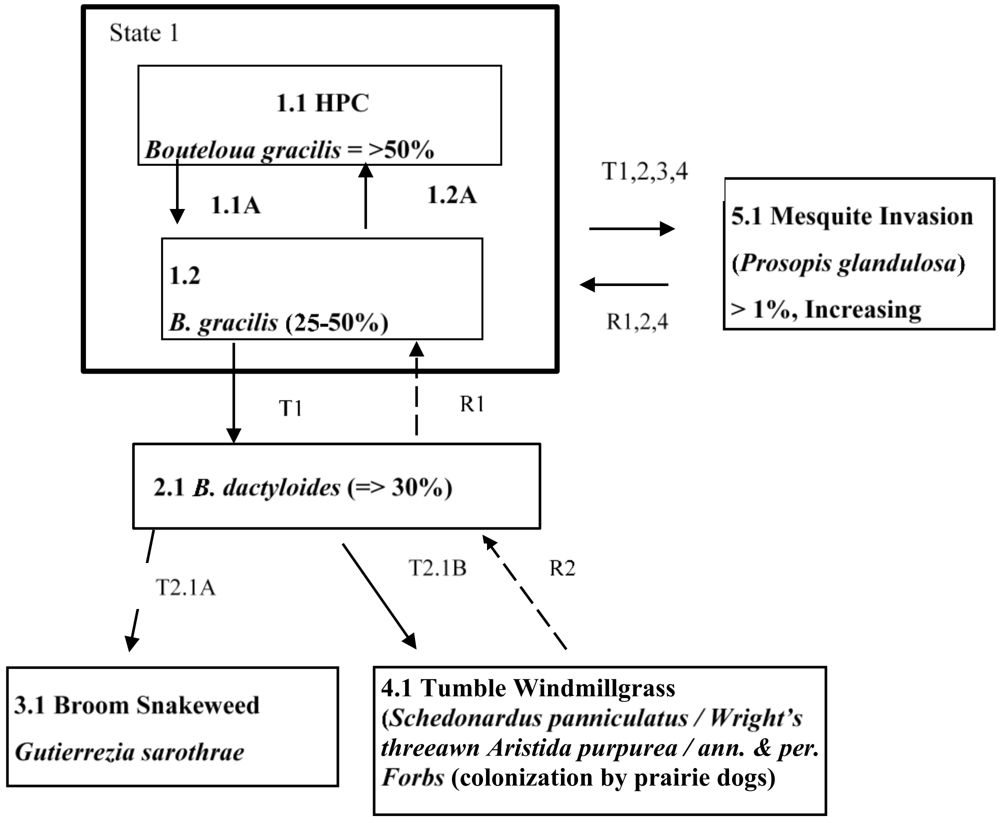
Ecological Site Description/Climate Description: Climate is semi-arid dry steppe. Summers are hot with winters being generally mild with numerous cold fronts that drop temperatures into the single digits for 24 to 48 hours. Temperature extremes are the rule rather than the exception. Humidity is generally low and evaporation high. Wind speeds are highest in the spring and are generally southwesterly. Canadian and Pacific cold fronts come through the region in fall, winter, and spring with predictability, and temperature changes can be rapid. Mean average precipitation is 21 in, most of which comes in the form of rain and during the period from May through October. Snowfall averages around 15 inches but may be as little as eight inches or as much as 36 inches. Rainfall in the growing season often comes as intense showers of relatively short duration. Long-term droughts occur on the average of once every 20 years and may last as long as five to six years (during these drought years moisture during the growing season is from 50 to 60 percent of the mean). Based on long-term records, approximately 60 percent of years are below the mean rainfall and approximately 40 percent are above the mean. May, June, and July are the main growth months for perennial warm-season grasses, whereas forbs make their growth somewhat earlier. Average frost-free days are 205; freeze-free days 210.

(5) Modeling Results and Discussion

(i) Modeling inputs are shown in table G-A-1.

(ii) Figures G-A-4 through G-A-9 provide an overview of plant communities and summary of precipitation, runoff, sediment yield, and soil loss rates for the annual average and 2, 5, 25, 50, and 100-year runoff recurrence intervals. For the Deep Hardland Loamy Ecological Site, hydrology and soil loss is highly variable across the respective states. As management and climate affect cover, production, and species composition, significant changes occur over time with respect to ecological changes (species composition) and hydrology. The decline of foliar plant cover and production affect the hydrologic regime. However, plant life/growth forms on a site greatly influence infiltration and runoff dynamics, such as tall grasses, mid grasses, shortgrasses, forbs, shrubs, halfshrubs, and trees, and their compositional differences. Infiltration is usually highest under trees and shrubs and decreases progressively in the following order: bunchgrass, sodgrass, and bare ground (Carlson et al. 1990, Thurow 1991, Weltz and Blackburn 1995).

Figure G-A-2. State and transition diagram for ecological site Deep Hardland site near Muleshoe, Texas (photos by NRCS).



Legend

1.1A	Lack of prescribed grazing, heavy grazing use
1.2 A	Prescribed grazing, above average spring, summer precipitation
T1	Traversed threshold, transition from State 1 to 2; lack of prescribed grazing, drought, prairie dog use
R1	Restoration from State 2.1 to 1.2, tenuous, time factor could be decades; climate pulse—above average summer precipitation; prescribed grazing; periodic deferment from grazing
T2.1A	Traversed threshold to State 3 due to stand deterioration, significant broom snakeweed increases > 2% cover
T2.1B	Traversed threshold to State 4 due to prairie dog colonization, significant bare ground increase
R2	Restoration from State 4.1 to 2.1 is tenuous, time factor could be decades, climate pulse—above average summer precipitation; prescribed grazing; periodic deferment from grazing
T1234	From any state, 1, 2, 3, 4: Mesquite invasion > 1%, increasing comp. of Cholla and prickly pear cactus
R124	Restoration from State 5.1 to 1.2 will require one or more of the following conservation practices (brush management, prescribed burning, and prescribed grazing).

(iii) Individual plant species also have a profound effect on hydrology and erosion dynamics, such as different grasses, forbs, and shrubs (Spaeth 1996 a, b). Field studies have documented infiltration capacity with individual species composition. Dee et al. (1966) found that water infiltrated three times faster in blue grama and silver bluestem (*Bothriochloa saccharoides*) stands than areas dominated by annual weeds such as summer cypress (*Kochia scoparia*) and windmill grass (*Chloris verticillata*). Blue grama terminal infiltration capacity was about four times higher than buffalograss stands, holding soil type constant.

Table G-A-1. RHEM model inputs for evaluation of hydrologic impact of transitions from one ecological state to another ecological state for Deep Hardland Loamy 16–21" PZ (R077CY022TX) site. Representative soil series is a Berda loam in the surface horizon.

Input Parameter	Reference State 1.1	State Phase 1.2	State 2.1	State 3.1	State 4.1
Soil Texture	Clay	Clay	Clay	Clay	Clay
Soil Water Saturation (%)	25	25	25	25	25
Slope Length (ft)	100	100	100	100	100
Slope Shape	Linear	Linear	Linear	Linear	Linear
Slope Steepness (%)	2	2	2	2	2
Foliar Canopy Cover (%)					
Bunch Grass Foliar Cover (%)	90	45	0	25	5
Forbs and/or Annual Grass Foliar Cover (%)	5	5	5	10	5
Sodgrass Foliar Cover (%)	5	50	90	10	5
Woody Foliar Cover (%)	0	0	0	0	90
Ground Surface Cover %					
Basal Cover (%)	10	6	5	1	1
Rock Cover (%)	0	0	0	0	0
Litter Cover (%)	30	20	5	0	10
Biological Crusts Cover (%)	0	0	0	0	0

- Figure G-A-3 shows comparative infiltration rates derived from rainfall simulation experiments for various ecological states and phases (Spaeth 1990). Initial infiltration capacity from the onset of rainfall to 25 minutes was slightly different for the reference state, blue grama (Bogr), and perennial broom snakeweed (Gusa) stands. However, long term infiltrability (near-saturated hydraulic conductivity) were the same. The Gusa stands had infiltration rates similar to the reference Bogr stands (representative of high similarity index), indicative of low similarity index values, higher percentage of bare ground, low graminoid and forb cover, and high sub-shrub cover. This demonstrates that the Gusa stands still maintain adequate hydrologic function, representative of low biotic integrity and similarity index with significant changes in plant functional groups (graminoid-to-woody), high composition of invasive plants, and loss of native grass cover. However, soil loss was higher in Gusa stands compared to the reference stands (1.1 Bogr and 1.2 Bogr/Buda) due to higher bare ground under snakeweed canopy (figure G-A-5). What factors may be responsible for the near identical infiltration curves for the reference Bogr sands and the Gusa stands? The answer most likely is due to the morphology of the plants and coppice dune formation, if present. Field studies show that infiltration capacity in bunchgrass stands have inherently higher rates compared to sodgrass stands (Mazurak and Conard 1959; Dee et al. 1966; Spaeth 1990; 1996a, b; Pierson et al. 2002b).
- Some shrubs and half-shrubs are associated with coppice dunes or mounds composed of litter and wind-transported soil. Coppice dunes form under broom snakeweed plants, which create a zone of high infiltrability and low runoff. Field experiments show that surface soil organic carbon, bulk density, percentage silt, and infiltration and interrill erosion rates are significantly higher for shrub-coppice and shrub-interspace areas (Blackburn 1975; Johnson and Gordon 1988; Blackburn et al. 1990; 1992; Pierson et al. 2001, 2002b, 2008).

(iv) Infiltration capacity of state phase 1.2 is different from the reference community 1.1, where blue grama is the dominant species (figures G-A-3 and G-A-4). State phase 1.2 is representative of increasing buffalograss, where the ratio of blue grama and buffalograss is close to 1:1. As buffalograss increases in the stand, infiltration capacity decreases. This is also evident in state 2.1 where buffalograss occurs almost in a monoculture (figure G-A-2). Dominant stands of buffalograss (state 2.1; figure G-A-2) are common around the periphery of active prairie dog colonies and in pastures where grazing has been consistently heavy. Buffalograss is a short shoot plant (grazing tolerant plant with protected meristematic tissue, growing points) that is more tolerant to drought and hot temperatures than blue grama (Weaver 1954) and reproduces sexually (seed) and vegetatively (surface runners-stolons). Research shows that buffalograss also exhibits a dense shallow fibrous root system (root pan) that is correlated with significantly reduced infiltration capacity (Spaeth 1990, 1996a, b).

In some grass stands, where roots are found in the inter-aggregate pores, water repellent compounds form on soil aggregates and soil structural peds as a result of decaying organic matter and the production of humic and fulvic acids (Bisdome et al. 1993, Dekker and Ritsema 1996). Ritsema et al. (1998) state that water repellency is considered a plant-induced soil property. Sources of water repellent compounds include accumulated plant derived organic matter from mulch, decomposing roots and plant material, and root exudates (Doerr et al. 1996, Czarnes et al. 2000). Particulate organic matter contains plant and microbial produced compounds such as waxes (Franco et al. 2000, Schlossberg et al. 2005); humic acids (Spaccini et al. 2002); a presence of a protective water-repellent lattice of long-chain polymethylene compounds around soil aggregates (Shepherd et al. 2001); aliphatic C present in organic matter (Ellerbrock et al. 2005); mycorrhizal and saprobic soil fungi (Bond and Harris 1964, Paul and Clark 1996, Hallett and Young 1999, White et al. 2000, Rillig 2004); basidiomycete fungi (Bond and Harris 1964, Fidanza 2003); fungal proteins such as hydrophobins (Rillig 2005, Rillig and Mummey 2006); and fatty acids, fulvic acids, extracellular enzymes, polysaccharides (Bisdom et al. 1993, Kostka 2000, Eynard et al. 2006).

(v) State 4.1 was produced by prairie dog colonization. Although plant cover is minimal in active colonies, plant species diversity can be greater than all the contrasting states associated with this ecological site (Spaeth 1990). In state 4.1, infiltration capacity is significantly reduced, and erosion potential is higher than any of the other states represented in this ecological site (figures G-A-3, G-A-4, G-A-5). In summary, the extent of vegetation cover and individual plant species (within a life/growth form or contrasting growth habit) can be primary factors that influence spatial and temporal variability of surface soil processes controlling infiltration and interrill erosion rates on rangeland.

(vi) Table G-A-2 and figure G-A-10 show the risk assessments for the five states depicted in the state and transition diagram (figure G-A-2). Interpretations are as follow: there is a 50 percent chance that soil loss (X) will be less than 0.49 t/ac in the Bogr state, a three percent chance in Bogr/Buda, and zero percent in Buda, Gusa, and Arol/Scpa. There is a 30 percent chance that soil loss will be within 0.49 and 0.72 t/ac in the Bogr state, six percent in Bogr/Buda. In the Bogr/Buda state, there is a five percent chance that soil loss will exceed 1.03 t/ac, whereas the probability of soil loss exceeding 1.03 t/ac is high in Bogr/Buda (70 percent), Buda (97 percent), Gusa (100 percent), and Arol/Scpa (100 percent).

Figure G-A-3. Comparative infiltration on five ecological states associated with a Deep Hardland Loamy Ecological Site, Berda loam soil in west Texas. Reference State 1.1 Bogr = blue grama; State phase 1.2 Bogr/Buda (blue grama and buffalograss); State 2.1 Buda = buffalograss; State 3.1 Gusa = perennial broom snakeweed; and State 4.1 Arol = perennial threeawn, Scpa = Texas tumblegrass.

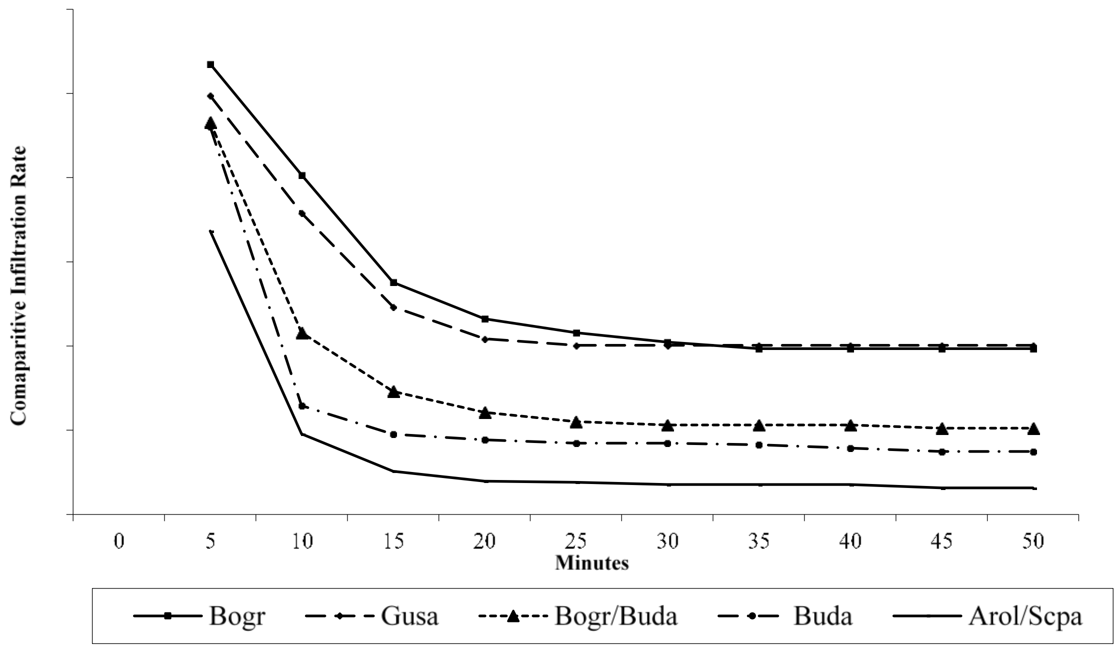


Figure G-A-4. Rangeland Hydrology and Erosion Model estimated average annual precipitation and runoff for Deep Hardland Ecological Site by ecological state near Muleshoe, Texas.

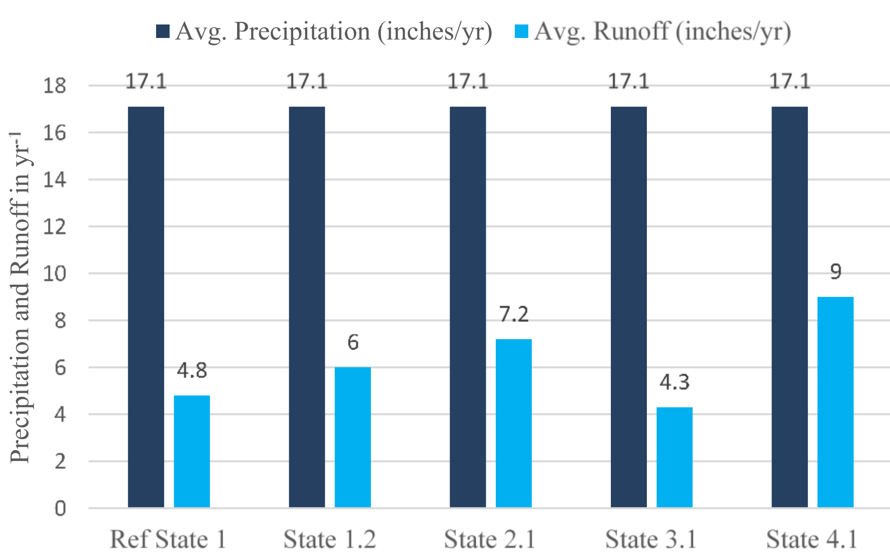


Figure G-A-5. Rangeland Hydrology and Erosion Model estimated average annual sediment yield and soil loss for Deep Hardland Loamy Ecological Site by ecological state near Muleshoe, Texas.

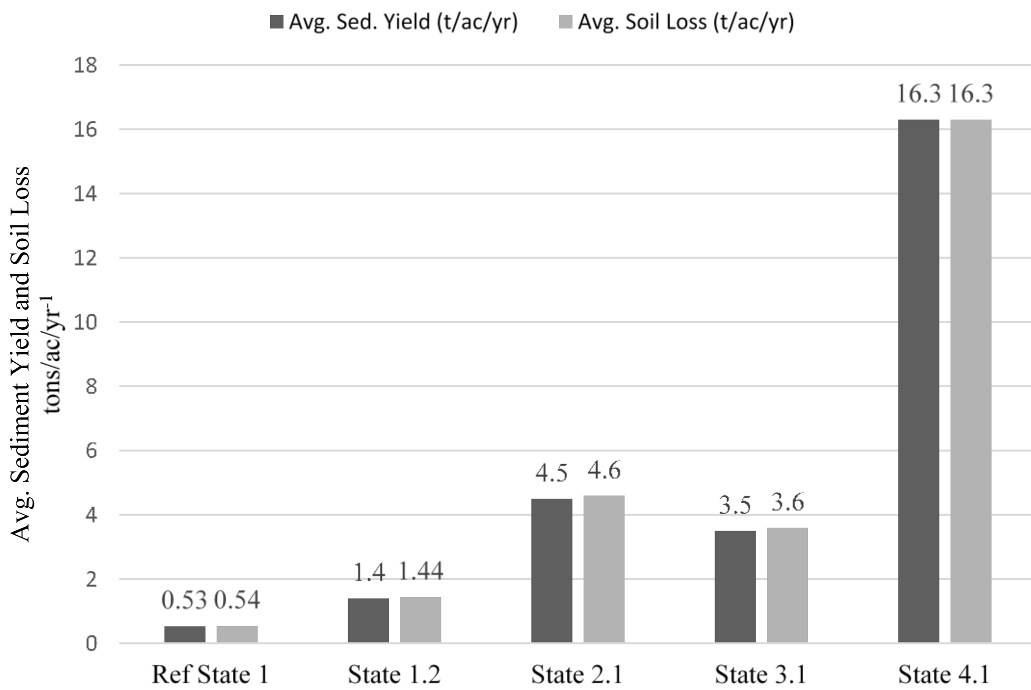


Figure G-A-6. Rangeland Hydrology and Erosion Model estimated storm return period precipitation for Deep Hardland Loamy Ecological Site by ecological state near Muleshoe, Texas.

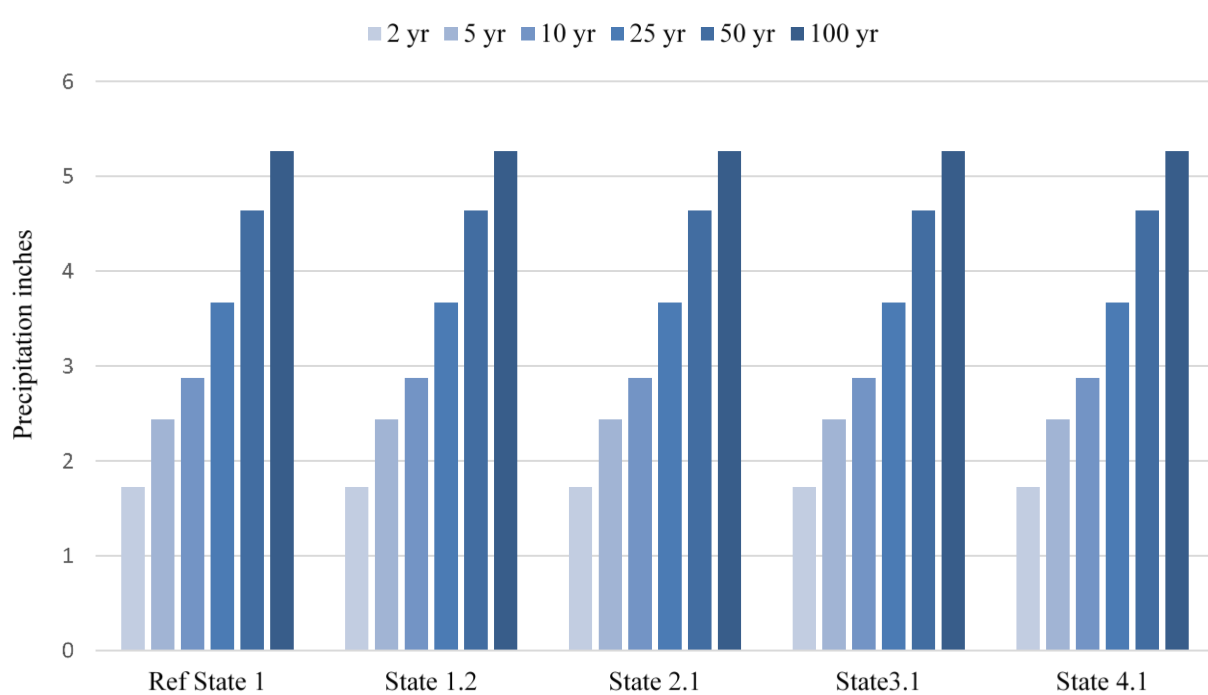


Figure G-A-7. Rangeland Hydrology and Erosion Model estimated storm return period runoff for Deep Hardland Loamy Ecological Site by ecological state near Muleshoe, Texas.

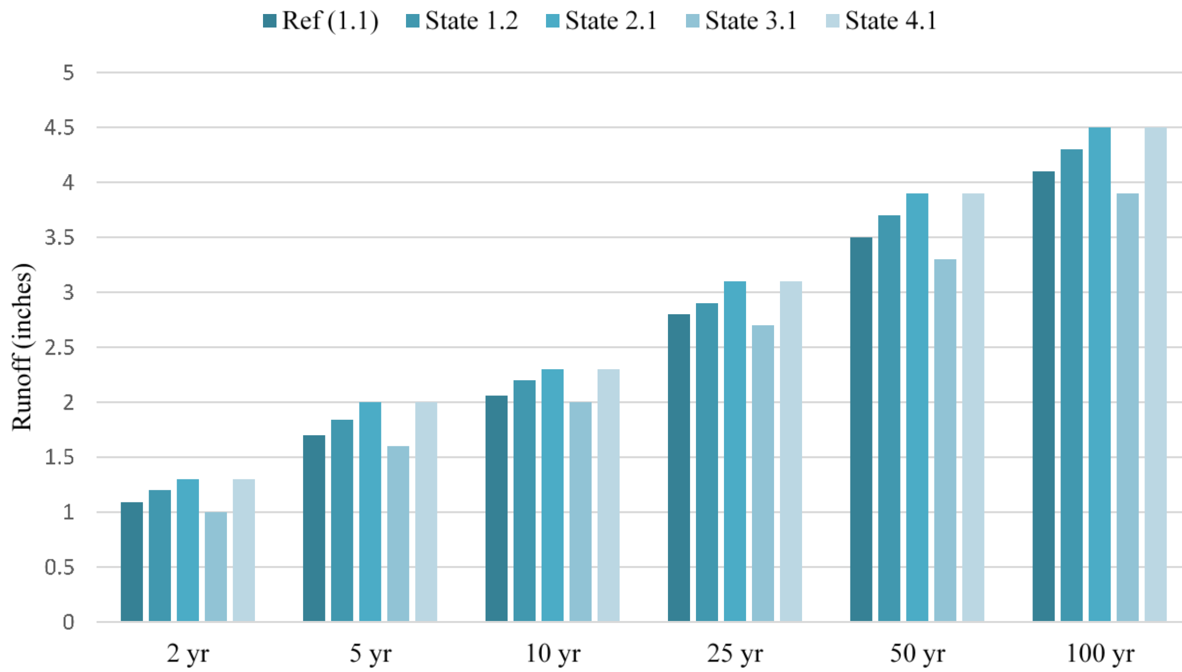


Figure G-A-8. Rangeland Hydrology and Erosion Model estimated storm return period soil loss for Deep Hardland Loam Ecological Site by ecological state near Muleshoe, Texas.

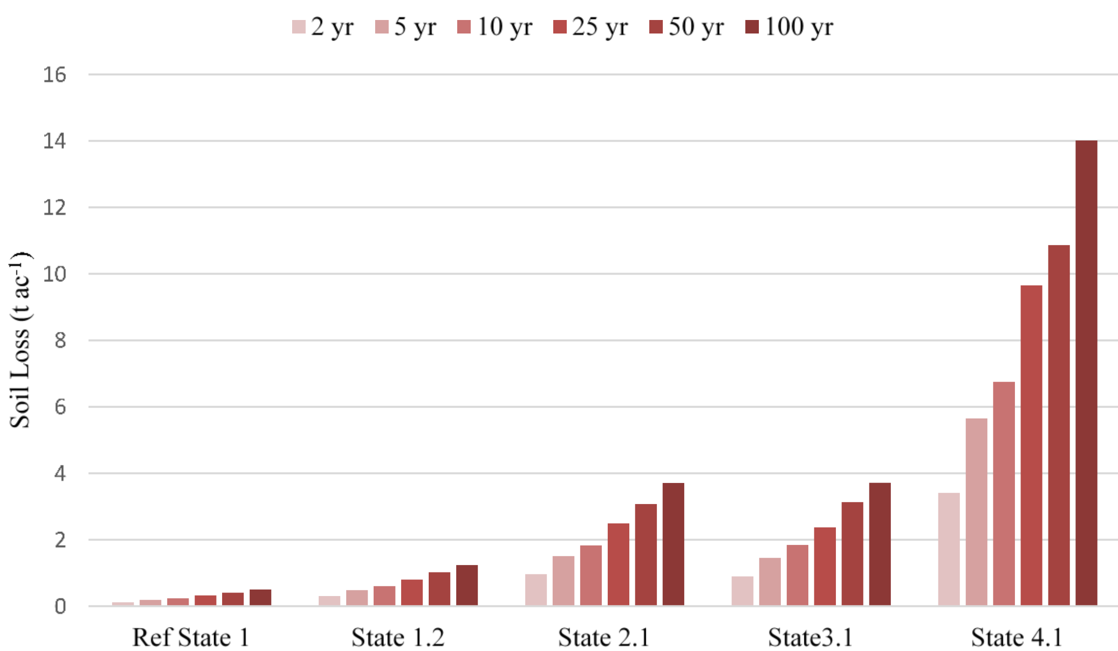


Figure G-A-9. Rangeland Hydrology and Erosion Model estimated storm return period sediment yield for Deep Hardland Loam Ecological Site by ecological state near Muleshoe, Texas.

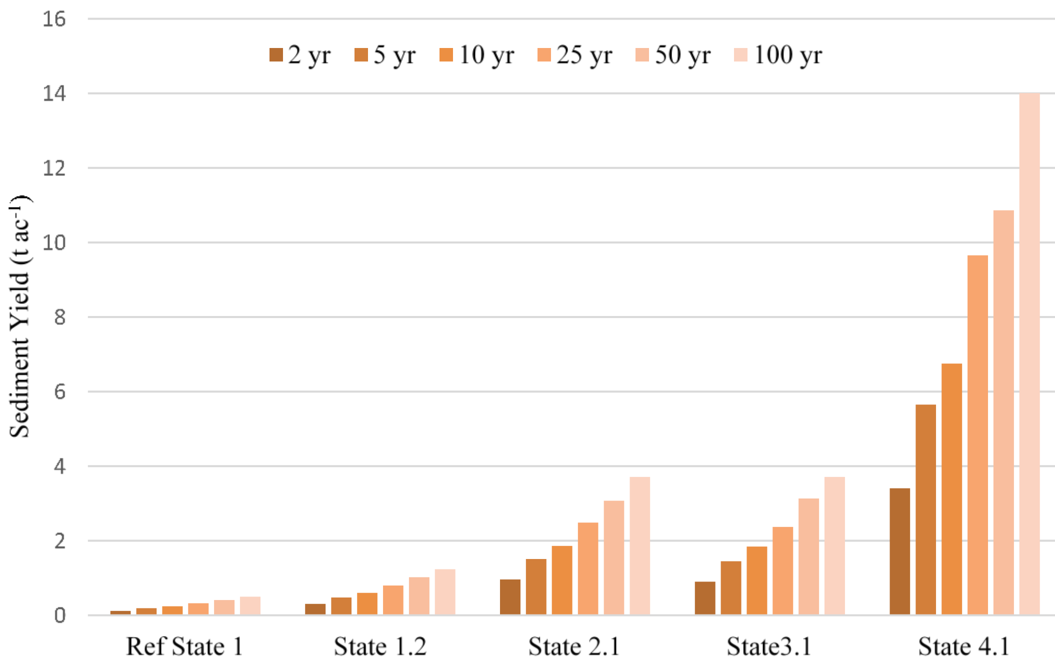


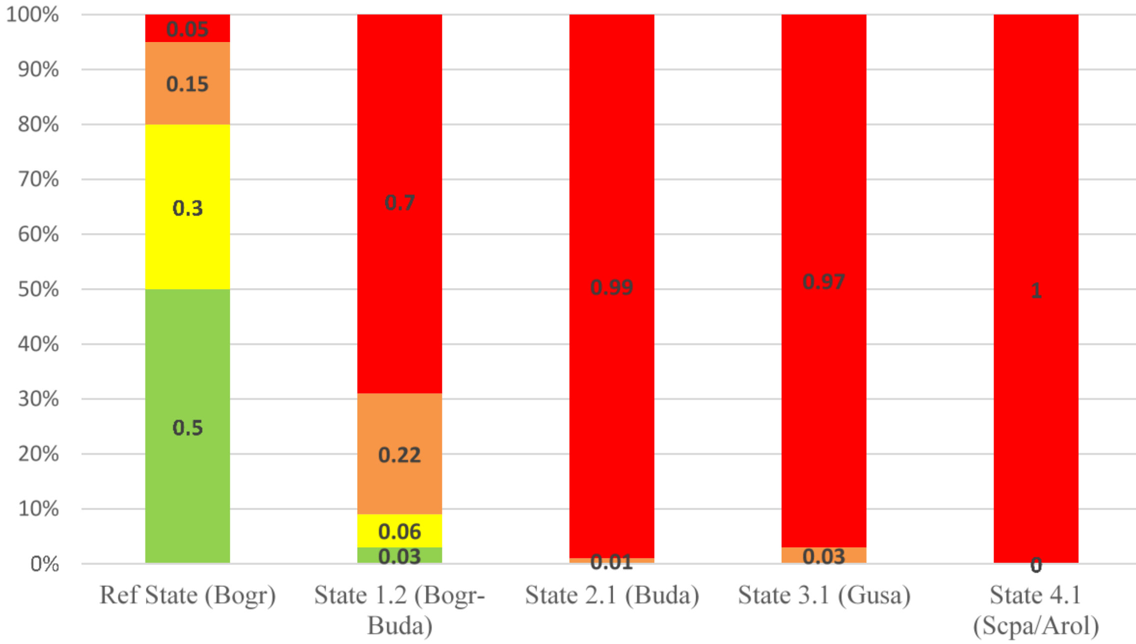
Table G-A-2. Risk Assessment of Accelerated Soil Erosion (ton ac^{-1})

Range of Annual Soil Loss (ton ac^{-1})	1.1 Bogr	1.2 Bogr/Buda	2.1 Buda	3.1 Gusa	4.1 Arol/Scpa
Low X < 0.49	0.50	0.03	0	0	0
Medium 0.49 <= X < 0.72	0.30	0.06	0	0	0
High 0.72 <= X < 1.03	0.15	0.22	0.01	0	0
Very High X > 1.03	0.05	0.70	0.97	1	1

Table G-A-3. Frequency Analysis by annual soil loss (ton/ac/year) by return period for Deep Hardland Loam Ecological Site.

Return Period	State 1.1 Bogr	State 1.2 Bogr-Buda	State 2.1 Buda	State 3.1 Gusa	State 4.1 Arol-Scpa
2	0.118	0.306	0.962	0.899	3.388
5	0.190	0.480	1.504	1.445	5.592
10	0.239	0.599	1.853	1.834	6.680
20	0.301	0.756	2.328	2.309	8.274
30	0.328	0.878	2.613	2.557	9.685
40	0.360	0.910	2.733	2.677	10.330
50	0.370	0.918	2.758	2.781	10.782
60	0.409	1.024	3.074	3.135	10.869
70	0.425	1.057	3.164	3.193	11.881
80	0.434	1.076	3.220	3.212	12.976
90	0.461	1.146	3.428	3.434	13.604
100	0.492	1.224	3.663	3.699	13.915

Figure G-A-10. Probability of occurrence for yearly soil loss for all scenarios using erosion classes of Low (50 percent), Medium (80 percent), High (95 percent), and Very High (>95 percent).



(6) Summary

(i) Analysis of the RHEM simulation runs on the Deep Hardland Loamy 16–21 inch precipitation ecological site provides a basis for interpreting the impacts of vegetative canopy cover, surface ground cover, and topography on dominant processes in controlling infiltration and runoff, as well as sediment detachment, transport and deposition in overland flow at each state. Our results suggest that RHEM can predict runoff and erosion as a function of vegetation structure and behavior of different plant community phases and amount of cover for the different states.

(ii) Significant differences in estimated annual soil erosion rate occur between the ecological states on this ecological site. The drivers are plant composition, largely the interaction between the two dominant C4 grass species, blue grama and buffalograss. As buffalograss increases in the stand, infiltration capacity will decrease. The causative factors are associated with root morphological differences between blue grama and buffalograss and the degree of water repellency found in buffalograss stands. Water repellent compounds appear to be associated with stands of buffalograss, although more research is needed to confirm the dynamics. Prairie dog activity has a profound effect on biotic integrity, hydrologic function, soil and surface stability, and similarity index calculations. A high degree of bare ground and significant changes in plant composition are associated with prairie dog colonization and runoff and soil loss can be extreme. Broom snakeweed stands and the reference state, blue grama, exhibit the highest infiltration capacity on this site. However, broom snakeweed stands have significantly higher soil loss (wind and water) because of a depauperate understory and a high percentage of bare ground in shrub interspaces.

(iii) High-intensive convective storms can have a significant impact on this site. During 5, 10, 25, 50, and 100-year storms, where there is a high short burst of rainfall, a significant amount of runoff and soil loss will occur (figures G-A-6 and G-A-9).

(iv) Management of this site should strive to maintain a higher ratio of blue grama to buffalograss. The threshold where increasing buffalograss begins to affect infiltration capacity is around 30 percent (Spaeth 1990). Infiltration experiments have also shown that plant-related variables such as cover, biomass, and species composition largely influence infiltration dynamics during the early phases of rainfall (0–15 minutes), whereas soil-related variables such as bulk density, aggregate stability, and porosity influence infiltration as storms progress > 15 minutes.

645.0722 References

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