

Rangelands, Water Balance on

Bradford P. Wilcox

Texas A&M University, College Station, Texas, U.S.A.

David D. Breshears

Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

Mark S. Seyfried

United States Department of Agriculture (USDA), Boise, Idaho, U.S.A.

INTRODUCTION

Rangelands are found in a variety of climate and moisture regimes and may include natural grasslands, savannas, shrublands, deserts, tundra, alpine ecosystems, marshes, and meadows. Most rangelands, however, are found in relatively dry climates where potential evapotranspiration is significantly greater than precipitation. For this reason, our discussion of water balance on rangelands will be generalized for dryland conditions. In water-limited rangelands, most of the incoming precipitation returns to the atmosphere via evapotranspiration. Of the other components, runoff will account for most of the remaining. Water moving to groundwater is generally relatively small.

WATER BALANCE

Water balance is an expression of how precipitation is partitioned after it arrives on the land surface. The relative proportions of its components define the water budget of a region. The water balance is driven by another fundamental physical relationship: energy balance. Together, these two relationships determine global vegetation patterns. The following equation presents a simplified interpretation of the water budget:

$$P = ET + R + G + \Delta S$$

where P = precipitation, ET = evapotranspiration, R = runoff, G = groundwater recharge, ΔS = change in soil water.

Evapotranspiration comprises all those processes by which water changes phase from a liquid to a gas. These processes include: a) evaporation from plant or litter surfaces (commonly referred to as interception loss); b) evaporation from the soil; and c) transpiration from the plant. Where snow constitutes a significant portion of the total precipitation on rangelands, sublimation, which is

the transfer of water from solid to vapor state, may be substantial and is included in this term. *Soil water* is the amount of water in the soil. Water that moves beyond the root zone is considered to be *groundwater recharge*, because eventually it will move to an underlying water body. *Runoff* is water that travels from the hillslope toward the stream channel, the portion of which (not captured by soils or evaporated en route) becomes streamflow.

EVAPOTRANSPIRATION

Because the different components of evapotranspiration can be difficult to separate, we often measure total evapotranspiration. At the plant community level, total evapotranspiration may be measured directly through knowledge of the energy budget. As an example, the Bowen ratio methodology,^[1] which is based on calculations of the energy budget, has been commonly used to estimate evapotranspiration from rangeland plant communities. Alternatively, evapotranspiration can be determined by difference using the water budget approach, where all the components of the water budget except evapotranspiration are measured directly, and evapotranspiration is assumed to be the difference between the sum of these components and the total water budget.

Interception Loss

Interception loss is that component of precipitation that is captured by the vegetation canopy or underlying litter layer and subsequently evaporates, thus never reaching the soil surface. On rangelands, interception loss may be and often is substantial. On a percentage basis, drylands lose considerably more water via interception than do more humid environments.^[2] Interception losses from rangelands may range from 1% to 80% of the annual water budget, but generally are between 20% and 40% (Table 1). Actual amounts depend on the character of the vegetation



and precipitation. For example, evergreen shrubs, such as juniper, capture a higher percentage of precipitation because they are continuously foliated, have a large leaf area, and a leaf shape conducive to interception. In addition, these shrubs lay down a thick litter layer that captures considerable water. Interception loss is generally small in arid shrublands because of lower canopy cover. In grasslands, interception loss may be as high or higher than in shrublands if cover is extensive. The vegetation canopy has only a finite capacity to capture water—therefore the percentage of precipitation intercepted for individual storms is highly variable. For small storms, most water may be intercepted, whereas for very large storms the amount intercepted may (on a percentage basis) be quite small.

Evaporation from Soil

Evaporation from a bare soil is a multistage process.^[16] Initially, after the soil is wetted, evaporation is relatively constant and limited only by the evaporative demand (which is regulated by meteorological conditions, such as radiation, wind, and air humidity). As the soil dries and its water content decreases, the evaporation rate progressively decreases. Evaporation from bare soil is limited to about the top 15 cm.

The relationship between evaporation from the soil and transpiration is of special ecological importance as it determines how much water is available to plants. The amount of evaporation depends on how much of the soil surface is bare. Where only small amounts of bare soil are found, soil evaporation will be low. But in regions where much of the soil is bare, such as arid and some semiarid rangelands, the percentage of evaporation is likely to be

very high. Reported values of soil water evaporation range from 30% to 80% of the water budget (Table 2).

Transpiration from Plants

Transpiration is the evaporation of water from the vascular system of plants into the atmosphere. The process begins with the absorption of soil water by plant roots and ends with its evaporation from stomatal cavities. Because the water is pulled through the plant by the potential energy gradient, transpiration is primarily a physical process. Plants exert physiological control through modification of the size of the stomatal openings.

The amount of transpiration depends on the amount of water that is available to the plant. Whereas evaporation from soils is primarily limited to water in the very uppermost layers, the water transpired by plants may be drawn from substantially greater depths, depending on the depth and development of plant roots. The plant roots may also redistribute water within the profile by removing water from a wet area of the soil and releasing it into a dry area—a process known as *hydraulic lift*.

RUNOFF

Runoff from rangelands is normally small but can nevertheless be very important. It is a principal agent of erosion, contaminant movement, and geomorphic change on many rangelands. Additionally, it serves a vital ecological function of redistributing and concentrating the limited water and nutrient resources in semiarid landscapes. Runoff generally accounts for less than 10%, and most often below 5%, of the annual water budget, and

Table 1 Measured values of interception loss, expressed as a percentage of precipitation, for selected U.S. rangeland shrubs and grasses

	% Interception
Shrubs	
Creosote (<i>Larrea tridentata</i> .)	36, ^[3] 12 ^[4]
Mesquite (<i>Prosopis</i> sp.)	32, ^[3] 16 ^[5]
Sagebrush (<i>Artemisia</i> sp.)	30, ^[6] 4 ^[7]
Chaparral (<i>Quercus</i> sp.)	8 ^[8,9]
Juniper (<i>Juniperus</i> sp.)	45, ^[10] 46, ^[11] 5–25 ^[12]
Oak mottes (<i>Quercus</i> sp.)	46 ^[13]
Grasses	
Big bluestem (<i>Andropogon gerardii</i>)	57–84 ^[14]
Buffalo grass (<i>Buchloe dactyloides</i>)	17–74 ^[14]
California annual grasslands	26 ^[15]
Tabosa grass (<i>Hilaria mutica</i>)	11 ^[13]
Sideoats grama (<i>Bouteloua curtipendula</i>)	18 ^[13]



Table 2 Experimental estimation of soil water evaporation (SE) relative to total evapotranspiration (ET) in various arid and semiarid ecosystems in North America

Desert—Location	Community type	% SE/ET
Sonoran—Arizona, USA	<i>Larrea</i>	90
Sonoran—Arizona, USA	Mixed	75–95
Mojave—Nevada, USA	Mixed shrub	65
Death Valley—California, USA	Mixed shrub	45
Great Basin—Utah, USA	<i>Ceratoides–Atriplex</i>	45
Chihuahuan—New Mexico, USA	<i>Larrea</i>	30
Sonoran—Arizona, USA	<i>Larrea</i>	20
Chihuahuan—New Mexico, USA	<i>Prosopis, Larrea, Flourensia</i>	30–60
Sahel—Niger	Tiger bush	30–80

(Modified from Ref. 17.)

most of this occurs as flood flow. The actual percentage depends partly on the scale of observation. For example, on piñon-juniper rangelands, it has been demonstrated that at a very small scale (1 m²), up to 100% of the precipitation from a particular storm may run off—while at the hillslope scale, runoff from the same storm will amount to only about 5% of the water budget.^[18] The difference is due to the fact that as the scale increases, so too does the opportunity for storage. Similarly, in the many desert landscapes, runoff as a percentage of the water budget will decrease with scale because of transmission losses in the alluvial stream channels.^[19]

Runoff from rangelands most often occurs as *Horton overland flow*,^[20] but it may travel other pathways as well, including saturation overland flow, shallow subsurface flow, and groundwater flow. *Horton overland flow* results when precipitation intensity exceeds soil infiltration capacity. *Saturation overland flow* is relatively uncommon on rangelands but may be observed when soils become saturated, because of either a rising groundwater table or a perched, saturated zone. Frozen soil runoff is a special type of saturation overland flow whereby a frozen soil layer forms an impeding horizon while the soil above it is unfrozen and saturated. *Shallow subsurface flow*, sometimes referred to as interflow or throughflow, is that portion of runoff that travels laterally through the soil, generally because of some impeding soil horizon. *Shallow subsurface flow* is more common in humid environments, but it can be important in semiarid environments, especially when macropores are present in the soil.^[21] *Groundwater flow* is generally the source for the base flow of a stream (prolonged flow, not attributable to a specific precipitation event).

GROUNDWATER RECHARGE

Groundwater recharge, especially deep recharge, is generally very small in rangeland environments. However,

it can be exceedingly important, especially with respect to long-term contaminant transport. Commonly, in arid and semiarid landscapes, only a few millimeters or less of water will move beyond the root zone each year—because in most cases the soils have the capacity to absorb all or most of the precipitation. Owing to the high evaporative demand in these regions, most water stored in the soil will eventually be evaporated or transpired. In some cases, however, the capacity of the soil to absorb water is overwhelmed, and substantial groundwater recharge does occur. In other cases, groundwater recharge may occur where there is an accumulation of water in concentrated locations, such as snow drifts or stream channels. In still other situations, surprisingly high groundwater recharge may occur in very dry environments if permeability is relatively high, owing to either the presence of fractures^[22] or very sandy soils.^[23]

SOIL WATER

The soil storage term ΔS , in the equation, is the difference between the amount of water stored within the plant root zone at the beginning of the period for which water balance is being calculated and the amount at the end. The magnitude of ΔS depends on weather patterns during that period, the duration of the period, and the storage capacity of the soil. For relatively short periods, the weather patterns are critical because they determine the initial and final S values (for periods of several years, ΔS becomes insignificant). The storage term is important because it determines, to some extent, the way incoming water is partitioned among the remaining terms. Where soils have a high storage capacity, flow to groundwater will tend to be much lower. The incoming water is instead available for plant uptake, enabling more plant production; and it also affects the rates of organic nutrient release to the soil and of carbon mineralization.



The storage capacity of a soil depends mostly on the depth of the soil, the coarse-fragment content, and the texture. Sandy soils hold about 60 mm of water per meter of soil, while finer-textured soils can store up to 200 mm. Deep, rock-free soils of medium texture may store over 300 mm of water. The ability of a soil to store water will decrease in direct proportion to the amount of coarse fragments in that soil. For example, a sandy soil with 50% rock content would be expected to store about 30 mm of water per meter of soil.

SUMMARY AND CONCLUSIONS

On rangelands, the water balance is driven and defined to a great extent by the fact that potential evapotranspiration is much greater than precipitation, which in turn contributes to a large soil water deficit. As a rule, therefore, evapotranspiration is the largest component of the water balance equation; the other components are generally quite small (nevertheless, they may be exceedingly important). In addition, both the magnitude and the definition of the different water balance components, particularly runoff, are very much scale-dependent.

Newer measurement technologies allow us to estimate more precisely than ever before the water balance components. It is now possible to directly measure plant-community-level evapotranspiration, soil water evaporation as a percentage of transpiration, interception loss during an actual rainstorm, groundwater recharge, and runoff—all at multiple scales. Application of these technologies promises to help us gain the vital information required to develop workable strategies for solving the growing problems of rangeland degradation.

REFERENCES

1. Evett, S.R. Energy and Water Balances At Soil-Plant-Atmosphere Interfaces. In *Handbook of Soil Science*; Sumner, M.E., Ed.; CRC Press: New York, N.Y., 2000; A.129–A.182.
2. Dunkerley, D. Measuring Interception Loss and Canopy Storage in Dryland Vegetation: A Brief Review and Evaluation of Available Research Strategies. *Hydrol. Process.* **2000**, *14*, 669–678.
3. Martinez-Meza, E.; Whitford, W.G. Stemflow, Throughfall and Channelization of Stemflow by Roots in Three Chihuahuan Desert Shrubs. *J. Arid Environ.* **1996**, *32*, 271–287.
4. Tromble, J.M. Water Interception by Two Arid Land Shrubs. *J. Arid Environ.* **1988**, *15*, 65–70.
5. Desai, A.N. Interception of Precipitation by Mesquite Dominated Rangelands in the Rolling Plains of Texas. M.S. Thesis, Texas A&M University, College Station, Texas, 1992.
6. Hull, A.C. Rainfall and Snowfall Interception of Big Sagebrush. *Utah Acad. Sci. Lett.* **1972**, *49*, 64.
7. West, N.E.; Gifford, G.F. Rainfall Interception by Cool-Desert Shrubs. *J. Range Manag.* **1976**, *29*, 171–172.
8. Rowe, P.B. Influence of Woodland Chaparral on Water and Soil in Central California; California Division of Natural Resources, Division of Forestry 1948.
9. Hamilton, E.L.; Rowe, P.B. Rainfall Interception by Chaparral in California; California Department of Natural Resources, Division of Forestry 1949.
10. Thurow, T.L.; Hester, J.W. How an Increase or a Reduction in Juniper Cover Alters Rangeland Hydrology. *Juniper Symposium Proceedings*; Texas A&M University: San Angelo, Texas, 1997; 9–22.
11. Young, J.A.; Evans, R.A.; Eash, D.A. Stem Flow on Western Juniper (*Juniperus occidentalis*) Trees. *Weed Sci.* **1984**, *32*, 320–327.
12. Skau, C.M. Interception, Throughfall, and Stemflow in Utah and Alligator Juniper Cover Types of Northern Arizona. *For. Sci.* **1964**, *10*, 283–287.
13. Thurow, T.L.; Blackburn, W.H.; Taylor, C.A. Rainfall Interception Losses by Midgrass, Shortgrass, and Live Oak Mottes. *J. Range Manag.* **1987**, *40*, 455–460.
14. Clark, O.R. Interception of Rainfall by Prairie Grasses, Weeds and Certain Crop Plants. *Ecol. Monogr.* **1940**, *10*, 243–277.
15. Kittredge, J. *Forest Influences*; McGraw-Hill: New York, 1948.
16. Hillel, D. *Applications of Soil Physics*; Academic Press: New York, 1980.
17. Reynolds, J.F.; Kemp, P.R.; Tenhunen, J.D. Effects of Long-Term Rainfall Variability on Evapotranspiration and Soil Water Distribution in the Chihuahuan Desert: A Modeling Analysis. *Plant Ecol.* **2000**, *150*, 145–159.
18. Reid, K.D.; Wilcox, B.P.; Breshears, D.D.; MacDonald, L. Runoff and Erosion in a Pinon-Juniper Woodland: Influence of Vegetation Patches. *Soil Sci. Soc. Am. J.* **1999**, *63*, 1869–1879.
19. Goodrich, D.C.; Lane, L.J.; Shillito, R.M.; Miller, S.N.; Syed, K.H.; Woolhiser, D.A. Linearity of Basin Response as a Function of Scale in a Semiarid Watershed. *Water Resour. Res.* **1997**, *33*, 2951–2965.
20. Dunne, T. Field Studies of Hillslope Flow Processes. *Hillslope Hydrology*; John Wiley and Sons: New York, 1978; Chap. 7, 227–293.
21. Wilcox, B.P.; Newman, B.D.; Brandes, D.; Davenport, D.W.; Reid, K. Runoff from a Semiarid Ponderosa Pine Hillslope in New Mexico. *Water Resour. Res.* **1997**, *33*, 2301–2314.
22. Flint, A.L.; Flint, L.E.; Kwicklis, E.M.; Bodvarsson, G.S.; Fabryka-Martin, J.M. Hydrology of Yucca Mountain Nevada. *Rev. Geophys.* **2001**, *39*, 447–470.
23. Stephenson, G.R.; Zuzel, J.F. Groundwater Recharge Characteristics in a Semi-arid Environment. *J. Hydrol.* **1981**, *53*, 213–227.

