Runoff and Erosion Estimates for Great Plains Dryland Agroecosystems

Kate Norvell[1], Neil Hansen[1], Dwayne Westfall[1], and Laj Ahuja[2]
[1]Colorado State University, Dept. of Soil and Crop Science, Fort Collins, CO
[2]USDA-ARS, Agric. Systems Res. Unit, Fort Collins, CO

Abstract. Water is the most production limiting factor for dryland cropping systems in semiarid Great Plains environments. Evaporation is responsible for the greatest amount of water loss and management practices such as notill have been adopted to reduce evaporative losses. Less is known about the magnitude of water loss due to runoff. An objective of this study is to estimate an expected range in rainfall runoff in dryland agroecosystems and the potential for improving precipitation use with management practices that reduce runoff. Another objective was to estimate soil-water erosion associated with runoff. The approach coupled an analysis of historical hourly rainfall intensity data and field measurements of runoff and erosion from dryland agroecosystems study sites in Sterling and Stratton, Colorado. Rainfall analysis was used to determine the frequency and quantity of high intensity rainfall expected to generate runoff. Runoff was estimated based on assumed fractions of high intensity rainfall for variable management and climate conditions and based on field observations at the same sites. Runoff was estimated to range between 8 mm for drought years and management with good surface protection to 80 mm for years with above average precipitation and management with poor protection of the soil surface. There is the potential to capture as much as 60 mm of precipitation through improved management practices, a quantity that can increase crop yield and profitability. Annual rates of erosion by water were estimated to range between 1 and 9 Mg ha^{-1}. Under management with poor surface protection, soil erosion rates in dryland cropping systems are too high to sustain crop production, while management that protects the soil surface and reduces the probability of runoff is an effective means of soil erosion control. Residue management achieved through no-till or minimum till practices is the most effective means of soil erosion control and sustaining dryland agriculture in the semi-arid Great Plains will depend on adoption of these practices.

1. Introduction

Crop productivity in dryland agroecosystems in the semi-arid Great Plains is limited by water availability (Peterson et. al., 1993). A mass balance equation illustrates the long-term water balance in dryland agroecosystems as

$$P = T_C + T_W + E + D + R \tag{1.1}$$

where P is the precipitation, TC is the crop transpired water, TW is the weed transpired water, E is the evaporation, D is the deep percolation, and R is the runoff. This equation assumes no run-on and neglects a storage term because over the long-term this value should not change. From the perspective of the agricultural producer, the water used to grow the crop is the only water that is not a loss from the system. Agricultural management practices interact with the hydrologic cycle and influence the fate of precipitation. Most attention to managing the hydrologic cycle in these systems has been

[1]Neil Hansen, Assoc. Professor, Dept. Soil and Crop Science, Colorado State University, Fort Collins, CO.
e-mail: neil.hansen@colostate.edu

on reducing evaporation, the most significant form of water loss (Baily 1979; Shultz 1995; Falkenmark, 1989). Potential evaporation in the semi-arid Great Plains exceeds the precipitation amounts during most months of the year and the period of the year with greatest precipitation is accompanied by high temperatures and low relative humidity (Peterson and Westfall, 2004). In the short grass steppe ecosystem, evaporation accounts for half of the water loss in the 0-15 cm soil layer and a third of the water loss in the 15-30 cm layer (Lauenroth and Bradford, 2006). Adoption of no-till (NT) systems reduces evaporation and increase the efficiency of precipitation storage in soil compared to conventional tillage (CT). No-till also improves soil properties, such as decreased bulk density, increased porosity, and increased proportion of macroaggregates (Shaver et al., 2002). Producers that have adopted no-till systems may be close to the practical limit of evaporation savings. Efforts to further increase precipitation use efficiency must address water lost by other pathways. Water transpired by weeds, deep percolation, and runoff are not well quantified in dryland agroecosystems. An objective of this study is to identify the importance of runoff in the hydrologic cycle of dryland agroecosystems in the West Central Great Plains environment. This study uses historical rainfall records as a means to estimate the likely importance of runoff in the dryland agroecosystems of Eastern Colorado.

In eastern Colorado, a majority of the annual precipitation comes in the form of summer thunderstorms that are often short in duration and have high rain intensity. These high intensity storms can induce runoff and erosion. According to Meyer et al. (1999) NT agriculture may only reduce runoff by 10% when compared to other management options. Runoff is usually coupled with erosion which can be detrimental to sustainability of the agricultural system. Runoff represents a short-term water loss to the cropping system, while soil erosion induced by runoff can cause long-term and permanent damage to agricultural systems. It has been estimated that between 2 and 6.8 billion tons of soil per year is lost from cropland in the U.S. due to erosion (Trimble and Crosson, 2000). Soil erosion can be decreased by up 80-90% in NT when compared to CT (Meyer et al., 1999). Most of the erosion reduction in NT systems can be attributed to the increased crop residue left on the soil surface. If residue cover is not maintained, the improved soil quality attributed to NT does not last a year (Wilson et al., 2004). Residue cover is important because it protects the soil surface from raindrop impact which triggers water erosion with rainwater runoff (Alberts and Neilbling, 1994).

The objectives of this study were to identify the importance of runoff from high intensity rainfall in dryland agroecosystems. The approach is to estimate runoff potential based on observed precipitation intensity data from dryland agroecosystems in Eastern Colorado. Estimates of potential runoff can be used to determine whether management practices that reduce runoff have the potential to improve dryland crop productivity and to reduce soil water erosion.

2. Materials and Methods

Study Locations

This study uses long term precipitation data from two Eastern Colorado dryland agroecosystems to estimate the significance of runoff in the hydrologic cycle. The weather data is collected as part of a long term dryland agroecosystem study with sites at Sterling, CO (40°22'12"N, 103°7'48"W) and Stratton, CO (39°10'48"N, 102°15'36"W). These sites have a long-term average precipitation of 420 mm and 400 mm respectively, and have open pan evaporation of 1600 mm and 1725 mm, respectively (Peterson et al., 1999). In 1985 (Peterson et al., 1999), the long-term dryland agroecosystem project was initiated and weather station with hourly observations and reporting were installed in 1988. Precipitation was measured with a tipping bucket type rain gauge and data from 1988 to 2006 are used in this study evaluation.

Evaluation of Climate Data

The climate data used to for this study is available from the High Plains Regional Climate Center. Comparisons are made of 1988-2006 average precipitation, on a year by year and month by month scale, and frequency of intense storms at both sites. The definition of a high intensity rain event is the major assumption of this study. The assumption is that rain occurring at or above an hourly rate of 13 mm is expected to cause runoff and rain events of this size were therefore classified as high intensity. The value of 13 mm hr-1 was chosen based on observations and measurements of runoff at these locations (data not reported, see Norvell, 2007). The historical rain data were evaluated to determine the frequency of high intensity rainfall events during each month. Further, the climate record was separated into pools of average and above or below average years of total annual precipitation to determine if there are fewer potential runoff and erosion inducing storms during drought years. The average precipitation used for this separation is based on the 1961-2006 weather record and was 420 mm for Sterling and 400 mm for Stratton.

Runoff Estimation

This study seeks to use combine an extensive climate record with a more limited set of runoff observations to generate reasonable estimates of runoff as a component in the hydrologic cycle for dryland agroecosystems in the Great Plains. Requisite assumptions are made to generate these estimates. The range in potential runoff was estimated by taking fixed percentage of the total amount of rainfall classified as high intensity for high runoff probability and low runoff probability scenarios. The percentages are based on 66 observations of runoff from rainfall events at the Sterling and Stratton locations on runoff plots with a 3-4% sloped surfaces and varying levels of residue and canopy cover (Norvell, 2006). The sites where the field observations were made are part of a long-term notill management study. During the period of the field observation (2005-2006), the sites had been in an extended period of drought, which resulted in low crop residue and canopy cover conditions. The high probability of runoff scenario is based on the maximum observed percent of high intensity rainfall measured as runoff and was 54%. This runoff observation came from a corn plot for a rain event of 22 mm and with a peak hourly intensity of 18 mm on August 23, 2005 in Stratton, CO. Although the field site is a no-till based system, it is assumed that this high runoff probability is representative of potential runoff in a tilled or fallow system because the crop residue levels at the time of the storm event were low, averaging 20% cover. Further, this rain event was preceded by high intensity rain event on August 16, 2005 that caused the soil surface to seal as is often observed in tilled systems. The percent of high intensity rain used to estimate runoff in the low runoff probability scenario is based on the average runoff for all 66 observations and is 14%. Here we assume that the average condition on the notill study observations represents a low runoff probability when considered over a broader range of tillage practices. Average crop residue cover for this scenario was 40%. Thus, the low runoff probability represents runoff potential for well protected soil surfaces and the high runoff probability represents tilled or fallow soils with very little protective cover. The intent of these assumptions is to provide a reasonable estimate of the potential range in runoff from dryland agroecosystems in the semi-arid Great Plains environment.

Erosion Estimation

The range in potential soil erosion associated with runoff was determined using a flow weighted mean sediment concentration of 1.1 g L^{-1} based on of 66 observed runoff events from the field study (Norvell, 2006). Actual sediment concentration in the study ranged from less than 1 g L^{-1} to greater than 10 g L^{-1}. The mean concentration is considered a reasonable value for the annual erosion estimates made in this study and is consistent with observed values reported elsewhere (Gessel et al., 2004; Hansen et al., 2000). The estimated runoff for Sterling and Stratton locations and for both high runoff and low runoff scenarios was multiplied by the average sediment concentration to calculate a potential range in soil erosion for each site and each runoff probability.

3. Results and Discussion

Evaluation of Climate Data

Long term average annual precipitation (1961-2006) is 420 mm for the Sterling location and is 400 mm for the Stratton location. During the study period (1998-2006) below average precipitation occurred for 13 of the 19 years at Sterling, including nine consecutive years (1998-2006). Below average precipitation occurred for 8 years at Stratton, including 7 consecutive years (2000-2006). Periods of prolonged drought are typical in this semi-arid region. Below average precipitation affects the entire system including crop production, residue cover, etc. No-till management in this study has been practiced for twenty years, which provides a good residue cover base for most of the crop rotations (Cantero-Martinez et al., 2006). However due to the drought conditions since 1998, the residue cover has decreased. The majority of the precipitation in eastern Colorado occurs between May and August (Figure 1.2), which is the typical growing season in this region.

At the Sterling, CO location an average of 6.5 high intensity rain events (>13 mm hr^{-1}) per year occur during years with average or above annual precipitation and 2.5 per year for years with below average precipitation (Figure 1.3). Intense storms account for 29% of the total precipitation during average and above average precipitation years in Sterling, which is approximately 150 mm of rain. Intense storms account for 17% of total precipitation in below average precipitation years, which is approximately 61 mm of rain (Table 1). The period of June through August has the greatest frequency of high intensity rain events and is therefore the period of time most likely for runoff to occur. Cropping systems that have exposed soil conditions during this time are most likely to experience runoff and erosion. For example, corn in dryland cropping systems has little canopy cover in June and in dry years fails to form a complete canopy even by the end of the growing season. There is little historical basis for runoff and erosion to occur due to high intensity rain from the period of October through April.

Frequency of high intensity rainfall has a much different trend at the Stratton, CO location (Figure 1.3). The number of high intensity rain events in years with average and above amounts of precipitation was 3.0 and was 3.1 per year for below average precipitation years. Intense storms account for 16% of the total precipitation during average and above years in Stratton, which is approximately 71 mm of rain. Intense storms account for 27% of total precipitation in below average precipitation years, which is approximately 89 mm of rain (Table 1). The time period between June and August had the highest number of occurrences of intensive events, which provides the greatest risk for a runoff and erosion event to occur.

A comparison between Sterling and Stratton, CO (Figure 1.3) shows that during years of average or above precipitation the likelihood of an intensive rainstorm event is greater in Sterling than in Stratton. Unlike Sterling, Stratton has a higher chance of an intensive event to occur during a below average precipitation year than in a year with average or above average precipitation in the month of July. This is a potential problem in Stratton because in periods of below average precipitation residue and canopy cover are low and the occurrence of intensive events runoff is more likely.

Runoff Estimation

The range in potential runoff was estimated by taking fixed percentages of observed high intensity rainfall events and for scenarios with a high or low probability or runoff. High runoff probability applies to land surface conditions with little cover or crop canopy such as fallow or row cropping. Low runoff probability applies to land surface conditions with high residue or canopy cover, such as grass or well developed small grain canopies. The percentages are based on 66 observations of runoff from rainfall events at the Sterling and Stratton locations on runoff plots with a 3-4% sloped surfaces and varying levels of residue and canopy cover (Norvell, 2006). Runoff for the high probability of occurrence is 54% of the high intensity rainfall. For conditions with a high probability of runoff and years with average or above annual precipitation, runoff is estimated to be 81 mm at Sterling and 39 mm at Stratton (Table 1). For conditions with a high probability of runoff and below average precipitation, runoff is estimated to be 33 mm at Sterling and 48 mm at Stratton. Thus, runoff in dryland agroecosystems with vulnerable surface conditions such as row cropping or fallow with little crop residue may represent between 8% and 19% of annual precipitation. For conditions with a low probability of runoff and years with average or above annual precipitation, runoff is estimated to be 21 mm at Sterling and 10 mm at Stratton (Table 1). For conditions with a low probability of runoff and below average precipitation, runoff is estimated to be 8 mm at Sterling and 12 mm at Stratton. Thus, runoff in dryland agroecosystems with well protected surfaces such as grass or well developed canopies of small grains may represent between 2% and 5% of annual precipitation.

A comparison of estimated runoff between Sterling and Stratton, CO (Table 1) shows that during years of average or above average precipitation the likelihood of runoff is greater in Sterling than in Stratton. In below average precipitation years, greater amounts of runoff are likely to occur at Stratton. Unlike Sterling, Stratton has a higher chance of runoff during a below average precipitation year than in a year with average or above average precipitation. These differences occur for two locations with very similar long term average precipitation, illustrating the importance of detailed weather pattern analysis in estimating runoff.

The importance of runoff as a component in the hydrologic cycle in dryland agroecosystems is clearly illustrated, especially for cropping systems with soil surface conditions that create a high probability of runoff (Table 1). Based on the assumptions of this study, as much as 14% of the annual precipitation lost as runoff could be captured with improved management practices. If that amount of precipitation could be successfully captured and utilized by crops, it would represent an economically significant increase in crop productivity. It has been shown that crop rotation, reduced frequency of fallow, and practice of no-till increase dryland crop yield and precipitation use efficiency (Peterson et. al., 1993).

Erosion Estimation

The range in potential soil erosion by water was estimated by multiplying runoff estimates by a fixed flow weighted mean sediment concentration of 1.1 g L^{-1} (Norvell, 2006). Soil erosion for the high runoff probability with above average precipitation is 9.3 and 4.5 Mg ha^{-1} for Sterling and Stratton locations respectively (Table 1). For below average precipitation years, soil erosion associated with high runoff risk is 3.8 T ac^{-1} for the Sterling location and 5.5 T ac^{-1} for the Stratton location. Average long term soil erosion rates will be somewhere between the estimated rates for the two climate regimes. These potential soil erosion rates are high enough to raise questions about the sustainability of dryland farming systems that fail to protect the soil surface against erosion. Estimates for dryland management scenarios with low runoff probability are 2.4 and 0.9 Mg ha^{-1} for the above and below average precipitation at Sterling and are 1.1 and 1.4 Mg ha^{-1} for Stratton. These erosion rates are relatively low and show the value of management practices that protect the soil surface from soil erosion. Residue management achieved through no-till or minimum till practices is the most effective means of soil erosion control. Sustaining dryland cropping practices in the semi-arid Great Plains will depend on adoption of these practices.

4. Conclusions

Based on a coupled analysis of historical hourly rainfall intensity data and field measurements from Sterling and Stratton, Colorado, estimates of potential runoff and soil erosion from dryland agroecosystems were made. The estimates were made separately for climate years with average to above average rainfall and for years with below average rainfall and for scenarios with low and high runoff probability. This approach generates the likely range in runoff and erosion over variable location, climate, and management. Runoff in dryland agroecosystems in semi-arid Great Plains environments similar to Eastern Colorado is estimated to range between 8 mm for drought years and management with good surface protection to 80 mm for wet years and management with poor protection of the soil surface. The potential to capture as much as 60 mm of precipitation through improved management practices can easily translate into greater crop yield and higher profitability. Annual rates of erosion by water were estimated to range between about 1 Mg ha^{-1} to as high as 9 Mg ha^{-1}. Under management with poor surface protection, soil erosion rates in dryland cropping systems are too high to sustain crop production, while management that protects the soil surface and reduces the probability of runoff is an effective means of soil erosion control. Residue management achieved through no-till or minimum till practices is the most effective means of soil erosion control and sustaining dryland agriculture in the semi-arid Great Plains will depend on adoption of these practices.

References

Alberts, E. E., and W.H. Neilbling. 1994. Influence of crop residues on water erosion. *Managing Agricultural Residues*, 19-39. P. W. Unger, ed. Chelsea, Mich.: Lewis Publishers.

Baily, H.P. 1979. Semi-arid climates; their definition and distribution. In: Hall, A.E., G.H. Cannell, and H.W. Lawton. (eds). Agriculture in semiarid environments. Ecological studies 34. Berlin: Springer pg. 73-97.

Cantero-Martinez, C., D.G. Westfall, L.A. Sherrod, and G.A. Peterson. 2006. Long-term crop residue dynamics in no-till cropping systems under semi-arid conditions. J. Soil and Water Cons. 61:84-95.

Falkenmark M. 1989. Comparative hydrology- a new concept. In: Falkenmark M., T. Chapman. (eds) pg. 10-42. Paris: UNESCO, 479.

Farahani, H.J., G.A. Peterson, D.G. Westfall, L.A. Sherrod, and L.R. Ahuja. 1998. Soil and Water Storage in Dryland Cropping Systems: The Significance of Cropping Intensification. Soil. Sci. Soc. Am. J. 62: 984-991.

Gessel, P.D., N.C. Hansen, J.F. Moncrief, and M.A. Schmitt. 2004. Application Rate Of Liquid Swine Manure: Effects On Runoff, Sediment And Phosphorus Transport. J. Environ. Qual. 33:1839-1844.

Hansen, N.C., J.F. Moncrief, and S.C. Gupta. 2000. Herbicide banding and tillage system impacts on runoff, sediment, and phosphorus losses in runoff. J. Environ. Qual. 29:1555-1560.

Jones, O.R., V.L. Hauser, and T.W. Popham. 1994. No-tillage effects on infiltration, runoff, and water conservation on dryland. Trans. ASAE37:473-479.

Lauenroth, W.K., and J.B. Bradford. 2006. Ecohydrology and the Partitioning AET Between Transpiration and Evaporation in a Semiarid Steppe. Ecosystems. 9: 759-767

Meyer, L. D., S. M. Dabne, C. E. Murphree, and W. C. Harmon. 1999. Crop production systems to control erosion and reduce runoff from upland silty soils. Trans. ASAE 42(6): 1645-1652.

Peterson, G. A., D. G. Westfall, and C. V. Cole. 1993. Agroecosystem approach to soil and crop management research. Soil Sci. Soc. Am. J. 57: 1354-1360.

Peterson, G.A., D.G. Westfall, F.B. Peairs, L. Sherrod, D. Poss, W. Gangloff, K. Larson, D.L. Thompson, L.R. Ahuja, M.D. Koch, and C.B. Walker. 1999. Sustainable dryland agroecosystem management. Techn. Bull. TB99-1. Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO.

Peterson, G.A. and D.G. Westfall. 2003. Managing precipitation use in sustainable dryland agroecosystems. Ann. Appl. Biol. 144: 127-138.

Peterson, G. A. and D. G. Westfall. 2004. Managing precipitation use in sustainable dryland agroecosystems. Ann. Appl. Biol. 144:127-138.

Raper, R.L. The Influence of Implement Type, Tillage Depth, and Timing on Residue Burial. 2002. Trans. of the ASAE. 45: 1281-1286.

SAS Institute Inc. 2003. SAS/STAT User's Guide. Version 9.1. SAS Inst., Cary, NC.

Shaver, T.M., G.A. Peterson, L.R. Ahuja, D.G. Westfall, L.A. Sherrod, and G. Dunn. 2002. Surface Soil Physical Properties After Twelve Years of Dryland No-Till Management. Soil Sci. Soc. Am. J. 66:1296-1303.

Shultz, J. 1995. The ecozones of the world. Berlin: Springer, 449.

Trimble, S. W., and P. Crosson. 2000. U. S. soil erosion rates- Myth and reality. Science 289: 248-250.

Wilson, G. V., S. M. Dabney, K. C. McGregor, B. D. Barkoll. 2004. Tillage and residue effects on runoff and erosion dynamics. Trans. of the ASAE. 47(1): 119-128.

Table 1. Average annual amount of high intensity rainfall (>13 mm hr-1) and estimates of runoff and soil water erosion from dryland agroecosystems in Sterling and Stratton, Colorado for years with average to above average annual precipitation (+) and years with below average precipitation (-).

	Annual Precip.	High Intensity Rainfall	High Runoff Probability		Low Runoff Probability	
			Runoff	Erosion	Runoff	Erosion
		--mm --	-- mm --	- Mg ha^{-1} -	-- mm --	- Mg ha^{-1} -
Sterling	+	150	81	9.3	21	2.4
	-	61	33	3.8	8	0.9
Stratton	+	71	39	4.5	10	1.1
	-	89	48	5.5	12	1.4

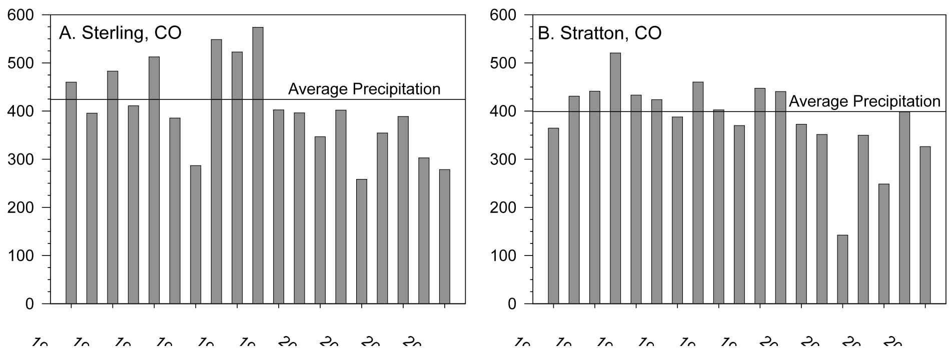

Figure 1.1 Average annual precipitation, indicated by solid line (1961-2006), and yearly precipitation total, indicated by bars, in (A) Sterling and (B) Stratton, CO from 1988 to 2006.

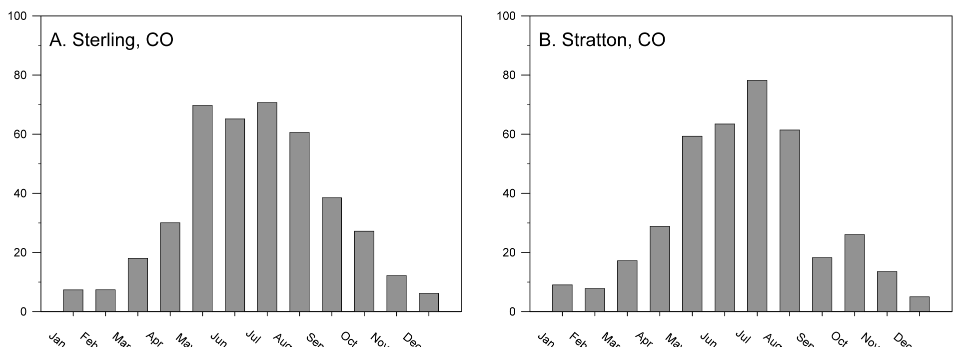

Figure 1.2. Average monthly precipitation in (A) Sterling and (B) Stratton, CO based on rainfall records from 1988 to 2006.

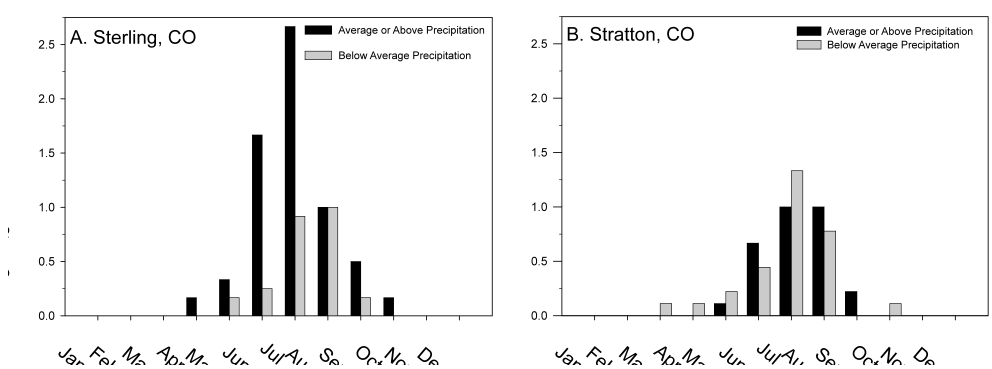

Figure 1.3. Monthly frequency of rainfall events ≥ 13 mm hr^{-1} for (A) Sterling and (B) Stratton. Frequency was determined separately for years with average or above average annual precipitation and years with below average precipitation.