HISTORIC ROLE OF FIRE IN DETERMINING ANNUAL WATER YIELD FROM TENDERFOOT CREEK EXPERIMENTAL FOREST, MONTANA, USA

by

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ABSTRACT

Water production from mountain watersheds depends on total precipitation input, the type and distribution of precipitation, the amount intercepted in tree canopies, and losses to evaporation, transpiration and groundwater. A systematic process was developed to estimate historic average annual runoff based on fire patterns, habitat cover types and precipitation patterns on the Tenderfoot Creek Experimental Forest.

A fire history study in the Little Belt Mountains of central Montana indicates much of the experimental forest watershed burned in the 1700's and 1800's. Fire scars and existing timber stands on the 3,709 ha experimental forest show that two fires occurred in the 1700's and six in the 1800's covering more than 1,660 ha (45 percent) and 2,415 ha (65 percent), respectively. One small 32 ha stand on the experimental forest has not burned since 1580. The last major fire (206 ha) occurred in 1902 and three other small fires (covering only 19 ha) have been observed since the implementation of active fire suppression in the early 1900's. There has been no logging on this 3,709 ha forest of which 9 percent of the total area is composed of non-timbered meadows or rock outcrops.

Annual water yield was estimated for Tenderfoot Creek Experimental Forest for the past 400+ years utilizing fire history, habitat cover types, current average annual precipitation and water yield/precipitation/cover type relationships. The maximum average annual runoff was estimated at 12,480 cubic dekameters (dams^3) in the late 1500's based on 30 years of average annual precipitation (1961-1991). The 1581 to 1997 average water yield was estimated to be 11,680 dams^3. The maximum water yield estimated for Tenderfoot Creek Experimental Forest, if all timber were removed, would be around 13,240 dams^3. The minimum runoff if the entire forest was composed of mature lodgepole pine would be 11,230 dams^3. The present yield of 11,360 dams^3 is near the lowest yield of 11,250 dams^3 estimated for 1873 and near the minimum possible for this experimental forest. During a wet year with all of the timber removed, runoff could be as high as 21,190, or in a dry year with most of the watershed covered with a mature forest as low as 5,620 dams^3. On TCEF, fire suppression and succession appear to be creating conditions for a major fire event unless portions of the forest are removed by management actions that mimic historic vegetation patterns.

INTRODUCTION

Watersheds composed of lodgepole pine (*Pinus contorta* Dougl. var. *latifolia*) cover 6 million hectares (ha) of commercial forest lands in the Rocky Mountains (Koch 1996). Lodgepole pine is the most widely distributed conifer in western North America and is the fourth most extensive timber type west of the Mississippi and the third most extensive in the Rockies (Wheeler and Critchfield 1984). Mountain watersheds composed of lodgepole pine are important because of the amount of water produced from winter snow and spring/summer rain that is used for irrigation, hydroelectric generation and a wide variety of recreational uses. These watersheds also provide high quality drinking water for municipalities and aquatic and riparian habitats for fish, aquatic insects, waterfowl and a host of wildlife species such as beaver (*Castor canadensis*), moose (*Alces americana*) and dippers (*Cinclus mexicanus unicolor*).

Hydrologists use computer models to predict the potential effects of vegetation manipulation on water and sediment yield from watersheds. Watershed models such as WATSED (USDA Forest Service 1991) provide hydrologists with information on projected water and sediment yields based on levels of forest manipulation. This modeled information is used in the management of watersheds where hydrologic limits are placed on management activities based on bank full and peak flows estimates. Historic water yield information is needed to

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determine the natural range of variability of water yields from our mountain watersheds before hydrologic limits can be determined. Streamflow data for the past 20 to 80 years may not be a good indicator of historic water yields from mountain watersheds because of fire suppression that has occurred during this time across the west. Generally, hydrologists have limited or no historic streamflow data on undisturbed and disturbed watersheds.

The Tenderfoot Creek Experimental Forest (TCEF) covers 3,709 ha of the headwaters of the Tenderfoot Creek watershed located in the Little Belt Mountains in central Montana. The experimental forest, established in 1961 for watershed research, has an average annual precipitation of 890 millimeters (mm) that varies from 595 mm in the lower elevations to 1,050 mm at the higher elevations in the watershed. Elevations range from 1,838 to 2,421 meters (m) with an average of 2,206 m. Fire suppression since the early 1900's has suppressed most fire processes on the experimental forest. A 1993 fire history study on the Tenderfoot Creek Experimental Forest shows over 400 years of fire history in lodgepole pine-dominated stands (Barrett 1993, unpublished report). The experimental forest is currently about 9 percent non-forested, 42 percent in single-aged stands and 49 percent in two-aged stands. The oldest stands on TCEF were last burned in 1580 and the most recent burn affecting any significant area occurred in 1902 (Table 1). The 1580 burn is now a mature Engelmann spruce/subalpine fir (Picea engelmannii/Abies lasiocarpa) stand with a few isolated mature lodgepole pine found where mortality has created gaps in the overstory. From 1580 to 1902, ten fires had an average fire size of 621 ha with an average of 32 years between fires. Three small burns in 1921, 1947 and in 1996 have affected less than 1 percent of the experimental forest in the last 95 years. Less than 20 acres were burned from 1903 to 1996 and the average fire size was 6 ha averaging 32 years between fires. In contrast, 1,660 and 2,415 ha have burned in each of the two proceeding centuries (Table 1).

Table 1. Year of fire, area burned and percent burned of total area of Tenderfoot Creek Experimental Forest (Barrett 1993, unpublished report).

Year	Size (ha)	Percent of total area
1580	1900	51
1676	32	1
1726	1108	30
1765	552	15
1831	41	1
1845	1008	27
1873	1317	36
1882	30	1
1889	19	<1
1902	206	6
1921	8	<1
1947	11	<1
1996	0.4	<1

Precipitation inputs, water yield outputs and forest canopy interception data have been collected on the experimental forest since 1992 and have been combined with data from adjacent watersheds to estimate 30-year averages. This paper presents the computational procedures and estimates of 400 years of historic average annual runoff based on fire patterns, annual precipitation and habitat cover types on Tenderfoot Creek within the Tenderfoot Creek Experimental Forest.

METHODS

A six step process was used to estimate average annual runoff on the Tenderfoot Creek Experimental Forest. This process involved the development of mathematical relationships between a variety of biological variables. In step one, average annual runoff from TCEF over the past 5 years was correlated with precipitation from nearby weather, SNOw survey TELemetry (SNOTEL), and stream gaging stations. These correlations were used to estimate the averages for 30 years(1961-1990) of average annual runoff, April 1 snow water equivalent (SWE), April through June precipitation and average annual precipitation on TCEF (Figure 1).

The second step developed a relationship between percent forest canopy and the amount of precipitation reduction due to forest canopy interception. Forest canopy cover and winter SWE data for stands with varying canopy cover on TCEF were combined with data from other studies (Farnes 1971; Farnes 1989; Farnes and Hartman 1989; Gary and Troendle 1982; Hardy and Hansen-Bristow 1990; Moore 1997; Moore and McCaughey 1997; Skidmore et al. 1994). Forest canopy cover within lodgepole pine and spruce/fir stands was measured with a spherical densiometer, photocanopyometer (Codd 1959) and a basal area gage.

In step three, data from TCEF and other studies were used to develop a relationship between percent forest canopy and habitat cover type (HCT) using the Despain (1990) classification system. The habitat type for a fire generated stand was combined with stand age to obtain a numerical habitat cover type index value. For example, a recently burned lodgepole pine stand is classified as an LP0. An LP1 is a mature forest and may be from 50 to 150 years old depending on site growing conditions. An LP3 is an overmature stand, generally older than 300 years with many dead and dying trees and near climax. Likewise, an SF1 is a mature spruce/fir stand approximately 150 to 200 years old and an SF2.5 stand is near climax and approximately 400 to 500 years old. For TCEF, the HCT for a lodgepole pine stand is computed by dividing the age by 100 (150-year-old stand = LP1.5 HCT) and the HCT for a spruce/fir stand is the stand age divided by 200.

Data from steps one, two and three were combined in step four to develop the relationship between the reduction in SWE (winter precipitation) due to canopy interception and HCT for lodgepole pine and spruce/fir stands on TCEF. Data from TCEF was combined with data from other studies (Arthur and Fahey 1993; Fahey et al. 1988; Wilm and Niederhof 1941) to develop a relationship of HCT versus precipitation throughfall (April - June precipitation) as affected by canopy interception for lodgepole pine and spruce/fir stands. Runoff is at a maximum when soils are saturated from recent snowmelt or rainfall and plant growth is nonexistent or just beginning.

Annual runoff was estimated in step five for each precipitation zone using precipitation versus runoff relationships adjusted for runoff patterns in TCEF (Farnes 1971, 1978; Farnes and Hartman 1989). The annual runoff was determined for each annual precipitation zone assuming no forest canopy cover representing a meadow, recently burned or logged area. The reduction in snow accumulation and precipitation throughfall for any HCT was then used to calculate runoff for any timber type and age stand in any precipitation zone on TCEF. A reduction in SWE and April - June precipitation was used to compute the runoff for a 900 mm precipitation zone within habitat cover types for lodgepole pine stands (Table 2). Average annual runoff for each precipitation zone and lodgepole pine HCT was computed (Table 3) from values obtained from table 2. Although changes may have occurred over time, it was assumed that precipitation and snowfall over the past 400+ years were comparable to the most recent 30-year average base period from 1961 to 1990.

The final step estimated average annual runoff from each fire-generated stand back to 1580 using changes and habitat cover type before and after each fire. A habitat cover type value was designated for each stand in each fire year and re-designated a lower value for the year after the fire reflecting the new open condition of the stand. Net precipitation for each HCT and precipitation zone was estimated by taking the total precipitation input and estimating the reduction due to canopy interception of snow (SWE) and April - June precipitation. Average annual runoff is calculated using the net precipitation for each HCT and the percent of precipitation that is runoff for each zone. Average annual runoff was accumulated for all stands and open areas to obtain average annual runoff for the entire watershed for each fire year.

RESULTS AND DISCUSSION

Average annual runoff, the amount of precipitation falling as snow (April 1 SWE) and the amount falling as rain (April - June) increased at different rates as the average annual precipitation increased (Figure 1). Runoff is a function of precipitation received and the amount remaining after vegetation use and sublimation losses. Sublimation is a function of the area in the forest, the age and species structure of the forest canopy, and the season in which precipitation occurs. April 1 SWE gives the greatest contribution to annual runoff because of saturated soils and minimal vegetation water use at the time of snowmelt. Average annual precipitation was positively correlated to elevation on TCEF.

Snow is an important component of the yearly precipitation accounting for 50 to 80 percent of the total annual runoff in lodgepole pine and spruce/fir stands of the Northern Rockies. Snow interception is expressed as the percent reduction of SWE in lodgepole pine and spruce/fir stands as compared to snow accumulation in an opening. The photocanopyometer provided the strongest correlation between percent forest canopy cover and snow interception. Regression correlation coefficients (R^2) were 0.62, 0.30 and 0.01 for the photocanopyometer, spherical densiometer and basal area gage respectively. Regression coefficients for lodgepole pine and spruce/fir stands were not significantly different and were combined for the relationship of percent forest canopy and SWE as a percent of an open condition (Figure 2). Snow accumulation dropped from 100 to 69 percent of an open condition when canopy cover increased from 0 to 70 percent for lodgepole pine and spruce/fir stands.

Forest canopy cover increased quickly as lodgepole pine and spruce/fir stands approached maturity (HCT of 1 to 1.5) and then decreased slowly as stands advanced into late successional stages (Figure 3). Mortality due to age, disease, windthrow and insects created gaps in late successional stands allowing increased amounts of snow and rain to reach the forest floor. Spruce/fir stands had greater canopy coverage than lodgepole pine stands throughout all successional stages because of their denser foliage and shade tolerance characteristics, enabling multi-structured stands to develop. This relationship of HCT to percent forest canopy cover eliminated the need to measure forest canopy cover on all stands.

Table 2. Calculations of the runoff for a lodgepole pine habitat cover type (HCT) for a 900 mm precipitation zone on the Tenderfoot Creek Experimental Forest.

Precipitation zone 900 mm Annual runoff 378 mm
April 1 SWE = 338 mm Runoff ÷ precipitation 42 %
April - June precipitation 246 mm

HCT LP	SWE reduction[1]	Precipitation reduction[2]	Total reduction[3]	Net precipitation[4]	Runoff[5] mm
.0	0	0	0	900	378
.1	7	7	14	886	372
.2	16	17	33	867	364
.3	24	25	49	851	357
.4	30	33	63	837	352
.5	37	41	78	822	345
.6	44	49	93	807	339
.7	49	58	107	793	333
.8	55	65	120	780	328
.9	61	69	130	770	323
1.0	65	71	136	764	321
1.1	69	71	140	760	319
1.2	72	71	143	757	318
1.3	75	71	146	754	317
1.4	77	70	147	753	316
1.5	78	69	147	753	316
1.6	78	69	147	753	316
1.7	78	68	146	754	317
1.8	78	66	144	756	318
1.9	77	65	142	758	318
2.0	77	64	141	759	319
2.1	76	64	140	760	319
2.2	75	63	138	762	320
2.3	74	62	136	764	321
2.4	73	60	133	767	322
2.5	72	59	131	769	323
2.6	71	59	130	770	323
2.7	69	58	127	773	325
2.8	67	57	124	776	326
2.9	65	55	120	780	328
3.0	63	54	117	783	329

[1]338 - (% open x 338)
[2]246 - (% open x 246)
[3]Sum SWE and precipitation reduction
[4]Precipitation zone minus total reduction
[5]Net precipitation times 0.42

The amount of snow (SWE) and rain (April - June precipitation) that reaches the forest floor decreased sharply as lodgepole pine and spruce/fir stands approached maturity (Figures 4 and 5). Precipitation throughfall and SWE remained constant for a short period after stands matured and then increased slowly as stands approached late successional stages. Mortality due to age, disease, windthrow and insects created gaps in late successional stands allowing increased amounts of precipitation to reach the forest floor. A higher percentage of snow reaches the forest floor under lodgepole pine than under spruce/fir stands (Figures 4 and 5). Precipitation throughfall as rain is nearly equal for lodgepole pine and spruce/fir stands. July through September precipitation was not considered to effect runoff in this study. This late summer precipitation adds little to stream runoff because of high evaporation rates, increased water use by vegetation and high soil moisture deficits.

Table 3. Average annual runoff for lodgepole pine habitat cover types (HCT) and average annual precipitation zones for Tenderfoot Creek Experimental Forest.

HCT	Average annual precipitation zone, mm									
LP	600	650	700	750	800	850	900	950	1000	1050
				Runoff	(mm)					
.0	126	169	210	255	296	340	378	418	460	504
.1	124	166	206	251	291	334	372	411	453	496
.2	121	162	202	245	285	328	364	403	444	486
.3	118	159	198	240	280	322	357	396	436	478
.4	116	156	194	236	275	316	352	389	428	470
.5	114	153	190	232	270	310	345	382	421	462
.6	111	150	187	227	264	304	339	376	414	454
.7	109	147	183	223	259	299	333	369	407	446
.8	107	144	180	219	255	294	328	363	400	440
.9	105	142	177	216	252	290	323	359	396	434
1.0	104	141	176	214	249	288	321	356	392	431
1.1	104	140	175	213	248	286	319	354	390	429
1.2	103	139	174	212	247	285	318	352	389	427
1.3	103	139	173	211	246	284	317	351	387	425
1.4	103	139	173	211	246	284	316	351	387	424
1.5	103	139	173	211	246	284	316	351	387	425
1.6	103	139	173	211	246	284	316	351	387	425
1.7	103	139	174	212	247	284	317	352	388	425
1.8	103	139	174	212	247	284	318	352	388	427
1.9	104	140	175	212	248	285	318	352	389	427
2.0	104	140	175	214	248	286	319	353	390	428
2.1	104	140	175	214	248	286	319	354	391	428
2.2	104	140	176	214	249	287	320	355	391	430
2.3	105	141	176	215	250	288	321	356	392	431
2.4	105	142	177	216	251	289	322	357	394	432
2.5	105	142	177	216	252	290	323	358	395	433
2.6	105	142	178	217	252	290	323	359	395	433
2.7	106	143	178	218	253	292	325	360	397	435
2.8	106	144	179	218	254	293	326	362	398	437
2.9	107	144	180	219	256	294	328	363	400	439
3.0	108	145	181	220	256	295	329	364	402	440

Average annual runoff was estimated at 12,480 cubic dekameters ($dams^3$) when fires burned 51 percent of TCEF in 1581, producing the highest estimated runoff during the past 400 years (Table 4 and Figure 6). The average annual runoff from 1581 to 1997 was estimated to be 11,680 $dams^3$. If all timber from TCEF were removed, the annual runoff is estimated to be 13,240 $dams^3$ in an average precipitation year, 21,190 $dams^3$ in a wet year (160 percent of average) and 6,620 $dams^3$ in a dry year (50 percent of average). The annual runoff was estimated at 11,230 $dams^3$ in an average year, 17,970 $dams^3$ in a wet year and 5,620 $dams^3$ in a dry year if all stands on TCEF were mature lodgepole pine (HCT of 1). The estimate of average annual runoff approaching this minimum value occurred in 1676, 1726, 1831, 1873 and is presently (1997)near this minimum threshold (Figure 6). During a wet year, with nearly all of the forest removed, the runoff could be as high as 160 percent of average. Runoff could be as low as 50 percent of average in a dry year with all of the forest in a mature condition.

Table 4. Estimated annual runoff in cubic dekameters (dams^3) from the Tenderfoot Creek Experimental Forest.

Period		dams^3
1581-1997	Average annual runoff =	11,678
1961-1990	Average annual runoff =	11,458
1997	Average annual runoff =	11,360
1581-1997	Maximum average annual runoff (1581) =	12,485
1581-1997	Minimum average annual runoff (1873) =	11,247
	Average annual runoff with all forest burned or harvested =	13,241
	Average annual runoff with 91% mature forest =	11,230
	Maximum annual runoff, no forest, wet year =	21,186
	Minimum annual runoff, 91% mature forest, dry year =	5,615

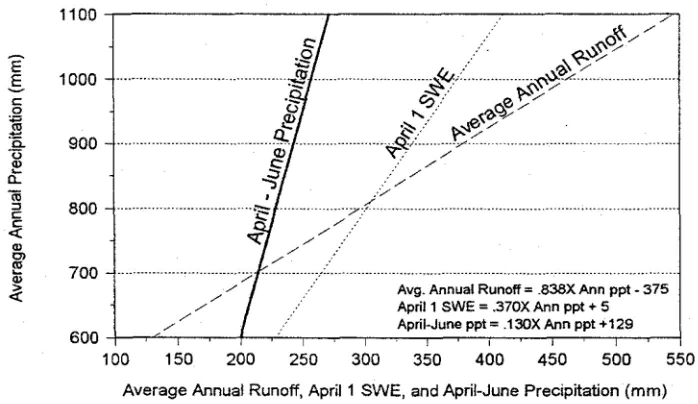

Figure 1. Average annual precipitation versus runoff, April 1 snow water equivalent (SWE) and April - June precipitation in open canopy areas on the Tenderfoot Creek Experimental Forest.

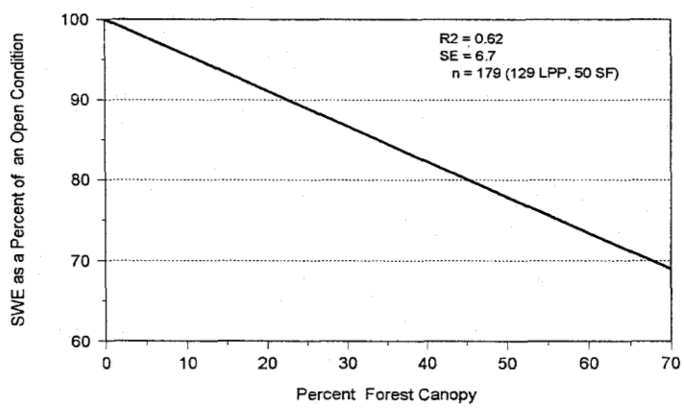

Figure 2. Snow water equivalent as a percent of an open condition compared to percent forest canopy for lodgepole pine and spruce/fir stands in and near the Tenderfoot Creek Experimental Forest. Percent canopy is measured with a photocanopyometer for a 30° cone.

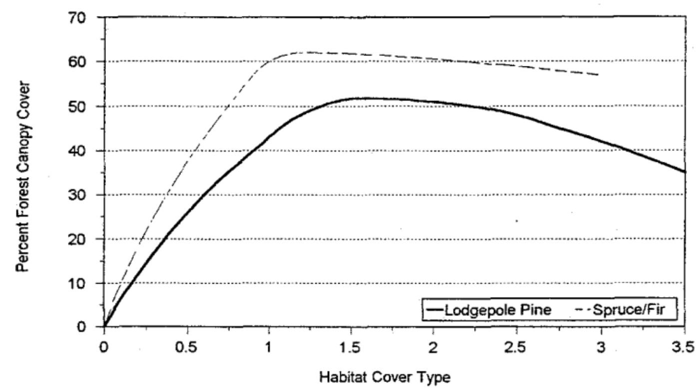

Figure 3. Relationship between percent canopy measured with a photocanopyometer and the habitat cover type index for lodgepole pine and spruce/fir stands on the Tenderfoot Creek Experimental Forest.

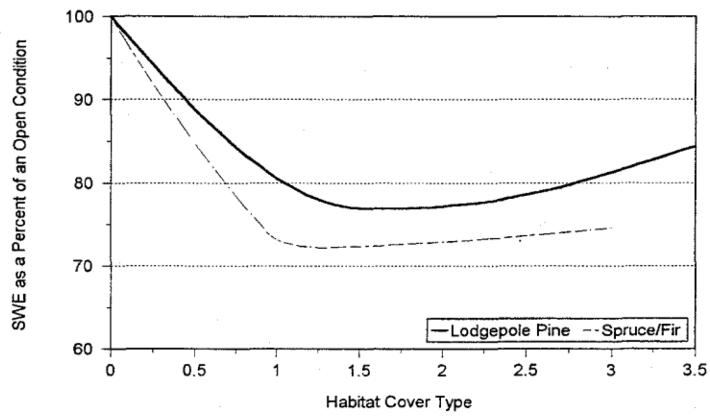

Figure 4. Relationship between snow water equivalent (SWE - winter precipitation) as a percent of an open condition and habitat cover type under lodgepole pine and spruce/fir stands on the Tenderfoot Creek Experimental Forest.

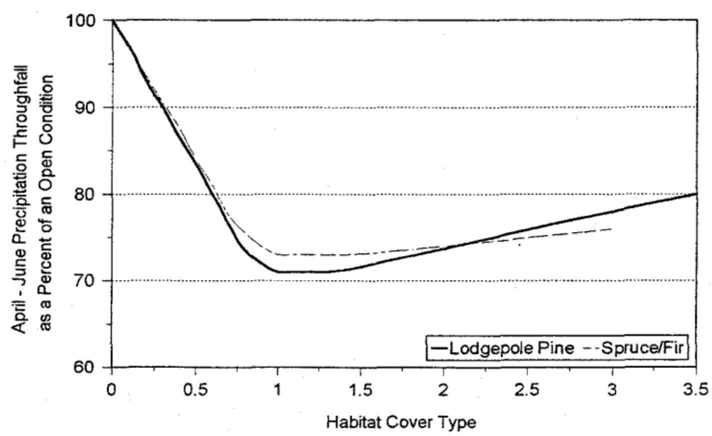

Figure 5. Relationship between throughfall of April - June precipitation (rain) throughfall and habitat cover type under lodgepole pine and spruce/fir stands on the Tenderfoot Creek Experimental Forest.

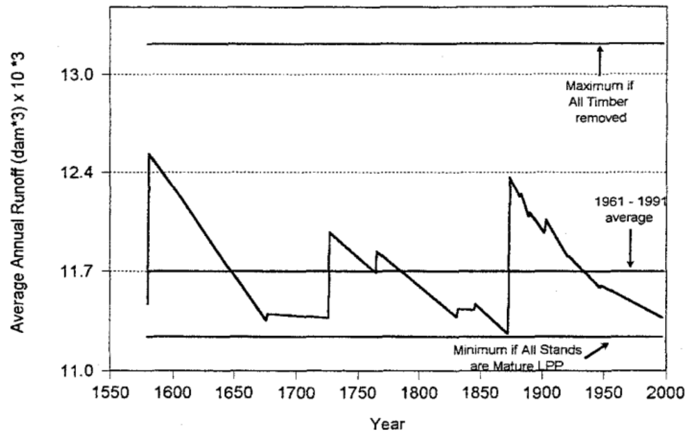

Figure 6. Average annual runoff from Tenderfoot Creek Experimental Forest based on fire history data and canopy cover/precipitation/runoff relationships under the 1961-1991 average precipitation regime.

SUMMARY

Fire has played a significant role in determining the average annual runoff patterns for Tenderfoot Creek Experimental Forest over the past 400+ years. Historically, when average annual runoff approached the minimum level expected under a mature forest scenario, fires removed some of the forest canopy resulting in increased runoff (Figure 6). Fire suppression over the last 90 years has allowed the forested areas to remain in a mature stage, resulting in water yields that are now approaching the minimum estimated level. It appears that continued fire suppression could result in a fuel buildup in TCEF that might result in a major fire event, unless portions of the forest are burned or logged through management actions that mimic historic fire patterns. The effects of a major fire event would not be acceptable because of the extreme impacts on stream channels, fisheries and wildlife. Water yields should increase in proportion to the amount of forest affected by burning or logging. This study shows that it is possible to estimate the historic variability in runoff using past fire patterns, average annual precipitation, April SWE, April - June precipitation and habitat cover type.

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