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Title: Do Vigorous Young Forests Reduce Streamflow? Results from up to 54 Years of Streamflow Records in Eight Paired-watershed Experiments in the H. J. Andrews and South Umpqua Experimental Forests.

Abstract approved:

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Julia A. Jones

This study quantified the magnitude and timing of summer streamflow deficits in paired-watershed experiments in the Cascade Range of Oregon where mature and old-growth conifer forests were subjected to clearcutting, patch cutting, and overstory thinning treatments in the 1960s and 1970s. Hydrologic effects of clearcutting, small-patch cutting, and overstory thinning in the mixed conifer/brush zone were studied (1 watershed (WS) each) in the Coyote Creek WS of the South Umpqua Experimental Forest at 42° 1′ 15″N and 122° 43′ 30″W. Hydrologic effects of clear cutting (3 WS), shelterwood cutting (1 WS), patch cutting (1 WS), and young forest thinning

(1 WS) were examined in the Tsuga heterophylla zone at the H. J. Andrews experimental forest at 44° 14′ 0″N and 122° 11′ 0″ W. Climate of both sites is marine west coast with winter precipitation and dry summers, producing minimum streamflows in August and September. Changes in flow frequency distributions were detected by counting days below streamflow thresholds where the thresholds were established using percentiles from pre-cutting streamflow records. Changes in relative streamflow were established by the station pair method. Summer streamflow deficits were largest and most persistent in 35 to 50-year-old forest plantations created from clearcutting and shelterwood cutting in the 1960s and 1970s. Summer streamflow deficits were smallest and most ephemeral in a stand that experienced 50% overstory thinning in 1971. Summer streamflow deficits of intermediate size and persistence developed in watersheds in which 25 to 30% of the area had been patchcut in the 1960s or 1970s. A sparse (12%) precommercial thin of a 27-year-old stand exhibiting summer streamflow deficits had comparatively little effect on streamflow deficits. Streamflow deficits emerged as early as March or April and persisted into October and November in the warmer, drier site in southern Oregon (Coyote Creek), whereas summer streamflow deficits were restricted to July through September in the cooler, wetter Andrews Forest. These findings are

consistent with previous studies demonstrating (1) increases in water use in certain conifer species relative to others (e.g. Douglas-fir versus pine); (2) higher water use in young (i.e., 10 to 50-yr-old) compared to old (100 to 250-yr-old) stands of many tree species; and (3) decreased interception capacity of young relative to old forest stands associated with loss of canopy epiphytes. Results appear to be robust, despite gaps in data availability, uncertainties associated with changes in stream gauging, streamflow trends over time in control watersheds, and multi-decadal fluctuations in regional climate over the study period. These findings support the notion that variable-intensity logging prescriptions over small areas to approximate natural forest structure may have the least effect on summer streamflows. However, more research, preferably new paired watershed experiments, is needed to quantify the magnitude and duration of summer streamflow effects from various levels of overstory and understory thinning treatments.

Do Vigorous Young Forests Reduce Streamflow? Results from up to 54 Years of Streamflow Records in Eight Paired-watershed Experiments in the H. J. Andrews and South Umpqua Experimental Forests.

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APPROVED

Major Professor, representing Geography

Chair of the Department of Geosciences

Dean of the Graduate School

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Timothy D. Perry, Author

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1. Introduction

1.1. Background

Eco-hydrology research has shown that young, vigorous forests use more water than old growth forests [*Hicks et al.*, 1991; *Jones and Post*, 2004]. In areas such as the Pacific Northwest where forest harvest occurs in pre-existing mature and old-growth forest, young stands are created by clearcutting and even-aged management. A typical legacy of forest cutting is streamflow deficits, although particular streamflow changes vary between watersheds (WS) with different harvest intensities, harvest methods, and forest ecologies. *Hicks et al.* [1991] and *Jones et al.* [2004] documented emerging summertime water deficits in several WS at the H.J. Andrews Experimental Forest, Oregon. Multiple explanations for the observed deficits have been proposed: *Moore et al.* [2004] showed that young conifer trees are more prodigious water consumers during the late summer than older conifer trees, while *Hicks et al.* [1991] noted herbaceous vegetation regrowth, shrub sprouting, deciduous tree dominance of riparian corridors, and young conifer establishment and regrowth were associated with increasing summer water deficits. This paper examines the magnitude and duration of summer-time streamflow deficits based on existing paired-WS experiments in the Pacific Northwest.

In the Marine West Coast climate, which includes seasonal (summer) drought, stream organisms and fish are adapted to, but still sensitive to, drought. Coho salmon (*Oncorhynchus kisutch*) smolt production is related to pool and pond density within streams [*Sharma and Hilborn*, 2001] and smolts (young fish) prefer pools and ponds to riffles and glides in summer [*Nickelson et al.*, 1992]. *May and Lee* [2004] found that in streams with thick alluvial deposits, summer low flows could result in desiccation of the stream bed and asphyxiate fish. This happened in pools with alluvial bottoms if the alluvium was thick enough for all flow to become hyporheic. Increased summer drought intensity would reduce the number of pools sustained by hyporheic, or subsurface, flow in alluvial reaches. By contrast, the bedrock reaches were less likely to dry out and fish survival was greatest in these areas [*May and Lee*, 2004]. However, crowding increases in bedrock reaches as flows decline [*Hicks*, 1990]. Thus, reduced summertime streamflow due to forest regrowth may significantly effect stream ecology.

Fire suppression and reduction in grazing frequency during the last century may have increased forest leaf area and contributed to summertime drought. *Taylor et al.* [1998] found fire return intervals in the northern Klamath Mountains increased from 14.5 years before settlement (1627-1849) to 21.8 years after fire suppression (1905-1995). Reduced fire frequency allows a vigorous understory to develop in areas where before fire suppression only a few small trees would have survived among old, thick-barked, fire-resistant trees [*Agee*, 1991; *Taylor and Skinner*, 1998]. In addition, fire suppression might reduce mortality of old trees, further increasing leaf area. Grazing also suppressed understory growth, but grazing on public lands has declined over the last century.

Paired-WS experiments which are relevant to this paper have been conducted in two Pacific-Northwest environments: the Douglas-fir dominated region of the western Cascade Range, represented by the H.J. Andrews Experimental Forest; and the mixed-conifer forest prevalent in southwestern Oregon and Northern California, represented by the Coyote Creek basins in the South Umpqua Experimental Forest. Southwestern Oregon has a drier climate than equivalent elevations in the western Cascade Range. The South Umpqua Experimental Forest was established in 1951 in recognition of climatic and ecological differences from more northerly research forests [*Hayes*, 1951], and seasonal water yield and quality studies commenced in 1963 [*Rothacher*, 1968] and continued until 1981. Recent streamflow study results from the H. J. Andrews prompted hydrologists at the Roseburg USDA Forest Service district office to revitalize the Coyote Creek streamflow gauges in 2000 so that results in southwestern Oregon could be compared to results at other locations.

This study examined low flow responses to various forest cutting treatments (100% clearcutting, shelterwood, 25-30% patch cutting, and 50-60% overstory thinning) over three to five decades. Clearcutting removes the original overstory in one cut. Shelterwood cutting consists of an initial dispersed cut that opens the canopy allowing establishment of young trees in the shelter of the remaining overstory. Young tree establishment is followed by removal of the remaining overstory converting the stands to a young, even-aged structure. Patch cutting consists of small clearcuts in a larger watershed. Overstory thinning consists of a dispersed cut throughout a watershed.

Streamflow changes were analyzed for all seasons, with a particular emphasis on summer flows, which are the lowest flows under this climate regime. This paper quantifies the time of onset, persistence, and intensity of summertime streamflow deficits in multiple basins and evaluates summer streamflow deficits according to the forest harvest method and climatic factors at the two sites. This paper builds on the hydrologic mechanisms [*Eberhardt and Thomas*, 1991; *Harr et al.*, 1979; *Harr et al.*, 1982; *Hicks et al.*, 1991; *Jones*, 2000; *Jones and Post*, 2004; *Moore et al.*, 2004; *Rothacher*, 1965] and methods [*Harr et al.*, 1979; *Harr et al.*, 1982; *Jones and Post*, 2004] of past research in combination with an extended streamflow record from previously analyzed, paired-WS experiment basins.

1.2. Definitions and hypotheses

For the purposes of this paper, we define

(1) A *low flow* as a flow that falls below the 5^{th} percentile flow observed in the pre-treatment period of record.

(2) *Low-flow frequency* as the number of days below the low flow threshold (5th percentile) and more generally *N^{th} percentile flow frequency* as the number of days below the N^{th} percentile threshold; thresholds are percentile flows calculated from the pre-treatment streamflow data.

(3) A *low-flow deficit* as the amount by which the flow in a treated WS is lower than the flow in the control WS on a particular day (in relative terms as percent, or in absolute terms as mm/day).

(4) *Intensity of the low-flow deficit* as the cumulative relative amount (%) or absolute amount (mm) of flow less than the control in any dry season;

(5) *Persistence of the low-flow deficit* as the number of days/yr (and number of years) in which the flow in the treated WS is lower than expected.

Hypotheses: H1: The low-flow frequency, intensity of low-flow deficits, and persistence of low-flow deficits are directly related to the mature forest leaf area removed by the logging treatment. Specifically, 100% clearcutting produces more pronounced and persistent low-flow deficits compared to 50% overstory thinning, which in turn produces more pronounced and persistent low-flow deficits than 25-30% patch-cut. The mechanism involved is the conversion of mature or old forest into young stands, which use more water per unit leaf area.

H1a: Alternatively, low-flow deficits may depend upon the spatial arrangement of leaf area removed. For example, controlling for leaf area removed, overstory thinning may produce less intense low-flow deficits than small patch-cuts. The mechanism would be that release of overstory trees captures the initial water surplus, mature trees (which use water more efficiently) are better adapted to reduce their water use in the dry summer, and there is less growth of sapling and young trees to produce a low-flow deficit after overstory thinning compared to small patch-cuts.

H2: Controlling for treatment, the intensity and persistence of low-flow deficits are not related to the precipitation, elevation, latitude, or hill-slope gradient of the WS. Specifically, H2 predicts that low-flow deficits will not differ after 100% clearcutting treatments between Coyote Creek and the H. J. Andrews, or between H. J. Andrews 10 (low), 1 (intermediate) and 6 (high) elevations; after 25-30% patch-cut treatments between Coyote Creek, 2 and H. J. Andrews 3; or after 50% overstory thin at Coyote 1 versus H. J. Andrews 7.

H2a: Alternatively, low-flow deficits may be less intense and persistent at higher latitudes where precipitation is relatively high and evapotranspiration is relatively low, or on deep soils, or where species compositional changes involve changes in water use efficiency.

H3: Low-flow frequency and intensity can be reduced for a significant number of years by thinning young stands. Specifically, H3 predicts that 12% thinning of young vigorous stands in H. J. Andrews 7 will eliminate low-flow deficits for five years.

H3a: Alternatively, thinning of young stands may only slightly affect low-flow frequency and intensity and practically significant low-flow deficits will continue.

2. <u>STUDY SITE DESCRIPTION</u>

2.1. <u>South Umpqua Experimental Forest: The Coyote Creek Study</u>

Three paired-WS studies were conducted at the Coyote Creek Study Area in the South Umpqua Experimental Forest (Coyote). The South Umpqua Experimental Forest consists of the Coyote Creek headwater streams located about 55 km southeast of Roseburg, Oregon at 42° 1′ 15″N and 122° 43′ 30″W (Figure 2-1). WS range from 49 to 69 ha and extend from 730 m to 1065 m above sea level (Table 2-A). Aspect varies between WS. Aspect of Coyote 1 is east-northeast, Coyote 2 northeast, Coyote 3 north-northeast, and Coyote 4 north. Slopes range from 20 to 80%, similar to those in the surrounding area [*Harr et al.*, 1979]. Mass wasting commonly occurs in these WS, resulting in side slope benches and poorly developed drainage patterns [*Swanson and Swanston*, 1977]. Watershed characteristics are summarized in Table 2-A.

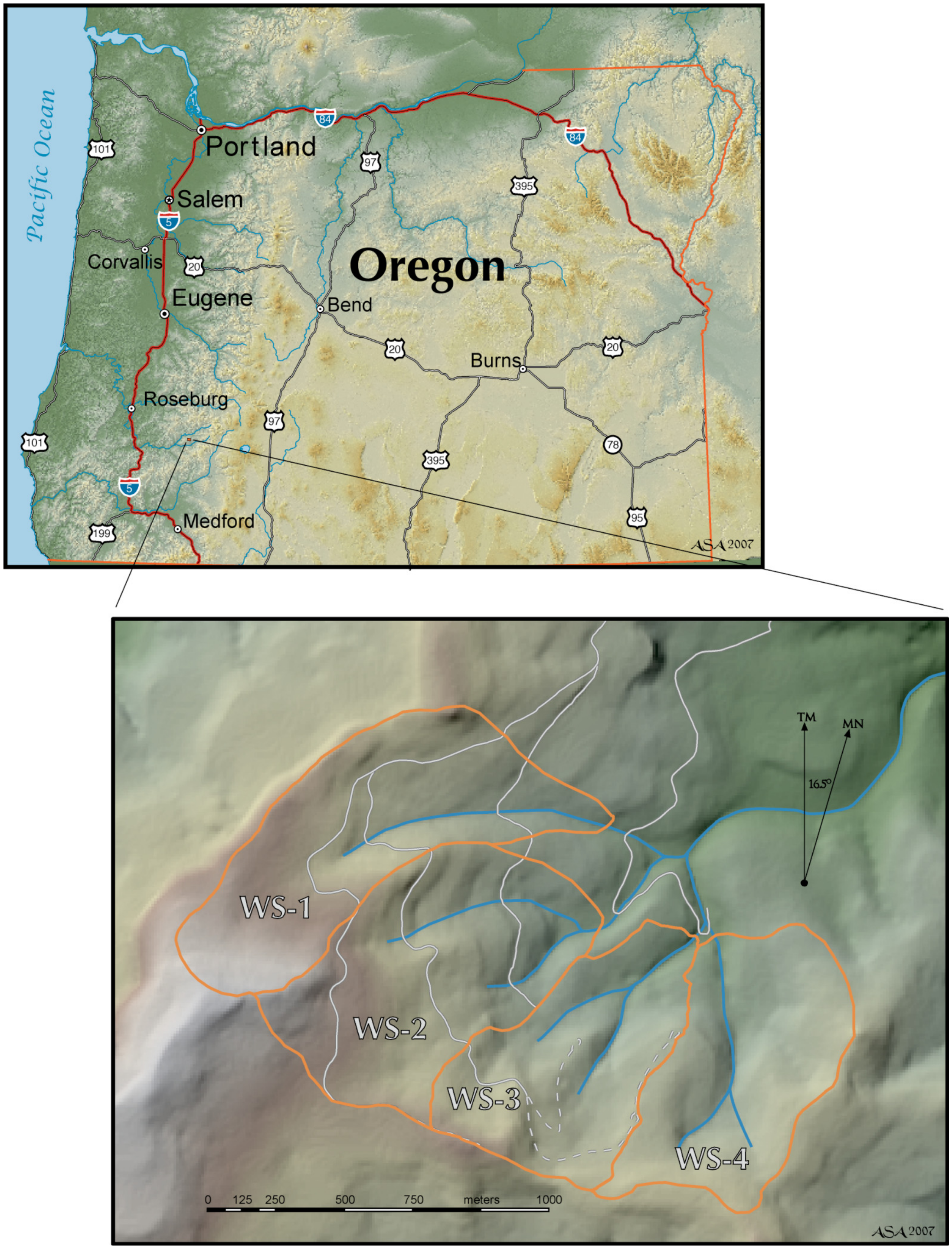


Figure 2-1: Coyote Creek in the South Umpqua Experimental Forest [*Arthur*, 2007].

Table 2-A: WS names, locations, areas, treatments, streamflow record lengths used in this study.

WS	Area (ha)	Treatment	Natural vegetation	Streamflow record length*	Logging method	Elevation range (m)
Coyote 1	69.2 [a]	Permanent roads 1970; 50% overstory selective cut, 1971 [a]	Mixed conifer [a]	1963-81 V; 2001-2006 V	Tractor yarded.	750-1065 m [e]
Coyote 2	68.4 [a]	Permanent roads 1970; 30 % small patch-cuts, 1971 [a]	Mixed conifer [a]	1963-81 V; 2001-2006 V	16% high-lead cable yarded; 14% tractor yarded.	760-1020 m [e]
Coyote 3	49.8 [a]	Permanent roads 1970; 100% clearcut 1971 [a]	Mixed conifer [a]	1963-81 V; 2001-2006 V	77% high-lead cable yarded; 23% tractor yarded.	730-960 m [e]
Coyote 4	48.6 [a]	Control [a]	Mixed conifer [a]	1963-81 V; 2001-2006 V	N/A	730-930m [e]
H. J. Andrews 1	95.9 [b]	100% clearcut 1962-1966 [b]	Douglas-fir forest [b]	1952-2005 T 1952-2005 (rebuilt 1956) 1999 -> Today V	100% skyline yarded.	460-990m[d]
H. J. Andrews 2	60.7 [b]	Control [b]	Douglas-fir forest [b]	1952-2005 T 1952-2005 1999 -> Today V	N/A	530-1070m[d]
H. J. Andrews 3	101.2 [b]	Roads 1959; 30% patch-cut 1962 [b]	Douglas-fir forest [b]	1952-2005 T 1952-2005 1999 -> Today V	30% high-lead cable yarded.	490-1070m[d]

Table 2-A (Continued)

WS	Area (ha)	Treatment	Natural vegetation	Streamflow record length*	Logging method	Elevation range (m)
H. J. Andrews 6	13.0 [c]	Roads before study; 100% clearcut 1974; broadcast burned 1975 [c]	130-year-old Douglas-fir with scattered 450-year-old Douglas-fir stands [c]	1964-2005 H 1964 -> 1997 T 1997 -> Today V 1998 -> Today	90% high-lead cable yarded; 10% tractor yarded	863-1013m [c]
H. J. Andrews 7	15.4 [c]	Spur roads 1974; 60% shelter-wood preparatory cut 1974; remaining overstory cut 1984; broadcast burned lower half of WS 1975 [c]; 12% basal area thinned 2001.	130-year-old Douglas-fir with scattered 450-year-old Douglas-fir stands [c]	1964-1987; 1995-2005 H 1964 -> 1997 T 1997 -> Today V 1998 -> Today	40% skyline yarded; 60% tractor yarded.	908-1097m [c]
H. J. Andrews 8	21.4 [c]	Control [c]	130-year-old Douglas-fir mixed with 450-year-old Douglas-fir stands [f]	1964-2005 H 1964 ->1987 T 1987 -> Today V 1973 -> 1979, 1997 -> Today	N/A	955-1190m [c]
H. J. Andrews 9	9 [d]	Control [d]	130-year-old Douglas-fir mixed with 450-year-old Douglas-fir stands [c]	1969-2005 H 1969 ->1973 T 1973 -> Today V 1973 -> 1979, 1997 -> Today	N/A	425-700m [d]
H. J. Andrews 10	10 [d]	100% clear-cut 1975 [d]	130-year-old Douglas-fir mixed with 450-year-old Douglas-fir stands [f]	1969-2005 H 1969 ->1973 T 1973 -> Today V 1973 -> 1979, 1997 -> Today	100% high-lead cable yarded	425-700m [d]

* H: H-flume; T: trapezoidal flume; V: v-notch weir or plate.
Broadcast burns were controlled burns over the cut area intended to consume logging debris.
(a) Harr et al., 1979; (b) Rothacher, 1965; (c) Harr et al., 1982; (d) Swanson and Jones, 2002; (e) Rothacher, 1968; (f) Jones and Post, 2004

In the Coyote Creek study area well-drained gravelly and very gravelly loams overlay the Little Butte Formation. This formation consists of rhyodacitic pyroclastic rocks (welded and non-welded ash-flow tuff) capped with andesite and basalt on ridges [*Harr et al.*, 1979; *Kays*, 1970]. *Richlen* [1973] described two soil series, Straight and Dumont soils, in the basin, although small inclusions of other soils may occupy small portions of the study area. Surface infiltration rates are rapid in both soils. In some areas dense layers in subsurface horizons have slower infiltration rates, slowing movement of water through deeper horizons. Both soil series form in colluvium and/or residuum of reddish welded breccias. Dumont soils are typically more than 150 cm deep, and have a very thick argillic horizon in which clay content varies by less than 20% within 150 cm of the surface (Palexerults) [*USDA NRCS*, 1997b]. Straight soils are similar but shallower, only 50-100 centimeters deep, and they do not meet clay content and distribution characteristics of Palexerults [*USDA NRCS*, 1997a]. More details including a digitized soil map and more complete soil description is available [*Arthur*, 2007].

The climate at Coyote is Mediterranean and is dominated by frontal storms with 89% of annual precipitation falling between October and March [*Harr et al.*, 1979]. These storms typically form over the Pacific and produce long-duration, low-intensity precipitation. Snow occurs at higher elevations of Coyote Creek and usually melts within 1-2 weeks but snowpacks have persisted up to three months [*Harr et al.*, 1979]. Average runoff peaks in January (Figure 2-2) and the low-flow season lasts from mid-July until mid-October. Fall is October–November; winter is December–March; spring is April–June; summer is July–September [*Harr et al.*, 1979] matching up to times of increasing streamflow, winter high-flows, dropping flows, and summer low flows respectively.

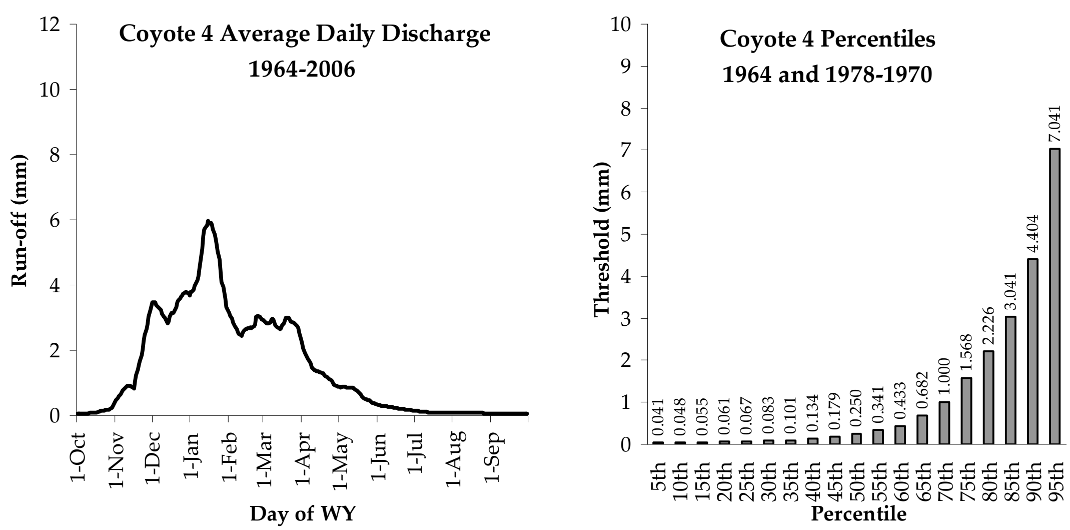


Figure 2-2: Coyote 4 streamflow averages. (a) average runoff from water years 1964-1981 and 2003-2006 (runoff was smoothed with a 15 day window) and (b) flow percentiles from the calibration period (Calendar years 1964 and 1968–70).

Annual precipitation averaged 1229 mm and ranged between 876–1565 mm from 1961 to 1976 at the base of WS 2. Precipitation for the same time span at nearby Toketee Falls (36 km northwest)was quite similar, with an average

1248 mm and range 870-1655 mm [*Oregon Climate Service*, 2007]. At Toketee Falls precipitation from 1951 through 2006 averaged 1231 mm and ranged from 870-2030 mm.

The Coyote Creek WS are in a mixed conifer vegetation zone [*Franklin and Dyrness*, 1973]. Sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* Laws.), and incense-cedar (*Calocedrus decurrens* (Torr.) Florin) characteristic of drier and warmer forest to the south and east mix with Douglas-fir (*Psuedotsuga menziesii* (Mirb.) Franco) that are more common in wetter regions to the north and west [*Harr et al.*, 1979]. Sites with ample moisture contain western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), grand fir (*Abies grandis* (Dougl.) Lindl.), and big-leaf maple (*Acer macrophyllum* Pursh) [*Harr et al.*, 1979]. Grand fir is a primary climax species with Douglas-fir and incense-cedar mixed in on warmer, drier sites [*Franklin and Dyrness*, 1973].

Studies detailing succession following major disturbance in the South Umpqua region is sparse. *Arthur* [2007] describes establishment of herbs in the first five years that are displaced by sclerophyllous shrub-fields within three to five years after logging. These shrub-fields are dominated by *Ceanothus* spp. and *Arctostaphylos* spp. [*Franklin and Dyrness*, 1973]. Then tree saplings became established and in some areas canopy closure excluded herbs and shrubs

[*Arthur*, 2007]. The canopy opens back up as mortality from competition kills weaker trees and mechanical damage from windthrow and snow loading kills other trees and opens small gaps [*Halpern*, 1989].

Before logging, all Coyote Creek sites had approximately 50% overstory cover [*Arthur*, 2007]. During pre-logging surveys, Coyote 4 contained the oldest stands and Coyote 3 contained variable-aged stands of timber [*Rothacher*, 1968]. Douglas-fir and grand fir were the dominant overstory trees with scattered incense-cedar, western hemlock, sugar pine, ponderosa pine, and madrone [*Arthur*, 2007]. Saplings were generally of shade tolerant varieties such as grand fir, western hemlock, and incense-cedar but Douglas-fir was present as well [*Arthur*, 2007].

Access roads were built during the summer of 1970 and logging occurred the summer of 1971 [*Harr et al.*, 1979]. WS 3 was 100% clearcut. Seventy-seven percent of WS 3 was clean-logged with a high-lead cable yarder and 23% was tractor logged with windrowing of slash (logging debris). Clean logging refers to the practice of yarding all slash more than 20 cm in diameter and longer than 2.4 m to landings for disposal, in this case by burning. Windrowing is the piling of slash, or logging debris, in long rows. WS 2 was 30% patch-cut with small clear cuts ranging from .7 to 1.4 ha. 14% of the total

WS area was tractor logged and 16% of the total WS area was high-lead cable yarded. Slash was pulled to landings in all patches. WS 1 was 50% overstory thinned with tractor logging. Slash was burnt on all WS in fall of 1973.

Road cuts and ditches intercepted subsurface flow in WS 1 and 2 and the uppermost road construction drained wet areas of WS 3 [*Harr et al.*, 1979]. Paths logs were transported on, or skid trails, and other areas with compacted soil in WS 1 and 3 were observed routing water directly into streams. Patches in WS 2 were separated from streams by buffers and overland flow from patches to streams was not observed.

Douglas-fir was planted in both WS 2 and 3 [*Rothacher*, 1978]. WS 3 was planted in 1972, 1973, and 1974. WS 2 was planted in 1973 [*Rothacher*, 1978]. However, most regeneration in the WS is natural because most planted seedlings died [*Franklin and Minore*, 1975].

Immediately after logging herb cover increased [*Arthur*, 2007] in WS 2 and 3. Shortly thereafter shrub cover increased and tree saplings became established [*Arthur*, 2007]. As these saplings grew up the canopy closed over herbs and shrubs and reduced their abundance in clearcuts and patch cuts [*Arthur*, 2007]. Thirty-five years after logging, Douglas-fir, incense-cedar, and western hemlock cover increased while cover of other overstory tree species decreased in these WS [*Arthur*, 2007]. Sugar pine was not observed in the clear-cut or patch-cuts. Grand fir abundance declined in WS 3.

Sugar pine cover increased in the overstory thinned WS 1 [*Arthur*, 2007]. Similarly, grand fir abundance increased in WS 1 [*Arthur*, 2007]. *Arthur* [2007] attributed sugar pine and grand fir increases in WS 1 to increased resource availability following 50% overstory removal. He also noted increased Douglas-fir presence in the watershed, which he attributed to soil disturbance during tractor logging and increased light.

2.2. H. J. Andrews Experimental Forest

WS research has been conducted in five treated/control pairs in the H. J. Andrews Experimental Forest (Andrews). The Andrews is located 80 km east of Eugene, Oregon, at 44° 14′ 0″N and 122° 11′ 0″ W (Figure 2-3) and encompasses the drainage of Lookout Creek (6400 ha). WS characteristics are summarized in Table 2-A. Within the Andrews, WS 2 and WS 8 each serve as the control for multiple treated WS. Andrews WS 2 serves as a reference for WS 1, 3, and 10. Andrews WS 8 serves as a reference for WS 6 and 7.

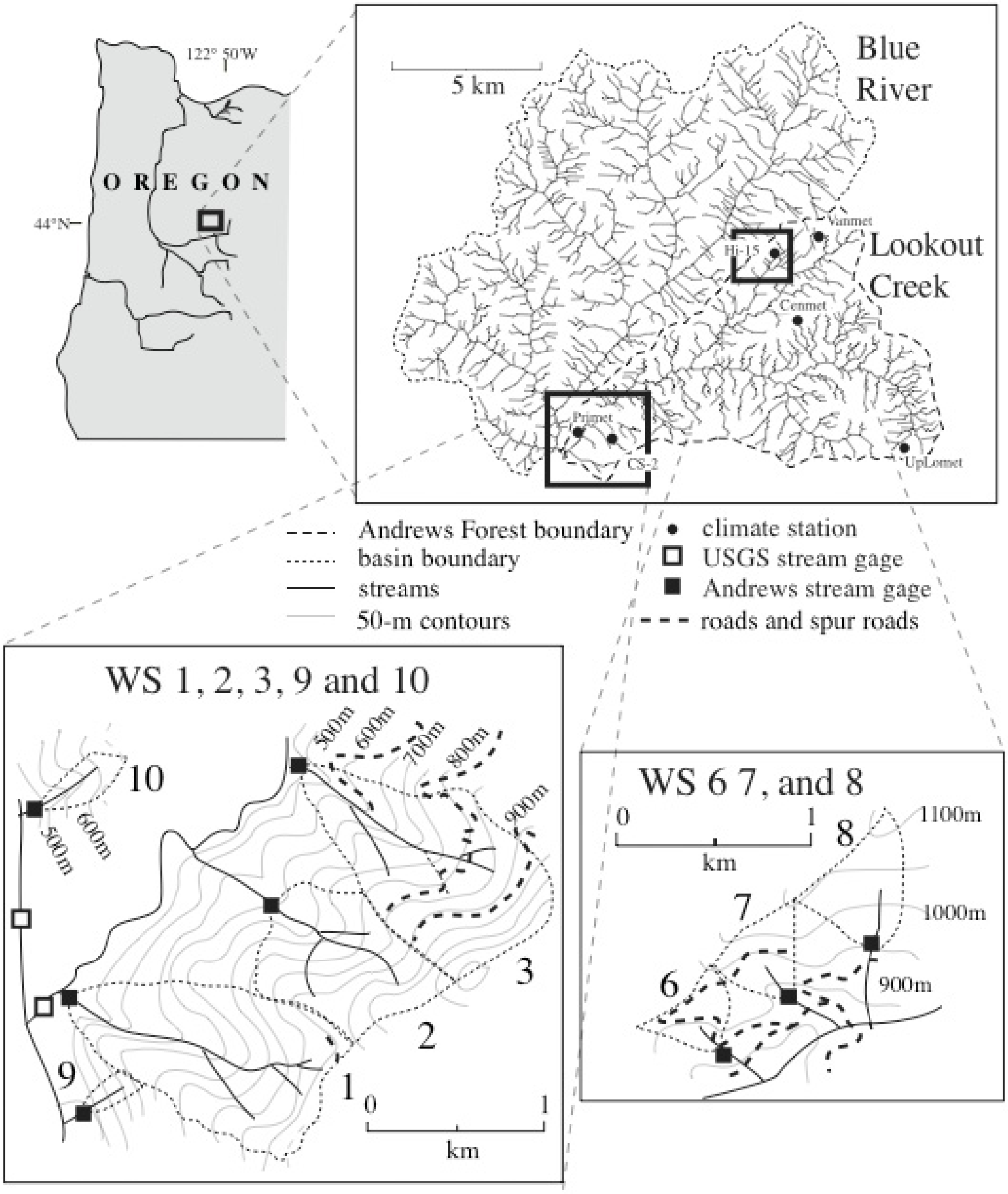


Figure 2-3: Andrews Forest study WS, climate stations, and stream network. Reproduced with permission [*Swanson and Jones*, 2002].

The first paired-WS studies occurred in Andrews WS 1, 2, and 3 [*Swanson and Jones*, 2002]. These WS have northwest aspects and side-slope gradients of 60% occur in more than half the landscape while "slopes of 80-100% are not uncommon" [*Rothacher*, 1965]. These WS range from 460 to 1070 m above sea level [*Swanson and Jones*, 2002]. Andrews WS 1 was clear-cut over four years (1962-1966) due to problems with sky-line yarding equipment [*Rothacher*, 1970]. Andrews WS 3 was 25% patch-cut between August 1962 and February 1963 in three patches of 5, 9, and 11 ha using high-lead yarding [*Rothacher*, 1970].

Andrews WS 6, 7, and 8 were selected for their south facing aspect where reforestation is often difficult [*Harr et al.*, 1982]. WS 6 faces south, and 7 and 8 face south-southeast [*Harr et al.*, 1982]. Elevations range from 865 to 1155 m making these the highest elevation sites in this study [*Harr et al.*, 1982]. Side slope gradients generally range from 20 to 40%. WS 6 was clear cut in 1974 [*Harr et al.*, 1982]. WS 7 was 60% shelterwood cut in 1974 [*Harr et al.*, 1982] and a completion cut remove remaining mature forest in 1984 [*Swanson and Jones*, 2002].

Andrews WS 9 and 10 have a southwest aspect. Side slope gradients average 40 to 60% [*Andrews Experimental Forest LTER*, 2007]. Elevations in both

WS 9 and 10 range from 425 to 700 m. WS 10 was 100% clearcut in 1975 [*Swanson and Jones*, 2002]. WS 9 was gauged to serve as a control for WS 10, but excessive variation in the record prompted previous researchers to substitute WS 2 as a control [*Jones and Post*, 2004].

Soils in all WS are well-drained loams with porosity of 60-70% [*Ranken*, 1974]. Surface runoff is uncommon due to high infiltration rates [*Harr*, 1977; *Harr et al.*, 1982; *Rothacher*, 1970]. Soils often cover a layer of unconsolidated rock that allows percolation [*Rothacher*, 1970]. Hydrothermally altered rocks from the late Oligocene to early Miocene age are common at below 850 m [*Swanson and James*, 1975]. Basalt flows are present at high elevations. Andesite lava flows lie on top of older hydrothermally altered rocks and form the bedrock at higher elevations [*Swanson and James*, 1975]. Landforms have been sculpted out of the volcanic parent rock through a combination of fluvial, glacial, mass movement, and other processes.

Climate at the Andrews is Mediterranean with wet winters and dry summers. The wet season lasts from October through April with 80% of precipitation falling during this time. The majority of precipitation results from frontal storms sweeping off the Pacific Ocean. Precipitation increases with elevation due to orographic enhancement. Snow is uncommon below 1000 m and typically melts within one to three weeks. Snow is common above 1000 m and snowpacks can persist one to three months [*Swanson and Jones*, 2002]. Fall is October–November; winter is December–March; spring is April–June; summer is July–September [*Harr et al.*, 1979] matching up to times of increasing streamflow, winter high flows, dropping flows, and summer low flows respectively (Figure 2-4, Figure 2-5, and Figure 2-6).

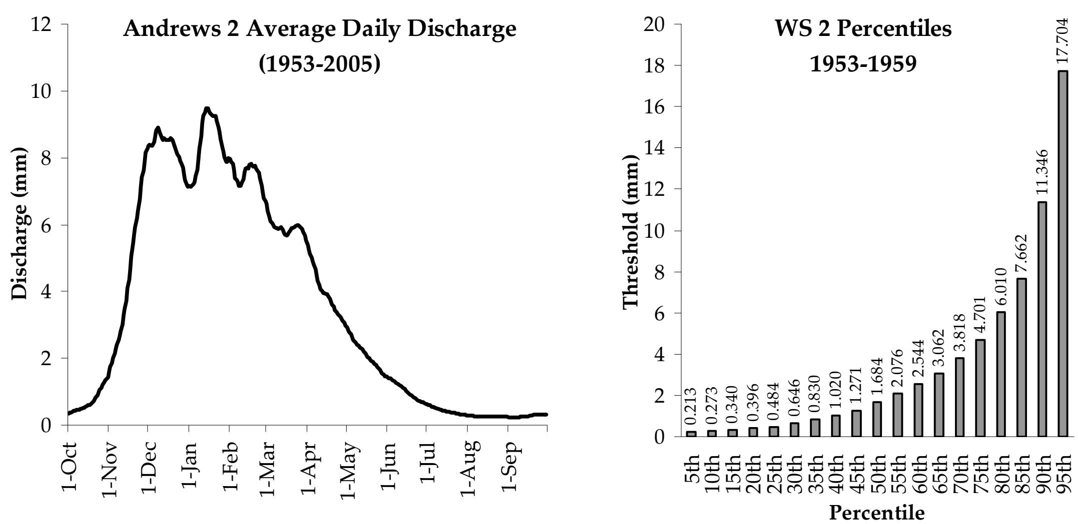


Figure 2-4: Andrews 2 streamflow averages. (a) average runoff from water years 1953-2005 smoothed with a 15 day window; and (b) flow percentiles from the calibration period 1953–1959.

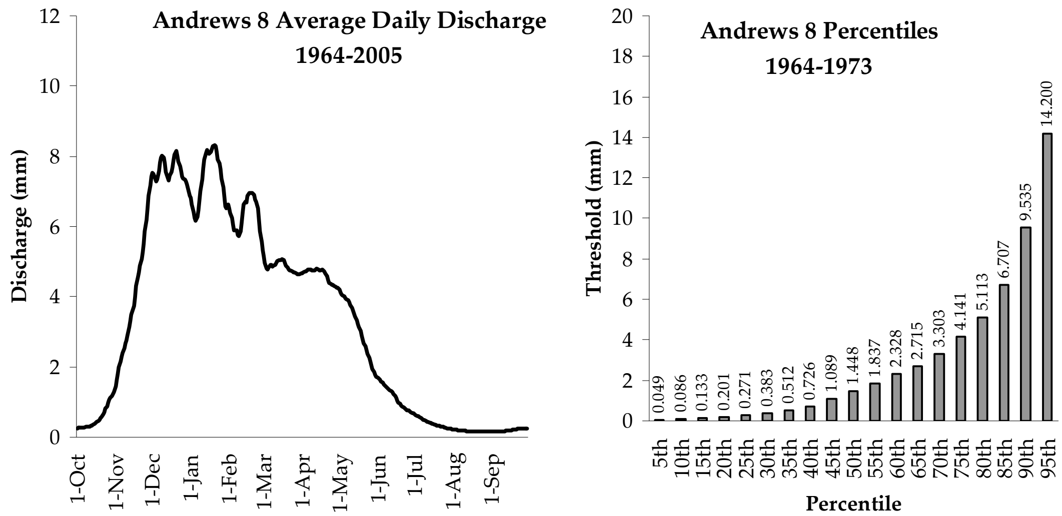


Figure 2-5: Andrews 8 streamflow averages. (a) average runoff from water years 1964-2005 smoothed with a 15 day window; and (b) flow percentiles from the calibration period 1964–1973.

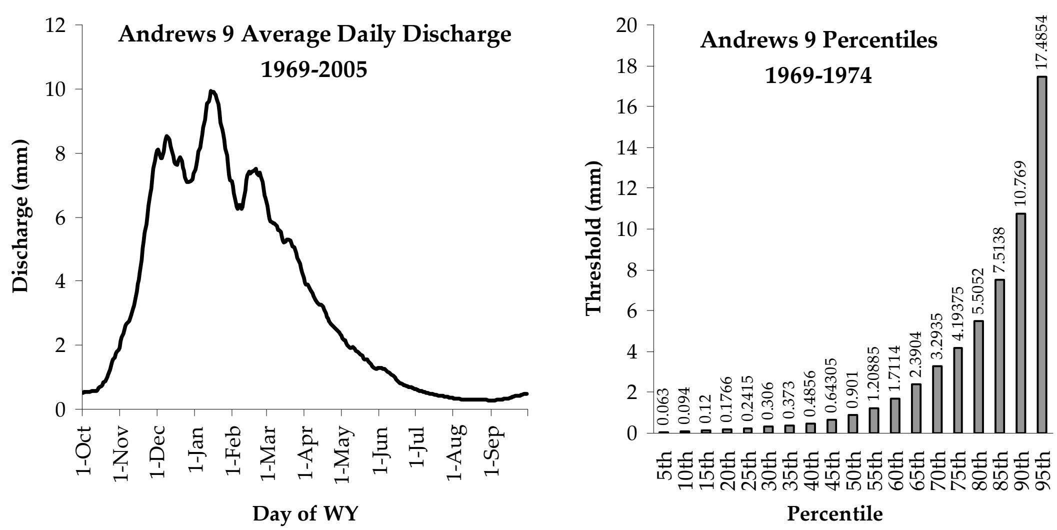


Figure 2-6: Andrews 9 streamflow averages. (a) average runoff from water years 1969-2005 smoothed with a 15 day window; and (b) flow percentiles from the calibration period 1969–1974.

Vegetation is typical of the western hemlock (*Tsuga heterophylla*) zone [*Franklin and Dyrness*, 1973]. Before logging forests in WS 1, 2, and 3 were dominated by Douglas-fir (*Psuedotsuga menziesii*), western hemlock, and red cedar (*Thuja plicata*) which were previously disturbed by severe wildfire in the 1500s [*Rothacher et al.*, 1967]. Andrews WS 6, 7, and 8 were disturbed by wildfire in the 1500s and again in the 1850s resulting in mature 130-year-old stands with 450-year-old clumps of Douglas-fir [*Harr et al.*, 1982]. Andrews WS 9 and 10 were also subjected to wildfire in the 1500s and 1850s [*Jones and Post*, 2004].

Logging treatments ranged from 25% patch cutting to 100% clearcutting (Table 2-A). Clearcutting occurred in WS 1 (1962-1966), WS 6 (1974), and WS 10 (1975). Patch cutting occurred in WS 3 (1962-1963). Andrews WS 7 was a shelterwood experiment. A 60%, dispersed, overstory-thin occurred in 1974 and was followed with removal of the remaining 40% of mature forest in 1984. WS 7 was accidentally thinned in November or December of 2001 when a logging crew conducted thinning operations at the wrong site [*Andrews Experimental Forest LTER*, 2007]. About 12% of basal area was removed during this thin (Bruner, personal communication, 2007).

Early forest succession in Andrews WS 1, 3 and 10 has been described [*Halpern*, 1989; *Halpern and Spies*, 1995] as has late succession [*Lutz and Halpern*, 2006]. These observations can be generalized to the Andrews WS in general. Herbs and low shrubs colonize following clearing of forest canopy and establish on bare ground with different species emerging on burned and unburned sites [*Halpern*, 1989]. Peak coverage of these herbs and low shrubs occurs about 6 years after logging begins. These species are gradually displaced by trees and tall shrubs. Regeneration is more consistent on north facing slopes than on south facing slopes. Conifers dominate most regenerating sites but deciduous trees dominate some south facing slopes [*Lutz and Halpern*, 2006]. These trees compete for resources and shade-intolerant individuals succumb when over-topped by faster growing individuals [*Lutz and Halpern*, 2006]. Shade tolerant species are less affected by competitive pressure but all species are affected by mechanical damage from windthrow, snow, and crushing when old-growth trees fall into cut WS [*Lutz and Halpern*, 2006]. Most sites are dominated by Douglas-fir but more than 20% of stems were hemlock in WS 1 and 3 [*Lutz and Halpern*, 2006].

Despite common trends there was variation between WS. South facing slopes of Andrews 1 and 10 experienced poor regeneration despite multiple plantings [*Halpern*, 1989; *Lutz and Halpern*, 2006]. Regeneration cover was higher in Andrews 3 than Andrews 1 at every observation [*Lutz and Halpern*, 2006]. Field observations during the fall of 2006 showed Andrews WS 6 regeneration is almost completely Douglas-fir, but hemlock was established in WS 7, probably because the shelterwood provided cover for establishment between 1974 and 1984. The shrub *Ceanothus velutinus* peaked 17 years after logging in WS 1 but only 10 years after logging in WS 3 because a major freeze the winter of 1972-1973 killed *Ceanothus velutinus* in WS 3 but not the WS 1 [*Halpern*, 1989].

3. METHODS

3.1. Data

Mean daily streamflow records for the time periods described in Table 2-A were downloaded from the LTER website (http://lterweb.forestry.oregonstate.edu/fsdbdata/data/flow.pl?get=hf00301&topnav=135) using the FLOW application. The FLOW application provides average daily streamflow in units of cfs/mi^2 which was converted to L/s/hectare using eq. 1 and then to mm/day using eq. 2 [*Jones and Post*, 2004].

$$\frac{\text{Liters / sec}}{\text{Hectares}} = .1093 * \frac{\text{cfs}}{\text{mi}^2} \qquad (1)$$

$$\frac{\text{mm}}{\text{day}} = 8.64 * \frac{\text{Liters}}{\text{sec} * \text{ha}} \qquad (2)$$

Control WS data were assessed to determine whether or not the WS behavior had remained stationary. Runoff ratios, the ratio between runoff and precipitation, [*Hibbert et al.*, 1975] for each water year were calculated. Linear regression of precipitation versus runoff was performed for calibration and current time periods. Changes in slope indicate changes in runoff ratio and indicated WS behavior was not stationary. In addition, deviations from expected distributions of flow up to the 95th percentile were inspected for evidence of climatic fluctuations. If known climatic fluctuations did not appear it was deemed evidence WS behavior was not stationary.

3.2. Analysis of Flow Frequency Distributions

We examined daily flow frequency distributions in pre- and post-treatment periods for eight paired-WS experiments at Coyote Creek and the H.J. Andrews Experimental Forest. The eight WS pairs were grouped into three treatment categories: 100% harvest (Coyote 3 v. 4, H. J. Andrews 1 v. 2, H. J. Andrews 6 v. 8, and H. J. Andrews 10 v. 2), 50% overstory thin or shelterwood-preparation cut (Coyote 1 v. 4 and H. J. Andrews 7 v. 8), and 25 to 30% patch-cut (Coyote 2 v. 4 and H. J. Andrews 3 v. 2) (Table 2-A). The analysis quantified changes in the frequency and magnitude of low flows (1) over time (years since logging), (2) as a function of logging treatment, and (3) as a function of location and geographic features of the WS experiment.

This paper extended an approach developed by *Harr et al.* [1982] to establish changes in flow frequency at Andrews 6, 7, and 8. They found changes in summertime low flow frequency using a threshold of .190 mm/day in Andrews 6, 7, and 8. Rather than use a single threshold this paper uses flow thresholds calculated from pre-logging streamflow records (henceforth the calibration period). We calculated 1st, 5th, 10th, 15th, 20th, 25th, 30th, 35th, 40th, 45th, 50th, 55th, 60th, 65th, 70th, 75th, 80th, 85th, 90th, 95th and 99th percentile flows for each WS during the calibration period. The .190 mm/day threshold used by *Harr et al.* [1982] is closest to the 20th percentile (.201 mm/day) threshold calculated for Andrews 8 in this study.

The water year runs from October 1 to September 30, so the water year begins in the low-flow period. This makes the water year unsuitable for examining changes in the flow frequency distribution during the dry portion of the year because one dry season is split into two water years. Since our primary interest in this study was to examine changes in the summertime drought resulting from forest management, we utilized calendar years rather than water years in the flow frequency distribution analysis.

Days at or below each threshold were called N^{th} percentile flow days. Flow days were counted in each calendar year and this count was called "N^{th} percentile flow frequency". This analysis creates a three-dimensional data set with time (year) along one axis, percentile on another axis, and low flow frequency along the third axis (e.g., the three-dimensional surface for Coyote 4 shown below (Figure 3-1)).

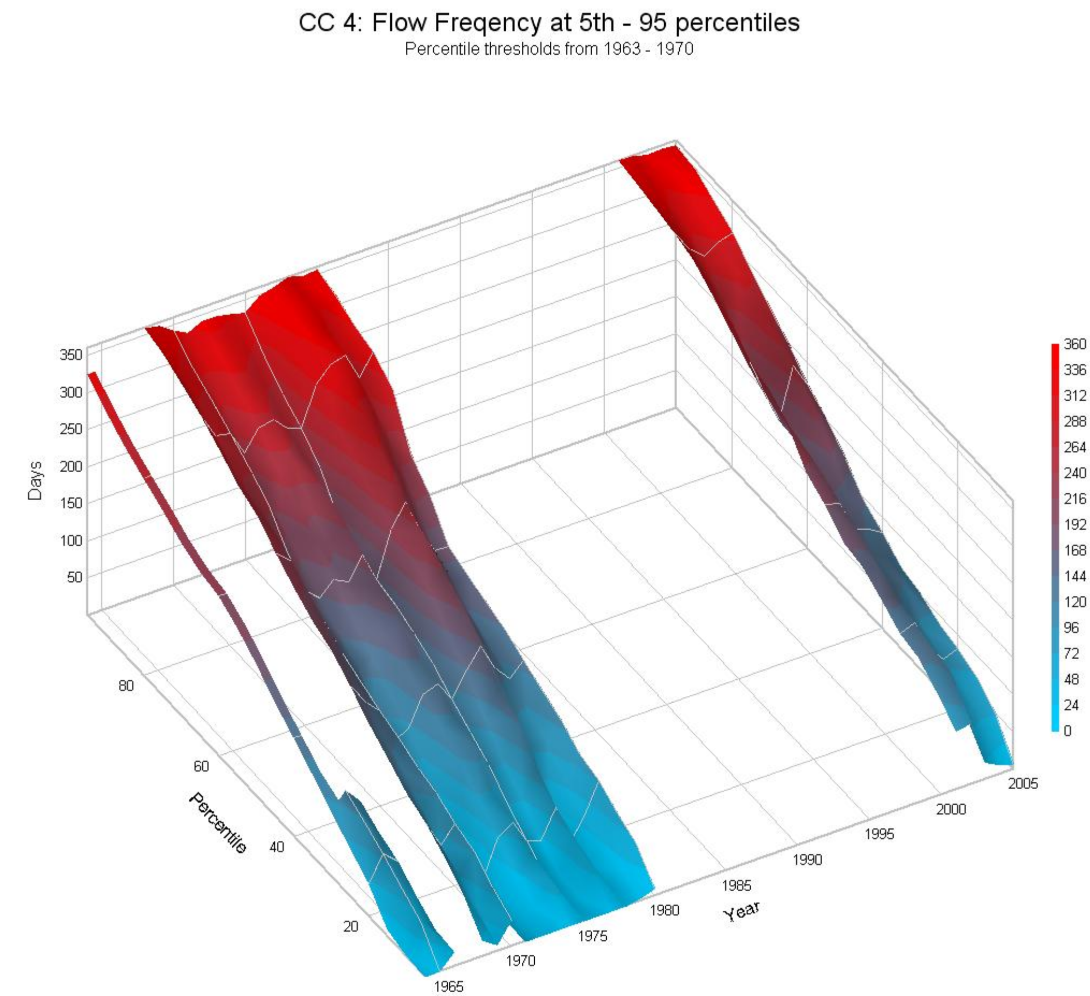


Figure 3-1: Cumulative flow frequency by percentile in Coyote 4.

This data set was plotted two ways for each treated/control WS pair: (1) low flow frequency at key percentile values (e.g., 5th, 15th, etc.) were plotted through time (Figure 3-2 and Figure 3-3) and (2) differences between treated WS and control WS flow frequency (Figure 3-4). Plots of type (1) allow inclusion of data from two or more WS enabling comparison of WS behavior through time (e.g., Figure 3-3). The approach used in this study differs from the common method (which plots a series of peak discharges, or sometimes a series of low flows) by focusing on the frequency of flows in a single year. Time series plots of frequencies such as Figure 3-2 are not commonly used, but they convey the same information as a double-mass analysis, which is commonly used to check for homogeneity of precipitation records [*Dunne and Leopold*, 1978, pgs 41-42].

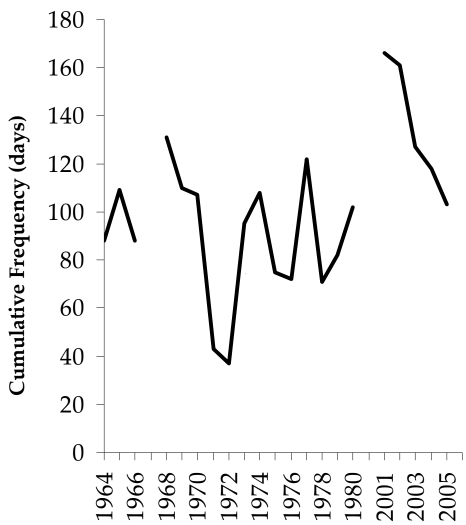


Figure 3-2: Coyote Ck. WS 4 30th percentile low-flow frequency.

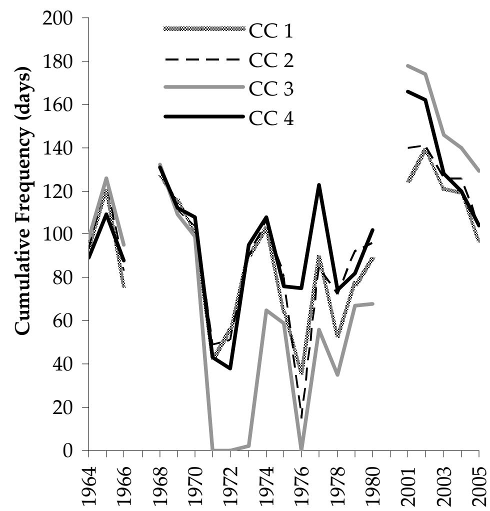


Figure 3-3: Coyote Ck: Annual 30th percentile low-flow frequency for 1963 to 1980 and 2001 to 2006

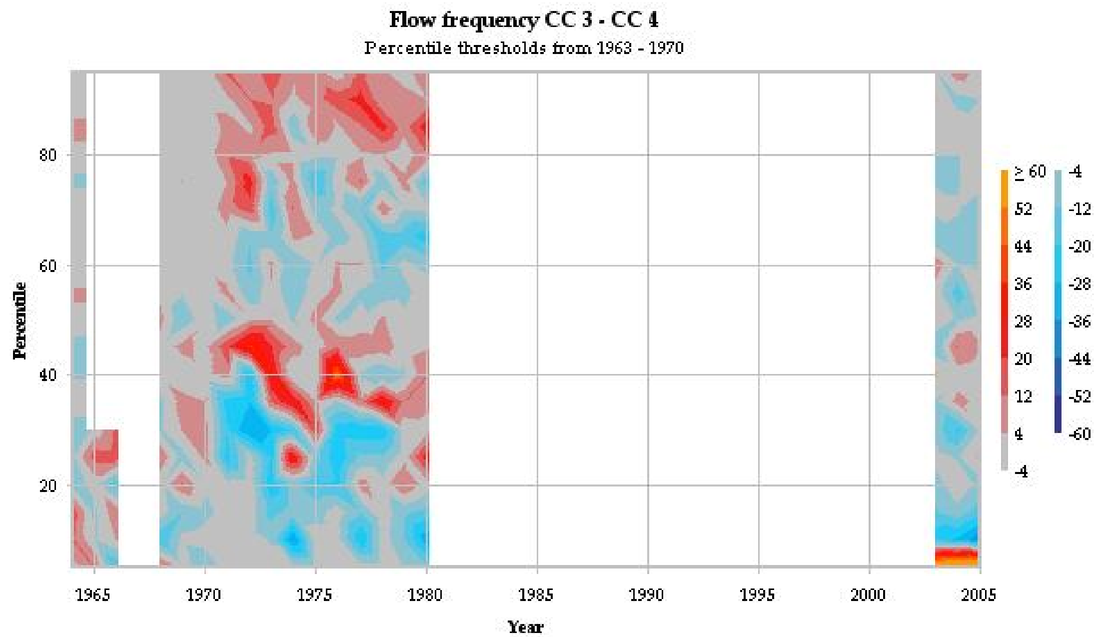


Figure 3-4: Difference in flow frequency between Coyote 3 (treated) and Coyote 4 (control) by calendar year. Color indicates number of days of increased (blue) or decreased flow (red) for a given percentile of flow for a given year in the treated WS compared to the control WS. WS 3 was 100% clearcut in 1971. White areas are periods with no data.

Some datasets contained missing values. Missing values were gaps in the streamflow record of two types: (1) missing values at a WS for which estimated flow has been calculated using a relationship with a nearby WS, and (2) missing values at a WS for which no estimation was calculated, often because of gaps in nearby WS records. Estimated flows were used when available. However, if more than 10 days were entirely missing from a year it was omitted from the calibration period for flow-frequency analysis and results do not include these years unless noted in the text.

At the H. J. Andrews and Coyote Creek streamflow records have been estimated for periods when streamflow gauges were inoperative (Table 3-A). It was assumed that these estimates were sufficiently accurate to be used for low flow frequency change detection. Despite the availability of synthesized records there were still gaps in some water years.

Table 3-A: Number of estimated daily values used in the analysis, and years omitted from analysis, by WS.

WS	Years used despite missing or estimated flows	Omitted years
H. J. Andrews 1	1954=33; 1955=12; 1956=37; 1957=14; 1958=11; 1959=2; 1960=6; 1961=11; 1963=16; 1964=1; 1966=10; 1972=20; 1973=4; 1974=2; 1975=48; 1976=35; 1977=17; 1978=4; 1979=10; 1980=5; 1983=4; 1986=19; 1987=6; 1988=16; 1989=9; 1990=11; 1991=11; 1994=4; 1995=4; 1997=3; 1998=16; 1999=69; 2001=5; 2002=1; 2003=1; 2004=2; 2005=93	
H. J. Andrews 2	1953=4; 1954=6; 1956=22; 1957=8; 1958=20; 1960=6; 1961=12; 1962=3; 1963=2; 1964=6; 1965=37; 1966=12; 1971=14; 1972=36; 1975=3; 1976=12; 1977=14; 1978=4; 1979=10; 1980=28; 1981=13; 1982=6; 1984=5; 1987=14; 1988=15; 1991=9; 1993=45; 1994=2; 1995=62; 1996=33; 1999=1; 2000=2; 2001=6; 2004=76; 2005=101	
H. J. Andrews 3	1953 = 41; 1954 = 10; 1956 = 22; 1958 = 26; 1959 = 2; 1961 = 8; 1962 = 13; 1963 = 2; 1965 = 25; 1966 = 30; 1972 = 50; 1976 = 15; 1977 = 14; 1979 = 14; 1980 = 28; 1981 = 13; 1982 = 6; 1985 = 5; 1988 = 29; 1991 = 9; 1993 = 45; 1994 = 2; 1995 = 62; 1996 = 216; 2000 = 3; 2001 = 6; 2004 = 76; 2005 = 9	
H. J. Andrews 6	1964=15; 1965=70; 1966=15; 1967=2; 1969=28; 1973=19; 1974=34; 1975=2; 1978=66; 1979=3; 1980=2; 1981=16; 1982=41; 1983=6; 1985=44; 1987=21; 1989=8; 1990=30; 1991=8; 1992=1; 1994=8; 1995=2; 1996=4; 1997=48; 1998=11; 1999=1; 2000=5; 2005=92	
H. J. Andrews 7	1964=39; 1965=34; 1967=2; 1973=10; 1974=6; 1975=13; 1976=2; 1977=9; 1978=37; 1980=34; 1982=43; 1986=6; 1987=112; 1995=1; 1996=3; 1997=57; 1998=8; 2000=1; 2004=1; 2005=92	
H. J. Andrews 8	1964=25; 1965=32; 1967=2; 1969=29; 1971=5; 1972=28; 1973=10; 1975=14; 1976=27; 1977=8; 1979=5; 1980=59; 1981=16; 1982=24; 1984=22; 1986=65; 1987=108; 1992=4; 1994=2; 1996=8; 1998=2; 2001=21; 2005=92	
H. J. Andrews 9	1969=67; 1970=89; 1971=75; 1972=14; 1974=14; 1975=14; 1976=77; 1977=31; 1978=8; 1979=26; 1980=17; 1982=19; 1985=8; 1986=3; 1987=39; 1988=4; 1990=4; 1991=17; 1993=13; 1994=15; 1995=7; 1996=2; 1997=4; 1999=2; 2000=14; 2001=2; 2005=92	
H. J. Andrews 10	1969=7; 1970=103; 1971=35; 1972=33; 1976=26; 1977=58; 1978=1; 1979=7; 1986=44; 1987=19; 1989=21; 1993=7; 1996=5; 1997=3; 1998=16; 2001=5; 2002=1; 2005=152	

Table 3-A (Continued)

WS	Years used despite missing or estimated flows	Omitted years
Coyote 1	1964 n=8	1965 n=77; 1966 n=92; 1967 n=272
Coyote 2		1966 n=92; 1967 n=272
Coyote 3	1964 n=4	1965 n=77; 1966 n=92; 1967 n=272
Coyote 4	1964 n=3	1965 n=77; 1966 n=92; 1967 n=272

At Coyote Creek, 1965, 1966, and 1967 were dropped from the flow-frequency calibration period because many streamflow values were missing and summertime readings from 2001 and 2002 were dropped due to gauge maintenance issues. In December 1964 large storms filled the Coyote 1, 3, and 4 weirs with sand and gravel which was not rectified until March 1965 [*Harr et al.*, 1979]. The 1967 water year is missing from digital streamflow records (Henshaw, e-mail, 2006) creating large gaps in the streamflow records for calendar years 1966 and 1967. The 1981 calendar year was dropped from the results because streamflow records ended in May. Maintenance issues interfered with summertime streamflow measurement during 2001 and 2002. Streamflow measurement equipment was modified leading to poor resolution early in the summer of 2001. In 2001 and 2002 sediment weirs were emptied late in the summer and did not refill for more than a month. None of the gages were measuring flow during this time and estimates were based on beginning and ending streamflow measurements and precipitation (C. Creel and D. Henshaw, personal communication, 2007). Since then, sediment measurements at Coyote Creek have been conducted early in the summer with streamflow recording lapses of only a couple of days.

Andrews WS 3 results for the 1964, 1965, 1966, and 1996 calendar years were used despite destruction of the gauge house by debris flows first in 1964 and then again in 1996 [*Henshaw and Creel*, 2005]. Estimates were generated from nearby WS 1 and 2. The original flume was not destroyed by these debris flows and after it was exhumed, flow measurements at the flume were used to increase the accuracy of the estimates [*Henshaw and Creel*, 2005].

3.3. Treated/Control Relationship

Daily average streamflow readings from treated and control WS were also analyzed following the methods used by *Jones and Post* [2004], which were an adaptation of methods of *Jones and Grant* [1996]. This study followed the methods described in *Jones and Post* [2004] except that (1) smoothing of percent change was accomplished with a weighted average rather than a simple average for reasons discussed below; and (2) the treatment/control ratio before forest harvest was used in absolute change calculations rather than assuming the ratio approximated one before logging. These changes will be addressed in detail after the formulas are explained.

This analysis was largely automated by writing a software application (Appendix A). The application compares two WS (treated and control), performs the necessary computations, and provides numerical output, which was used to produce the graphs included in this thesis.

For each set of WS the period of record was broken up into a pre-treatment calibration period and post-treatment analysis periods (Table 3-B). The pre-treatment calibration period began with the first year records were available in both the treated and control WS. In most cases the calibration period ended the year before logging began. Andrews 3 was an exception: the calibration period ended the year before road-building was conducted.

Table 3-B: Pre- and Post-treatment Periods.

Treated/Control	**Periods [calibration] treatment 1 (years after); treatment 2 (years after); …**
Coyote 1/4	[1963-1970] 1971-1976 (0-5); 1977-1981 (6-10); 2003-2006 [c] (32-35)
Coyote 2/4	[1963-1970] 1971-1976 (0-5); 1977-1981 (6-10); 2003-2006 [c] (32-35)
Coyote 3/4	[1963-1970] 1971-1976 (0-5); 1977-1981 (6-10); 2003-2006 [c] (32-35)
Andrews 1/2	[1953-1961] 1962-1966 (logging); 1967-1971 (1-5); 1972-1976 (6-10); 1977-1981 (11-15); 1982-1986 (16-20); 1987-1991 (21-25); 1992-1996 (26-30); 1997-2001 (31-35); 2002-2006 (36-39)
Andrews 3/2	[1952-1958] 1959-1962 (road study); 1963-1966[a] (0-4); 1967-1971 (5-9); 1972-1976 (10-14); 1977-1981 (15-19); 1982-1986 (20-24); 1987-1991 (25-29); 1992-1996 (30-34); 1997-2001 (35-39); 2002-2005 (40-43)
Andrews 6/8	[1964-1973] 1974-1979 (0-5); 1980-1984 (6-10); 1985-1989 (11-15); 1990-1994 (16-20); 1995-1999 (21-25); 2000-2006 (26-30)
Andrews 7/8	[1964-1973] 1974-1978 (0-4) [b]; 1979-1983 [b] (5-9); 1984-1987 [c] (10-13); 1995-1997 [d] (21-23); 1998-2001[d] (24-27); 2002-2006[d] (28-32)
Andrews 10/2	[1969-1974] 1975-1980 (0-5); 1981-1985 (6-10); 1986-1990 (11-15); 1991-1995 (16-20); 1996-2000 (21-25); 2001-2005 (26-30)

Post-treatment periods are 5 years long except when (a) adjusted to minimize length of analysis period influenced by debris flow; (b) shortened due to shelterwood completion cut; (c) shortened to accommodate gap in streamflow record or (d) shortened due to thinning.

Post-treatment analysis periods were five years long when possible and did not overlap. However, in some cases it was necessary to shorten analysis periods to fit them within the length of record or to fit an analysis period in between disturbance events (e.g. forest thinning or gaps in streamflow measurements). The first analysis period in Andrews WS 3 was shortened to four years for two reasons: it encapsulated times when the gauge house and stilling pond were being rebuilt following the 1964 debris flow and it lined WS 3 analysis periods up with WS 1 analysis periods. In Andrews WS 7 the gauges were shut off from 1988 through 1994 and thinning occurred in 2001. Periods were shortened both before and after these events to ensure the maximum number of years was included in each analysis period.

The treated/control ratio was calculated for each day of the water year. The ratio for each day was log-transformed and averaged over the pre-treatment calibration period and each post-treatment period. Absolute and relative changes were calculated on each day of the water year based on the change in the treated/control streamflow ratio between pre- and post-treatment time periods (Eqns. 1 to 8).

The daily natural-log transformed treatment/control ratio, “R”, between treatment WS "T" and control WS "C" for year “y” and day “d” is:

$$R_{yd} = \ln(T_{yd} / C_{yd}) \quad (1)$$

The average (or mean, “M”) natural-log transformed treatment/control ratio for day “d” of period “p” comprised of years “y” is:

$$M_{pd} = \text{Average}(R_{yd}) \text{ for all “y” in “p”} \quad (2)$$

The back-transformed, “B”, average natural-log transformed control flow for day “d” of period “p” comprised of years “y” is:

$$B_{pd} = e^{(\text{Average}(\ln(C_{yd})))} \quad (3)$$

The predicted, or expected, “E”, treatment flow for day “d” of post-treatment period “p” in the absence of disturbance is:

$$E_{pd} = B_{pd} * e^{M_{0d}} \quad (4)$$

The percent difference, “P”, on day “d” between post-treatment period “p” and the pre-treatment calibration periods is:

$$P_{pd} = 100*(e^{(M_{pd} - M_{0d})} - 1) \quad (5)$$

The 15-day smoothed percent change, "S", centered on day "d" between post-treatment period "p" and the pre-treatment calibration periods is:

$$S_{pd} = (\sum P_{pD} * E_{pD}) / \sum(E_{pD}) \text{ over } D = d\text{-}7, d\text{-}6, \ldots, d, \ldots, d + 6, , d{+}7 \qquad (7)$$

The absolute difference, "A," between post-treatment period "p" and the pre-treatment calibration period is:

$$A_d = E_{pd} * \exp(M_{0d}) / 100 \qquad (8)$$

where variables are defined in Table 3-C and indexes in Table 3-D. The notation used here is slightly different than that used in *Jones and Post* [2004].

Table 3-C: Variables

Variable	Meaning
T	Treated WS flow in mm/day for day "d" in water year "y".
C	Control WS flow in mm/day for day "d" in water year "y".
A	Absolute change in streamflow for day "d" in analysis period "p".
P	Percent change in streamflow for day "d" in analysis period "p".
B	Back-transformed average of log transformed control flows.
R	Log-transformed ratio between the treated and control WS for day "d" in water year "y".
M	Mean log-transformed ratio between the treated and control WS for day "d" in analysis period "p".
N	Number of years of record in the control WS
S	Smoothed Percent change
E	Predicted (expected) treated flow in the absence of logging based on control period relationship.

Table 3-D: Indexes

Index	Meaning
P	Refers to an analysis period. 0 refers to the calibration period. Numbers greater than zero referred to post-treatment periods.
D	Day of the water year.
Y	Water year.

A more detailed description of these methods is available in *Jones and Post* [2004]. This study used the approach of *Jones and Post* [2004] with two modifications. The first modification was the use of a weighted average to smooth percent changes rather than a simple average. In *Jones and Post* [2004] percent changes were smoothed using a simple average over a 15-day moving window. However, when percent change values are averaged it is necessary to consider whether or not the original groups were identical in size. If so, a simple average can be used. If not then a weighted average must be used; in this case values should be weighted by the expected flow in the absence of forest treatment.

Table 3-E shows a hypothetical example where a weighted average yields the correct result but a simple average does not. In this example streamflow response to precipitation in a clear-cut basin is accelerated one day following logging but there has been no change in net outflow from the basin over a three-day window. This is erroneously labeled a 16.6% increase in flow

over the three-day window using a simple average. However, a weighted average correctly shows there has been no increase in flow over the three-day window. This thesis uses weighted averages rather than simple averages for the reason described above and so there are minor deviations from published results utilizing this method.

Table 3-E: Pitfalls of simple averages

<table>
<tr><td colspan="2">Calibration</td><td colspan="2">Comparison</td><td></td><td></td><td></td></tr>
<tr><td>Control</td><td>Treated</td><td>Control</td><td>Treated</td><td>% Change</td><td>Average Change</td><td>Weighted Average Change</td></tr>
<tr><td>1</td><td>1</td><td>1</td><td>2</td><td>+100%</td><td rowspan="3">(100-50+0)
3
=+16.6%</td><td rowspan="3">(1*100+2*-50+1*0)
(1+2+1)
= 0 %</td></tr>
<tr><td>2</td><td>2</td><td>2</td><td>1</td><td>-50%</td></tr>
<tr><td>1</td><td>1</td><td>1</td><td>1</td><td>0%</td></tr>
</table>

The second modification of the method to *Jones and Post* [2004] was the inclusion of the original treatment/control ratio in the absolute change formula. *Jones and Post* did not include this term because there was parity between flows in the control and treated basins in their study and this term reduced to approximately one (Jones, personal communication, 2007). In this study it became necessary to explicitly include the original treatment/control ratio in the absolute change equation to correctly calculate streamflow changes in Coyote WS 2 where pre-treatment stream flows were not approximately equal. Addition of the original treatment/control ratio to the absolute change formula improves accuracy and changes absolute value slightly. Thus the results presented here vary slightly from those published by *Jones and Post* [2004].

This method calculates the relative and absolute change of the geometric mean of streamflow due to the use of log transformation. Because changes in the arithmetic mean would be easier to interpret, the method proposed by *Jones and Post* [2004] was tested without log transformation of the treatment/control ratio. Estimated changes were very similar for both methods (Table 3-F), but results for the untranformed data were not resistant to outliers. Thus, the method proposed by *Jones and Post* [2004] was used as published with treatment/control ratios log transformed and results are presented as changes in geometric means as these statistics are more resistant to outliers.

Table 3-F: Seasonal % change with and without log transformation of the treatment/control ratio.

Summer Streamflow Change				
		1971 -1975 (0-4)	1976 -1981 (5-10)	2001 – 2006 (30-35)
Log	%	88.8	32.6	-56.1
	mm	7.2	2.6	-2.8
No Log	%	94.7	33.6	-54.1
	mm	8.3	3.4	-2.8

Significance of streamflow changes was assessed by creating 90% confidence intervals around the estimate of each change, based on the pooled estimate of standard error for the difference in means and a t value for n-2 degrees of freedom where n is the number of years in the pre-treatment and post-treatment analysis periods combined. *Jones and Post* [2004] used the standard error of daily flows at the control WS over the period of record as a reference for defining meaningful changes in flow. Neither of these confidence intervals account for autocorrelation among successive years. For clarity these confidence intervals are omitted from the figures, but in almost all cases the confidence intervals are less conservative than ±25% change. Moreover, analysis of synthetic data sets showed noise less than ±25% when the timing of flows was changed both with and without a 20% increase in streamflow. Therefore, changes in relative streamflow greater than 25% were deemed practically significant.

3.4. Run-off Ratio

To test whether the Coyote control WS are using more water in the early 2000s compared to the pre-treatment and early post-treatment periods, runoff ratios were calculated for all periods. Linear regression models were fitted to predict runoff at control WS (e.g. Coyote 4) from precipitation (at Toketee Falls) for the pre-treatment and early post-treatment periods (1966-81) and the recent period (2002-2006). Andrews watersheds run-off changes were previously documented [*Andréassian et al.*, 2003] so this analysis was only applied to Coyote 4.

4. RESULTS

4.1. Magnitude and Seasonal Timing of Streamflow Deficits

Lowflows (flows below the 5th percentile threshold) occur between June and September in the pre-treatment period. Less than 15% of annual precipitation falls during these months, which have high evapotranspirative demand and mean daily temperatures ranging from 15 to 20 degrees C. Average daily discharge and low flow thresholds summary graphs are shown in the site description for both Coyote (Figure 2-2) and Andrews control watersheds (Figure 2-4, Figure 2-5, and Figure 2-6).

All forest harvest treatments that replaced mature or old forest with young (30-50-year-old) forest were associated with summer streamflow deficits ranging from -20 to -80% (Figure 4.1). Streamflow deficits occurred in July, August, and September, and streamflow deficits at high elevations (Andrews 6) emerged later in the season than those at low elevation or further south (Andrews 1, Coyote 1, 2, and 3) (Figure 4.1). In clear-cut and shelterwood-cut WS, streamflow deficits emerged over a six-week period from the last week of June through the first week in August and continued into September (Figure 4-1). Depending on the WS, streamflow deficits disappeared over a two-month window between the first week of October and the first week of December. In contrast, water deficits in overstory thinned and patch-cut WS were discontinuous and spread through spring, summer, and fall. Streamflow deficits in the overstory thinned WS 1 at Coyote Creek occurred in the last two weeks of April and the last week of August. Streamflow deficits in one patch-cut WS (Coyote 2) occurred the last week of August, disappeared, and reappeared for the last week of September and the first three weeks of October. Streamflow deficits in another patch-cut WS (Andrews 3) occurred in July and the first two weeks of August.

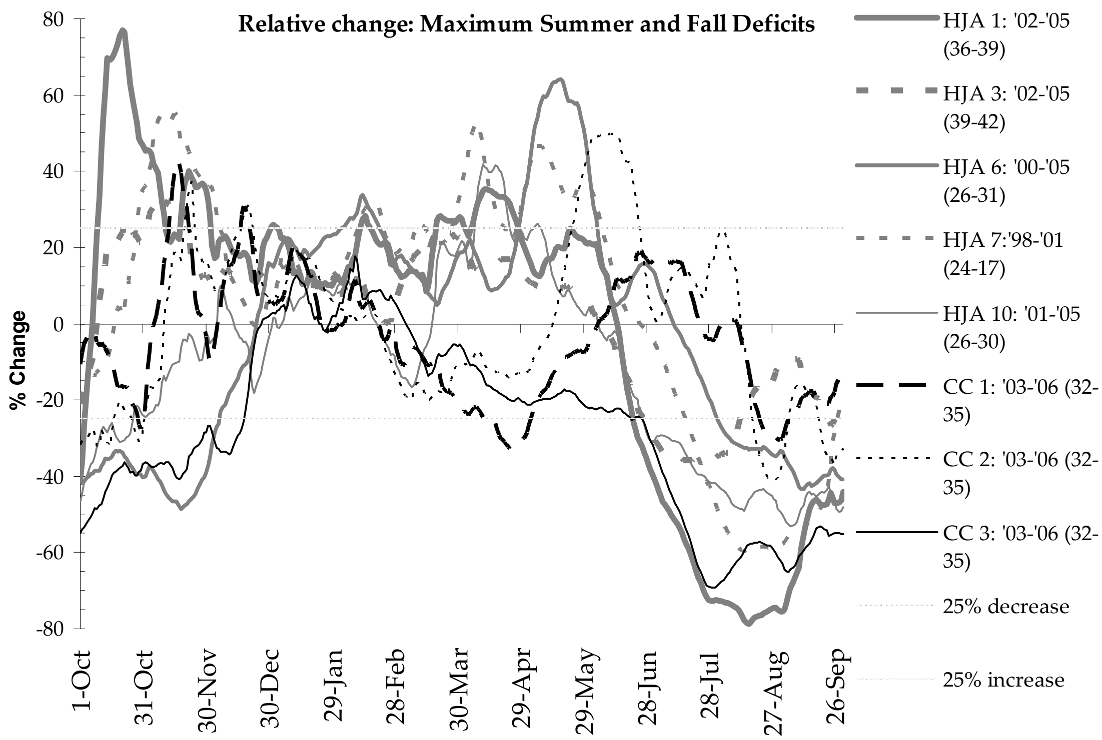


Figure 4-1: Periods of maximum summer and fall streamflow deficit for each WS. Maximum relative deficit occurs in the most recent analysis period for every WS except WS 7 where thinning occurred in late 2001. Clear cuts are represented with solid lines and other treatments are represented with dashed lines. Andrews 1: 2002 – 2005 (36 – 39 yrs after clearcutting); Andrews 3: 2002 – 2005 (39-42 yrs after large patch cutting); Andrews 6: 2000 – 2005 (26-31 yrs after clearcutting); Andrews 7: 1998-2001 (24-27 yrs after the shelterwood preparation cut); Andrews 10: 2001 – 2005 (26-30 yrs after clearcutting); Coyote 1: 2003-2006 (32-35 yrs after overstory thin); Coyote 2: 2003-2006 (31-35 yrs after small patch cutting);Coyote 3: 2003-2006 (32-35 yrs after clearcutting).

The maximum streamflow deficit for every treatment occurred in the most recent period, when young forests ranged in age from 25 to 40 yrs (Figure 4.1). Streamflow deficits developed in June and were most intense in late August and early September (Figure 4.1).

4.2. Intersite Differences in Flow Thresholds

Comparison of the control-WS unit-area flows at each percentile yield some interesting patterns (Table 4-A). The first percentile flows are approximately of the same magnitude for all small forested control basins. However, the first percentile flow of Lookout Creek is an order of magnitude larger than first percentile flows in other Andrews' watersheds. At the H. J. Andrews the first, fifth, 10th, 15th and 20th percentile reference flows in WS two and nine are almost twice that of WS eight.

While the Coyote Creek reference flow is similar to those of the H. J. Andrews at the first percentile, reference flows at Coyote Creek do not increase as quickly as the H. J. Andrews reference flows. At the 45th percentile the Coyote Creek reference flow is approximately 1/5 the size of the 45th percentile flows at the H. J. Andrews. The 99th percentile the reference flows at Coyote Creek are only 50% of those at the H. J. Andrews.

Table 4-A: Percentile flows (mm/day) for control WS (1969 to 1980). Deviation from expected surfaces were generated by (1) calculating the annual flow frequency at percentile thresholds from the fifth to the 95th percentile (number of days with < the percentile flow); (2) calculating the expected number of days at a percentile "p" as 365*p/100; (3) subtracting the expected number of days from the frequency to arrive at a deviation from expected; and (4) graphing the results in DPlot™.

Percentile	**HJA 2**	**HJA 8**	**HJA 9**	**Lookout Ck.**	**CC 4**
1st	0.072	0.022	0.051	0.325	0.039
5th	0.128	0.055	0.094	0.392	0.048
10th	0.168	0.091	0.162	0.509	0.060
15th	0.213	0.128	0.254	0.587	0.066
20th	0.263	0.177	0.313	0.666	0.076
25th	0.322	0.249	0.366	0.784	0.088
30th	0.418	0.345	0.431	0.979	0.110
35th	0.539	0.475	0.536	1.254	0.138
40th	0.698	0.654	0.636	1.709	0.187
45th	0.947	0.961	0.766	2.294	0.264
50th	1.238	1.332	0.996	2.860	0.356
55th	1.658	1.782	1.249	3.409	0.483
60th	2.139	2.313	1.632	3.958	0.658
65th	2.739	2.761	2.131	4.702	0.881
70th	3.246	3.401	2.902	5.369	1.188
75th	3.983	4.170	3.782	6.191	1.592
80th	4.979	5.182	4.814	7.257	2.132
85th	6.687	6.828	6.508	8.543	3.003
90th	9.755	9.458	9.087	10.893	4.282
95th	16.770	14.462	16.132	16.300	6.941
99th	30.400	28.666	33.202	34.264	17.421

4.3. Coyote Creek Differences in Flow Thresholds

Coyote 2 had smaller percentile flows than other watersheds below the 65th percentile (Table 4-B). This difference was greater than one order of magnitude. Percentile flows above the 65th percentile were quite similar.

Table 4-B: Coyote percentile flows from 1964-1970. Deviation from expected surfaces were generated by (1) calculating the annual flow frequency below the fifth to the 95th percentile threshold in the treated and control basins; (2) calculating flow frequency between thresholds by subtracting the frequency at the next lowest level from the current level; (3) deviations were calculated by subtracting the control flow frequency at a given level from the treatment frequency at the same level; and (4) graphing the result in DPlot™.

Percentile	Coyote 1	Coyote 2	Coyote 3	Coyote 4
1st	0.014	0.001	0.030	0.035
5th	0.020	0.002	0.039	0.041
10th	0.024	0.004	0.045	0.048
15th	0.032	0.006	0.050	0.055
20th	0.042	0.009	0.060	0.061
25th	0.053	0.014	0.074	0.067
30th	0.072	0.025	0.090	0.083
35th	0.097	0.040	0.121	0.101
40th	0.136	0.071	0.168	0.134
45th	0.177	0.116	0.224	0.179
50th	0.238	0.190	0.312	0.250
55th	0.319	0.282	0.401	0.341
60th	0.430	0.394	0.504	0.433
65th	0.581	0.581	0.702	0.682
70th	0.757	0.892	0.984	1.000
75th	1.109	1.371	1.487	1.568
80th	1.654	1.950	2.014	2.226
85th	2.392	2.602	2.685	3.041
90th	3.361	3.792	3.827	4.404
95th	5.245	5.762	5.999	7.041
99th	11.163	13.246	13.436	16.214

4.4. Andrews Differences in Flow Thresholds

Percentile flows in Andrews WS 1, 2, and 3 show similar magnitudes and trends (Table 4-C). Percentile flows in Andrews 6, 7, and 8 indicate WS 7 behaves differently than WS 6 and 8. WS 7 has higher thresholds between the first and 20th percentile but lower thresholds between the 25th and 99th percentile (Table 4-D). Andrews 9, 10, and 2 show similar percentile thresholds for the 1969–1974 calibration period with Andrews 2 presented a second time due to the different calibration period (Table 4-E).

Table 4-C: Andrews 1, 2, and 3 percentile thresholds from 1953–1959. Deviation from expected surfaces were generated by (1) calculating the annual flow frequency below the fifth to the 95th percentile threshold in the treated and control basins; (2) calculating flow frequency between thresholds by subtracting the frequency at the next lowest level from the current level; (3) deviations were calculated by subtracting the control flow frequency at a given level from the treatment frequency at the same level; and (4) graphing the result in DPlot™.

Percentile	Andrews 1	Andrews 2	Andrews 3
1st	0.098	0.115	0.174
5th	0.134	0.213	0.264
10th	0.168	0.273	0.333
15th	0.196	0.340	0.401
20th	0.230	0.396	0.482
25th	0.299	0.484	0.605
30th	0.427	0.646	0.807
35th	0.571	0.830	0.986
40th	0.724	1.020	1.181
45th	0.915	1.271	1.387
50th	1.254	1.684	1.741
55th	1.656	2.076	2.135
60th	2.073	2.544	2.571
65th	2.536	3.062	3.052
70th	3.109	3.818	3.631
75th	3.908	4.701	4.409
80th	5.017	6.010	5.437
85th	6.928	7.662	6.853
90th	9.930	11.346	9.822
95th	16.265	17.704	14.529
99th	38.740	34.843	31.329

Table 4-D: Andrews 6, 7, and 8 percentile thresholds from 1964–1973. Deviation from expected surfaces were generated by (1) calculating the annual flow frequency below the fifth to the 95th percentile threshold in the treated and control basins; (2) calculating flow frequency between thresholds by subtracting the frequency at the next lowest level from the current level; (3) deviations were calculated by subtracting the control flow frequency at a given level from the treatment frequency at the same level; and (4) graphing the result in DPlot™.

Percentile	Andrews 6	Andrews 7	Andrews 8
1st	0.035	0.087	0.027
5th	0.066	0.114	0.049
10th	0.099	0.142	0.086
15th	0.161	0.165	0.133
20th	0.225	0.199	0.201
25th	0.302	0.246	0.271
30th	0.416	0.316	0.383
35th	0.548	0.413	0.512
40th	0.808	0.557	0.726
45th	1.161	0.777	1.089
50th	1.530	1.051	1.448
55th	2.002	1.449	1.837
60th	2.491	1.745	2.328
65th	3.068	2.136	2.715
70th	3.760	2.608	3.303
75th	4.654	3.206	4.141
80th	5.818	4.027	5.113
85th	7.565	5.206	6.707
90th	10.212	7.107	9.535
95th	16.296	10.859	14.200
99th	35.552	24.892	30.863

Table 4-E: Andrews 2, 9, and 10 percentile thresholds from 1969–1974. Deviation from expected surfaces were generated by (1) calculating the annual flow frequency below the fifth to the 95th percentile threshold in the treated and control basins; (2) calculating flow frequency between thresholds by subtracting the frequency at the next lowest level from the current level; (3) deviations were calculated by subtracting the control flow frequency at a given level from the treatment frequency at the same level; and (4) graphing the result in DPlot™.

Percentile	Andrews 2	Andrews 9	Andrews 10
1st	0.069	0.042	0.065
5th	0.109	0.061	0.101
10th	0.166	0.094	0.126
15th	0.220	0.120	0.162
20th	0.297	0.180	0.206
25th	0.380	0.246	0.281
30th	0.495	0.314	0.388
35th	0.640	0.389	0.504
40th	0.864	0.534	0.691
45th	1.177	0.692	0.917
50th	1.561	0.968	1.257
55th	1.970	1.330	1.737
60th	2.533	1.902	2.197
65th	3.175	2.653	2.834
70th	3.876	3.565	3.739
75th	4.600	4.408	4.805
80th	5.878	5.855	6.055
85th	7.738	7.792	8.292
90th	12.095	11.010	12.226
95th	18.406	17.682	20.907
99th	33.336	33.977	41.695

4.5. Effect of Treatment on Streamflow Deficits and Lowflow Frequency

100% clearcutting and shelterwood (initial removal of 60% of the overstory, followed by removal of remaining overstory 10 years later) treatments produced greater relative streamflow deficits and more persistent streamflow deficits than 30% patch cutting and 50% overstory thinning (Figure 4-1). Observed maximum daily deficits ranged from -48% (Andrews 6) to -79% (Andrews 1) in clear-cut WS, from -36% (Andrews 3) to -41% (Coyote 2) in patch-cut WS, and were –33% in the overstory thinned WS (Coyote Creek 1). Relative streamflow deficits in the shelterwood treatment (Andrews 7) were similar to those in 100% clearcut WS (Andrews 1, Andrews 6, Andrews 10, Coyote 3) (Figure 4-1).

The smallest and least persistent streamflow deficits occurred in the 25 to 30% patch-cut and 50% overstory thinned WS (Figure 4-1). The maximum relative streamflow deficits associated with patch cutting were -35% (in July) in the 25% patch-cut Andrews WS 3 and -40% (in late August) in the 30% patch-cut Coyote WS 2. The maximum relative streamflow deficit associated with 50% overstory thinning was -30% (in August) at Coyote WS 1.

The clear-cut and shelterwood-cut WS experienced the greatest increase in frequency of low flows (5^{th} percentile flows) (Figure 4-2 to Figure 4-6). Low-flow frequency changes in the patch-cut and overstory thinned WS were less noticeable (Figure 4-7 to Figure 4-9). Low-flow days became more frequent at 14 to 26 years after harvest in 100% clearcut WS (Andrews WS1, WS6, and WS10, and Coyote WS 3), and 35 to 41 years after harvest in patch-cut WS (Andrews WS 3). However, as of 2005 when regenerating forests were 34 years old, lowflows had not become much more frequent in overstory thinned and patchcut WS at Coyote Creek (Coyote 1: Figure 4-8 and Coyote 2: Figure 4-9).

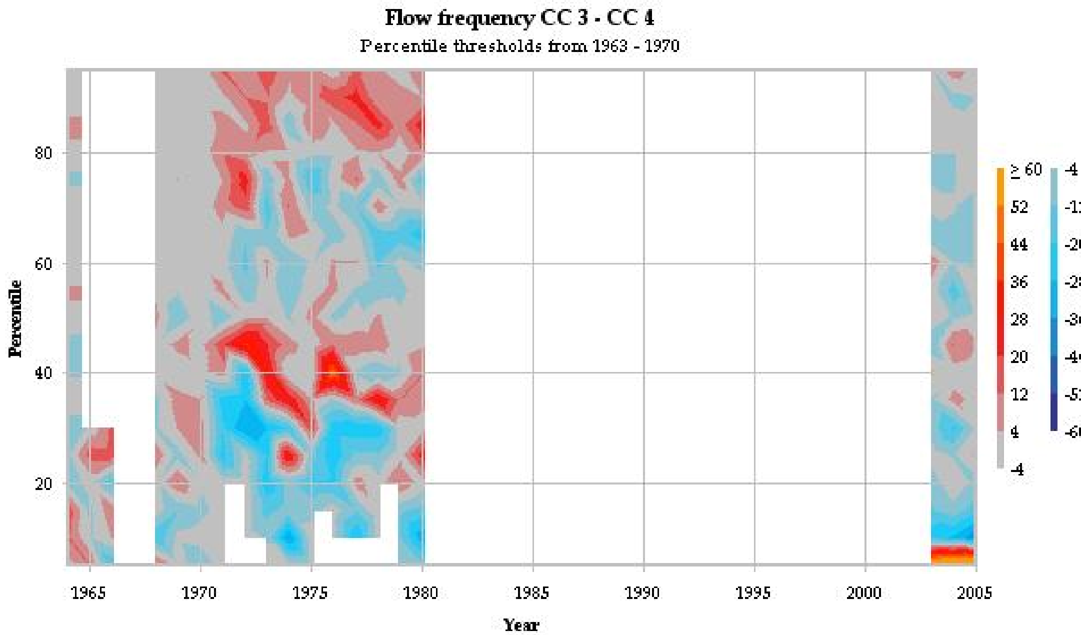


Figure 4-2: Coyote 3-4: Difference in flow frequency between Coyote 3 (treated) and Coyote 4 (control) by calendar year. Color indicates the number of days of increased (blue) or decreased flow (red) for a given flow percentile in a given year in the treated WS compared to the control WS. WS 3 was 100% clearcut in 1971. Zero to 10 years after logging (1971-1981) decreased evapotranspiration increased streamflow showing up as increased 35th to 45th percentile flow frequency (red) and decreased 15th to 30th percentile flow frequency (blue) in Coyote 3 (100% clearcut) vs. Coyote 4 (control). Increased lowflow frequency in the treated WS 32 to 35 years after logging relative to the control watershed is shown by the orange shading in the lower RH Corner. Low flows lasted 88 days longer in the treated WS than the control in 2005. White areas indicate missing data, including periods of flow >30th percentile in 1964 and 1965 and periods of flow < 20th percentile between 1971 and 1979.

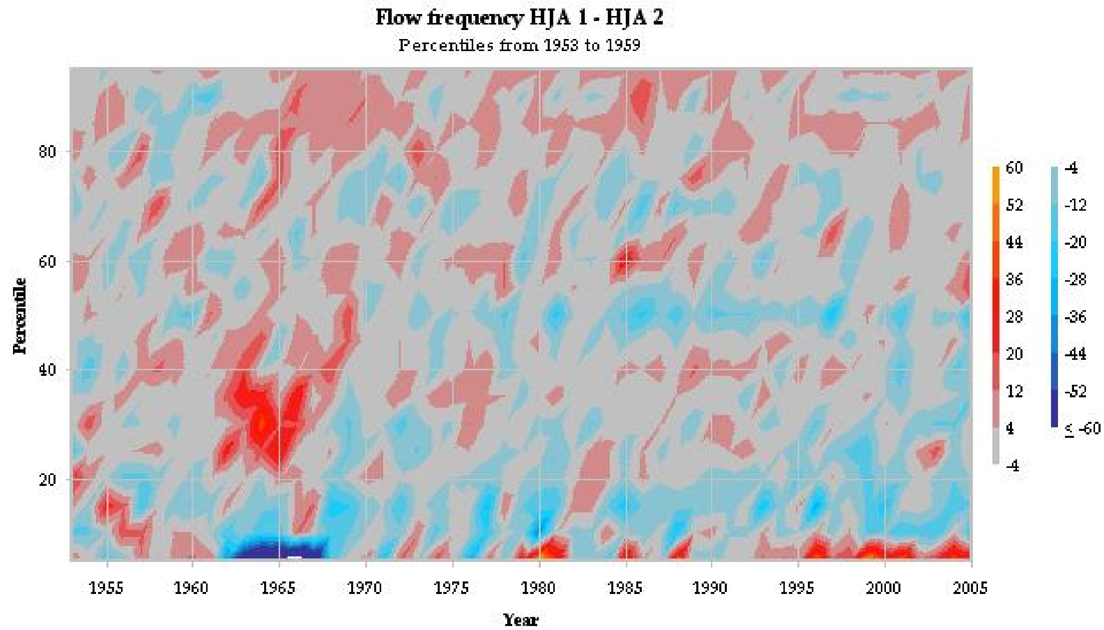


Figure 4-3: Andrews 1-2: Difference in flow frequency between Andrews 1 (treated) and Andrews 2 (control) by calendar year. Color indicates the number of days of increased (blue) or decreased flow (red) for a given flow percentile in a given year in the treated WS compared to the control WS. Andrews 1 was 100% clearcut over 4 years: 1962–1966. During and immediately after logging (1963–1967) decreased evapotranspiration increased streamflow showing up as increased 35th to 45th percentile flow frequency (red) and decreased 15th to 30th percentile flow frequency (blue). Drier conditions associated with vegetation regrowth are shown by the increased incidence and intensity of low flows (red to orange shading along the bottom edge starting in 1980s). The summer of 1974 flows below the fifth percentile threshold lasted 52 days longer in the clearcut WS than in the control, 39 days in 1980, 56 days in 1988 and 69 days in 2002.

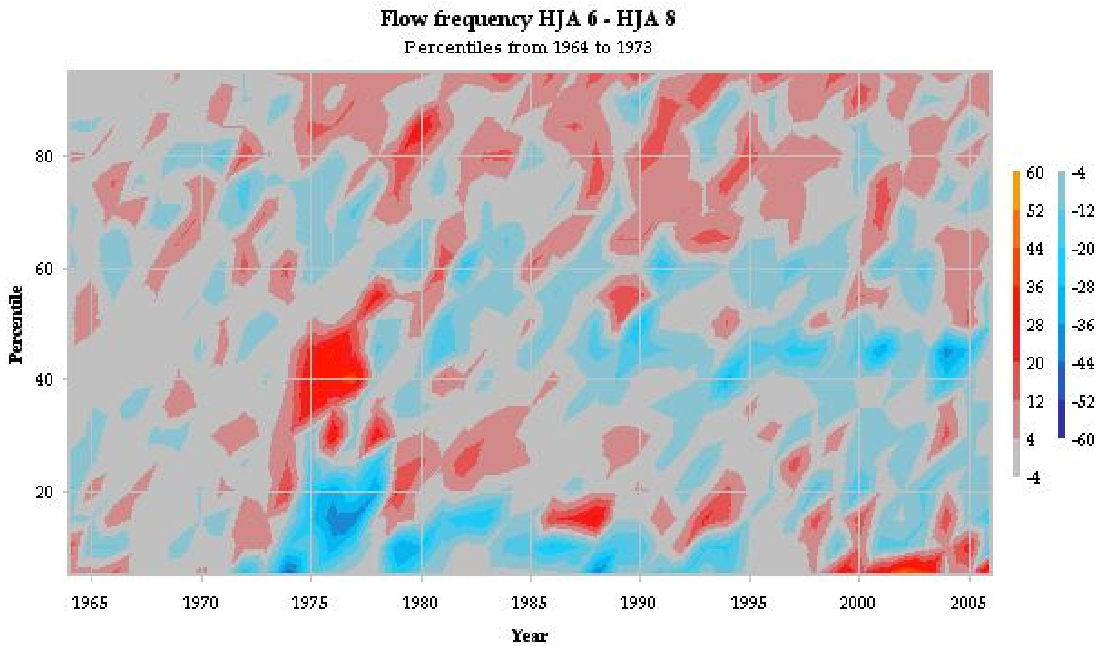


Figure 4-4: Andrews 6-8: Difference in flow frequency between Andrews 6 (treated) and Andrews 8 (control) by calendar year. Color indicates the number of days of increased (blue) or decreased flow (red) for a given flow percentile in a given year in the treated WS compared to the control WS. Andrews 6 was 100% clearcut in 1974. Zero to 10 years after logging (1974-1984) decreased evapotranspiration increased streamflow showing up as increased 35th to 45th percentile flow frequency (red) and decreased fifth to 20th percentile flow frequency (blue). Twenty-five to 31 years after logging (1999–2006) increased evapotranspiration reduced streamflow which shows up as increased lowflows (fifth percentile flow). The summer of 2001 low flows lasted 37 days longer in the treated than the control WS and low flows lasted 56 days longer in 2006!

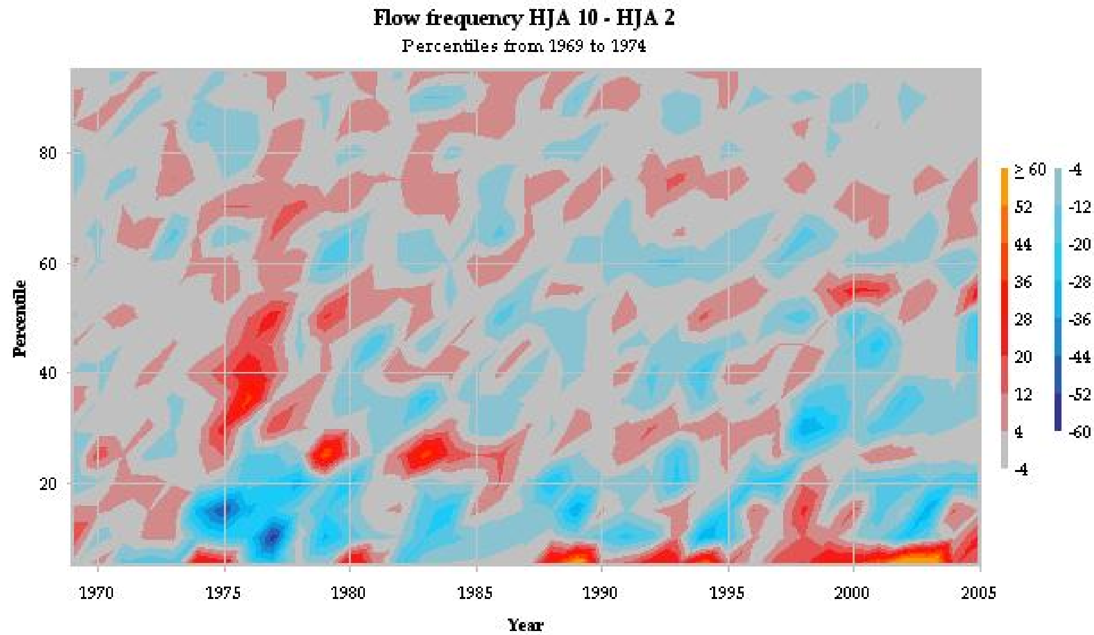


Figure 4-5: Andrews 10-2: Difference in flow frequency between Andrews 10 (treated) and Andrews 2 (control) by calendar year. Color indicates the number of days of increased (blue) or decreased flow (red) for a given flow percentile in a given year in the treated WS compared to the control WS. Andrews 10 was 100% clearcut in 1975. Zero to 5 years after logging (1975 to 1980) decreased evapotranspiration increased streamflow showing up as increased 25th to 40th percentile flow frequency (red) in Andrews 10 (100% clearcut) vs. Andrews 2 (control). Increased lowflow frequency in the treated WS 17 to 30 years after logging relative to the control watershed is shown by the red and orange shading in the lower RH Corner. The summer of 2002 fifth percentile flows lasted 69 days longer in the treated WS than in the control WS.

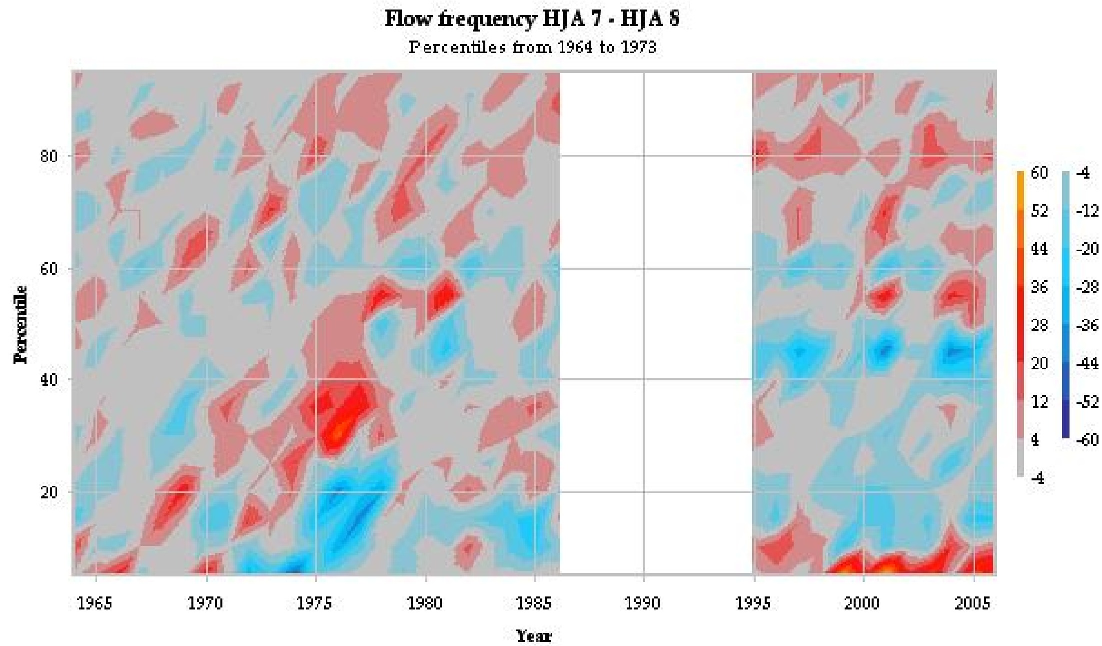


Figure 4-6: Andrews 7-8: Difference in flow frequency between Andrews 7 (treated) and Andrews 8 (control) by calendar year. Color indicates the number of days of increased (blue) or decreased flow (red) for a given flow percentile in a given year in the treated WS compared to the control WS. Andrews 7 was 60% cut in 1974 and the remaining overstory was cut in 1984. Zero to 12 years after logging (1974-1986) decreased evapotranspiration increased streamflow showing up as increased 30th to 45th percentile flow frequency (red) and decreased fifth to 25th percentile flow frequency (blue) in Andrews 7 (shelterwood 60%/100%) vs. Andrews 8 (control). The orange shading in the lower RH Corner indicate 21 to 32 years after logging, low flows are more frequent than in the calibration period. Thinning in 2001 may have slightly reduced low-flow frequency as seen by the lack of orange after 2001. Low-flow days (below the fifth percentile threshold) lasted 64 days longer than expected in 2001, but only 37 days longer than expected in 2006! White areas indicate missing data.

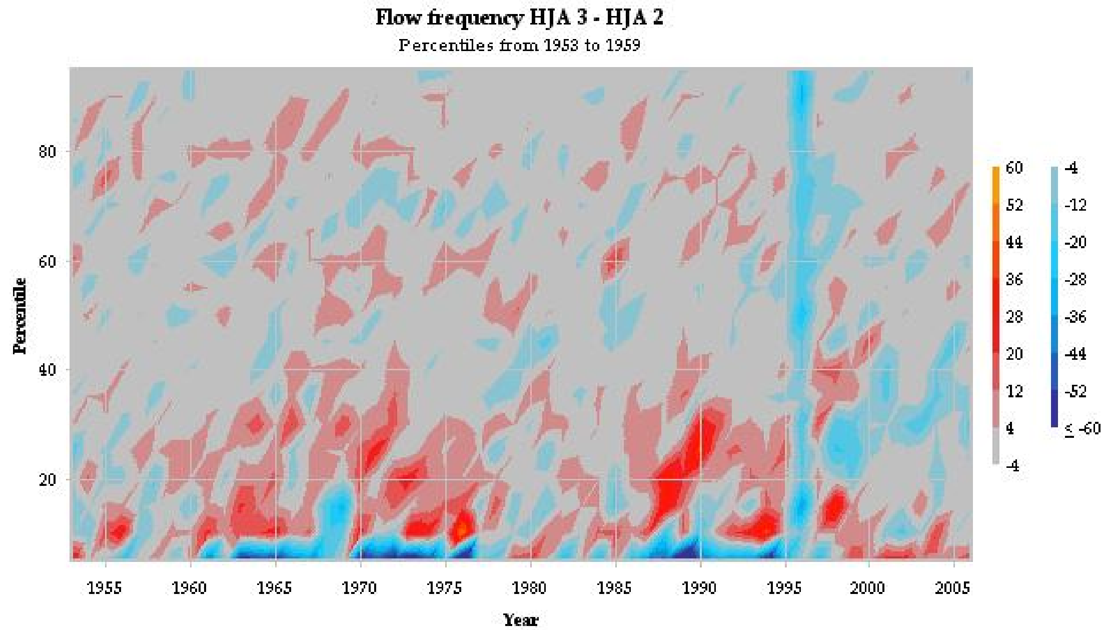


Figure 4-7: Andrews 3-2: Difference in flow frequency between Andrews 3 (treated) and Andrews 2 (control) by calendar year. Color indicates the number of days of increased (blue) or decreased flow (red) for a given flow percentile in a given year in the treated WS compared to the control WS. Roads were constructed in 1959 and patch clearcutting occurred in 1963. Zero to 14 years after logging (1963–1977) decreased evapotranspiration increased streamflow showing up as increased 15th to 35th percentile flow frequency (red) and decreased lowflow frequency (blue) in Andrews 3 (100% clearcut) vs. Andrews 2 (control). Red shading along the bottom RH edge of the plot starting in 1999 indicates that lowflows (below the fifth percentile threshold) have become more frequent relative to the control. The blue stripe in 1996 is an artifact of flow estimation after the February 1996 debris flow. During the summer of 2002 lowflows occurred 56 more days in the treated WS than the control.

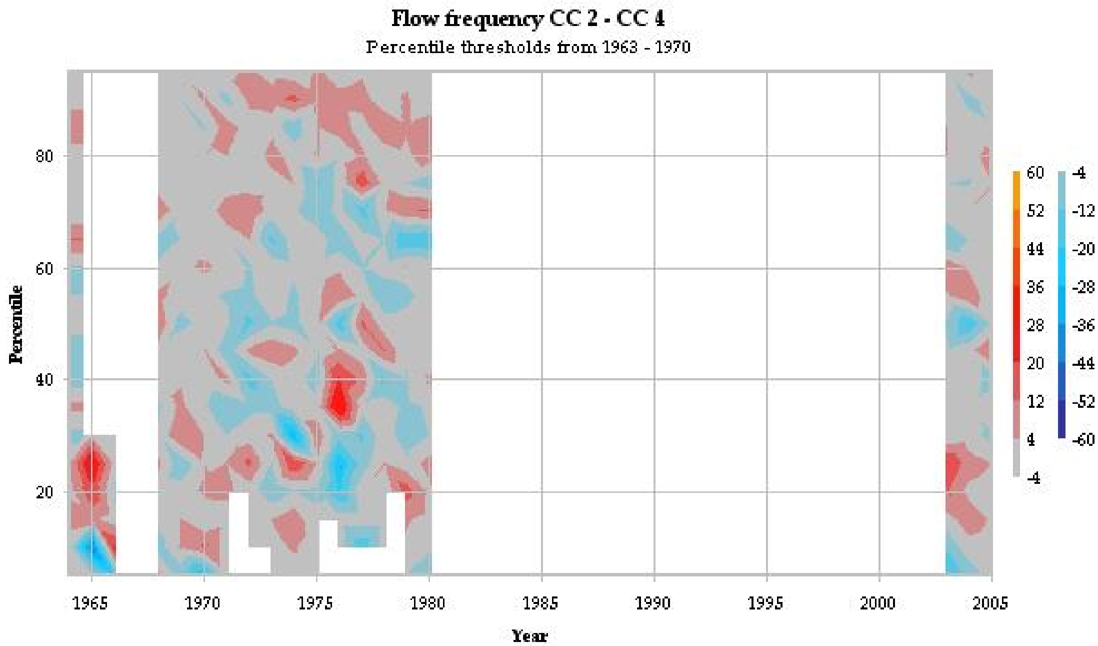


Figure 4-8: Coyote 2-4: Difference in flow frequency between Coyote 2 (treated) and Coyote 4 (control) by calendar year. Color indicates the number of days of increased (blue) or decreased flow (red) for a given flow percentile in a given year in the treated WS compared to the control WS. Patch cutting occurred in 1971. From 1975 through 1978 an increase in flow frequency between the 25th and 45th percentile thresholds indicates wetter conditions in the treated WS. Flow frequency distributions from 1971 to 1975 and from 2003 to 2005 are similar to those observed in the calibration period. 1964 and 1965 stream flow measurements were incomplete and were not included in the threshold calculations. White areas indicate missing data, including periods of flow >30th percentile in 1964 and 1965 and periods of flow < 20th percentile between 1971 and 1979.

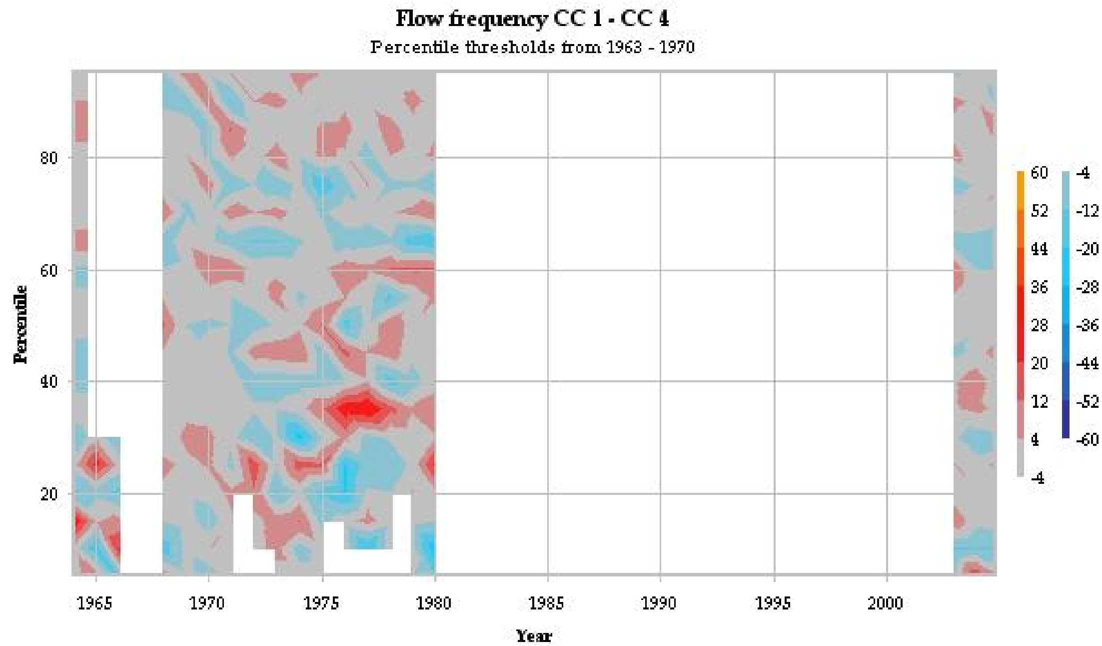


Figure 4-9: Coyote 1-4: Difference in flow frequency between Coyote 1 (treated) and Coyote 4 (control) by calendar year. Color indicates the number of days of increased (blue) or decreased flow (red) for a given flow percentile in a given year in the treated WS compared to the control WS. Overstory thinning occurred in 1971. Reduced evapotranspiration increased streamflow leading to less frequent flows below the 20th percentile flow threshold and more frequent flows around the 35th percentile flow threshold from 1975 to 1977. Increased lowflow frequency in the treated WS 32 to 35 years after logging relative to the control watershed is shown by the red shading in the lower RH Corner. Lowflows lasted 21 days longer in the streated WS than the control WS in 2004; a difference twice as large as that which was seen before forest cutting. White areas indicate missing data, including periods of flow >30th percentile in 1964 and 1965 and periods of flow < 20th percentile between 1971 and 1979.

4.6. <u>Interannual Timing of Streamflow Deficits</u>

The largest streamflow deficits in each WS occurred in the most recent analysis period with only one exception: the thin in Andrews WS 7 (Table 4-F). The summertime deficit in Andrews WS 7 declined from 35 to 32% following

12% basal area thinning. Andrews 1 and 3 show a trend towards wetter conditions from 1982 until 1991. Andrews 1 and 7 are the only two WS to exhibit a summertime deficit in the first 10 years.

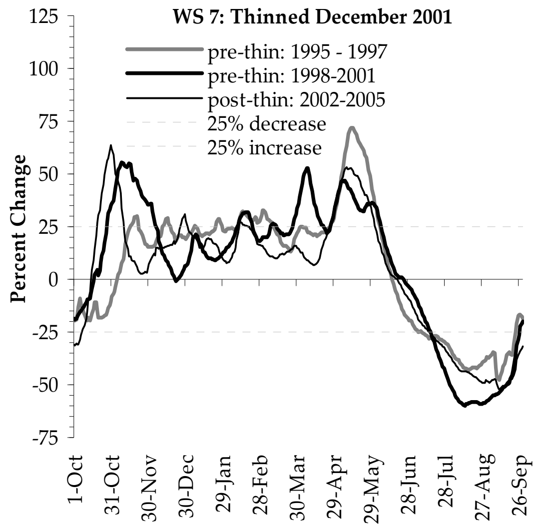
Table 4-F: Relative streamflow change (%) in summer flows (June–September) at treated versus control WS by analysis period. Numbers are the average relative change in daily flows averaged from June 1 – September 30 for the post-treatment period. Actual post-treatment periods are shown in Table 3-B.

		Years since forest cutting								
100% clearcut		**0-5**	**6-10**	**11-15**	**16-20**	**21-55**	**26-30**	**31-35**	**36-40**	**41-45**
Coyote 3/4 [d]		88.8	32.6					-56.1		
Andrews 1/2	213.7 [b]	64.6	-13.7	-29.4	-13.4	-10	-19.8	-45.8	-61.3	
Andrews 6/8		78.6	24.8	34.5	42.2	-4.5	-15.4			
Andrews 10/2		45.1	22.9	-19.6	-22.8	-31	-40.4			
Andrews 7/8[a]				10.8	-31.4	-35.2	-32.5			
25 to 30% patch cut										
Coyote 2/4 [d]		77.1	91.5					1.9		
Andrews 3/2 [e]	1.2[c]	66.0	50.4	46.8	-5.2	12.7	62.0	38.9	-17.6	-27.0
50% overstory removal										
Coyote 1/4 [d]		37	56.8					1.3		
Andrews 7/8 [a]		25	-10.8							

(a) Andrews 7 was not 100% harvested until year 10. Results are dated with respect to tree establishment following initial cutting. (b) Andrews 1 results during harvest (1962-1966). (c) Andrews 3 road study period. (d) Coyote is 32-35 years after instead of 31-35 years after. (e) Andrews 3 periods are one year earlier than expected (0-4, 5-9, etc.) lining up analysis periods with nearby Andrews 1 and encapsulating the estimated flows from the 1964–66 in the smallest possible analysis period (a debris flow occurred in December 1964 destroying the permanent gauge house).

4.7. Effect of Understory Thinning on Summer Streamflow Deficit

An understory thinning (12% basal area removed) of the then 15 to 25-yr-old forest plantation in Andrews 7 in 2001 slightly reduced summertime streamflow deficits compared to the pre-thinning levels. Maximum pre-thinning deficits observed in early August were reduced from -60% to -43% (Figure 4-10) Fifth-percentile lowflows became somewhat less frequent for a few years in 2002 to 2005 relative to before 2002 (Figure 4-6), but overall the streamflow deficits in the pre-thinning and post-thinning periods were not very different (-35 and –32%, Table 4-F). However, thinning did not exacerbate the summer streamflow deficits, whereas summer streamflow deficits intensified in an adjacent, similar-aged, unthinned young forest plantation over the 2000-2005 period (Figure 4-10 a, b). The frequency of lowflows increased in the adjacent unthinned forest plantation over this period, whereas it did not increase at the thinned WS (Figure 4-4, Figure 4-6). The persistence of summer streamflow deficits (number of days of deficit per season) was not affected by the understory thin (Figure 4-10).



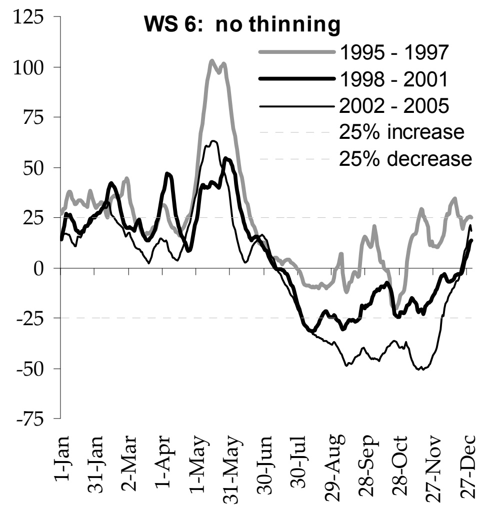


Figure 4-10: Relative change in daily streamflow (%) in (a) Andrews 7 (60% thin 1975, 40% overstory removal 1985, 12% thin of young plantation 2001) relative to Andrews 8 (mature and old-growth forest) before and after thinning in December 2001, and (b) Andrews 6 (100% clearcut 1975) relative to Andrews 8. Post-treatment periods are: 1995-1997, 21-23 years after 60% overstory removal in Andrews 7 and 100% clearcutting in Andrews 6 and 11-13 years after removal of the remaining mature overstory in Andrews 7; 1998-2001, 24-27 years after these treatments; and 2002-2005, 28-31 years after these treatments and 1-4 years after 12% basal area thinning of the young forest plantation in Andrews 7.

4.8. <u>Effects of Latitude, Elevation (Snowpack), and Forest Regeneration on Streamflow Deficits</u>

Streamflow deficits in April and May occurred only at the Coyote Creek WS; no springtime deficits occurred at any Andrews WS. Deficits persisted into November in two clearcut WS: Coyote 3 and Andrews 6. Fifth-percentile lowflows became slightly more frequent in 2000-2005 in Andrews 3 (25% patchcut) than in Coyote 2 (30% patchcut).

Over the period of study, clear-cut WS with seasonal snow packs (Andrews 6, 7) or snow packs at their higher elevations (Andrews 1) developed seasonal deficits later in the season than Andrews 10, which experiences transient snow (Figure 4-11). Andrews 7 and 10 experienced the most intense deficits 21 to 30 years after logging. Thirty to 35 years after logging Coyote 3 experienced a more intense and persistent deficit than Andrews 1. Seasonal flow deficits developed and ended most rapidly (over just a couple of weeks) in Andrews 1.

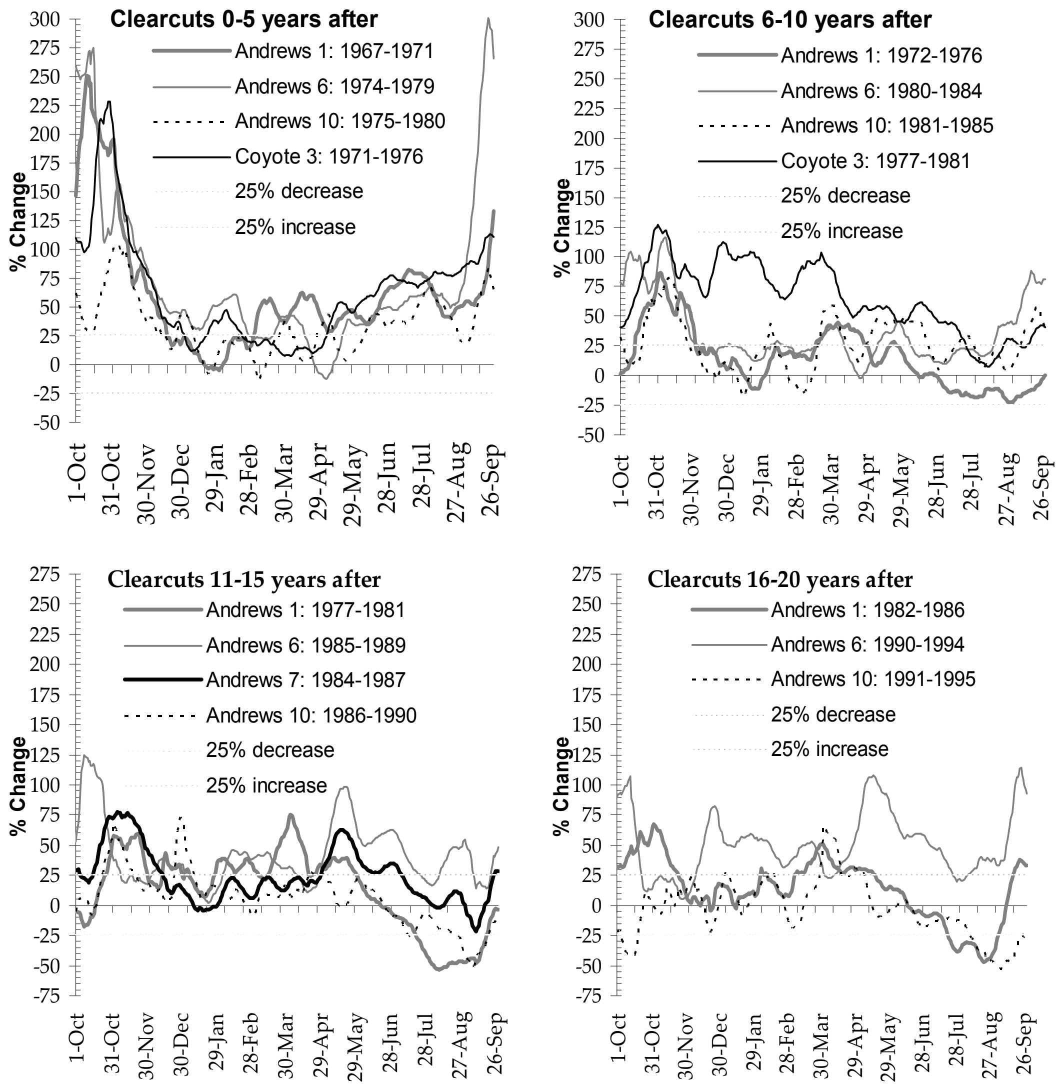


Figure 4-11: Relative change in daily streamflow by day of water year in 100% clear-cut WS, compared for 5-year post-treatment periods. WS only appear in time periods where streamflow measurements were obtained and 100% of old-growth trees had been removed. Thus, Andrews 7 does not appear for years zero - ten because it was only 60% harvested at this time. Andrews 7 time periods do not precisely agree with titles because of gaps in the streamflow record and the timing of forest cutting.

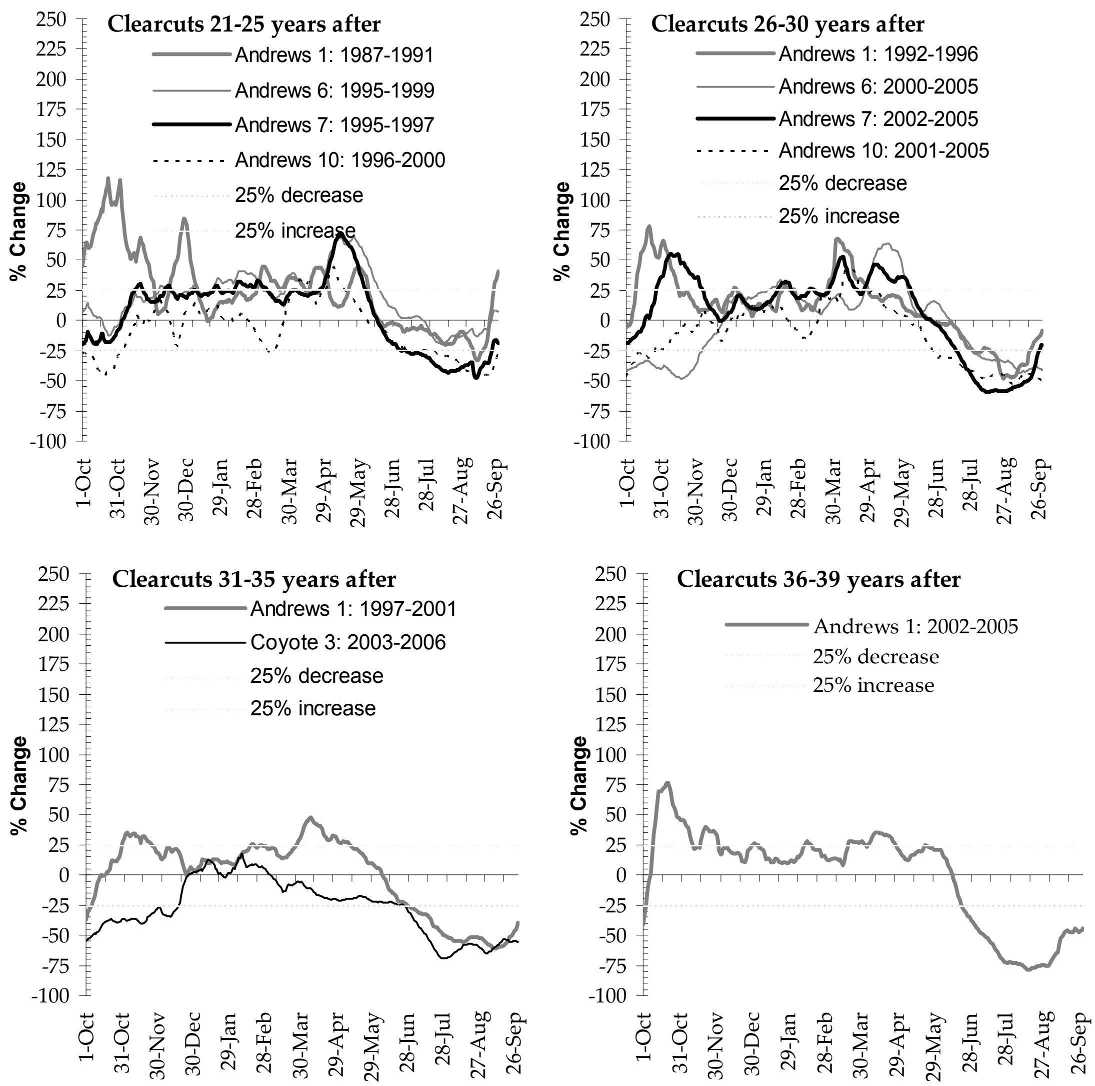


Figure 4-11 (Continued)

4.8.1. Detailed changes in daily streamflow over the water year: 100% clearcut WS

The first five years after cutting all clearcut WS experienced large relative increases in fall and moderate increases throughout the rest of the water year

(Figure 4-11). Large relative increases also occurred during late summer at Andrews 6.

Six to 10 years after forest cutting, streamflow remained elevated in late summer and fall at all WS except Andrews 1, (where small, but insignificant summer streamflow deficits occurred (Figure 4-1). Daily streamflow surpluses were smaller in years six to ten compared to years zero to five after logging in all WS except Coyote 3 where wintertime streamflow surpluses were higher in year six to ten than in years zero to five after logging (Figure 4-11).

By 11 to 15 years after forest cutting, most streamflow surpluses had almost disappeared and significant summertime streamflow deficits emerged in Andrews 1 and 10 (Figure 4-11). However, streamflow surpluses persisted in late April at Andrews 1, 6, and 7, but not at Andrews 10.

Sixteen to 20 years after forest harvest, Andrews 1 and 10 continued to experience streamflow deficits in late summer and short periods of streamflow surplus between October and May (Figure 4-11). Summer streamflow deficits were larger in Andrews 10 than in Andrews 1. However, Andrews 6 continued to experience streamflow surplus throughout most of the water year especially in early May (Figure 4-11).

By 21 to 25 years after forest harvest, summer streamflow deficits emerged in all 100% cut WS but the deficits were significant only in Andrews 1, 7, and 10 (Figure 4-11). Relative streamflow increases in October disappeared from most WS during this time period except in Andrews 1. Minor streamflow increases in the winter months persisted in most WS except Andrews 10 in this post-treatment period. As in previous post-treatment periods, the highest elevation WS (Andrews 6 and 7) experienced a relative streamflow surplus at the end of April lasting into the beginning of May, and the summer streamflow deficit developed later in the season at Andrews 6 than at other WS.

Twenty-six to thirty years after forest cutting minor streamflow increases occurred during the winter and significant summertime streamflow deficits in all 100% cut WS. Maximum deficits occurred in late July, August, and early September. Deficits in Andrews 6 last until early December but deficits in other basins disappear by mid-October. Relative surpluses are seen at the high elevations sites at the end of April and beginning of May. Deficits begin sooner at low-elevation Andrews 10 than other Andrews WS because Andrews 10 develops only transient snowpacks while other Andrews WS develop snowpacks which persist for weeks to months.

Thirty-one to thirty-five years after logging maximum streamflow deficits in Andrews 1 and Coyote 3 are quite similar. However, streamflow deficits build more gradually at Coyote Creek and linger much longer after summer; significant deficits are observed into mid-December at Coyote Creek! The relatively rapid onset of streamflow deficits in Andrews 1 may be the result of a "step increase" of transpiration following red alder (*Alnus ruba Bong.*) leaf out; red alder dominates the Andrews 1 riparian corridor. Coyote 3 does not show significant winter increases while Andrews 1 does.

Combining results from 26 to 30 and 31 to 35 years post-harvest allows comparison of summer deficits associated with forest regrowth in clearcuts at Coyote Creek and H. J. Andrews. The streamflow deficit at Coyote 4 begins at the start of June and it predates the deficits in all basins at the H. J. Andrews. The Coyote 4 streamflow deficit ends in late November postdating all Andrews WS. In WS 1 at the H. J. Andrews the deficit appears in mid-to-late June and lasts until the beginning of October. In WS 6 the deficit appears in August and lasts until the beginning of October. In WS 10 the deficit appears in late June and lasts until the end of October. Thus, the Coyote streamflow deficit starts earlier in the water year and lasts longer into the next water year as compared to results from the H. J. Andrews.

4.8.2. Detailed changes in daily streamflow over the water year: 25 to 30% patchcut WS

Patch cutting results are variable and inconsistent at Andrews 3 and Coyote 2. Andrews 3 results zero to four years after patch cutting are difficult to interpret because the gauging station was destroyed by a debris flow in December 1964 and not reestablished until January 1966. Thus, almost one third of the streamflow measurements are estimates during this period. Five to nine years after cutting in Andrews 3 and six to 10 years after cutting in Coyote 2 summer and fall streamflow increases at both locations. Increases are more persistent at Coyote than at the Andrews. Summertime and fall streamflow deficits emerged at Coyote Creek 32 to 35 years after forest cutting but streamflow surpluses were seen in Andrews. The largest streamflow surpluses in Andrews 3 are seen 26 to 30 years after cutting. The largest relative change in other WS occur either zero to five or six to ten years after forest cutting. WS 3 developed summertime streamflow deficits 36 years after cutting.

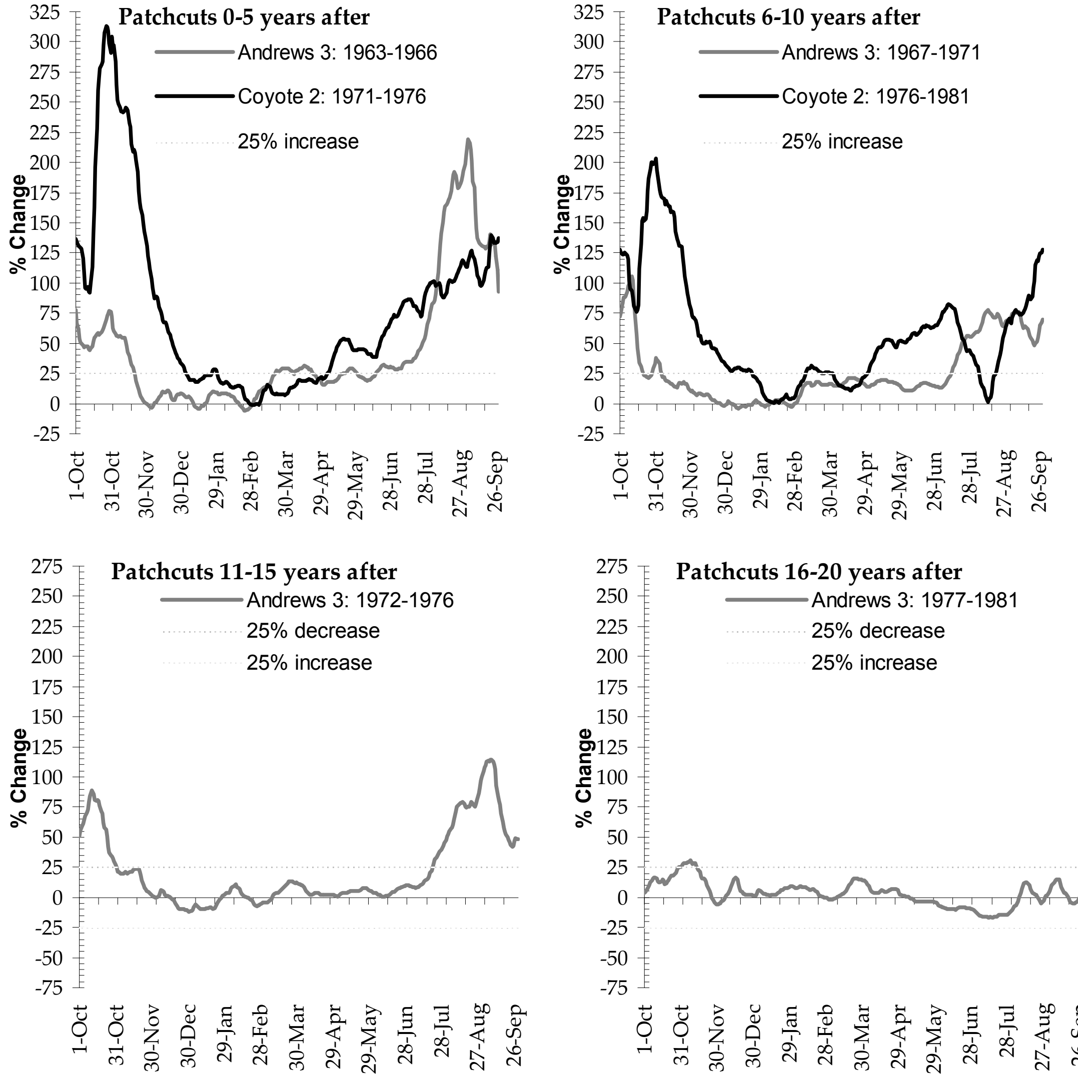


Figure 4-12: Relative streamflow change in patch-cut WS.

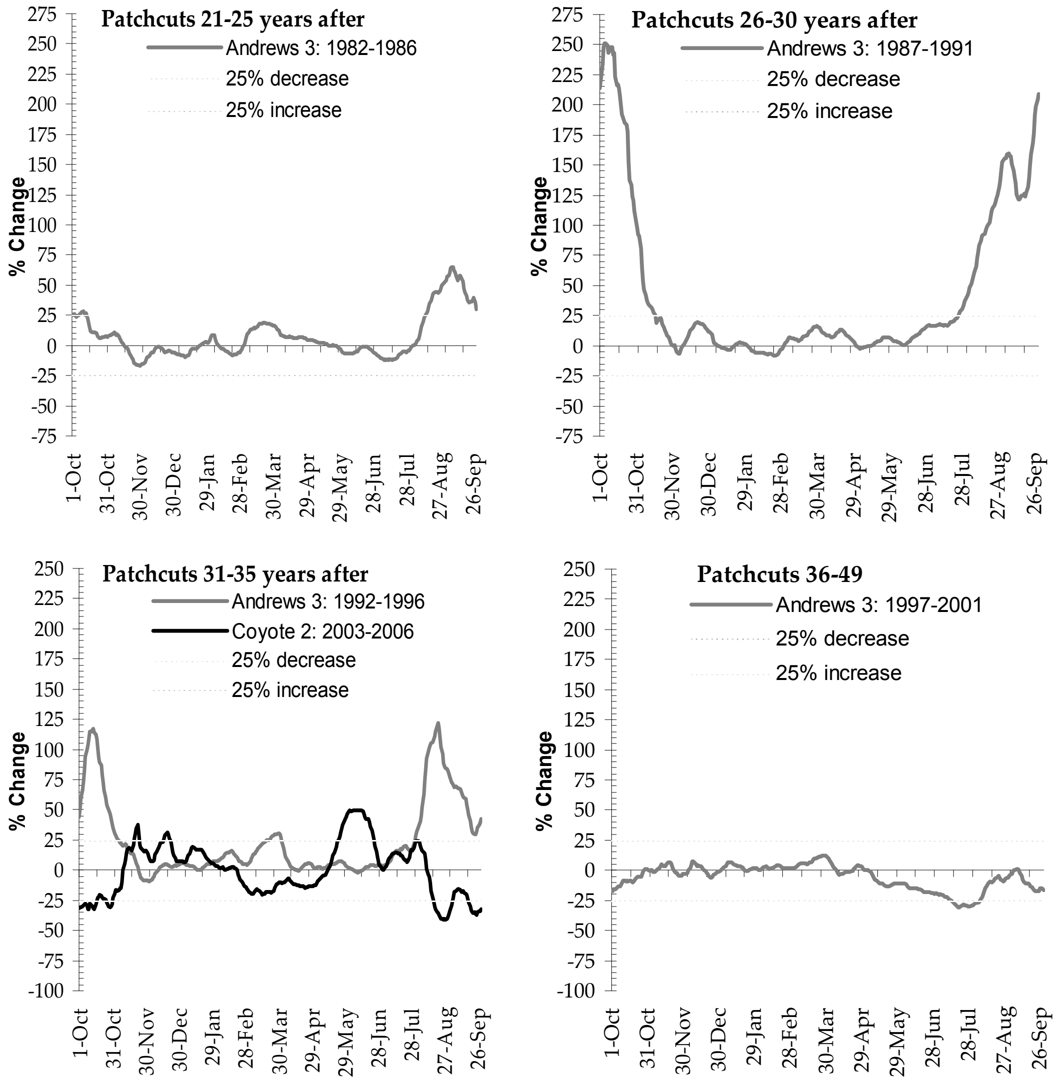


Figure 4-12 (Continued)

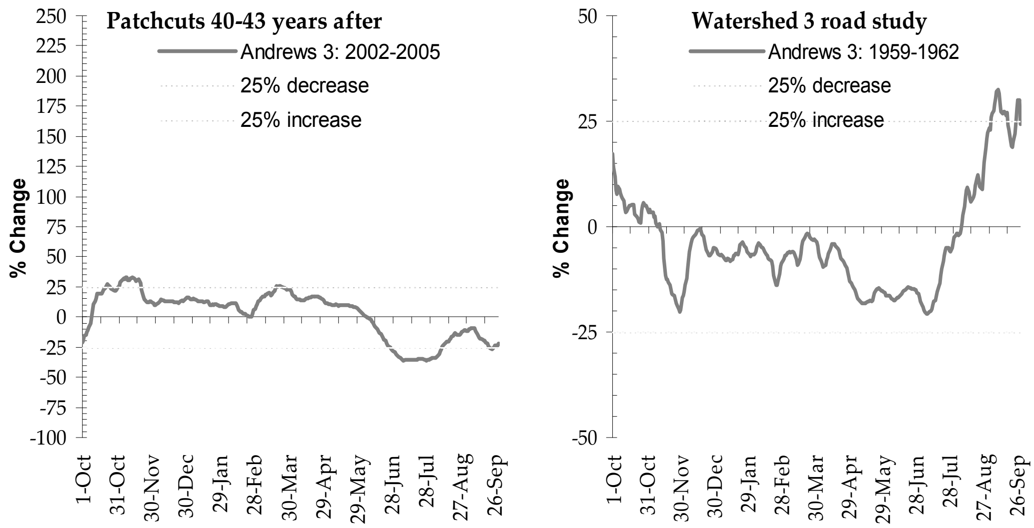


Figure 4-12 (Continued)

The relative streamflow decreases associated with the large patch cuts in WS 3 at the H. J. Andrews occurred much earlier in the water year than other relative streamflow decreases. Similar streamflow decreases occurred during the road study from 1959 through 1962 (Figure 4-12).

4.8.3. Detailed changes in daily streamflow over the water year: overstory thinned WS

Overstory thinning can only be compared in the first ten years after cutting because additional cutting was performed at Andrews 7 leading to 100% original overstory removal. Streamflow changes were different between Coyote 1 and Andrews 7. Similar spring time streamflow changes but different summertime streamflow changes occurred the first ten years after logging

(Figure 4-13). Spring time flow declined in both WS. Twenty-eight percent summertime deficits occurred in WS 7 five to nine years after forest cutting at Andrews 7 while summertime streamflow surpluses remained at Coyote 1 six to ten years after logging. This result is surprising given the similarity in treatment (60% basal area removed at Andrews 7 vs. 50% basal area removed at Coyote 1). Later results compared 100% second-growth forest in Andrews 7 to 50% original old-growth forest by basal area with second-growth understory at Coyote 1. Summertime streamflow deficits emerged in Andrews 7 but not Coyote 1.

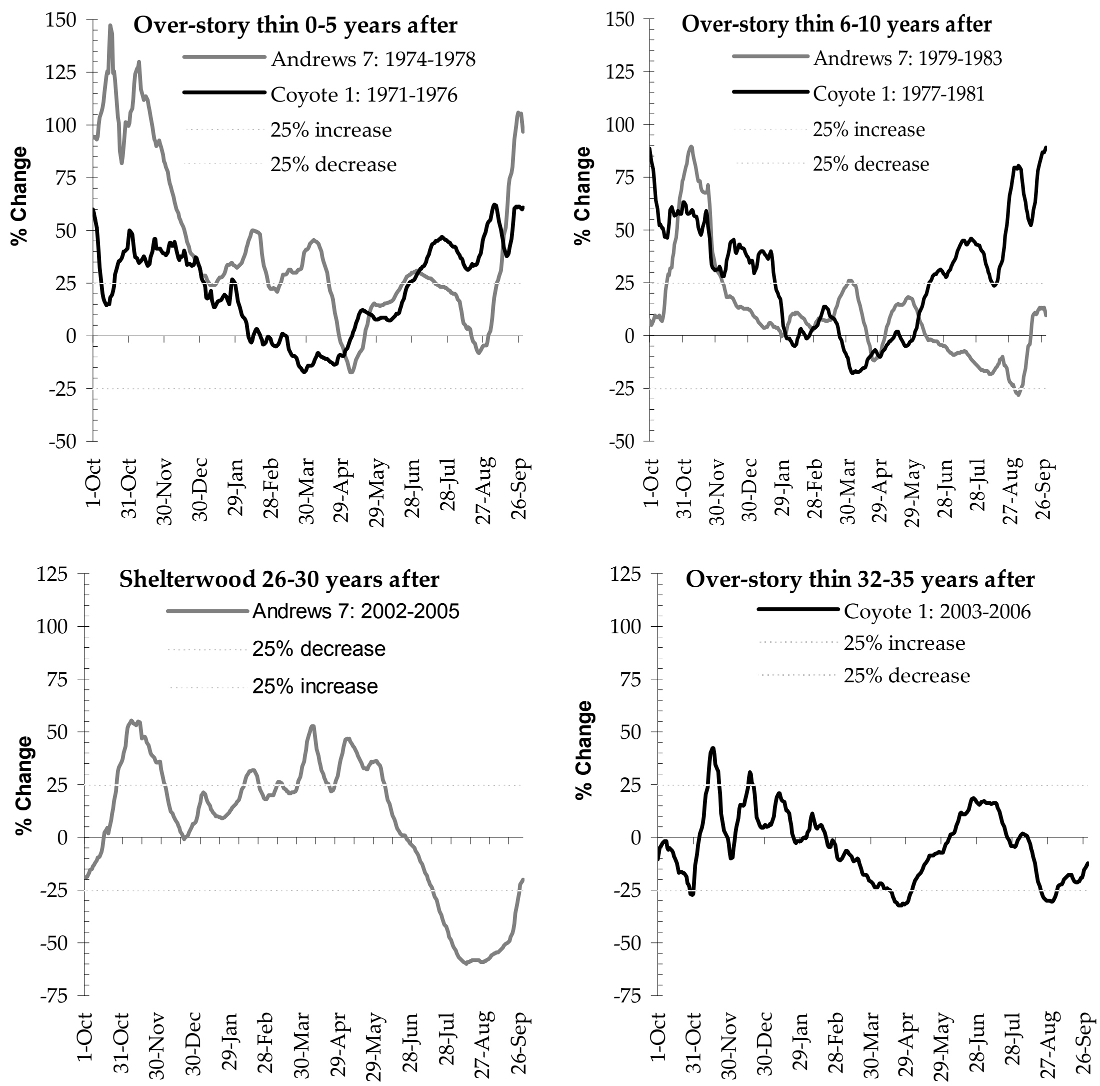


Figure 4-13: Relative streamflow change following 50% basal area removal at Coyote Creek (black lines) and 60%/100% basal area removal H. J. Andrews (grey lines). Andrews 7 was in an overstory thinned condition for the first nine years after cutting. The 10th year after initial cutting the remaining 40% of original timber was cut. Coyote 1 was originally intended to be a shelterwood treatment but the completion cut never occurred.

4.9. Effects Of Interannual Climate Variability and Forest Succession on Flow Frequency at Control WS

Flow frequencies changed over time at control WS (Andrews 2, 8, 9, and Coyote 4) in response to (1) interannual climate variability, (2) forest succession, and (3) changes in streamflow gauging. Low flows frequency increases at all control WS during years with lower than average precipitation at Andrews 2 and 8 as indicated by concentration of red and yellow values at intermediate and low flow percentiles during these years (mid 1960s, 1977, 1986/7, 1993/4, and 2001/2) (Figure 4-15 and Figure 4-16). Low flows are less frequent during wetter than average years as indicated by blue values for most flow percentiles during these years (mid 1950s, 1972, 1974, 1996, and 1999) (Figure 4-15 and Figure 4-16). In addition, frequency distributions at Andrews 9 contain many more days of low flow detected during periods when V-notch plate was installed, but expected climate fluctuations are missing when the V-notch was not installed (Figure 4-14 and Figure 4-17). Coyote Creek 4 shows reduced flow 32-24 years after logging (Figure 4-18). Plots from control WS 2 (Figure 4-15) and 8 (Figure 4-16) include climatic variation consistent with nearby precipitation records, but Andrews 9 (Figure 4-17) or Coyote 4 (Figure 4-18) do not.

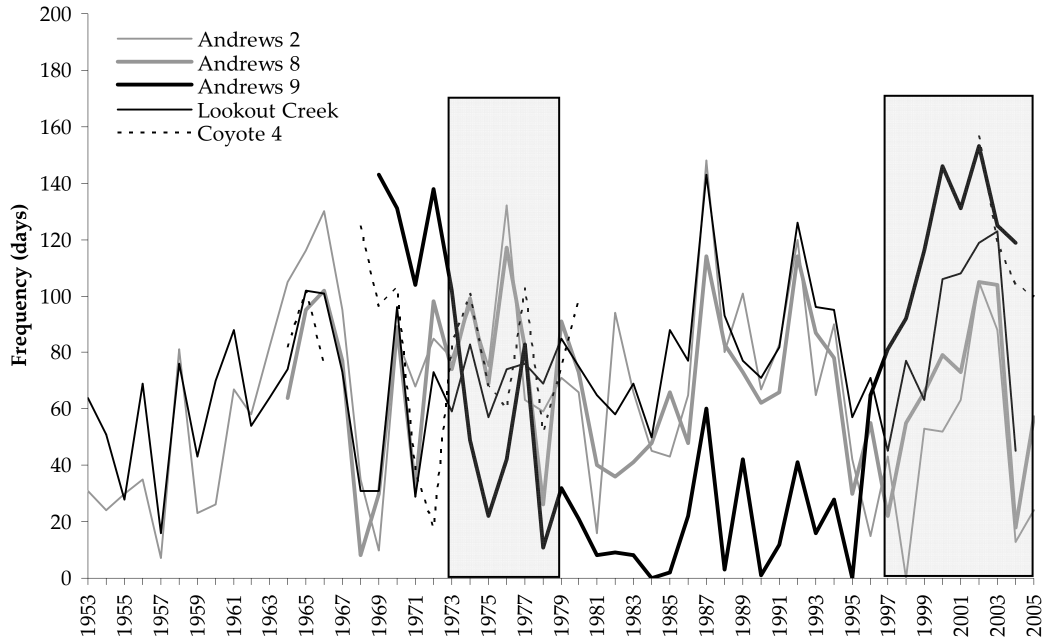


Figure 4-14: Annual frequency of flows below the 20 percentile threshold in control WS at the Andrews (Andrews 2, 8 and 9), Lookout Creek and Coyote 4. Grey boxes outline time periods where a V-notch plate was in use at HJA 9 during summers (June to October). In 1973 the original H. Flume at Andrews 9 was replaced with a trapezoidal flume. A V-notch plate was installed each summer from August 1973 through October 1979 and a different V-notch plate was installed each summer from 1997 through the present. V-notch weirs were installed at Andrews 2 each summer from June to October starting in 1999. The H. Flume at Andrews 8 was replaced with a trapezoidal flume in 1987; V-notch plates were installed at Andrews 8 each summer from June to October starting in 1997. Percentiles are shown in Table 4-A.

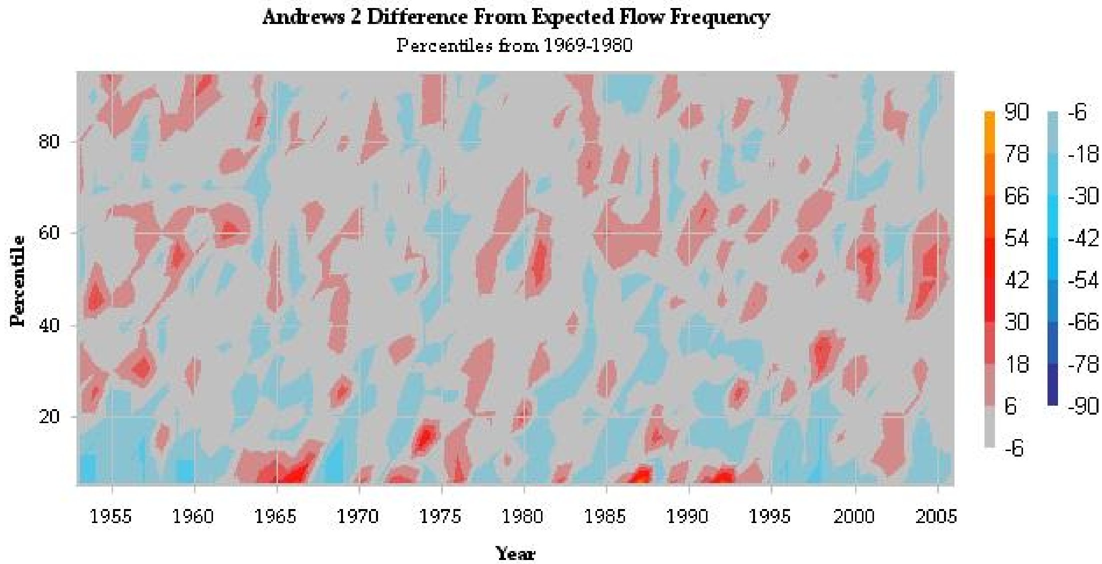


Figure 4-15: Andrews 2: Numbers of days above (red and yellow) and below (blue) expected flow frequency by percentile and year. Expected flow frequencies were the average over a reference period (1969-80). V-notch plates were installed summers from 1999 to the present.

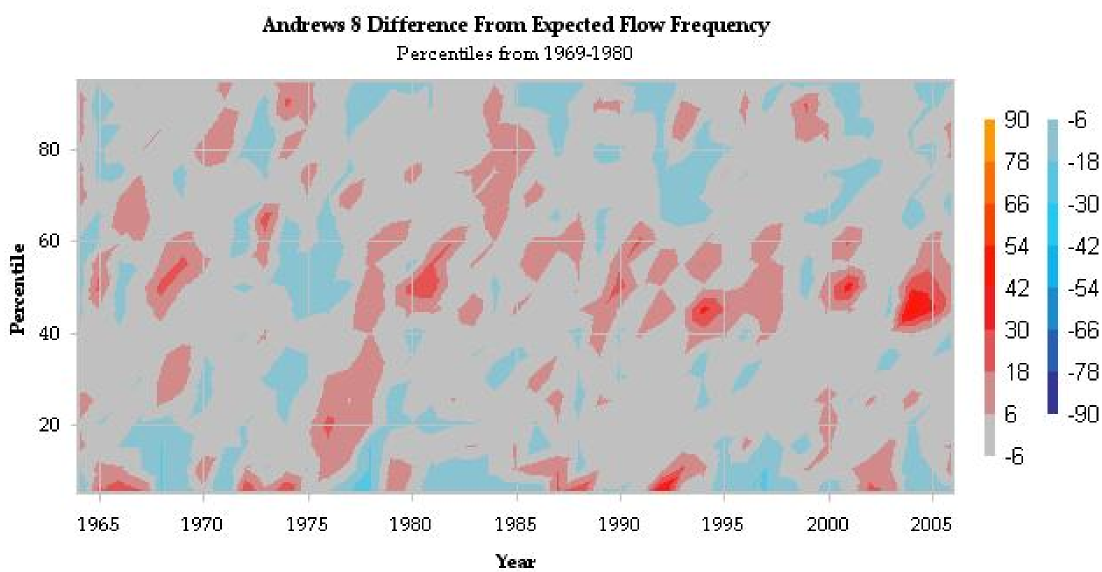


Figure 4-16: Andrews 8: Numbers of days above (red and yellow) and below (blue) expected flow frequency by percentile and year. Expected flow frequencies were the average over a reference period (1969-80). V-notch plates were installed summers from 1997 to the present.

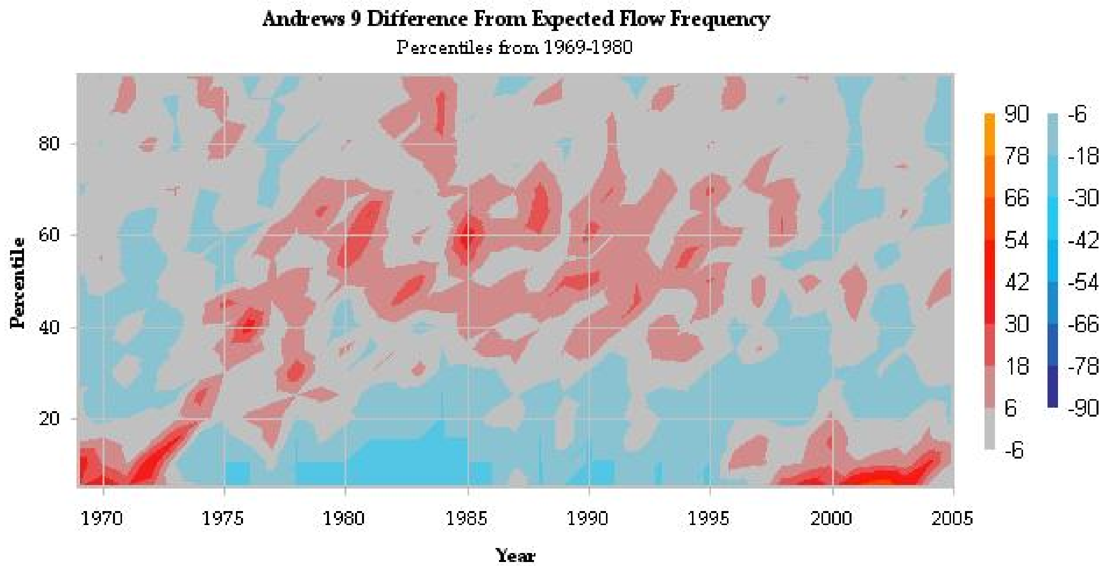


Figure 4-17: Andrews 9: Numbers of days above (red and yellow) and below (blue) expected flow frequency by year based on comparison to expected flow frequencies determined from a reference period (1969-80). Expected flow frequencies were the average over a reference period (1969-80). V-notch plates were installed in Andrews 9 from June to October in 1973-79 and 1997-present. Low flows are much more frequent since 1997 compared to 1973 to 1996 (a mix of dry and wet years). However, climate fluctuations are missing from the record when V-notch plates were not installed.

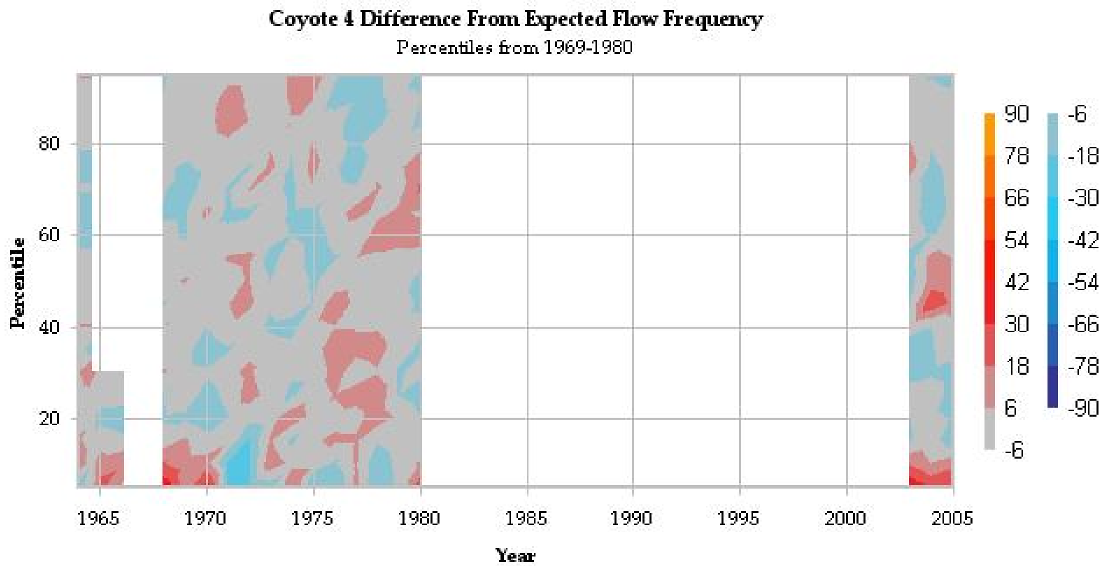


Figure 4-18: Coyote 4: Numbers of days above (red and yellow) and below (blue) expected flow frequency by percentile and year. Expected flow frequencies were the average over a reference period (1969-80). Low flows are much more frequent since 2003 compared to 1973 to 1978–80.

4.10. Coyote 4 Run-off Ratio Changes

Results from linear regression indicate runoff at Coyote 4 declined relative to precipitation. An intercept change of -114 mm (95% CI: -15 to -213 mm) was statistically significant. The regression did not support a statistically significant change in slope for the run-off ratio ($p = 0.5$). These results indicate that controlling for precipitation over the range of 1100 to 1500 mm, annual streamflow was 114 mm (10 to 15%) less in 2002 to 2006, compared to the pre-treatment and early post-treatment period (1966-1981) (Figure 4-19).

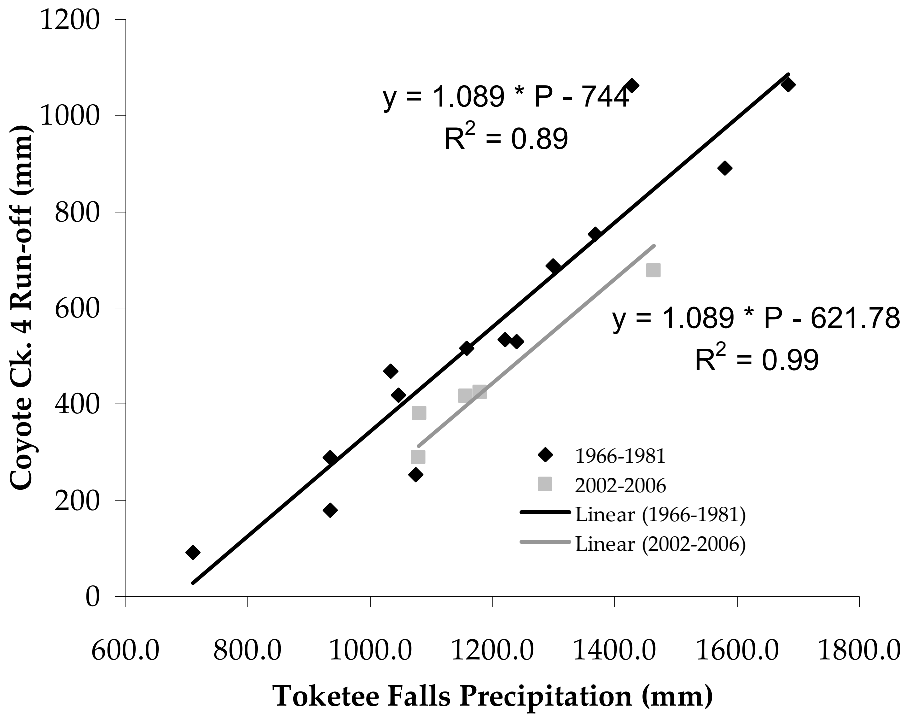


Figure 4-19: Run-off Ratio changes at Coyote Creek 4. Run-off declined an average of 114 mm/water year over the period of record.

5. DISCUSSION

This thesis presents original results from novel analysis of long-term streamflow records from paired WS studies in the Pacific Northwest. Methods developed by Jones and Post [2004] were extended to longer stream records spanning a wider range of forest treatment types (shelterwood cutting, patch-cutting, and overstory thinning) in the H.J. Andrews and Coyote Creek Experimental Forests. This thesis also presents a novel method for examining changes in annual flow frequency distributions over time. Results appear to be robust, despite gaps in data availability, uncertainties associated with changes in stream gauging, trends over time in streamflow in control watersheds, and multi-decadal fluctuations in regional climate over the study period.

Summer streamflow deficits were largest and most persistent in 35 to 50-yr-old forest plantations created from clearcutting in the 1960s and 1970s, and smallest and most ephemeral in a stand that had experienced overstory thinning in 1971. Summer streamflow deficits of intermediate size and persistence developed in watersheds in which 25 to 30% of the area had been patchcut in the 1960s or 1970s. Streamflow deficits emerged as early as March or April and persisted into October and November in the warmer, drier site in southern Oregon (Coyote Creek), whereas summer streamflow deficits were restricted to July through September at the cooler, wetter Andrews Forest. These findings are consistent with previous studies demonstrating (1) increases in water use in certain conifer species relative to others (e.g. Douglas-fir versus pine); (2) higher water use in young (i.e., 10 to 50-yr-old) compared to old (100 to 250-yr-old) stands of many tree species; and (3) decreased interception capacity of young relative to old forest stands associated with loss of canopy epiphytes. More research, preferably new paired watershed experiments, are needed to quantify the magnitude and duration of summer streamflow effects from various levels of overstory thinning.

5.1. Sources of Error

Paired WS studies depend on (1) a consistent pre-treatment relationship between WS; (2) stationarity of the reference WS; (3) homogeneity of streamflow records or no change in gauge accuracy or precision; (4) geographically close basins with similar climate so the reference WS can control for climatic variations; and (5) geologically similar basins [*Andréassian*, 2004]. All pairs of WS conform to requirements 1, 4 and 5 with the possible exception of Andrews 10 when it was paired with control Andrews 2. However, the reference WS Andrews 2, Andrews 9, and Coyote 4 were not entirely stationary.

Flows at Andrews 8 are close to stationary despite gauging changes (Figure 4-14 and Figure 4-16). Homogeneity of streamflow records was affected by changes in streamflow gauging in Andrews 9. Addition of V-notch plates to WS 1, 2, 3, 6, and 7 since the late 1990s may have affected the detection of lowflows, but extensive quality control efforts occurred during these transitions (C. Creel and D. Henshaw, personal communication, 2007). Carefully constructed gauges such as those in Andrews 1, 2, and 3 and the Coyote 1, 2, 3, and 4 were interpreted to have an error range of +- 5% in a conservative analysis [*Beschta et al.*, 2000].

5.1.1. Gauging Changes

Craig Creel and Don Henshaw explained some streamflow gauging issues in the Andrews WS. At Andrews WS 6, 7, 8, 9 and 10, H. flumes, or rectangular flumes, were initially installed and later replaced with trapezoidal flumes. After flume replacement at WS 8, 9, and 10, it was discovered that the manufacturer's flow rating curves were highly dependent on the angle at which the H. flumes were installed, and the H-flumes had not been set at the proper angle. Corrected flow rating curves were created for WS 6 and 7 based on empirical flow measurements. No such correction could be applied to H flume measurements at WS 8, 9 or 10 because the H flumes were replaced in 1973 at

Andrews 9 and 10, and in 1987 at Andrews 8 without calibration data collection. Thus, the streamflow records in WS 1, 2, 3, 6, and 7 are relatively homogeneous while records in 8, 9, and 10 are in a somewhat unknown state.

Results presented in this thesis (Figure 4-14, Figure 4-15, and Figure 4-16) show that the flow frequency distribution at Andrews WS 8 was consistent through out the period of record (1964-present). Thus, it can be considered a reasonably good control with only slight concerns about deviations in the record. However, flow frequency distributions at WS 9 (Figure 4-14 and Figure 4-17) were quite sensitive to the presence or absence of the V-notch weir and perhaps also affected by the flume change.

Because of uncertainty associated with stream gauging changes at Andrews 9, Andrews 2 was used as the control for Andrews 10, following Jones and Post [2004], despite the differences in size and elevation range of Andrews 2 (60 ha, 500-1000 m) and Andrews 10 (10 ha, 450-700m). Changes in the flow frequency distribution at Andrews 10 associated with the flume replacement (August 1973) cannot be separated from effects of the treatment (100% clearcut starting June 1975). However, the magnitude of change from one analysis period to another is accurate as long as both analysis periods are before or after flume remodeling. For example, the Andrews 10 streamflow deficit relative to

Andrews 2 increased from the 1996–2000 period to the 2001–2005 period (Figure 4-11 e, f). When V-notch plates were installed in all flumes starting in the late 1990's, an extensive campaign to correct the rating curves was undertaken (C. Creel and D. Henshaw, personal communication, 2007). Flow measurements were taken before and after addition of V-notch plates to ensure rating curves were as accurate as possible and streamflow records are reasonably homogeneous across this transition in gauging methodology (C. Creel and D. Henshaw, personal communication, 2007). Thus, it is reasonable to compare streamflow deficits before and after installation of the V-notch plates.

Coyote Creek watersheds have not had gauge structure changes. All four watersheds are gauged using 120° V-notch weirs, and the same weir has been used over the entire period of record. Minor repairs to the V- notches have occurred over the years following damage from debris. Changes in stage recording equipment have occurred, but they have had a negligible effect on streamflow records (C. Creel, personal communication, 2006).

5.1.2. Out of control controls: changes in reference WS behavior

A control watershed might be considered to be "out of control" if its rainfall/runoff ratio changes over time. This would produce changes over time in the treated/control relationship that are attributable to the control watershed, not just the treated watershed. The rainfall/runoff relationships in control watersheds have varied somewhat over the period of record, in conjunction with changes in climate (precipitation and temperature effects on evapotranspiration), and changes in forest species composition and cover as a result of disturbances, cessation of disturbances (e.g. grazing), and forest succession. In watersheds where no gauging changes occurred, this change over time in rainfall/runoff can be quantified. For example, Andreassian (2003) detected increases in the frequency of lowflows in the 1990s relative to the 1950s [*Andréassian et al.*, 2003]. Results in this thesis indicate that lowflows at Coyote 4 were more frequent in 2002-2006 than during calibration from 1963 to 1970.

Because lowflows have become somewhat more frequent over time in Andrews 2 and Coyote 4 as a result of changes in those forests, it is possible that the results presented here underestimate the true increase in lowflow frequency and magnitude in the treated watersheds. That is, streamflow deficits reported here are if anything smaller than would have been calculated had there been no drift in the control watershed lowflows. However, the control watershed flumes should also be tested for leaks.

5.1.3. Effect of climate variability on estimated streamflow changes

In this study, absolute streamflow changes were calculated by multiplying relative changes by the mean daily flow for the ~5-yr period. For wet periods, this produces absolute changes that cannot be compared between periods. Absolute streamflow should be computed with the average flow in the control basin over the entire period of record following Jones and Post [2004].

The results presented here also may be affected by the timing of the pre-treatment periods, which occurred from 1952-1970, during a generally cool phase of the Pacific Decadal Oscillation (PDO, an index of sea surface temperature anomalies in the northern Pacific), whereas post-treatment periods span both cool and warm sea surface temperatures.

Climate variability in the Pacific Northwest is driven by the Pacific Decadal Oscillation at multi-decadal timescales (Figure 5-1) and El Niño/Southern Oscillation at sub-decadal timescales [*Hare and Mantua*, 2000]. Both oscillations influence the Pacific Northwest but climate variation is mainly driven by the Pacific Decadal Oscillation with more limited influence from the El Niño/Southern Oscillation [*Lluch-Cota et al.*, 2001]. In the Pacific Northwest the cool phase of the Pacific Decadal Oscillation is associated with higher precipitation and streamflow than the warm phase. A switch from the cool phase to the warm phase of the Pacific Decadal Oscillation occurred in Winter 1976-1977 [*Hare and Mantua*, 2000; *Lluch-Cota et al.*, 2001]. Limited evidence suggests a moderation of the warm phase in 1989 and a return to the cool phase the winter of 1997-1998 [*Hare and Mantua*, 2000].

During warm phases of PDO, summer precipitation is higher at the Andrews (J. Jones, personal communication, 2007). Higher summer precipitation would be expected to reduce the frequency of lowflows in both treated and control watershed. If young forest is more sensitive than older forest to summer precipitation, wetter summers might reduce the relative frequency of lowflows in the treated vs. the control watershed. This may be a fruitful avenue for future research.

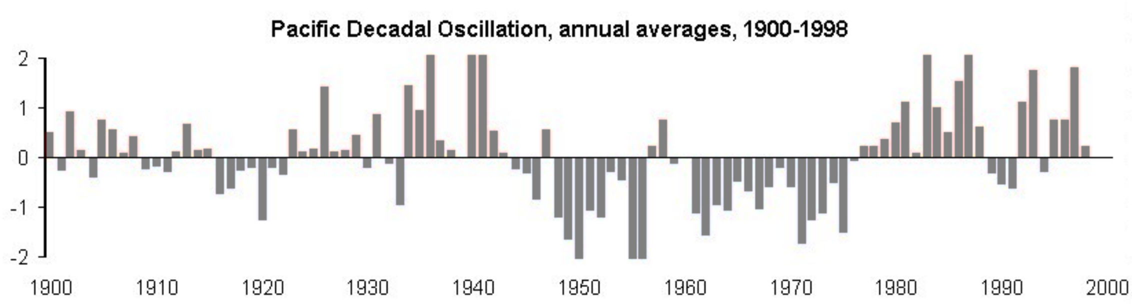


Figure 5-1: Pacific Decadal Oscillation intensity over the study period. Adapted from Hare [1999].

5.1.4. Confidence intervals for change in daily streamflow

Assessing the statistical significance of changes in daily streamflow is problematic. The standard error of the difference in treatment/control ratio can be computed by pooling treatment/control standard deviation for the analysis and calibration periods [*Ramsey and Schafer*, 2002, pg 39]. Then a confidence interval can be constructed using the appropriate t-multiplier and the pooled standard error (Figure 5-2). However, these confidence intervals are biased (too narrow) because streamflow is autocorrelated at the daily and interannual timescales, as well as at multi-decadal timescales which exceed the calibration periods of these studies. To correct for autocorrelation this data could be filtered with Bayesian Information Criterion methodology to remove serial correlation analysis residuals, but this method requires more than 100 observations (100 years of data) [*Ramsey and Schafer*, 2002, pgs 453-454].

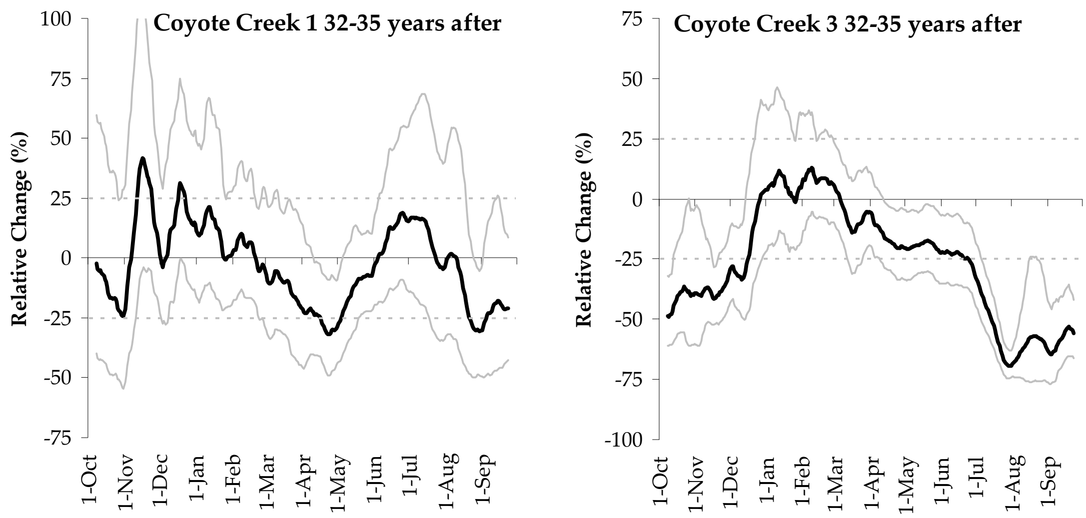


Figure 5-2: Relative change in Coyote Creek 1/4 and 3/4 32 to 35 years after forest cutting with confidence intervals. These confidence intervals account for the variation seen in the calibration period but do not account for autocorrelation over longer timescales.

Because of these problems, a practical significance level was defined as a relative change of 25% or an absolute change of 0.5 mm/day following *Jones and Post* [2004]. Experiments with synthetic data showed that changes in day-to-day flow timing do not produce changes larger than these practical significance thresholds. More work is needed to develop meaningful criteria for statistical significance of daily streamflow changes.

5.2. Forest succession and the timing and persistence of summer streamflow deficits

The observed summer lowflow deficits are consistent with known changes in species composition and leaf area over the course of early forest succession. Hicks et al. [1991] attributed streamflow deficits in Andrews WS 1 the increased leaf area of red alder (*Alnus ruba* Bong.), which has higher stomatal conductance and therefore water usage per unit leaf area than the conifer species that were present in the riparian zone of Andrews 1 prior to logging. Forest harvest that results in replacement of conifers by alder and other broadleaf species such as willow (*Salix* spp.), and cottonwood (*Populus trichocarpa*) could be expected to increase summer water use [*Hicks et al.*, 1991]. Summer streamflow deficits also intensified in Andrews 3 in the late 1990s and early 2000s, associated with regenerating red alder that established after debris flows in 1996 scoured the channel in Andrews 3 [*Adams et al.*, 2007]. *Moore et al* [2004] estimated that young forest stands of Andrews WS 1 (dominated by 35-yr-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and red alder) used 3.27 times more water in summer (June-September) compared to the forest (dominated by 150- to 450-year-old Douglas-fir and western hemlock(*Tsuga heterophylla* (Raf.) Sarg.)) in adjacent WS 2. According to Moore et al. [2004], the average age of Douglas-fir trees was dominant control on stand transpiration .

The findings of Hicks et al.[1991] and Moore et al. [2004] also may explain summer streamflow deficits in other watersheds at the H.J. Andrews and Coyote Creek experimental forests. After clearcutting, young Douglas-fir plantations have replaced 130-yr-old forest in Andrews WS 6, and 450-yr-old forest in Andrews10, while shelterwood cutting has led to regenerating stands of mixed Douglas-fir and western hemlock in Andrews 7 [*Harr and McCorison*, 1979; *Harr et al.*, 1982]. Summer streamflow deficits emerged by 25 years after logging in all these basins. Prior to logging in 1970, mixed-conifer forests at Coyote Creek were dominated by old-growth and mature Douglas-fir (Pseudotsuga menziesii) with subdominants grand fir (Abies grandis), sugar pine (Pinus lambertiana), and incense cedar (Calocedrus decurrens) and smaller numbers of ponderosa pine (Pinus ponderosa), western hemlock (Tsuga heterophylla) and Pacific madrone (Arbutus menziesii) [*Arthur*, 2007]. In 2006, the clearcut (Coyote 3) and patch-cuts (in Coyote 2) watersheds were mono-specific stands of Douglas-fir [*Arthur*, 2007]. As early as 1967, Baumgartner [1967, cited in Dunne and Leopold, end of chapter 4] reported that Douglas-fir forests transpire nearly twice as much as pine forests.

Many tree species exhibit declining transpiration with increasing stand age, although the age at which transpiration is maximized, and the rate of decline in transpiration with age varies by species. For example, *Delzon and Loustau* [2005] found a 54-year-old maritime pine (*Pinus pinaster Ait.*) transpired 70% less water than an adjacent 10-year-old maritime pine stand. A stand of 140-year-old Norway spruce (*Picea abies*) transpired about 40% less than 40-year-old stands [*Alsheimer et al.*, 1998; *Köstner*, 2001]. A 240-year-old forest stand of *Eucalyptus regnans* transpired 66% less than 15-year-old stands [*Vertessy et al.*, 2001], and a 230-year-old stand transpired 56% less than a 50-year-old stand [*Roberts et al.*, 1982]. *Pinus sylvestris* forests in Siberia do not reach peak transpiration until 64 years of age after which transpiration declines [*Zimmermann et al.*, 2000]. In one study *Pinus ponderosa* showed similar transpiration between 14-year-old and 250-year-old stands, but higher leaf area index was observed in the old stand [*Irvine et al.*, 2002].

Because both the magnitude of transpiration reduction and maximal potential transpiration vary by species one would not expect streamflow deficits to emerge at the same time under all forest canopies. Stands of fast-growing *Eucalyptus* spp. in Australia reach maximal sapwood area and stand transpiration rates 15 to 20 years after establishment [*Andréassian*, 2004]. Peak transpiration in post-disturbance forest stands coincides with streamflow deficits in Australia [*Andréassian*, 2004]. Transpiration declines with age after about 20 years and there is a corresponding reduction in summertime streamflow deficits.

Because transpiration rates vary with stand age in many species, streamflow deficits may be common, but accurately detecting the magnitude and timing of the deficit requires paired-watershed experiments such as those examined in this study. Summer streamflow deficits observed in this study have increased to the present, and it is not clear at what age the transpiration rate of Douglas-fir stands, and hence the summer streamflow deficit, will maximized. In the federal forest lands of the Pacific Northwest, where these and other paired-watershed experiments have been conducted, the oldest forest plantations date from the late 1940s and early 1950s when patch clearcutting began on federal forests (e.g. *Jones and Grant*, 1996). As a result of regional wildfire [*Weisberg and Swanson*, 2003] the forests in control watersheds ranged in age from 130 to 450 yrs at the time forest treatments were imposed. Streamflow increases after clearcutting in Andrews WS 6 (dominated by 130-year-old Douglas-fir) were similar to increases after clearcutting in Andrews 1 (dominated by 450-year-old Douglas-fir) [*Harr et al.*, 1982]. This suggests that stand-level transpiration may return to near old-growth levels by 130 years in Douglas-fir-dominated stands. The duration and magnitude of summer streamflow deficits depends on annual precipitation and temperature in the dry summers characteristic of the marine west coast climate. Summer deficits were longer in the drier, warmer site in southern Oregon (Coyote Creek) than in the wetter, cooler site in the central Cascade Range of Oregon. At Andrews 1, forest transpiration was correlated to diel fluctuations in streamflow in June, but the strength of this correlation decreased over the course of summer, apparently because by late August, streamflow was sustained from sources too deep in the soil mantle to be affected by vegetation [*Bond et al.*, 2002]. Streamflow deficits in Andrews 1 end in late August or early September which coincides with decoupling between sapflow and diel streamflow fluctuations observed by *Bond et al*. [2002].

In addition to summertime streamflow deficits, young (35-50-yr-old) forest plantations have persistent winter time streamflow surpluses averaging 25% in clearcut WS. Old-growth forest in the Pacific Northwest intercepts and subsequently evaporates about 25% of rainfall [*Link et al.*, 2004]. Interception values range from nine to 48% of precipitation in coniferous forest [*Hörmann et al.*, 1996] and much of this range is attributed to lichen and bryophyte abundance in the forest canopy [*Link et al.*, 2004]. These lichens and bryophytes can store between 1.5 and 15 times their weight in water [*Pypker et al.*, 2006].

However, lichen and bryophyte species are less abundant in younger forests reducing interception and evaporation [*McCune*, 1993; *Peck and McCune*, 1997]. The change in forest structure following logging including the relative dearth of lichen and bryophyte species may partially explain the persistent 25% increase in wintertime streamflow observed in all clearcuts (Figure 4-11). Persistent winter surpluses were not observed in the patch-cut or overstory thinned watersheds, where more old trees were retained (Figure 4-12 and Figure 4-13).

This study provides some evidence that road construction alone altered flowpaths and drainage efficency, creating streamflow surpluses in the fall and deficits in the summer during the "roads only" period in Andrews 3 (Figure 4-12). However, no other paired watershed experiments in the Pacific Northwest included a "roads-only" period.

5.3. Ecological implications of summer streamflow deficits

Summer streamflow deficits, which were observed under every forest treatment studied, may exacerbate contractions of stream networks during dry seasons and thereby potentially limit aquatic habitat. If the minimum flow requirement for a hypothetical aquatic organism does not vary with channel morphology, then 1.7 times as much contributing area is required to generate the minimum flow when 40% streamflow deficits are present and 3.3 times as much contributing area is required for a 70% deficit. Streamflow networks display fractal affinity and so a power law associates stream channel area (S) to minimum required contributing area (C): S is proportional to $C^{-0.45}$ based on both empirical and theoretical investigation [*Rodríguez-Iturbe et al.*, 1992]. Thus the change in stream channel area with changes in minimum contributing area can be calculated. If the original contributing area of 100 ha contained 0.12 ha of channel suitable for an aquatic organism of interest, then the power law implies that the suitable channel area would drop to 0.10 ha with a 40% decline in streamflow and to 0.07 ha with a 70% decline in streamflow. A drop from 0.12 ha to 0.07 ha is a 42% reduction in available habitat.

Ratner et al. [1997] project spring-run Chinook salmon (*Oncorhynchus tshawytscha*) populations in the South Umpqua River will remain viable for over 200 years if there is no further degradation in habitat. However, these spring-run Chinook salmon will become extinct in less than 100 years if habitat degradation continues at its current pace. Summer-run steelhead (*Oncorhynchus mykiss*) are considered extinct and Coho (*Oncorhynchus kisutch*), and sea-run cutthroat trout (*Oncorhynchus clarki*) are considered endangered in the South Umpqua River.

The South Umpqua spring-run Chinook salmon typically "hold" in deep pools in summer and move into shallow reaches to spawn in mid-September [*Ratner et al.*, 1997]. This study shows that streamflow from the clear-cut Coyote Creek WS, a tributary to the South Umpqua River, is significantly reduced in mid-September compared to streamflow from watersheds with mature and old-growth forest cover. In 2002 the US Forest Service estimated 70% of forests in the Pacific Northwest were under the age of 100 [*Lindh and Muir*, 2004]. Although salmon do not occupy first- and second-order streams like those of Coyote Creek, lower flows from tributary streams may reduce spawning habitat in larger streams.

Lower summer and early fall streamflows might concentrate fish in the remaining habitat. During lowflows, riffles and glides in bedrock and thin-alluvial reaches become too shallow for fish, increasing their densities in nearby pools [*Hicks*, 1990]. Higher densities may lead to increased competition which can be especially problematic for steelhead which are less aggressive than Coho; steelhead typically remain in riffles and glides while Coho prefer pools and ponds [*Hicks*, 1990]. Flow reductions also might reduce or eliminate pools in alluvial reaches sustained through the summer by hyporheic flow [*May and Lee*, 2004].

In Washington, Oregon, and California salmon harvests (a measure of population size) are higher during the cool phase than the warm phase of the Pacific Decadal Oscillation [*Hare et al.*, 1999; *Mantua et al.*, 1997] (Figure 5-3). Both ocean biology and streamflow patterns shift with changes in the Pacific Decadal Oscillation, making it difficult to attribute fish viability changes to ocean or stream conditions [*Hare et al.*, 1999; *Hare and Mantua*, 2000; *Mantua et al.*, 1997]. Hare et al [1999] suggest the current warm-phase Pacific Decadal Oscillation conditions may offset the effects of salmonid restoration efforts. If, as indicated by this study, the current forest age class distributions in the Pacific Northwest (with large areas in relatively young Douglas-fir plantations) are reducing summer lowflows, this effect may exacerbate the climatic impacts on ocean conditions and streamflow, counteracting efforts aimed at salmonid restoration.

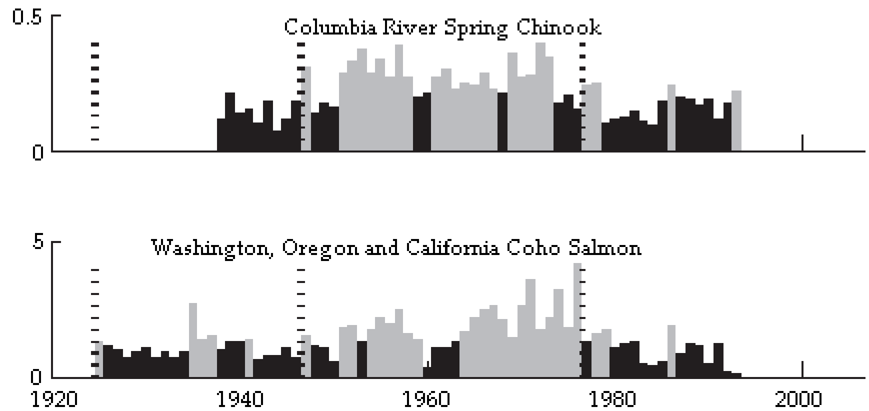


Figure 5-3: Transitions between harvest levels appear shortly after phase changes in the Pacific Decadal Oscillation. Dashed bars indicate Pacific Decadal Oscillation phase changes. Gray bars indicate the catches above and black bars indicate catches below the median. Adapted from [*Mantua et al.*, 1997].

5.4. <u>Effects of thinning on summer lowflow deficits</u>

Forest thinning of both young and old stands may mitigate summer streamflow deficits, helping improve conditions for aquatic organisms in general and salmonid species in particular. In this study, 50% overstory thinning of mature to old-growth forest stands produced summer streamflow surpluses for the first five years after logging at both the Coyote Creek and H.J. Andrews study sites. However, these increases were short-lived, and persisted for only five years in the northern site (H.J. Andrews) and less than ten years at the southern site (Coyote Creek). More research, preferably new paired-WS experiments, are needed to quantify the magnitude and duration of summer streamflow effects from various levels of overstory thinning.

Overstory thinning and patch-cutting produced less intense and less persistent summertime-streamflow deficits than clearcut and shelterwood treatments. *Franklin et al.* [2002] noted that clearcutting is unlike any natural disturbance, and shelterwood treatments create horizontal homogeneity in stand structure, unlike structures created by frequent, low-intensity natural disturbance such as wildfire and windthrow. Franklin et al (2002) recommend variable intensity logging prescriptions over small areas to approximate natural forest structure. The results from this study indicated that patches of 0.6 to 1.5 ha and 50% overstory thinning did not lead to intense or persistent summertime streamflow deficits compared to adjacent clearcuts. However, these cut watersheds still exhibited streamflow deficits compared to old-growth control WS. These results indicate that in landscapes historically subjected to low-intensity fire, such as the South Umpqua Experimental Forest, the forestry treatments recommended by *Franklin et al.* [2002] would produce smaller and less persistent summer streamflow deficits than clearcutting over the long term (40 to 50 years). In addition, over the short term (zero to 10 years after harvest) these treatments might increase streamflow during summer lowflow periods.

Thinning of a young stand on a south-facing slope (Andrews 7) had only a temporary effect on summer streamflow deficits; within five years after a 12%

basal area removal, streamflow deficits were again comparable to those from an adjacent un-thinned stand. These results are unsurprising given thinning of young Douglass-fir is followed by increased growth in the remaining trees [*Lindh and Muir*, 2004]. Repeated or more intense thinning in young stands may be necessary to prevent further intensification of streamflow deficits. The thinning in Andrews 7 was intended for an adjacent, younger plantation. A much lower percentage of basal area was removed them would be expected with a standard pre-commercial or commercial thinning. A second, standard commercial thin could be performed in this watershed to improve our understanding of current forest thinning practices.

Effects of young stand thinning at the H.J. Andrews Forest were similar to the effects of thinning in paired-watershed studies involving *Pinus radiata*, *Eucalyptus grandis*, and *Pinus patula* stands in South Africa [*Lesch and Scott*, 1997]. In these studies, young stand thinning reversed streamflow deficits under *P. radiata*, and prevented increasing streamflow deficits under *E. grandis* and *P. patula*.

Overstory thinning and patch cutting may increase peak flows. Significant increases in peak flows may increase scour and kill eggs, and pre-emergent fry in the gravel, where salmonids bury their eggs deeply enough to be protected from bed load moving downstream, but not so deep that the fry have difficulty emerging [*Montgomery et al.*, 1995]. Overstory thinning increased peak flows in the Coyote Creeek WS [*Adams and Stack*, 1989; *Harr et al.*, 1979]. *Harr et al.* [1982] reported no increase in peak flows after 60% overstory removal in Andrews WS 7, but Jones [2000] examined a longer streamflow record and found statistically significant peak flow increases after 60% overstory removal in Andrews 7. These responses may in part be due to the logging practices of the 1960s and 1970s, which included ground disturbance by tractor logging. In the 50% overstory removal at Coyote 1 in 1970, trees were tractor logged throughout the watershed [*Harr et al.*, 1979]; skid trails and roads delivered runoff directly to streams, and infiltration was still reduced 6 years after logging [*Johnson and Beschta*, 1980]. In the 60% overstory removal at Andrews WS 7 in 1975, 60% of the watershed (upper slope positions) was tractor logged and 40% of the watershed near the stream was cable yarded [*Harr et al.*, 1982]. Contemporary logging treatments may mitigate peak flow increases from thinning of young stands, but no paired watershed experiments have documented these effects.

6. CONCLUSION

6.1. Hypothesis Outcomes

This study quantified the magnitude and timing of summer streamflow deficits in paired-watershed experiments in the Cascade Range of Oregon where mature and old-growth conifer forests were subjected to clearcutting, patch cutting, and overstory thinning treatments in the 1960s and 1970s, followed by a pre-commercial thin in one watershed in the early 2000s. Streamflow gauging begin in 1963 and clearcutting, small-patch cutting, and overstory thinning treatments were imposed in 1970 in the mixed conifer/brush zone (1 WS each) in the Coyote Creek watersheds of the South Umpqua Experimental Forest at 42° 1′ 15″N and 122° 43′ 30″W. Streamflow gauging began in 1952, 1963, and 1968, clearcutting (3 WS), shelterwood cutting (1 WS), and patch cutting (1 WS), treatments were imposed in the mid-1960s and mid-1970s, and a very light precommercial thin (1 WS) was conducted in 2001, in the Tsuga heterophylla zone at the H. J. Andrews experimental forest at 44° 14′ 0″N and 122° 11′ 0″ W. Climate of both sites is marine west coast with winter precipitation and dry summers, producing minimum streamflows in August and September.

The following hypotheses were evaluated based on the results of this study:

H1. The spatial arrangement of forest cutting within a small watershed is unimportant, and streamflow changes can be predicted from mature forest leaf area removed. This hypothesis was rejected as results presented here indicate 50% overstory thinning leads to smaller streamflow deficits than 30% patch cutting. Fine scale arrangement of cutting does affect streamflow; overstory thinning treatments, in which trees are selectively removed, produces smaller streamflow changes than less basal area removal arranged in small (2-3 ha) or large (10-15 ha) patches.

H2. Controlling for treatment, the intensity and persistence of low-flow deficits is not related to the precipitation, elevation, latitude, or hill-slope gradient of the WS. This hypothesis was rejected as results show more protracted summer streamflow deficits at the site in southwestern Cascade Range of Oregon (Coyote Creek) compared to the site in the central western Cascade Range of Oregon (HJ Andrews), and more intense summer streamflow deficits on south-facing (equatorward) slopes compared to north-facing (poleward) slopes, and at low elevations compared to high elevations.

H3. Young stand thinning eliminates or greatly mitigates low-flow deficits for five years. This hypothesis was rejected as results from this study indicate that summer streamflow deficits in the first five years after a very light precommercial thin with only 12% basal area removal of a 27-year-old shelterwood stand (17 and 27 years after removal of 60% of the overstory and removal of the remaining overstory, respectively) were about equal to those before thinning, and not significantly different from those in an adjacent un-thinned young plantation of similar age. Unfortunately this experiment was unrepresentative of current forest practices; a stand of this age is usually commercially thinned with about 35 to 45% basal area removal (Norm Michaels, personal communication, 2007).

6.2. Future work

Based on this study, the magnitude and timing of summer streamflow deficits are controlled by three factors: forest treatment, species composition changes, and species-specific water use changes with age. Additional studies quantifying water use by forest stands as a function of species, age, and location for major commercial tree species are needed to explore the specific effects of various stand age and species effects on summer lowflows, especially in areas of the United States where summer lowflow deficits are alleged to affect native or endangered species, or where water shortages are occurring. The effects of lowflows on stream habitat and fisheries presented here are speculative; more studies like those of Torgerson et al [1999] are needed to determine endangered fish sensitivity to summer drought and their interactions with other effects of logging such as increased sedimentation and wood removal. Given the likely future prevalence of both overstory and understory thinning treatments for fuels reduction in forest stands of all ages in the western United States, new paired-watershed experiments are needed to test the effects of contemporary and future thinning treatments on streamflows. Landscape-scale studies are needed to estimate the effect on summer streamflows of the forest age class distributions that would occur under the natural wildfire regime [Nonaka and Spies, 2005; Pennington and in press] and compare them to the estimated effect on summer streamflows of the current forest age class distribution resulting from the last half-century of forest harvesting on public and private lands in the Pacific Northwest.

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APPENDICES

Appendix A: SOFTWARE DESCRIPTION

The method used by Jones and Post [2004] is time consuming to implement by hand for multiple basins. A software application was written in the Java™ programming language to decrease time and potential for errors performing the calculations in Excel™ spreadsheets. An undergraduate computer science student, Yousef Alhashemi, wrote the majority of application to gain software design experience. Code for this application is located in a CD in the back pocket of the thesis.

Data was not available in a single unified format and so a simple file format was created. Data files are expected to be comma delimited. The first line in the file is a header defining the columns: site code, date, flow, and error code. Each subsequent line represents a daily mean streamflow at a particular site. The error code field is not currently processed. In the future the program should be enhanced to examine the error code following the H. J. Andrews quality control standards.

Streamflow dates are required to be in the form of YYYY-MM-DD. This form is easily generated in Excel by changing the cell format to be an international date. Failure to use this date format will likely result in application failure.

The application does not require streamflow to be in any particular units and makes no transformations for the user. Thus, the user is responsible for ensuring all input files use the same units.

The application can be run from a command prompt on any computer with Java™ installed. The command line is:

java SFApp wyStartDate controlFlowFile ControlID treatedFlowFile TreatedID CalibrationYears "AnalysisYears1;AnalysisYears2;…" minimumFlowThresold allowableFractionMissingDays LogYN

where:

wyStartDate is the start day of the water year as MMDD or 1001 for October first.

controlFlowFile is the full path to the file containing the control flows.

ControlID is the name identifying the control flow in a file.

treatedFlowFile is the full path to the file containing the control flows.

TreatedID is the name identifying the control flow in a file.

CalibrationYears is the comma-separated beginning and ending of the calibration period.

"AnalysisYears1;AnalysisYears2;…" is a semicolon delimited list of streamflow analysis periods. The beginning and ending year of each analysis period is separated by a comma.

minimumFlowThresold is the minimum allowable flow. Any flow lower than this is replaced with this flow following Jones and Post [2004].

allowableFractionMissingDays defines the maximum fraction of days that can be missing before the day is entirely discarded from the analysis. For example, if allowableFractionMissingDays=.5 and a day is missing from two out of five water years than the day will be retained in the analysis. However, if allowableFractionMissingDays=.2 and the day is missing from two out of five water years than the day will be discarded from the analysis.

LogYN tells the program whether or not you want to log transformed the treatment/control ratio. If LogYN = log then treatment/control values are natural log transformed. If LogYN = noLog than treatment/control values are not transformed.

To make this more clear, consider the following line 4 coyote Creek watershed 3:

java SFApp 1001 cc_1963to2006_GoodFormat.csv GSCC04 cc_1963to2006 _GoodFormat.csv GSCC03 1963,1970 "1971,1976;1977,1981;2003,2006" 0.001 .4 log

The water year begins on October 1. Control watershed values have a site code "GSCG04" and mean daily streamflow values are found in a file named cc_1963to2006_GoodFormat.csv. Treated watershed values have a site code "GSCG03" and mean daily streamflow values are found in the same file. The calibration lass from 1963 to 1970. Analysis periods last from 1971-1976, 1977-1981, 2003-2006. Flows less than .001 mm/day are rounded up to .001. If .4 (2/5) streamflow values are missing for a day of the water year it has dropped from a given an analysis period. Data was log transformed.

Appendix B: ANDREWS ABSOLUTE CHANGE GRAPHS

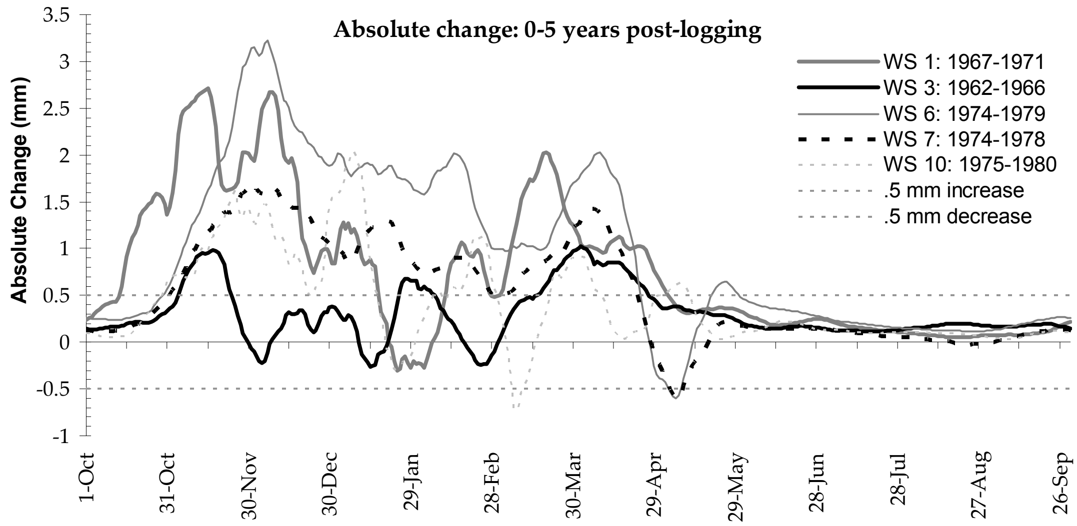

Figure B-1: Andrews WS absolute change 0-5 years post-logging.

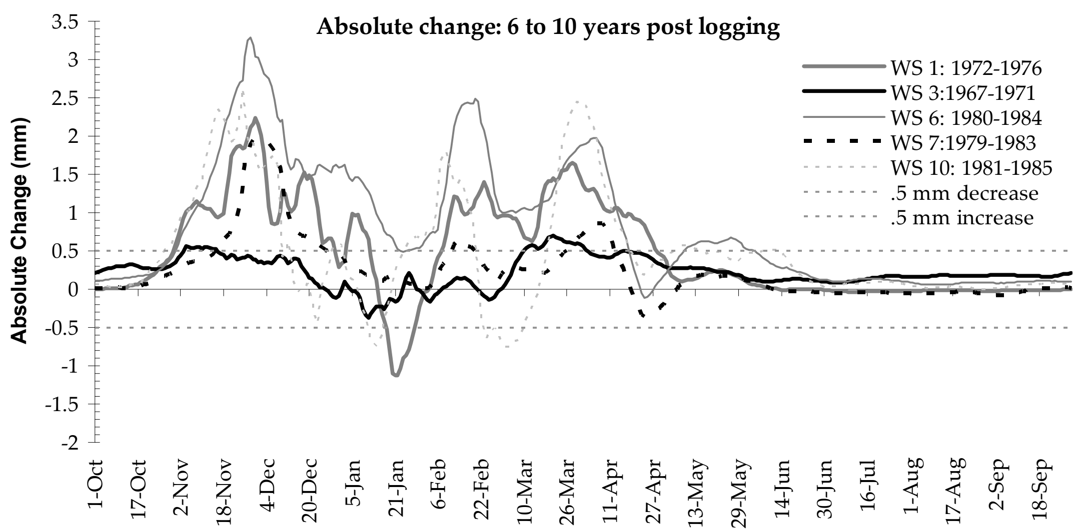

Figure B-2: Andrews WS absolute change 6-10 years post-logging.

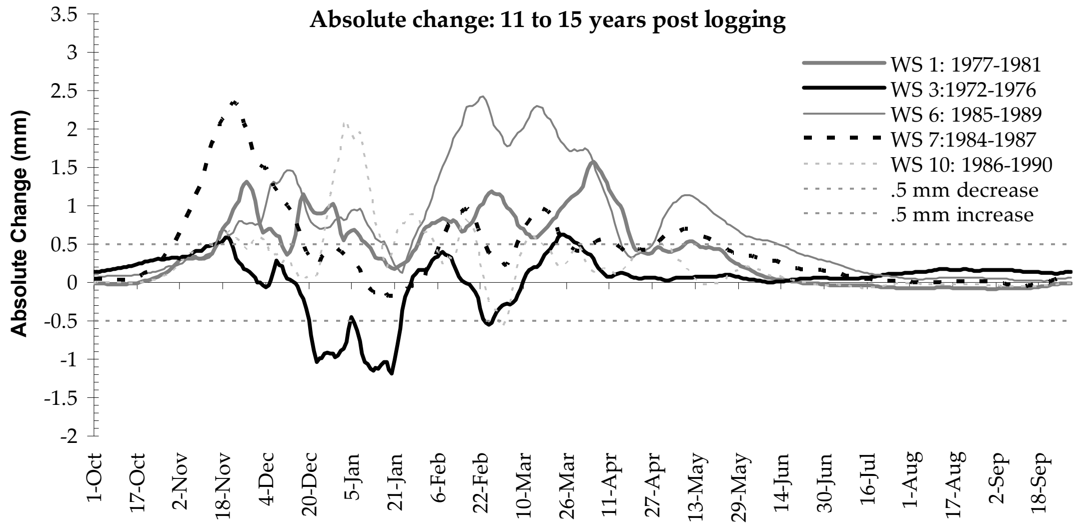

Figure B-3: Andrews WS absolute change 11-15 years post-logging.

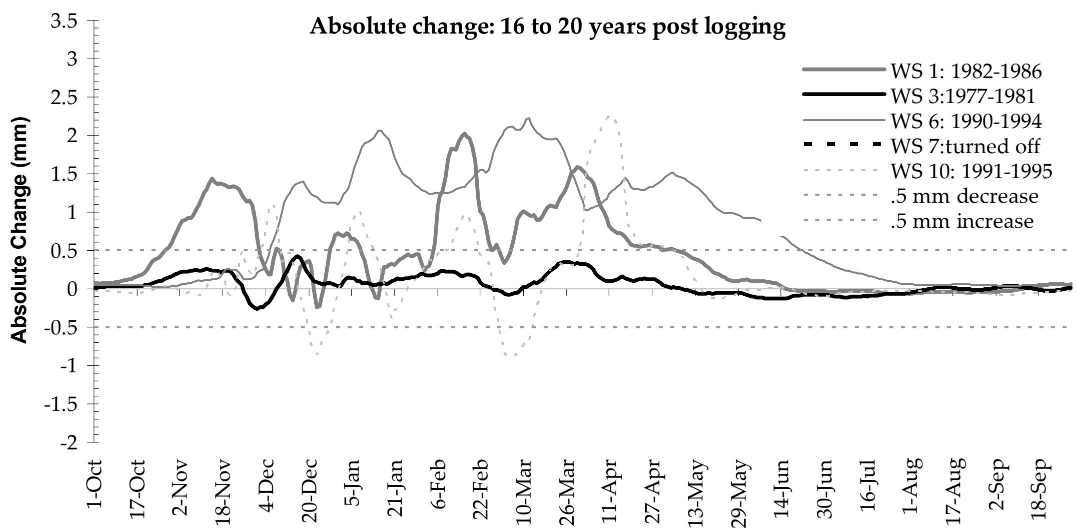

Figure B-4: Andrews WS absolute change 16-20 years post-logging.

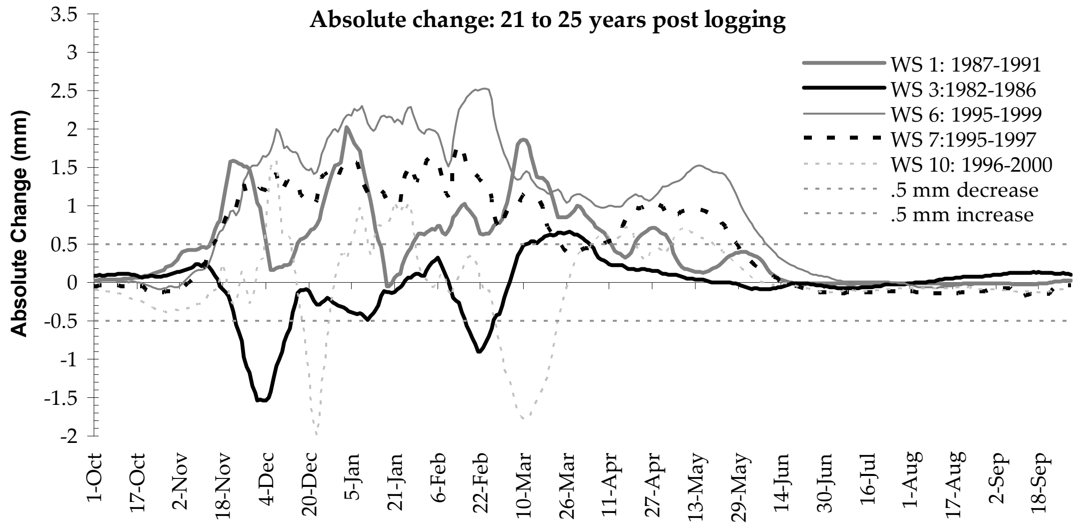

Figure B-5: Andrews WS absolute change 21-25 years post-logging.

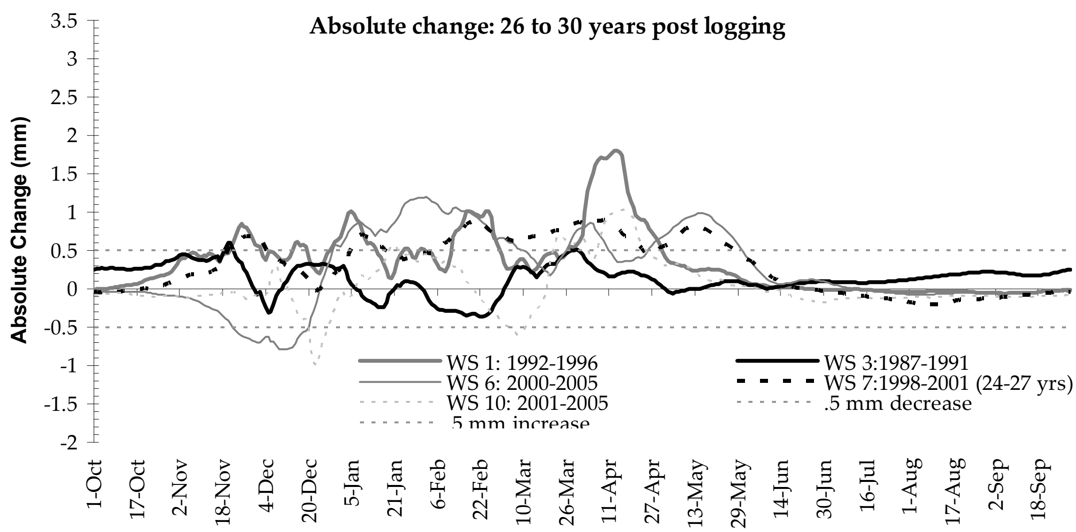

Figure B-6: Andrews WS absolute change 26-30 years post-logging.

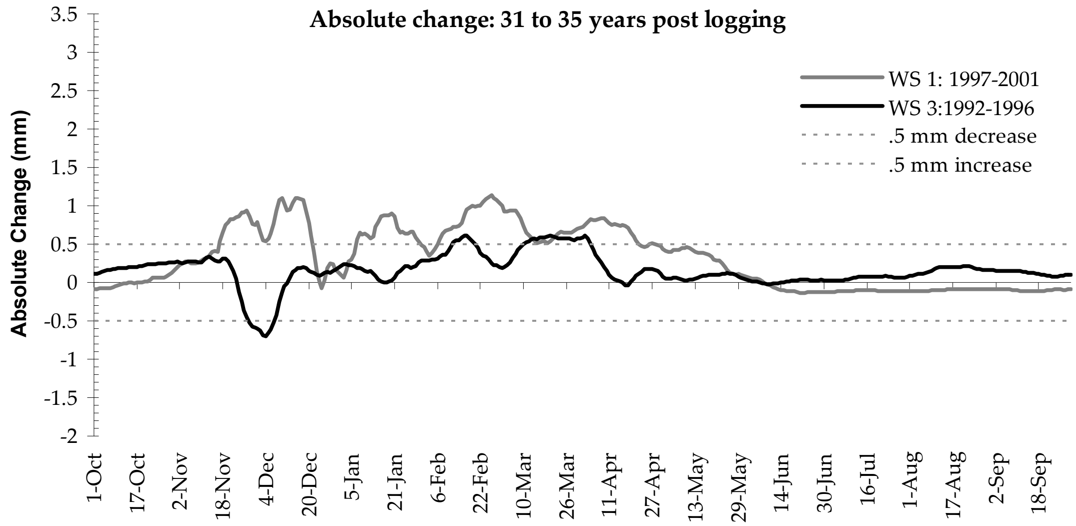

Figure B-7: Andrews WS absolute change 31-35 years post-logging.

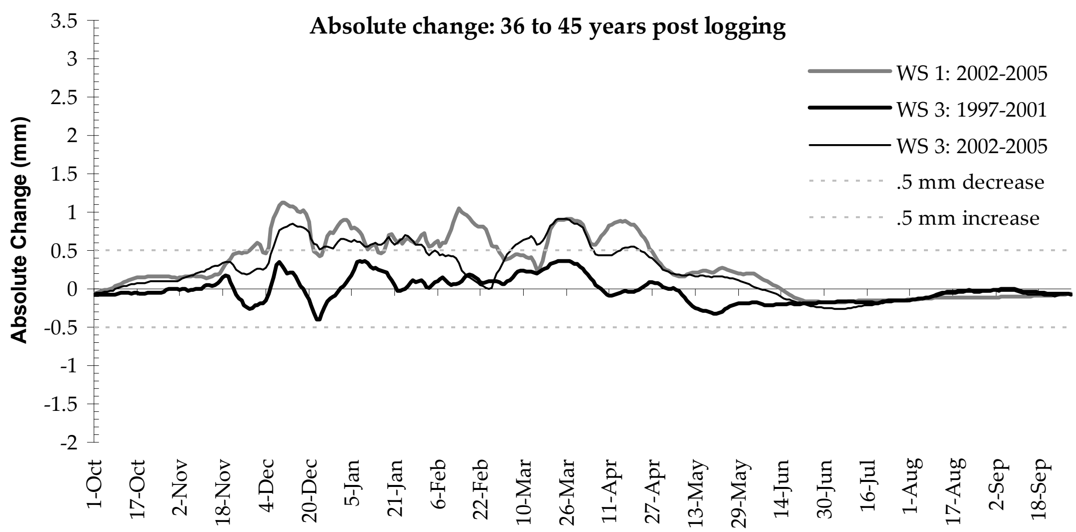

Figure B-8: Andrews WS absolute change 36-45 years post-logging.

Appendix C: Coyote Creek Absolute Change Graphs

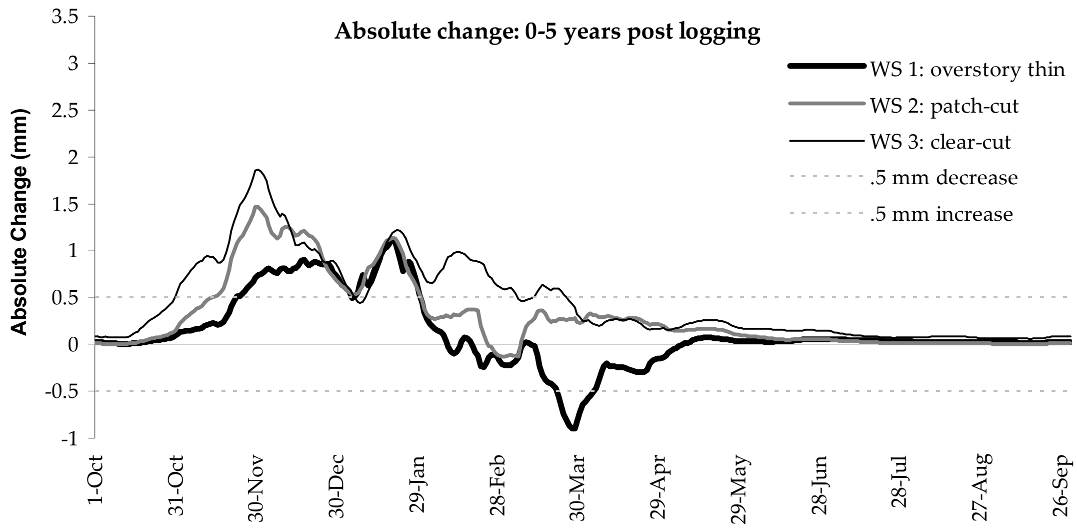

Figure C-1: Coyote WS absolute change 0-5 years post-logging.

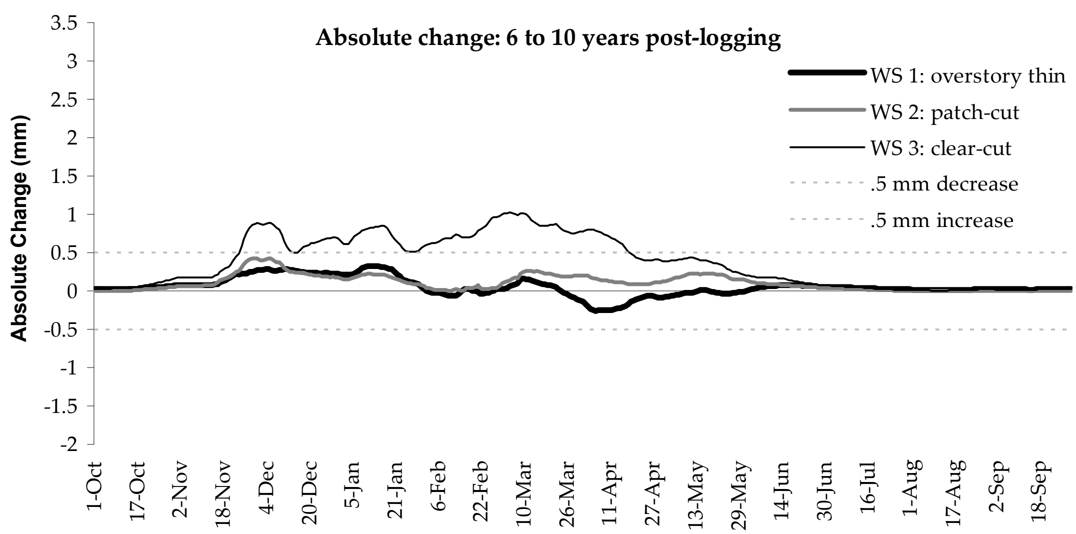

Figure C-2: Coyote WS absolute change 6-10 years post-logging.

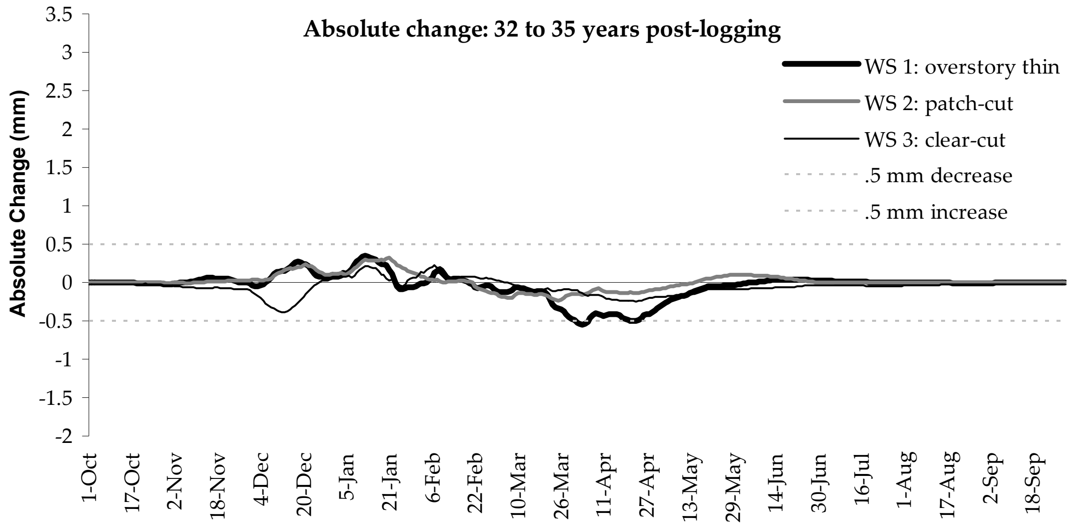

Figure C-3: Coyote WS absolute change 32-35 years post-logging.