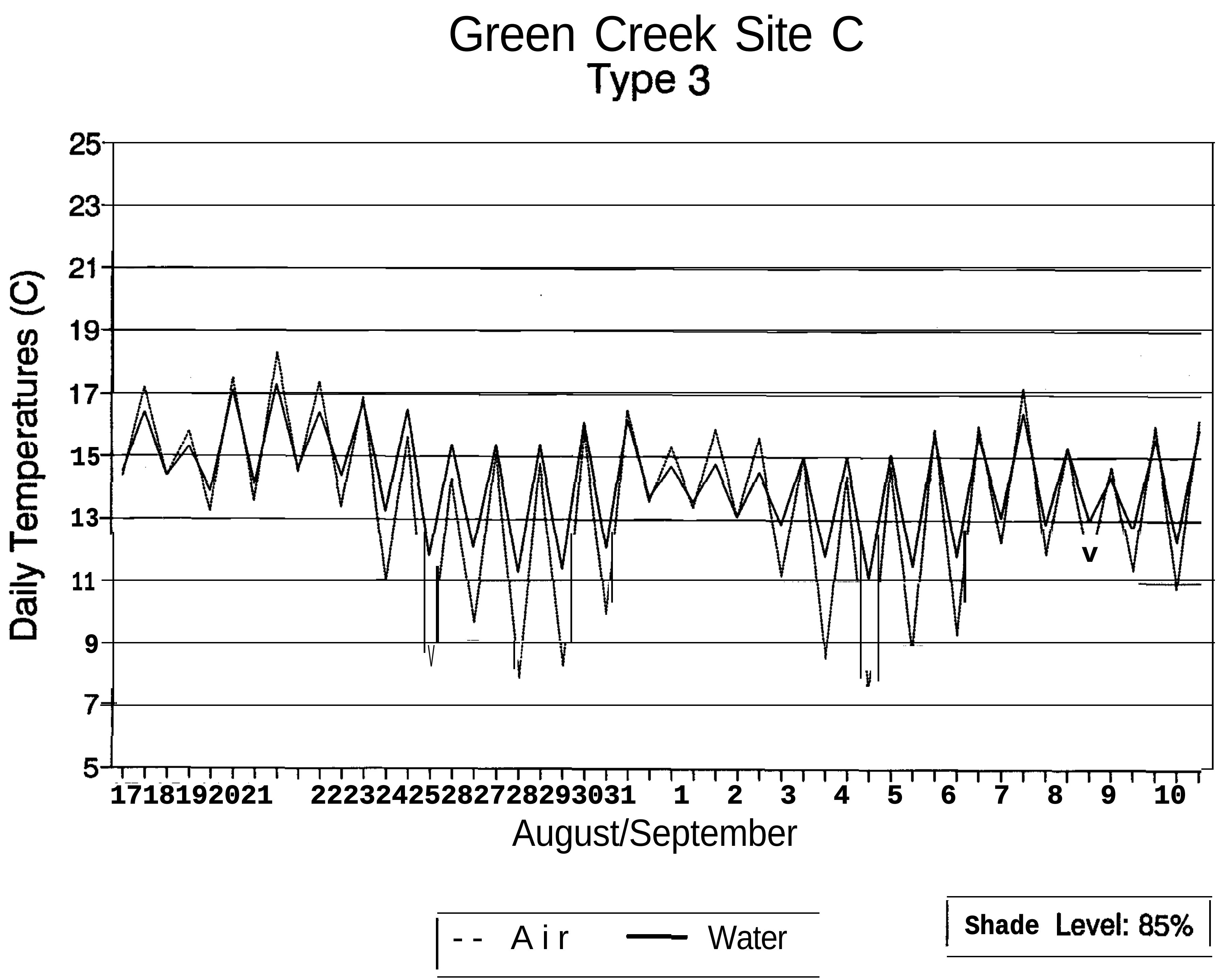
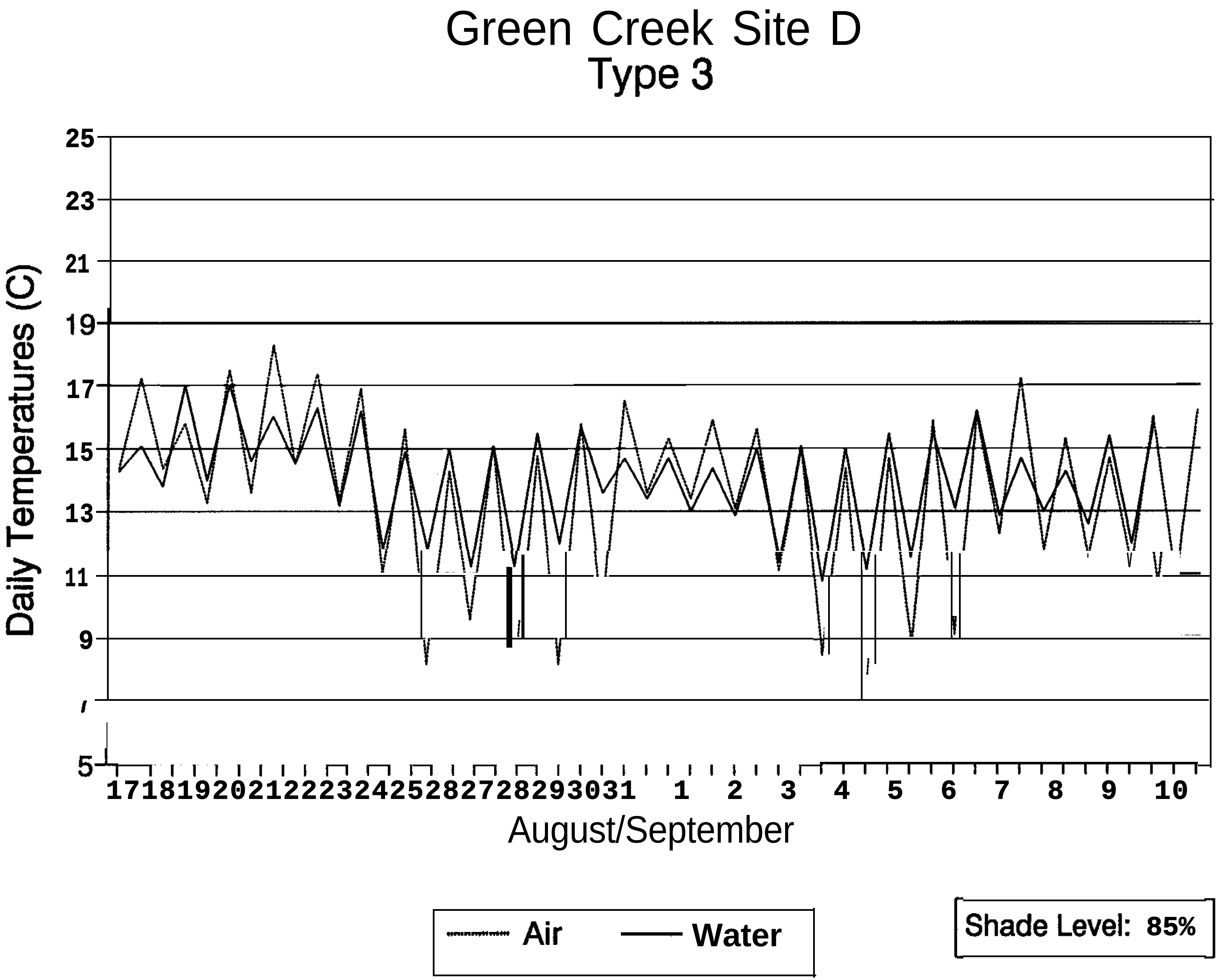
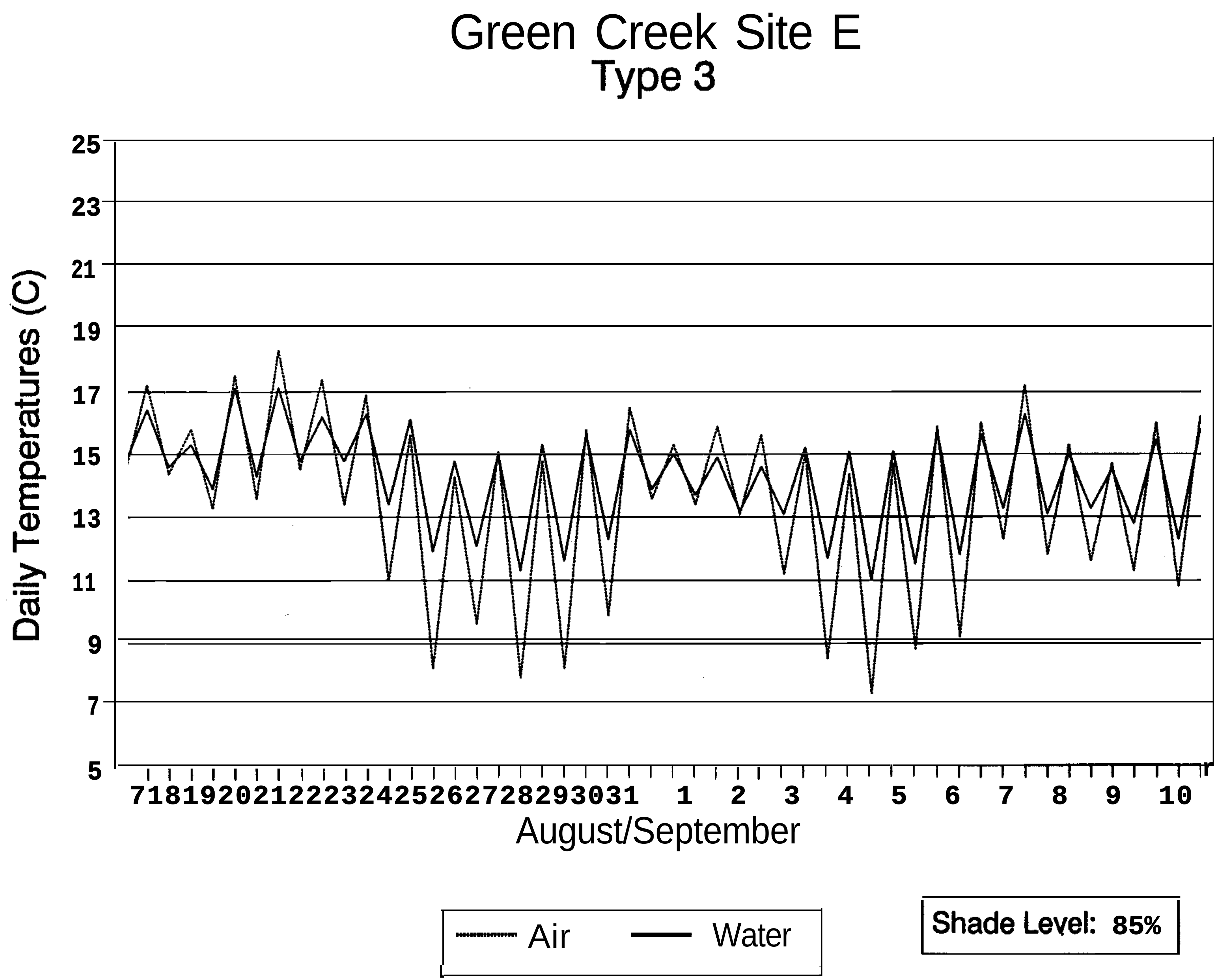
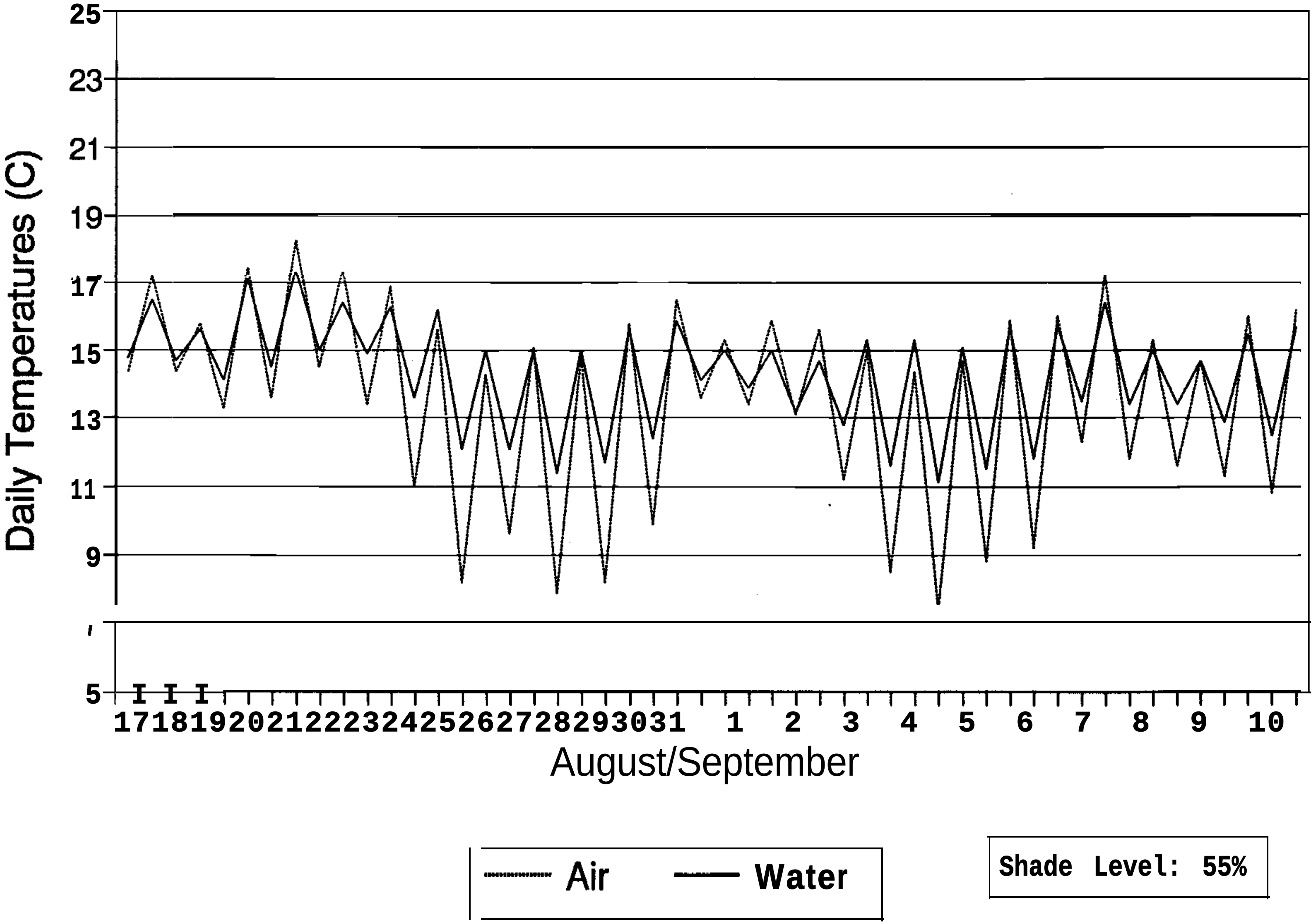


Green Creek Site C
Type 3
Daily Temperatures (C)
25
23
21
19
17
15
13
11
9
7
5
17 18 19 20 21 22 23 24 25 28 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10
August/September
-- Air
Water
Shade Level: 85%


Green Creek Site D
Type 3
Daily Temperatures (C)
25
23
21
19
17
15
13
11
9
5
17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10
August/September
Air
Water
Shade Level: 85%

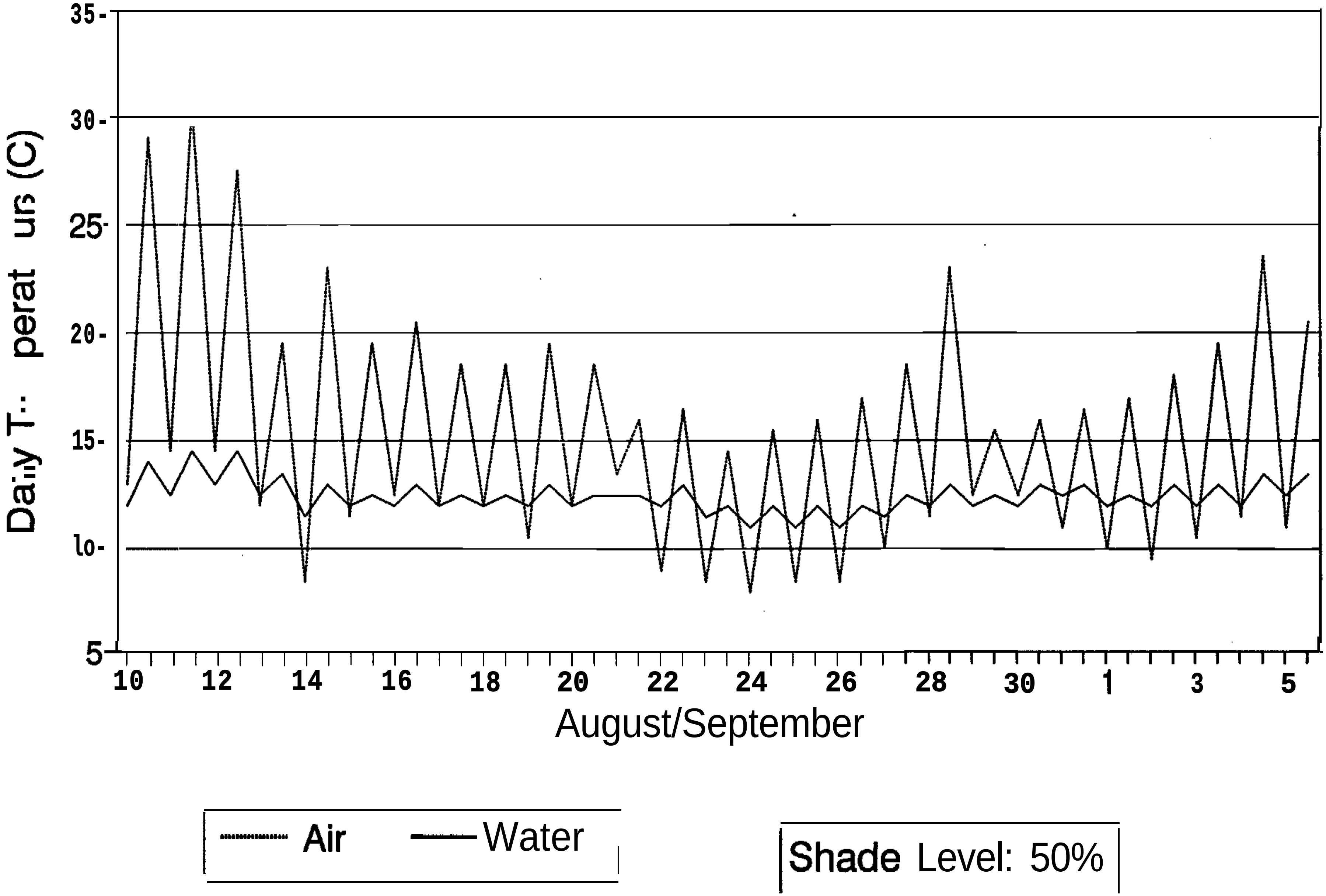

Green Creek Site E
Type 3
Daily Temperatures (C)
25
23
21
19
17
15
13
11
9
7
5
17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10
August/September
Air
Water
Shade Level: 85%

Green Creek Site F
Type 3



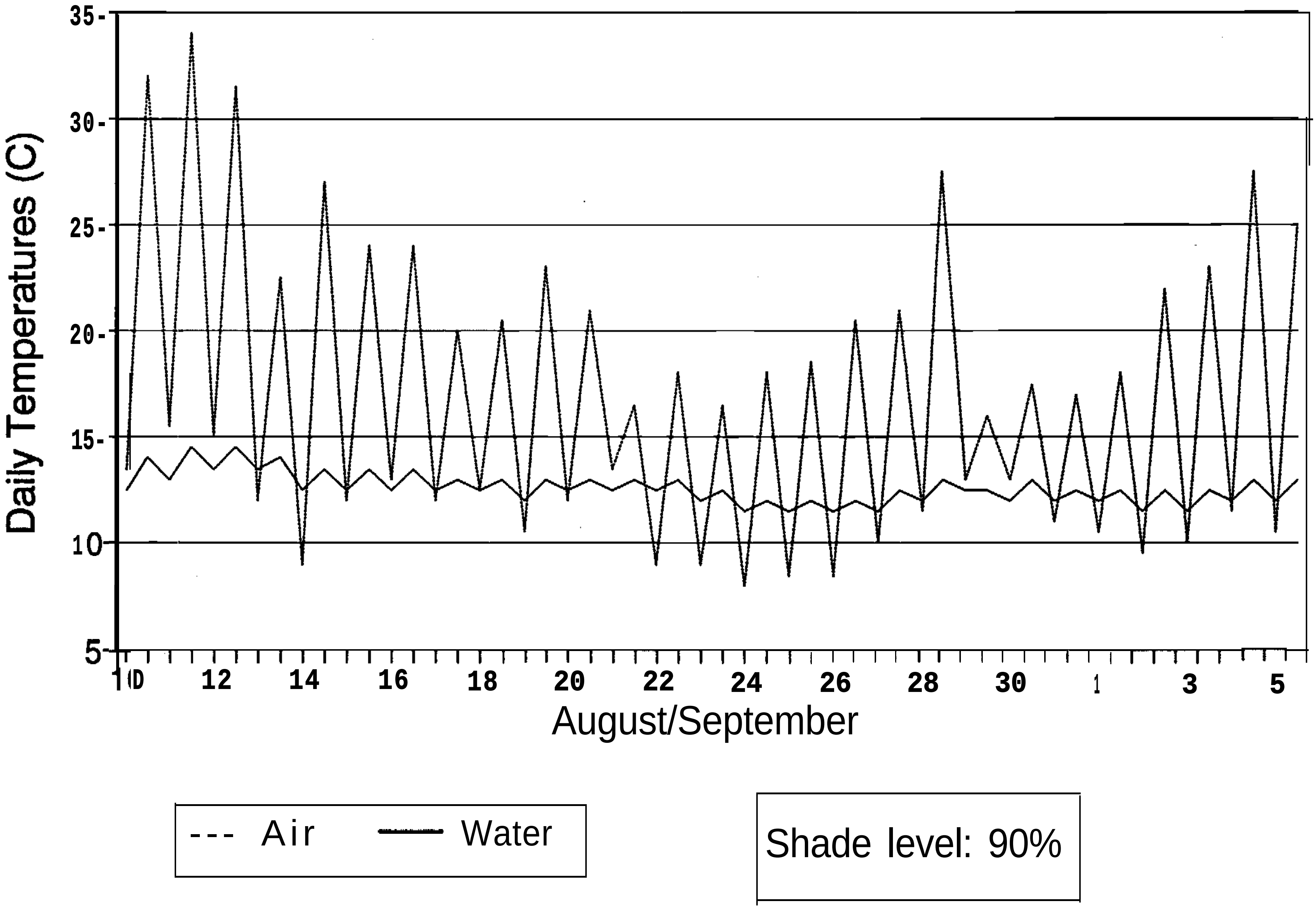
Shade Level: 55%

Hanaford Creek Site A
Type 3, above tributaries

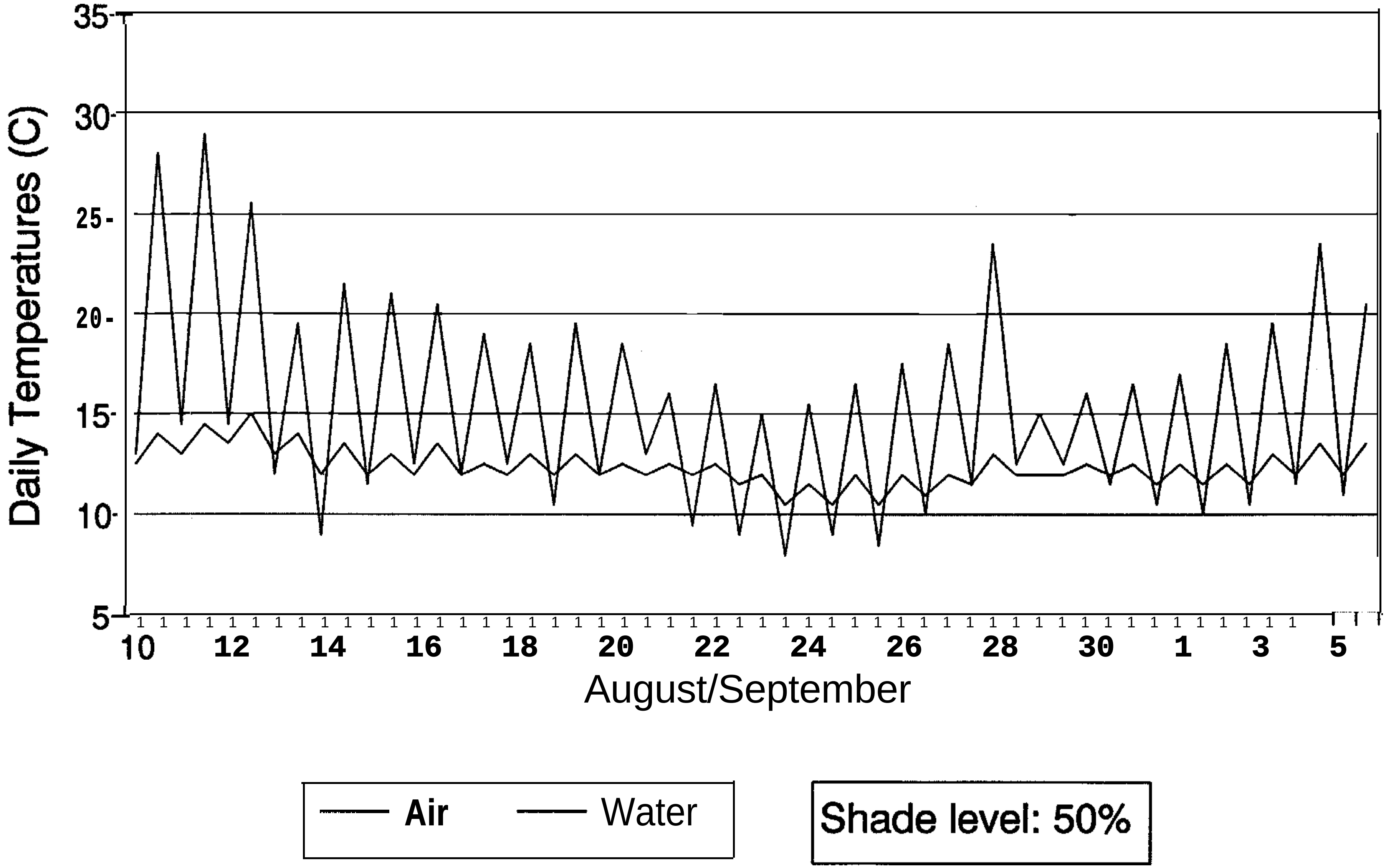


Shade Level: 50%

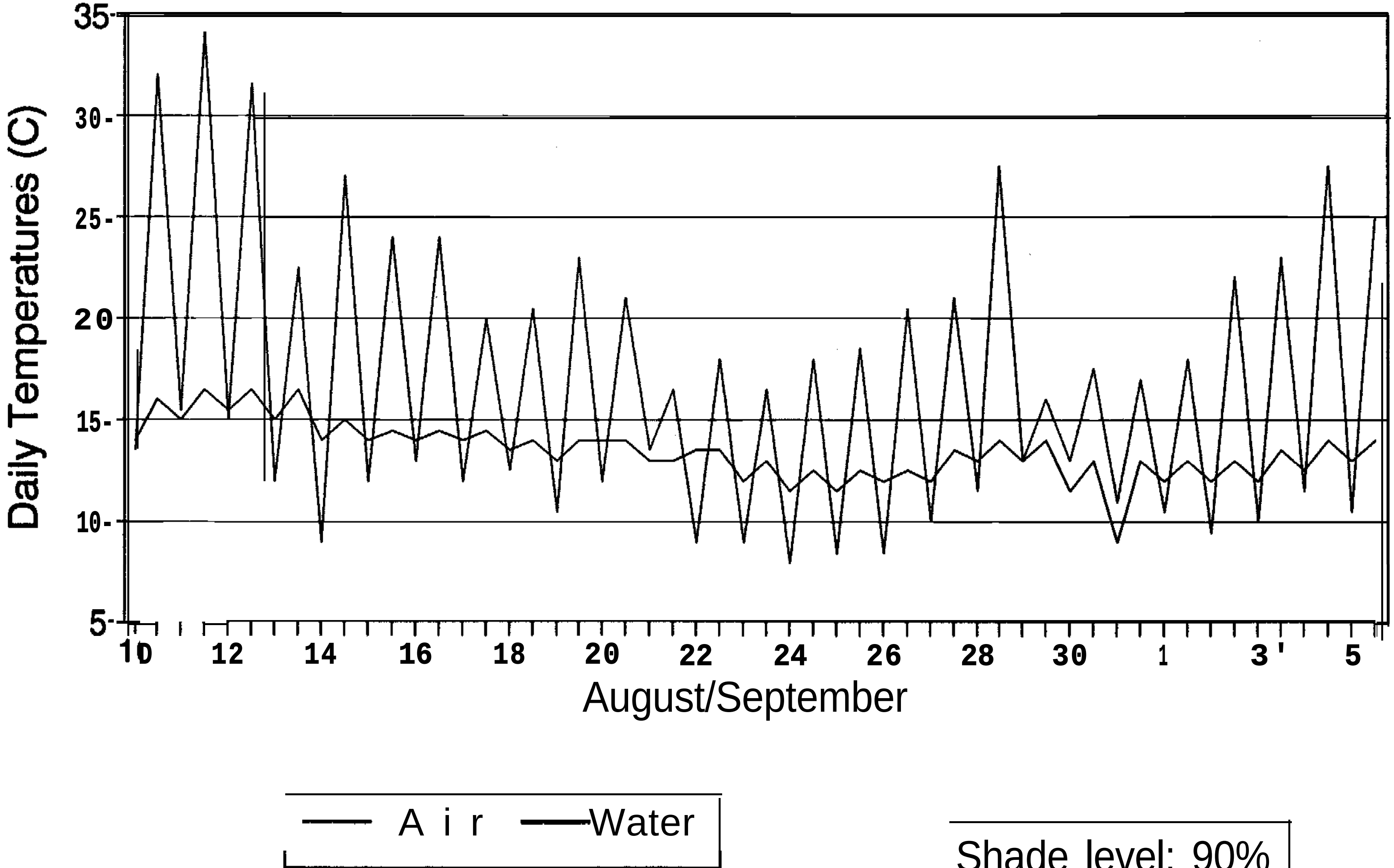
Hanaford Creek Site B
Type 4 Harvested



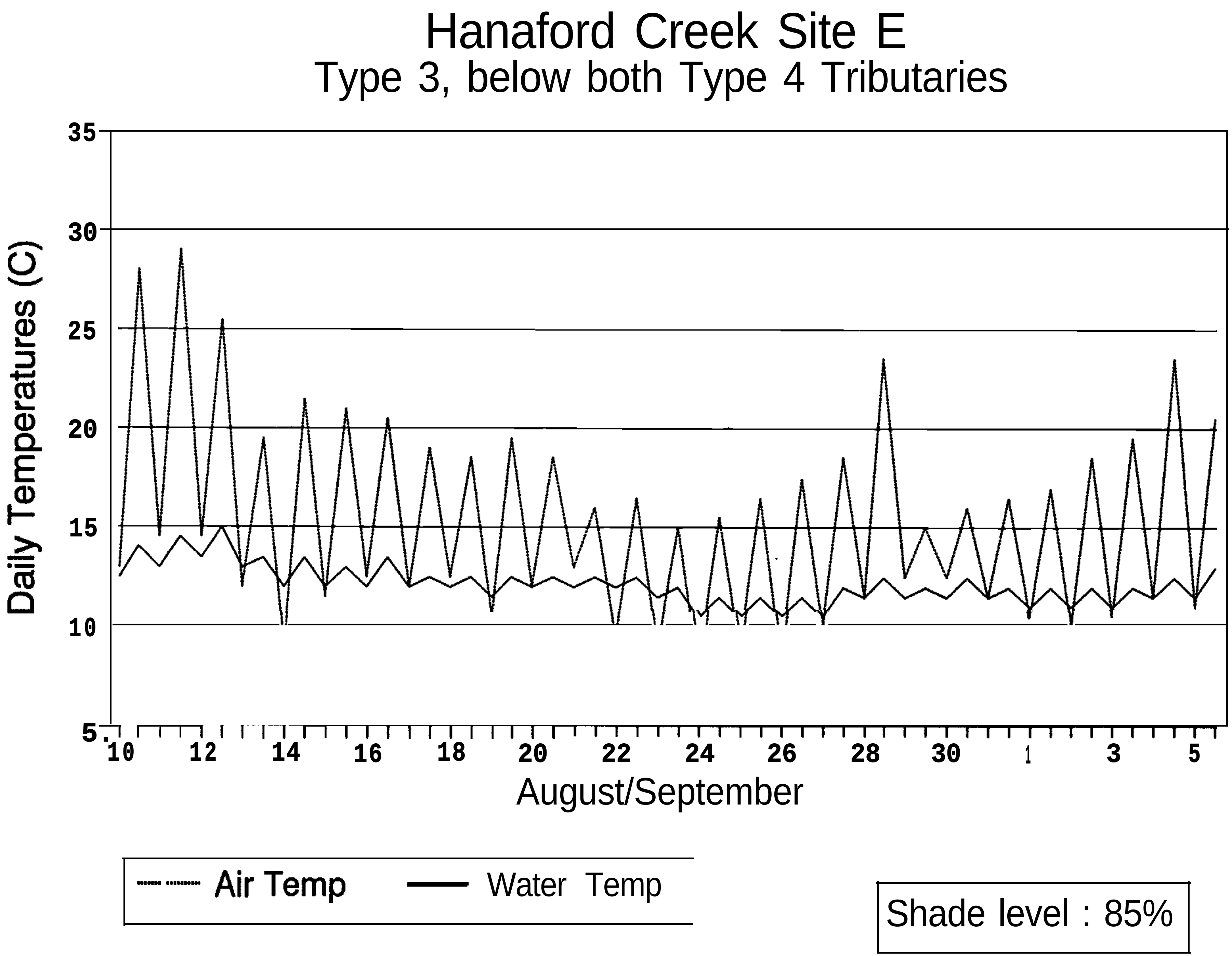
Hanaford Creek Site C
Type 3, Mainstem between Tributaries

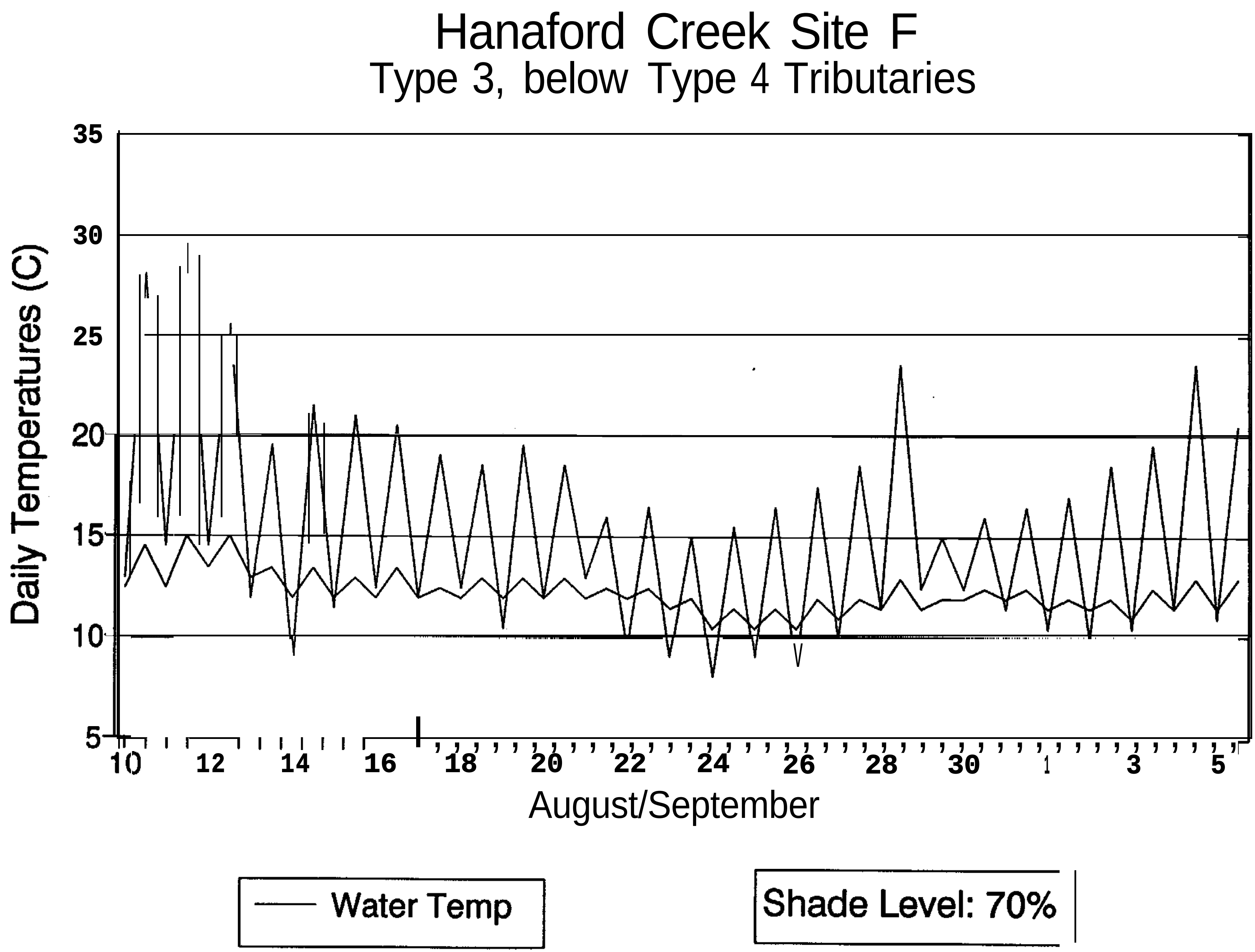


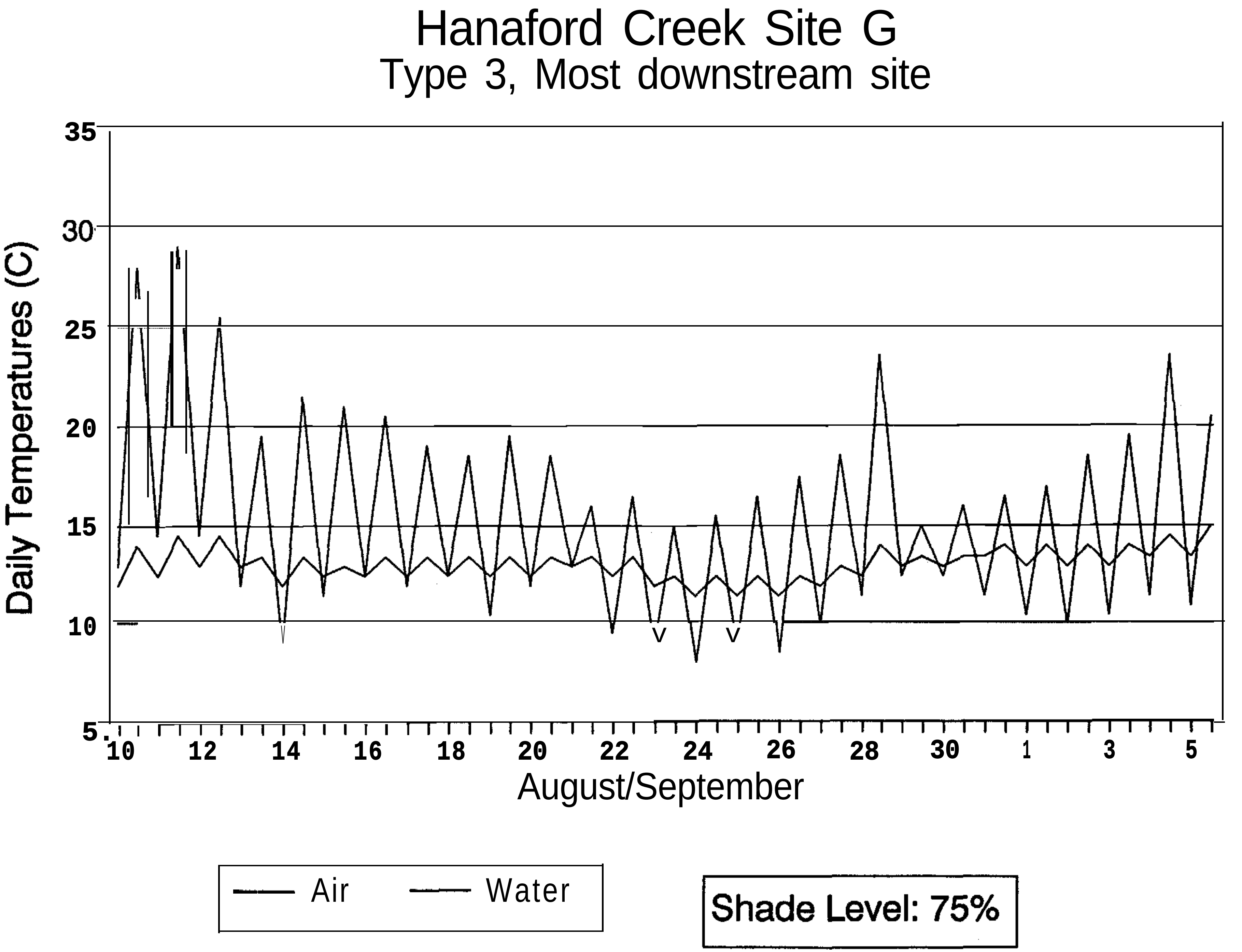
Hanaford Creek Site D
Type 4 Harvested

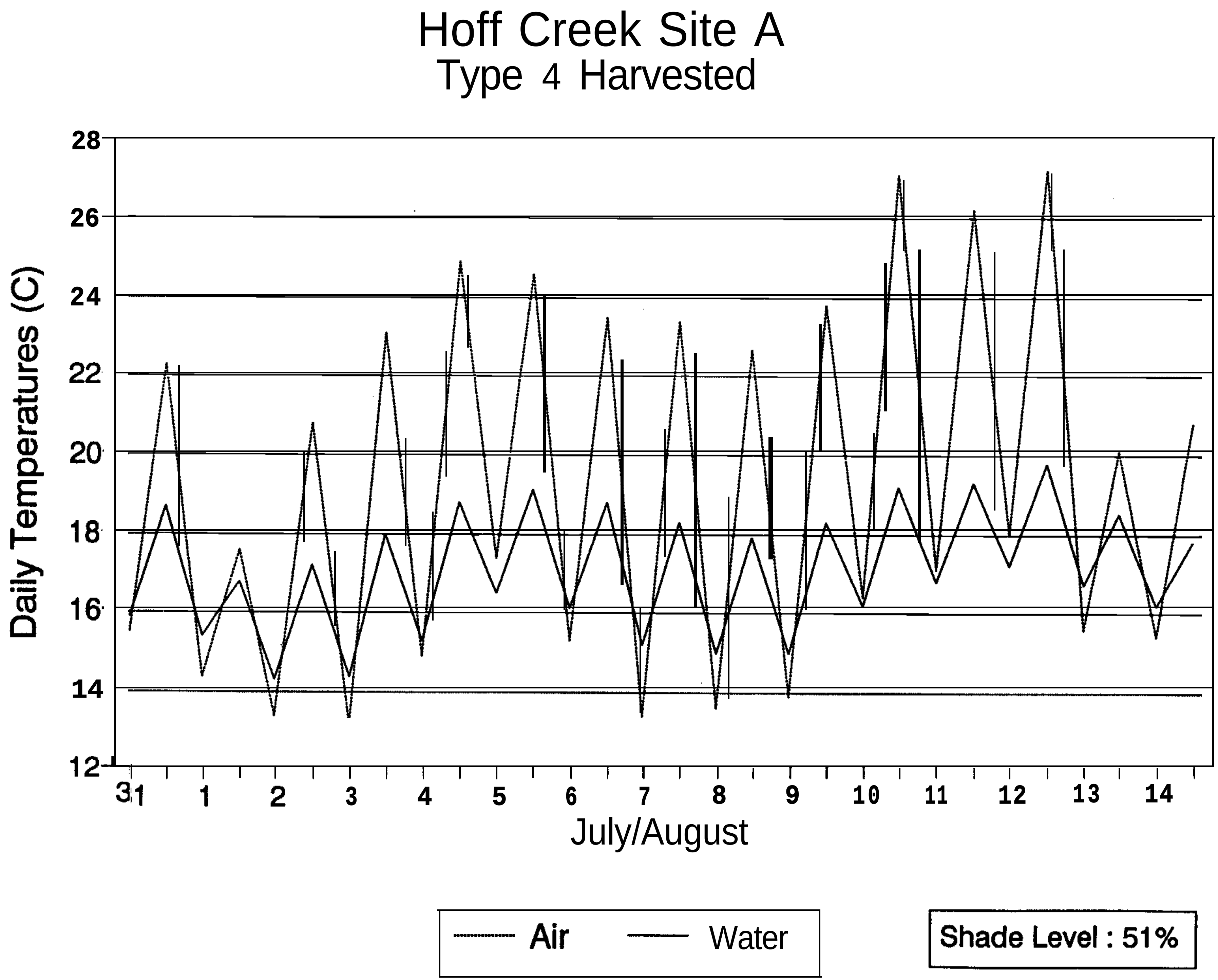


Shade level: 90%

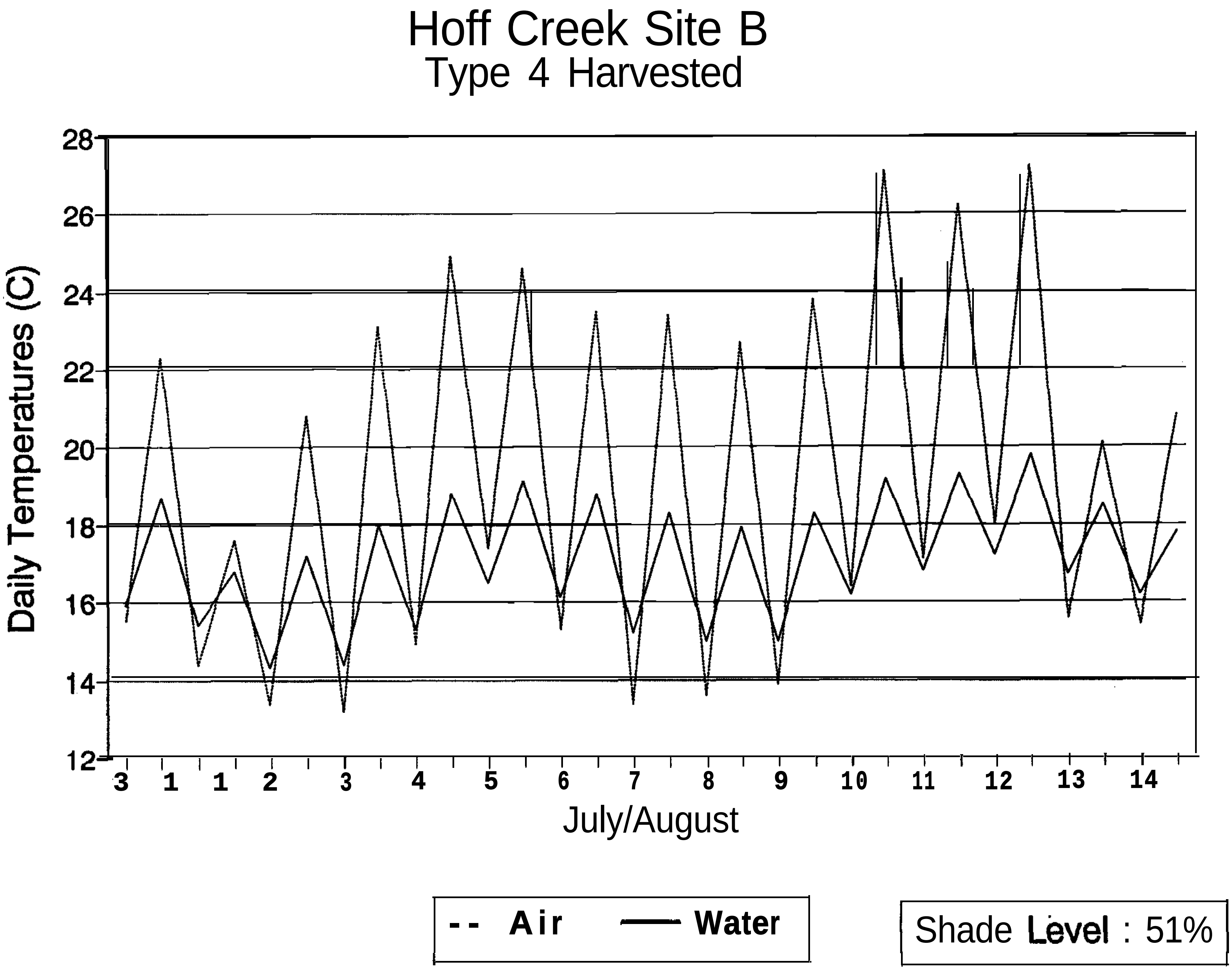

Hanaford Creek Site E
Type 3, below both Type 4 Tributaries
Daily Temperatures (C)
35
30
25
20
15
10
5
10
12
14
16
18
20
22
24
26
28
30
1
3
5
August/September
Air Temp
Water Temp
Shade level : 85%

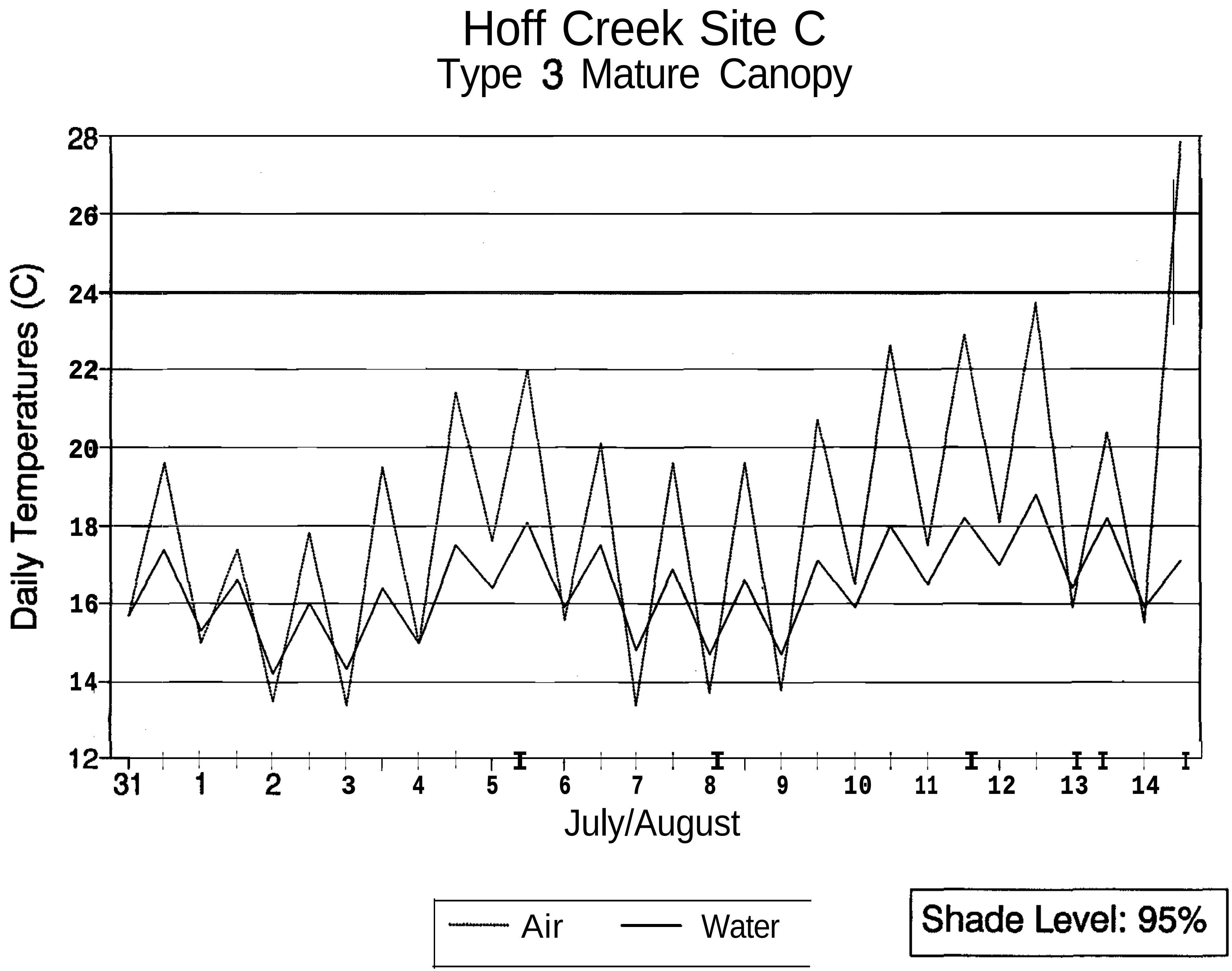

Hanaford Creek Site F
Type 3, below Type 4 Tributaries
Daily Temperatures (C)
35
30
25
20
15
10
5
10
12
14
16
18
20
22
24
26
28
30
1
3
5
August/September
Water Temp
Shade Level: 70%


Hanaford Creek Site G
Type 3, Most downstream site
Daily Temperatures (C)
35
30
25
20
15
10
5
10
12
14
16
18
20
22
24
26
28
30
1
3
5
August/September
Air
Water
Shade Level: 75%



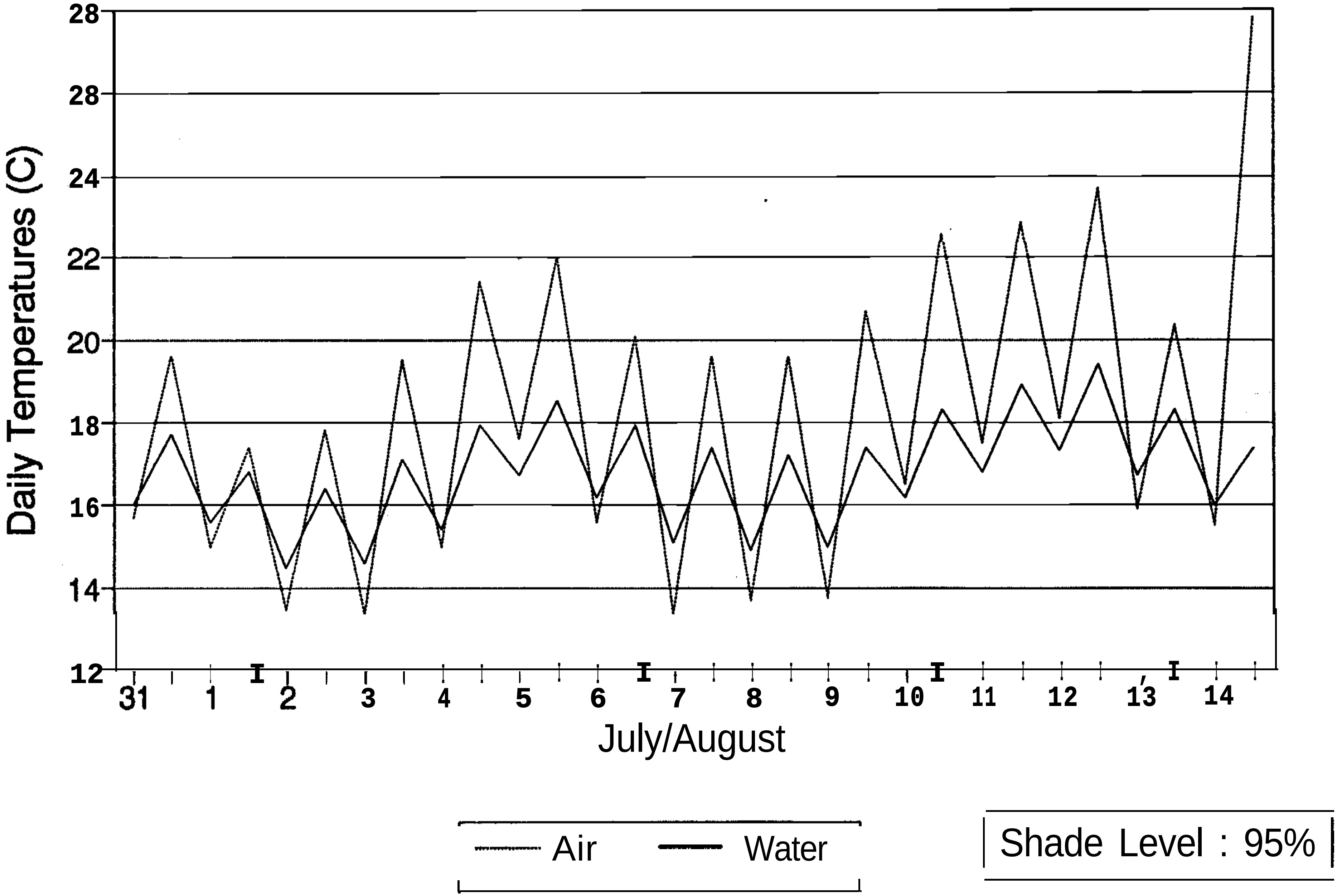
Hoff Creek Site A
Type 4 Harvested
Daily Temperatures (C)
28
26
24
22
20
18
16
14
12
31
1
2
3
4
5
6
7
8
9
10
11
12
13
14
July/August
Air
Water
Shade Level : 51%

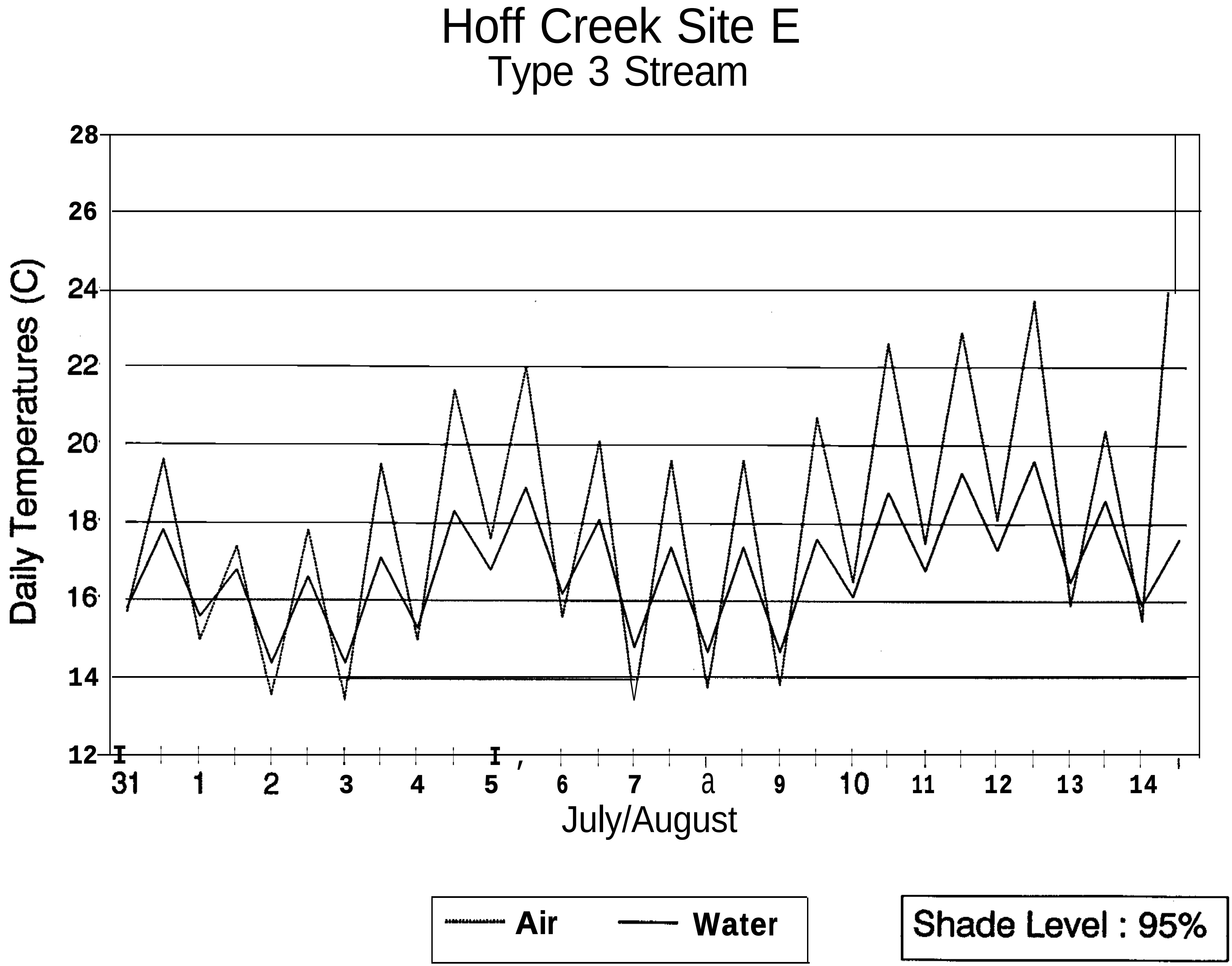

Hoff Creek Site B
Type 4 Harvested
28
26
24
22
20
18
16
14
12
Daily Temperatures (C)
3
1
1
2
3
4
5
6
7
8
9
10
11
12
13
14
July/August
-- Air
Water
Shade Level : 51%

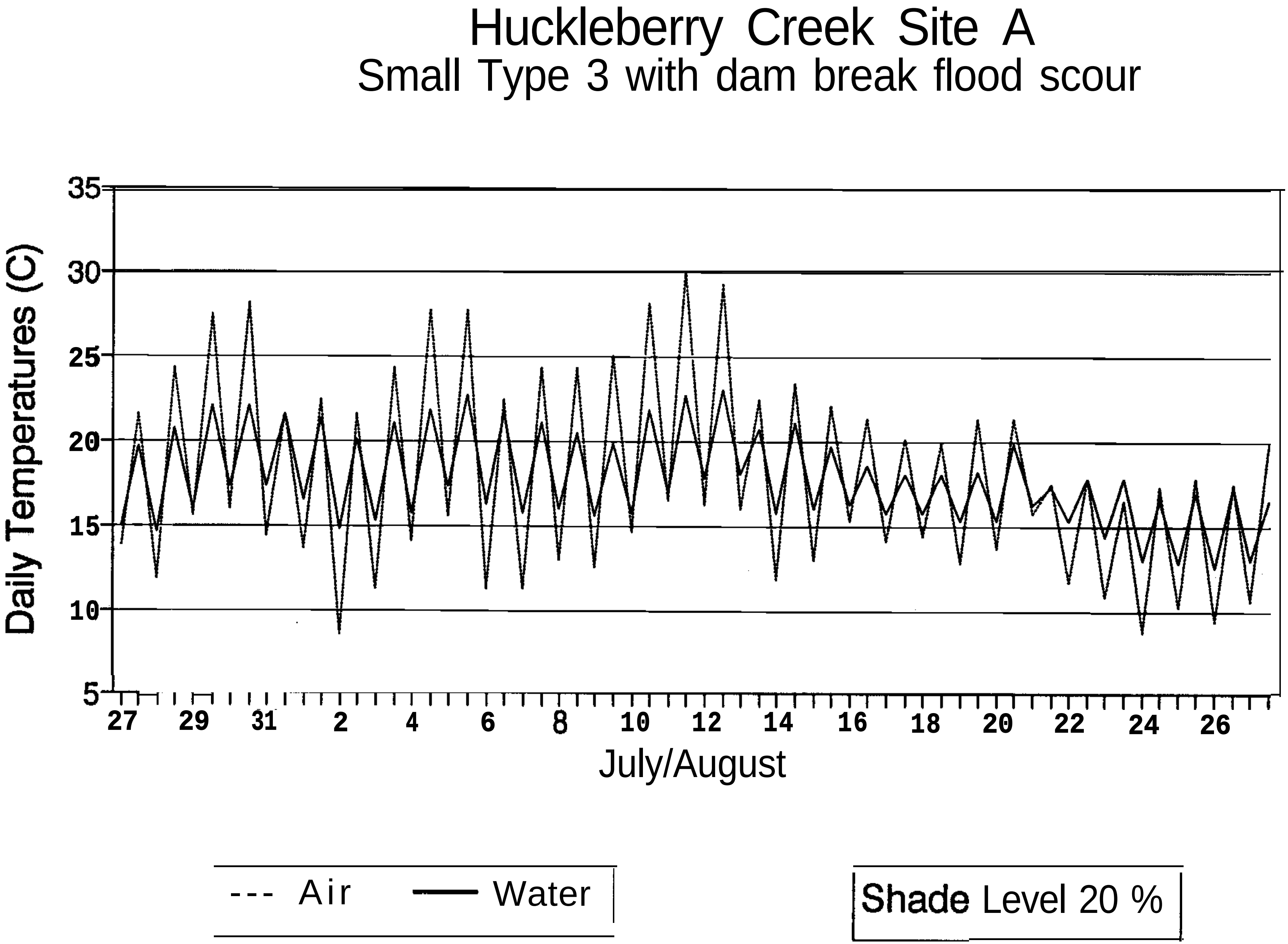


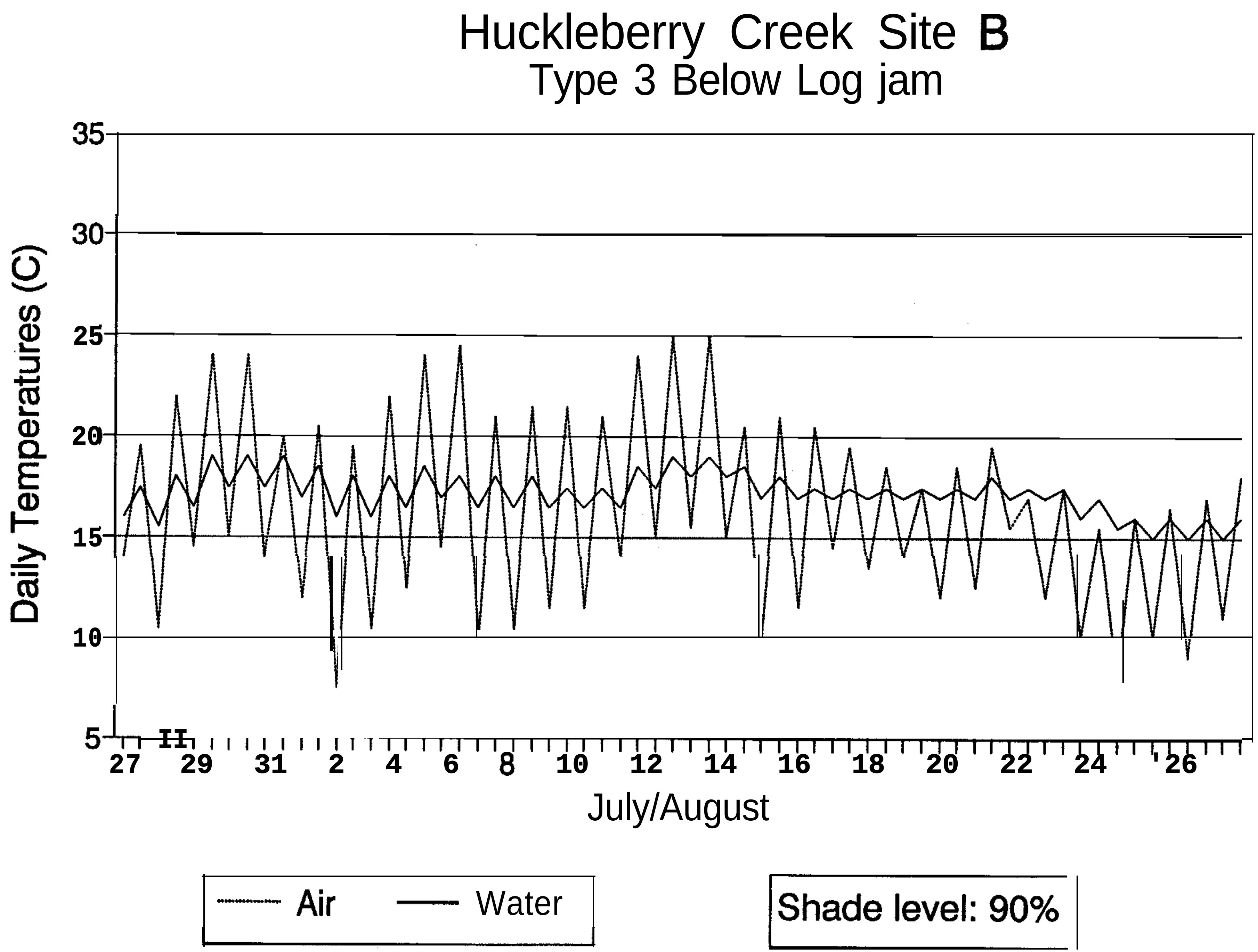
Hoff Creek Site C
Type 3 Mature Canopy
Daily Temperatures (C)
28
26
24
22
20
18
16
14
12
31
1
2
3
4
5
6
7
8
9
10
11
12
13
14
July/August
Air
Water
Shade Level: 95%

Hoff Creek Site D
Type 3 Stream

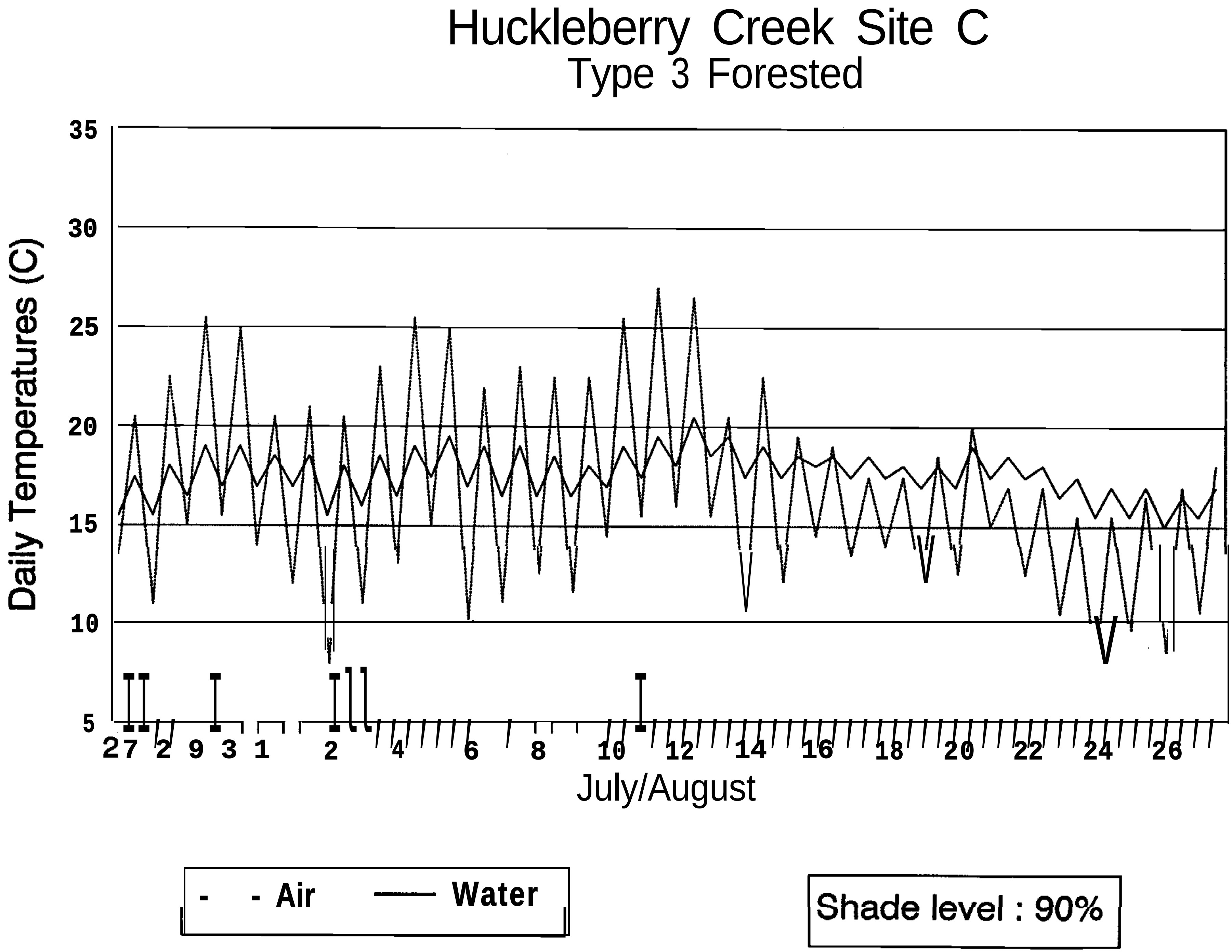



Hoff Creek Site E
Type 3 Stream
28
26
24
22
20
18
16
14
12
Daily Temperatures (C)
31
1
2
3
4
5
6
7
a
9
10
11
12
13
14
July/August
Air
Water
Shade Level : 95%

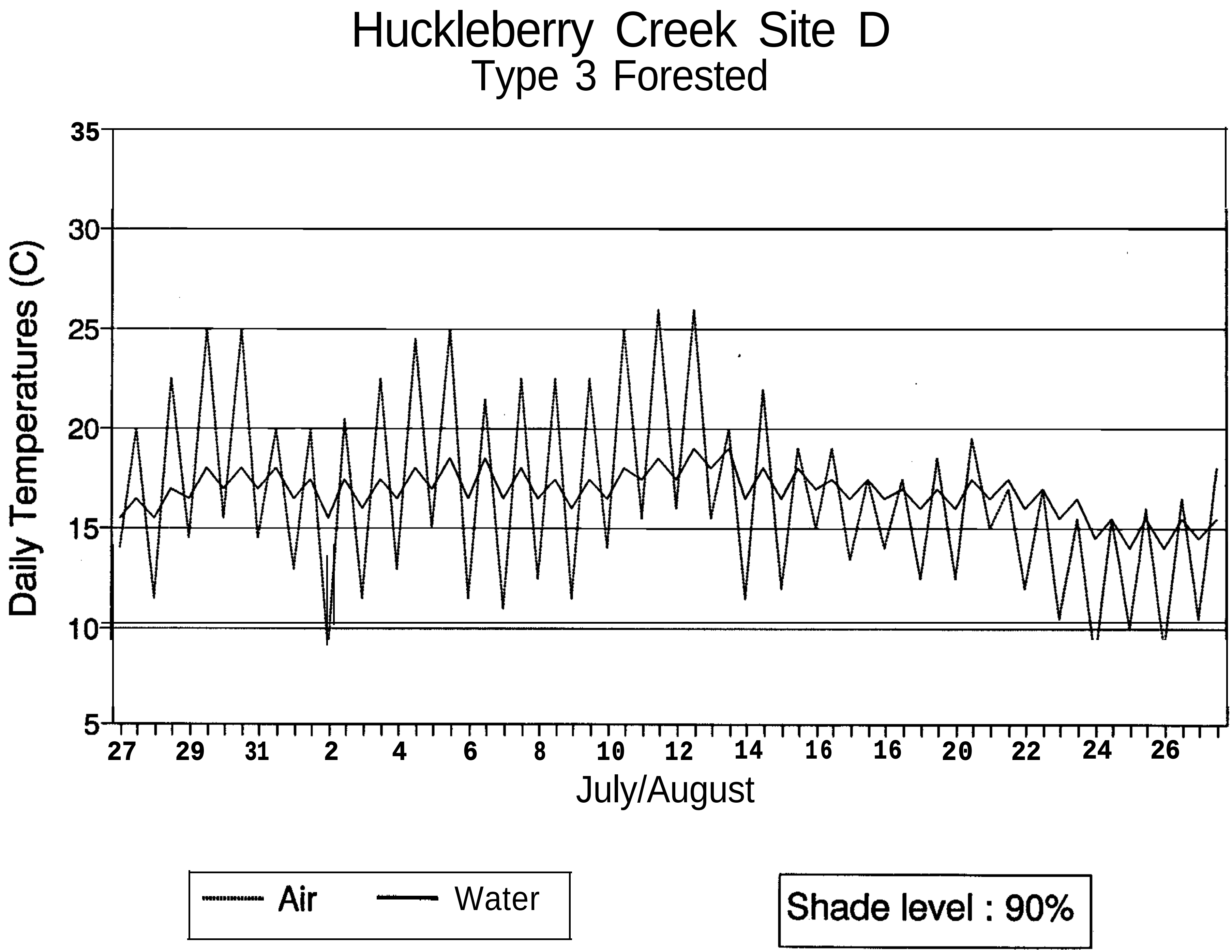

Huckleberry Creek Site A
Small Type 3 with dam break flood scour
Daily Temperatures (C)
35
30
25
20
15
10
5
27
29
31
2
4
6
8
10
12
14
16
18
20
22
24
26
July/August
--- Air
Water
Shade Level 20 %

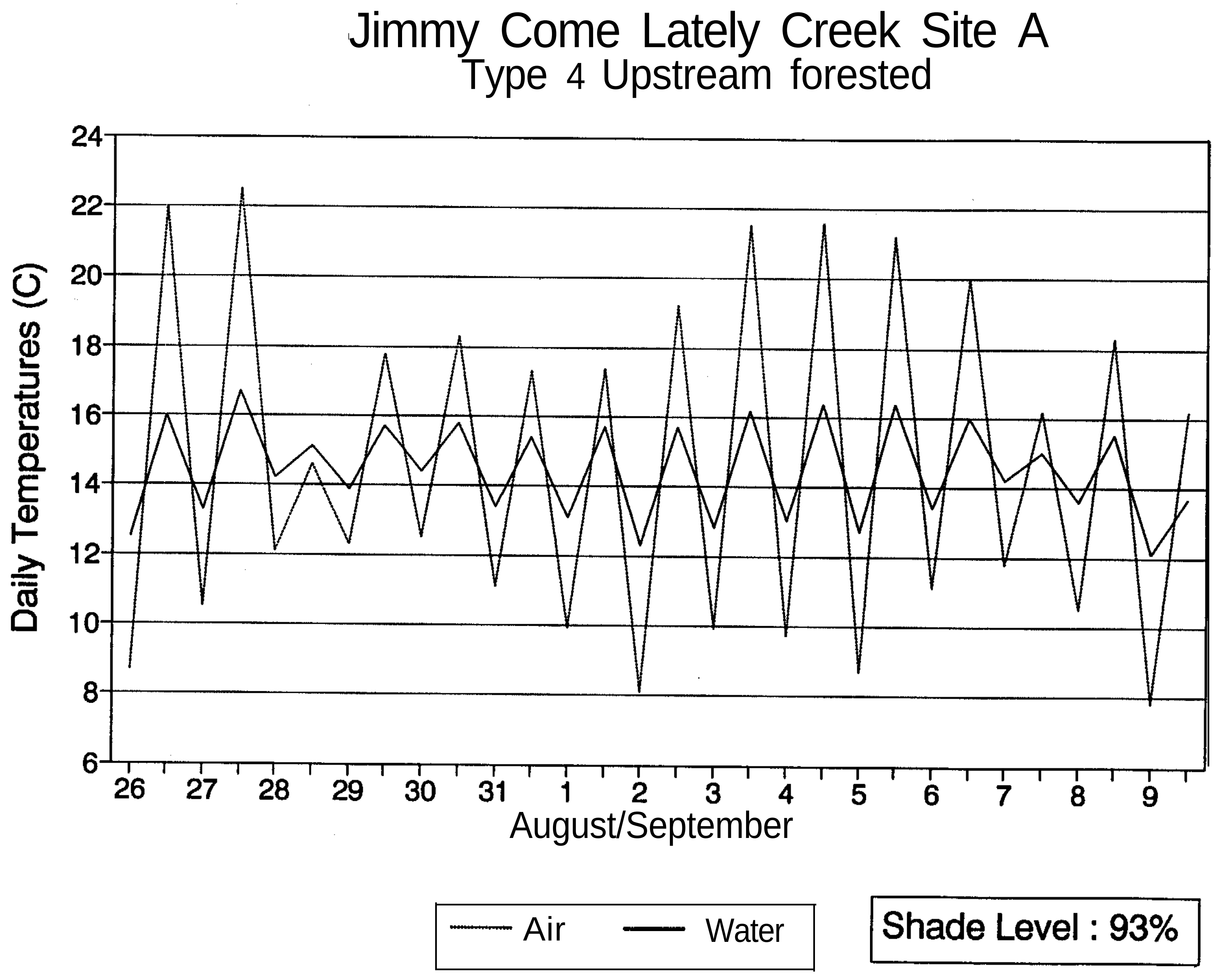


Huckleberry Creek Site B
Type 3 Below Log jam
Daily Temperatures (C)
35
30
25
20
15
10
5
27
29
31
2
4
6
8
10
12
14
16
18
20
22
24
26
July/August
Air
Water
Shade level: 90%



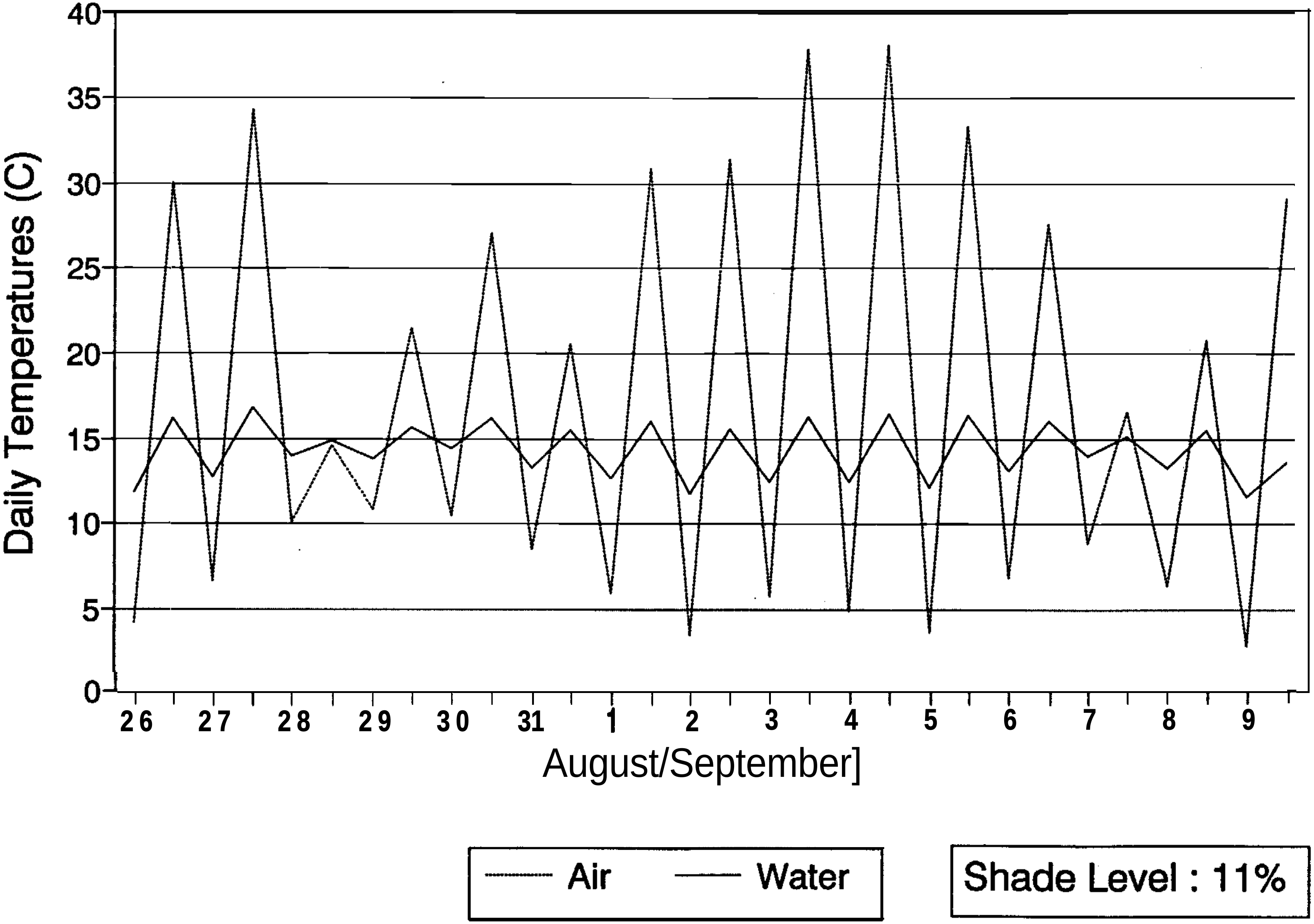
Huckleberry Creek Site C
Type 3 Forested
Daily Temperatures (C)
35
30
25
20
15
10
5
27 2 9 3 1 2 4 6 8 10 12 14 16 18 20 22 24 26
July/August
- - Air
Water
Shade level : 90%

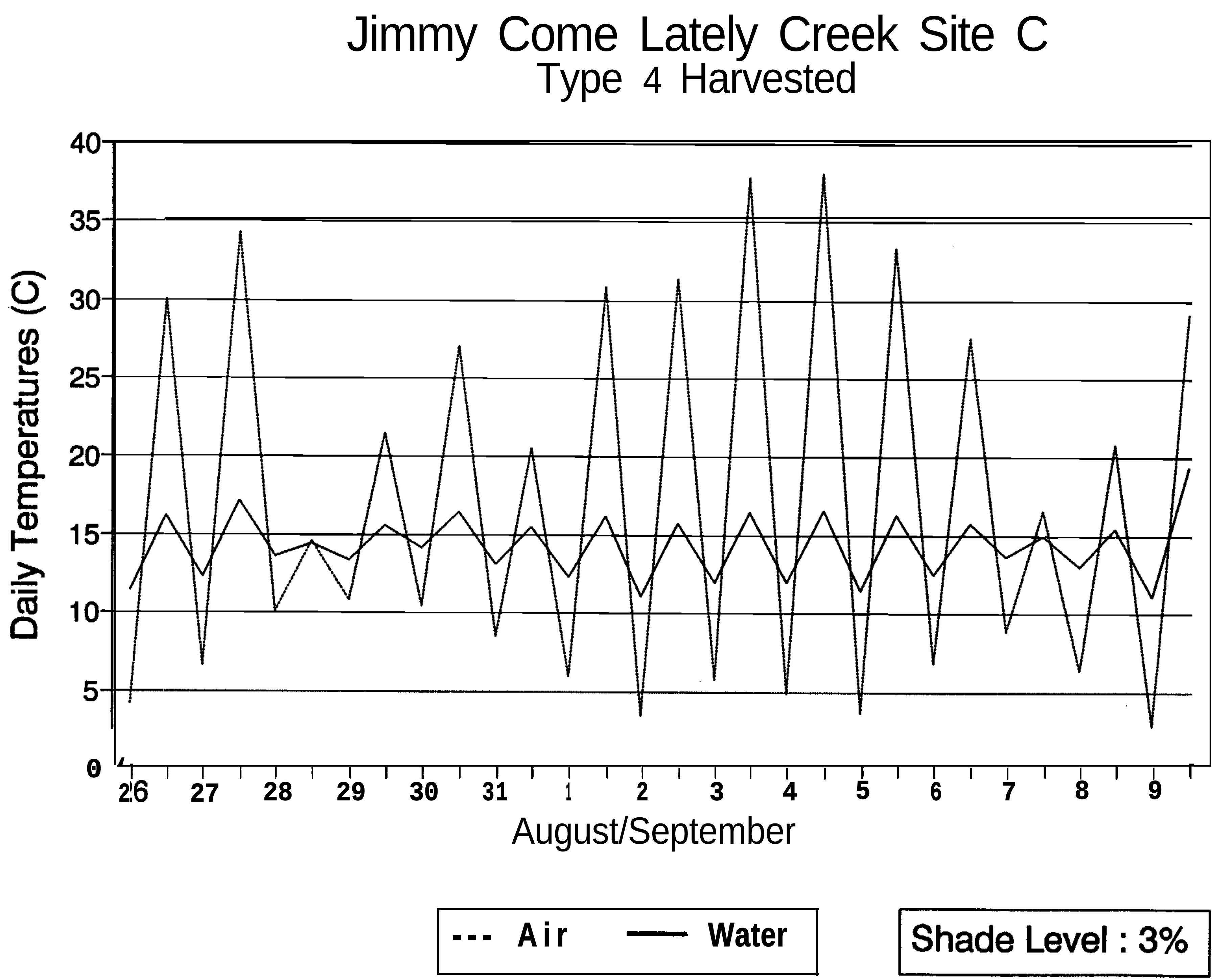

Huckleberry Creek Site D
Type 3 Forested
Daily Temperatures (C)
35
30
25
20
15
10
5
27
29
31
2
4
6
8
10
12
14
16
16
20
22
24
26
July/August
Air
Water
Shade level : 90%



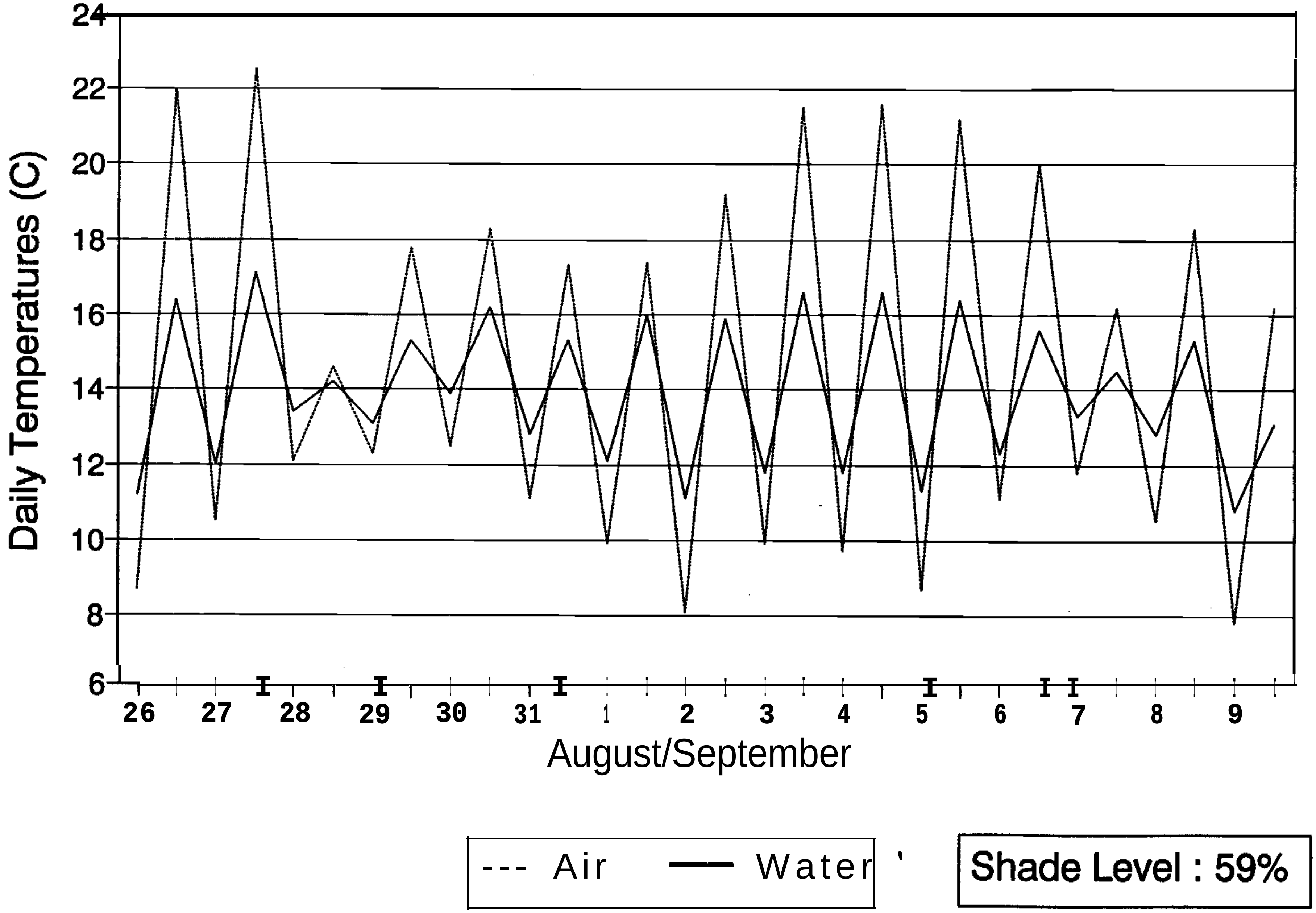
Jimmy Come Lately Creek Site A
Type 4 Upstream forested
Daily Temperatures (C)
24
22
20
18
16
14
12
10
8
6
26
27
28
29
30
31
1
2
3
4
5
6
7
8
9
August/September
Air
Water
Shade Level : 93%

Jimmy Come Lately Creek Site B
Type 4 Harvested

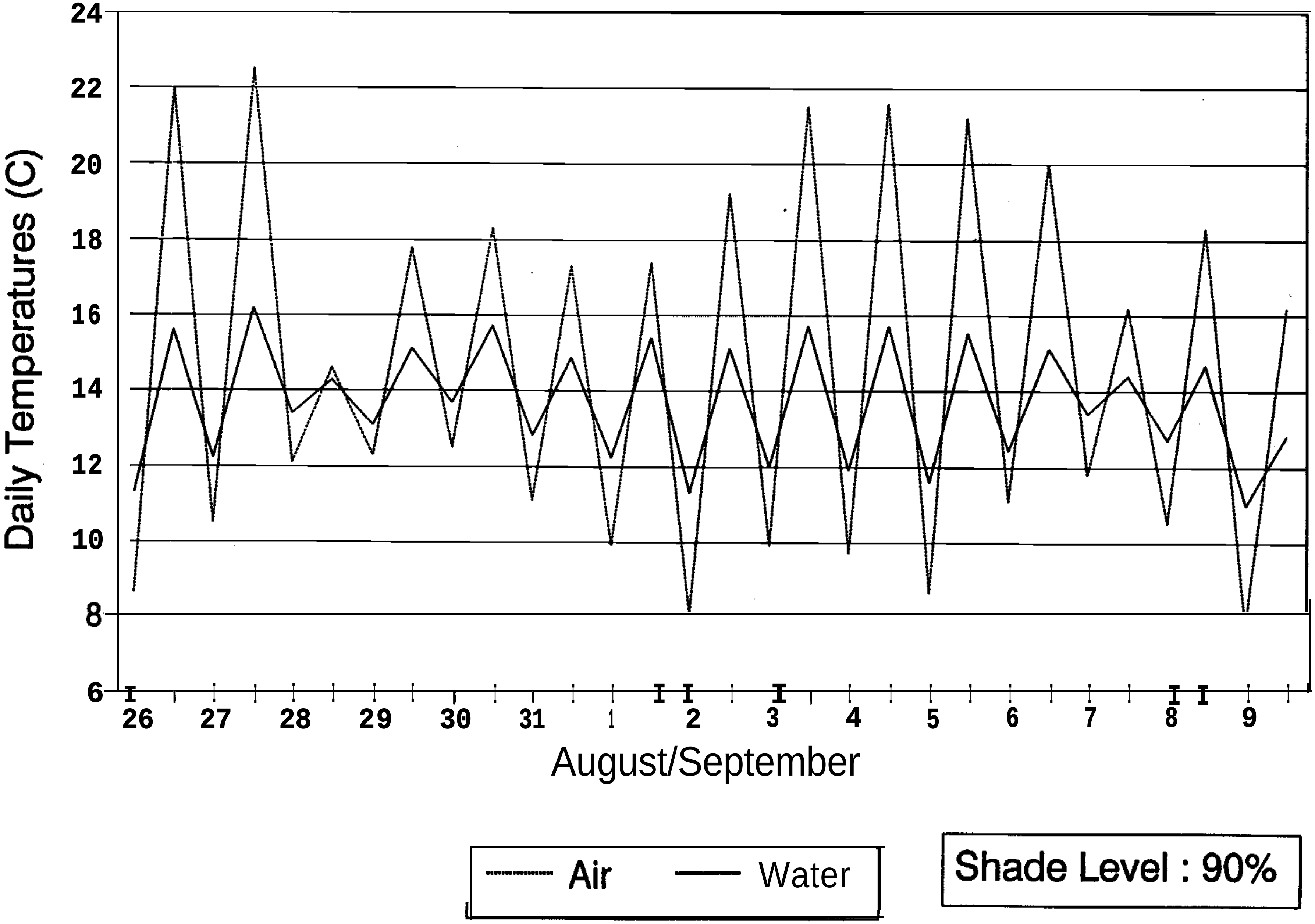



Jimmy Come Lately Creek Site C
Type 4 Harvested
Daily Temperatures (C)
0
5
10
15
20
25
30
35
40
26
27
28
29
30
31
1
2
3
4
5
6
7
8
9
August/September
Air
Water
Shade Level : 3%

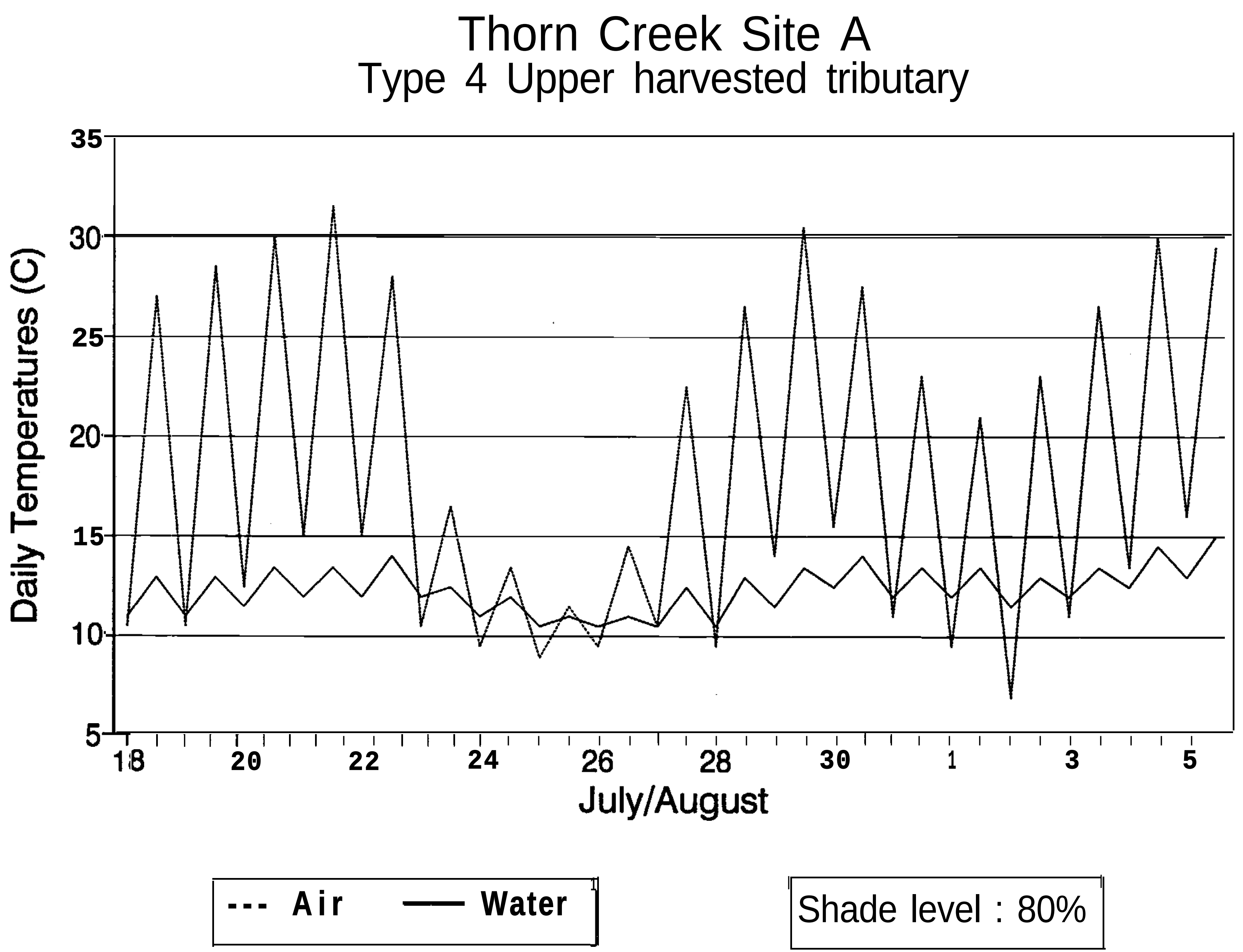
Jimmy Come Lately Creek Site D
Type 3 Selective harvest riparian

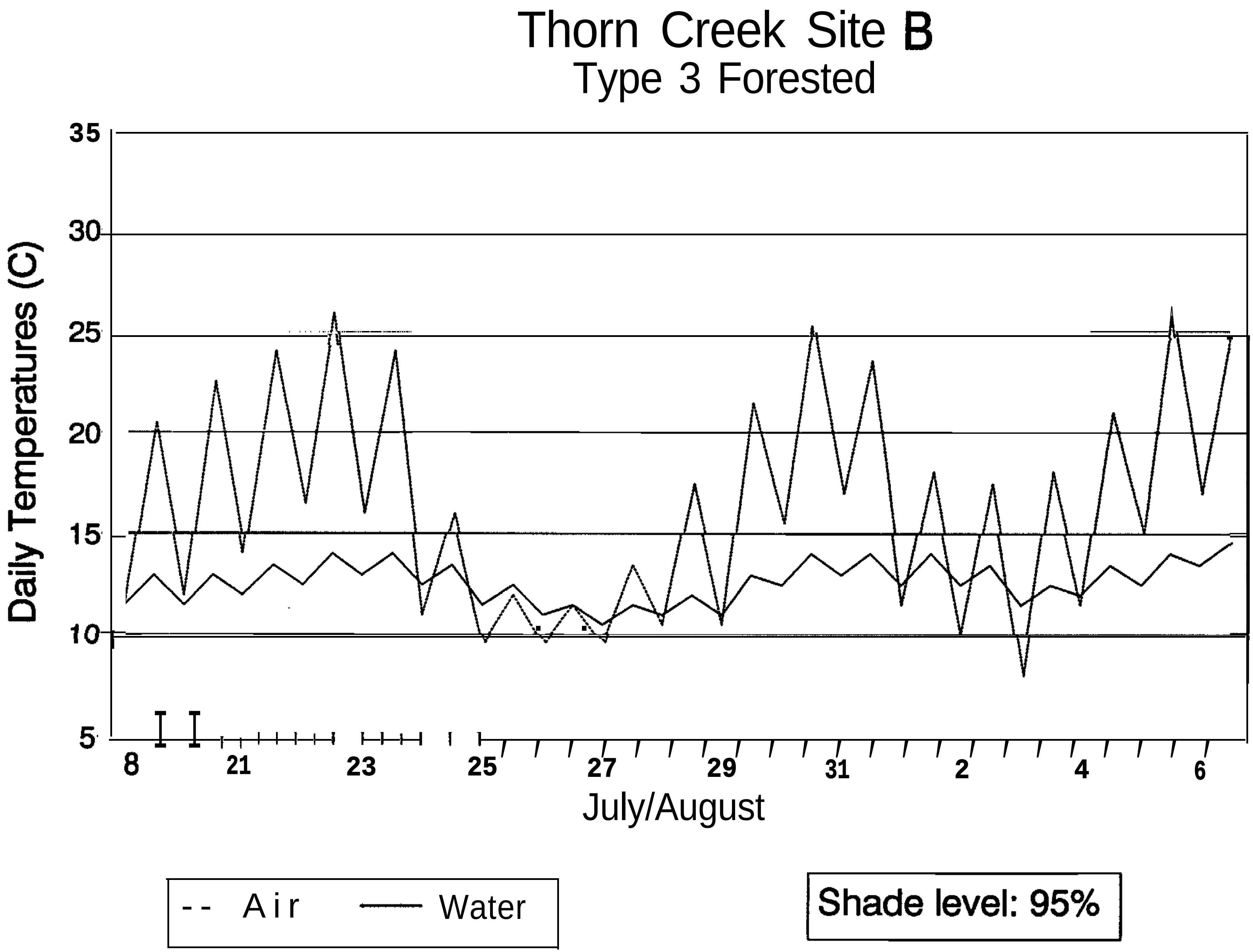


Jimmy Come Lately Creek Site E
Type 3 Selective harvest riparian

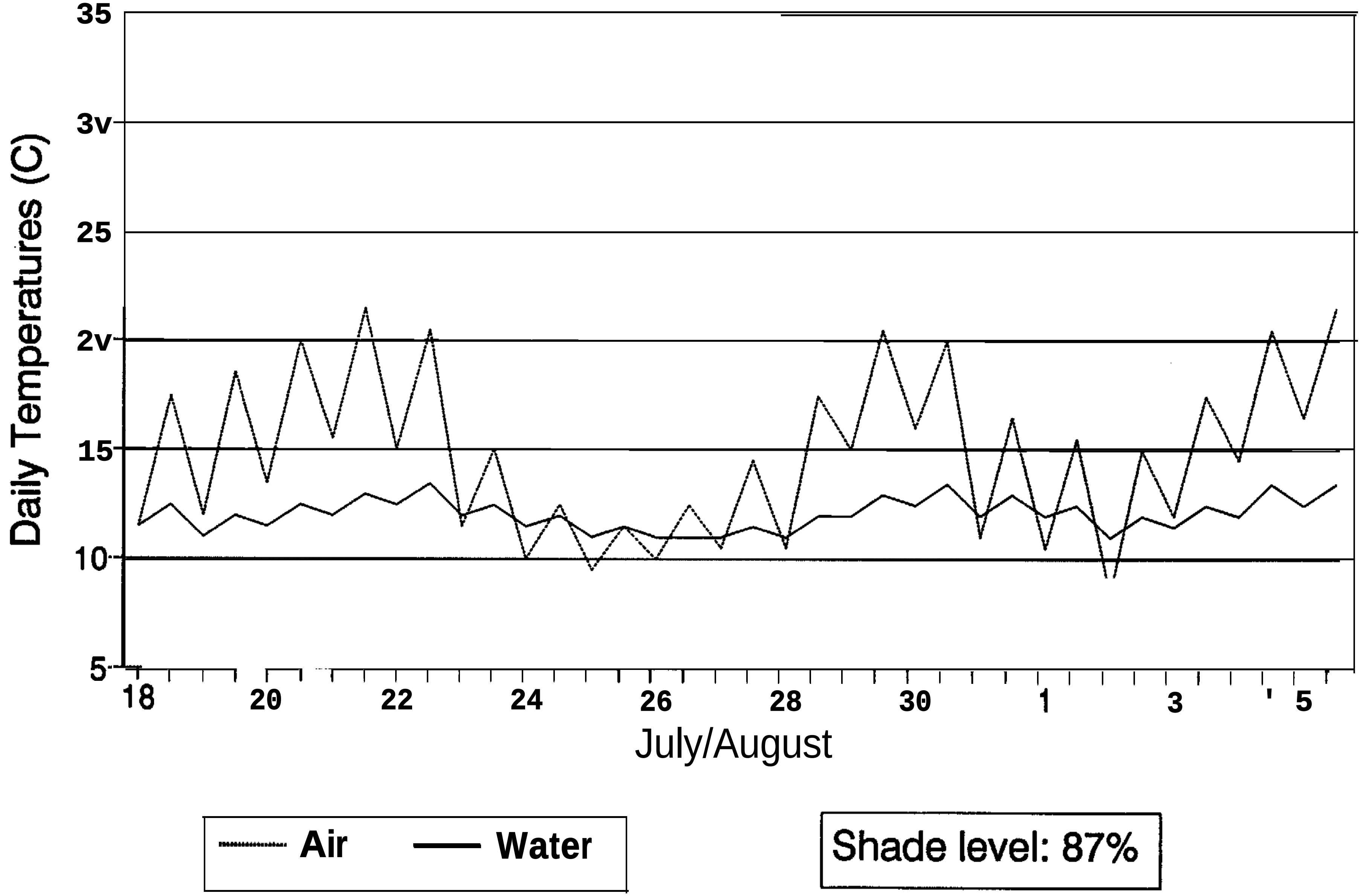


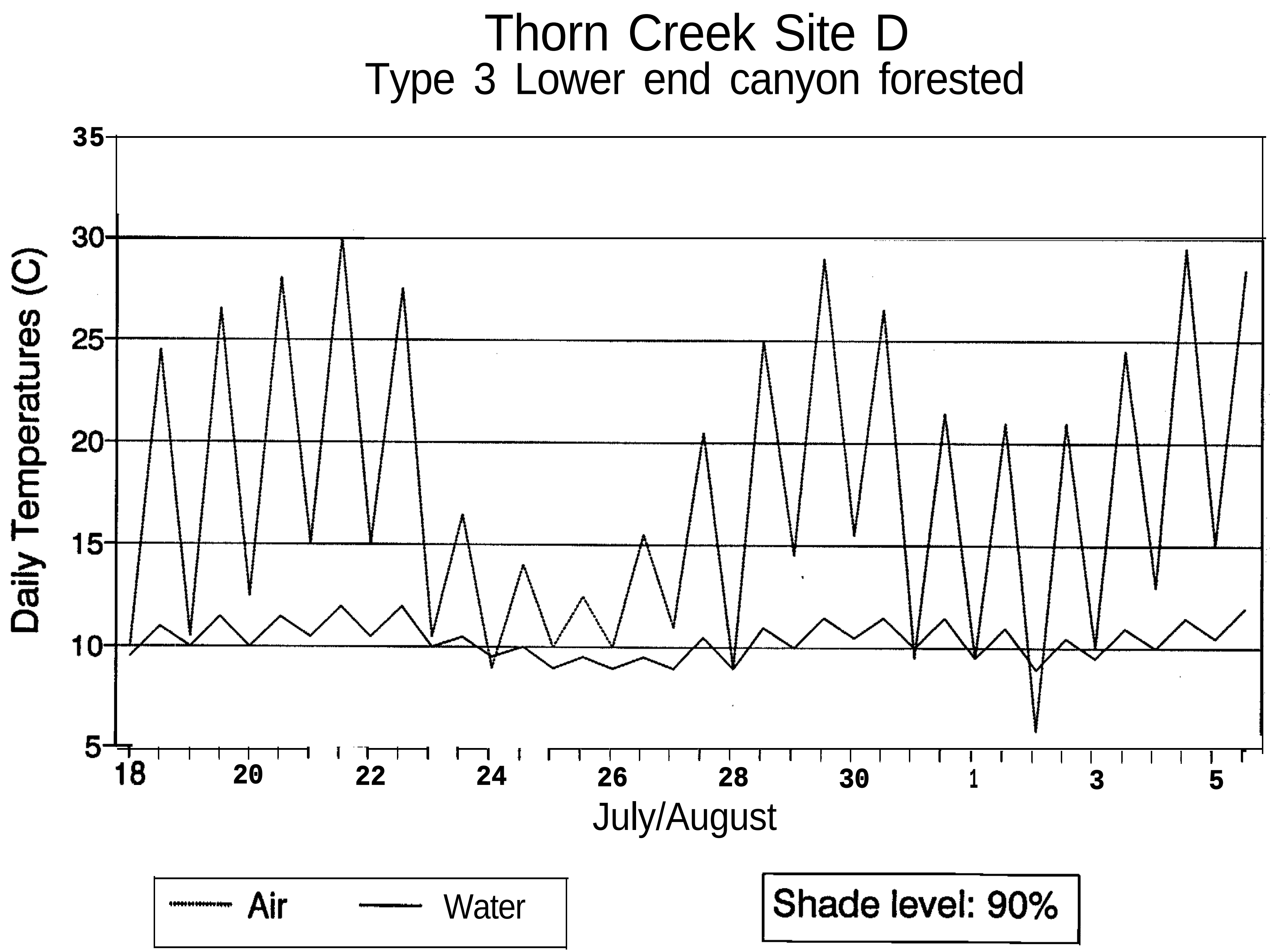
Shade Level : 90%


Thorn Creek Site A
Type 4 Upper harvested tributary
Daily Temperatures (C)
35
30
25
20
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
--- Air
Water
Shade level : 80%

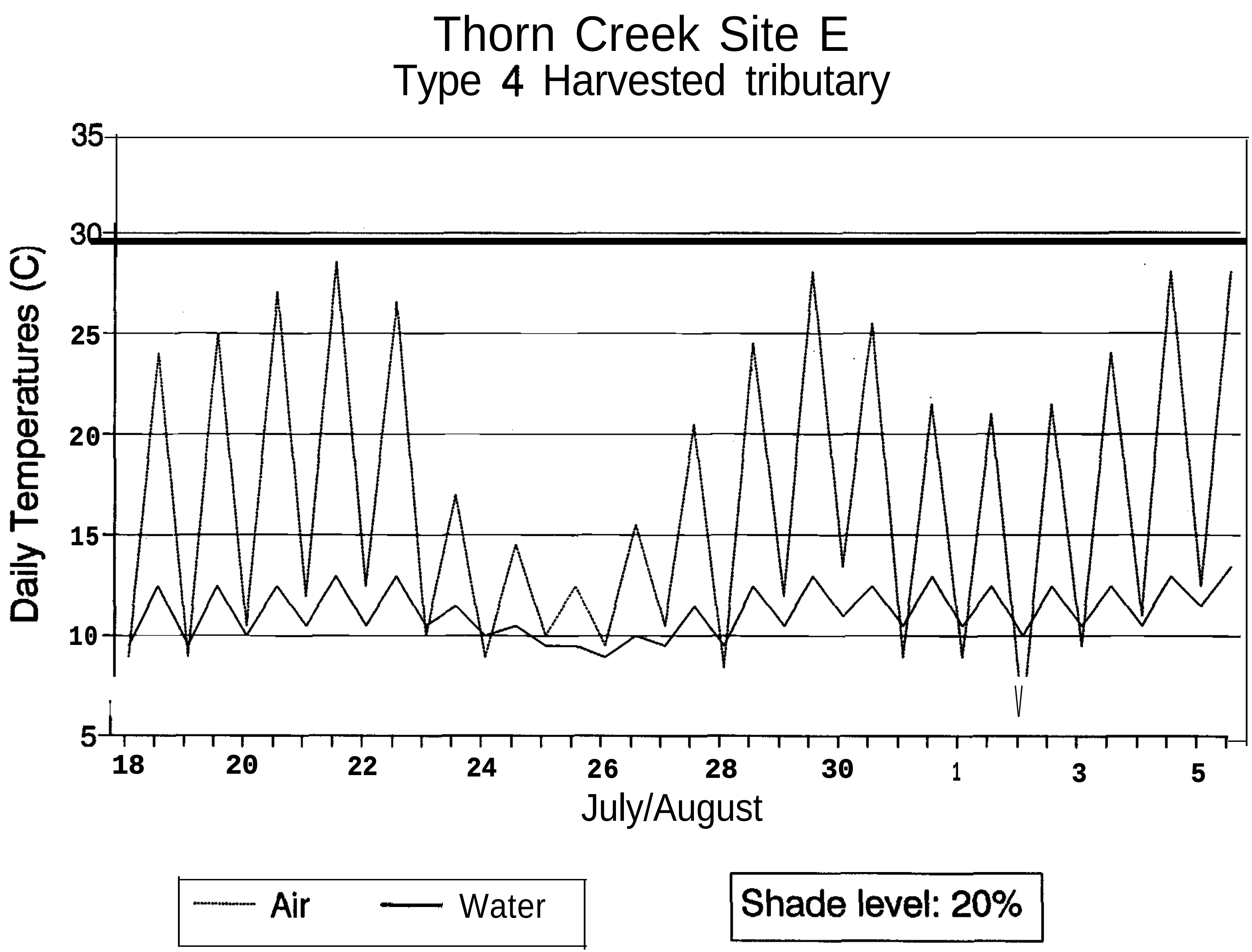

Thorn Creek Site B
Type 3 Forested
Daily Temperatures (C)
35
30
25
20
15
10
5
8
21
23
25
27
29
31
2
4
6
July/August
-- Air
Water
Shade level: 95%

Thorn Creek Site C
Type 3 Mid-canyon, forested

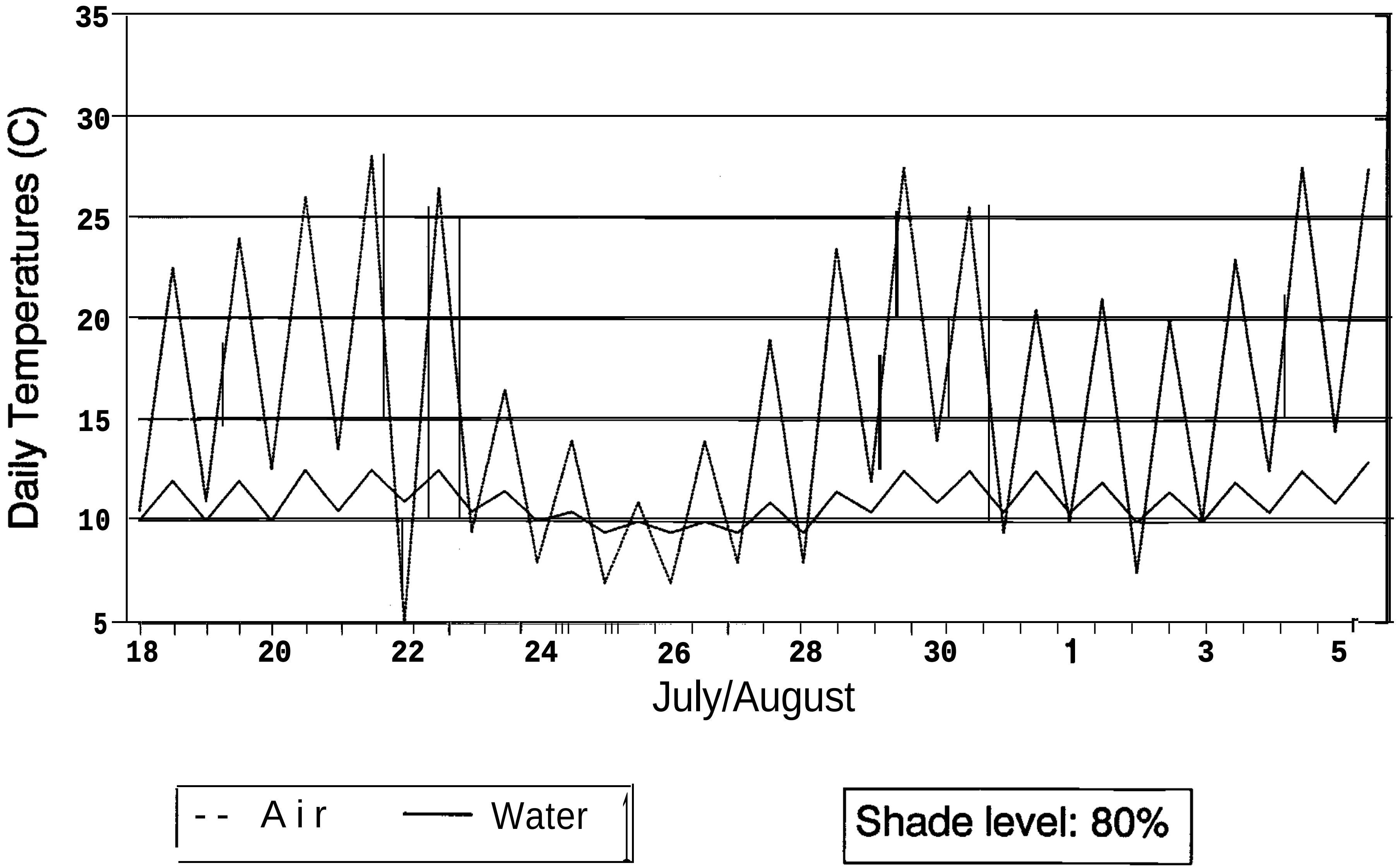


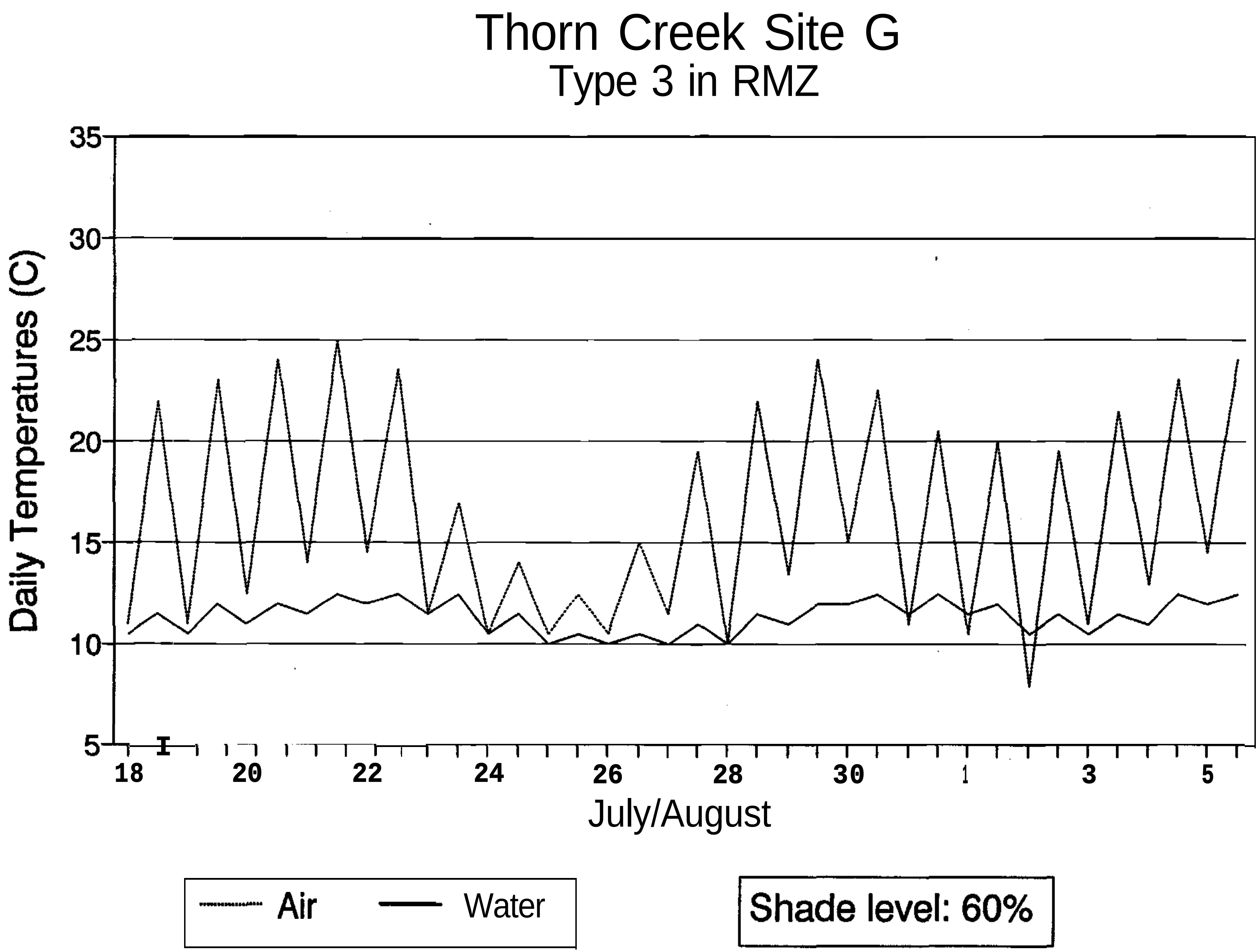


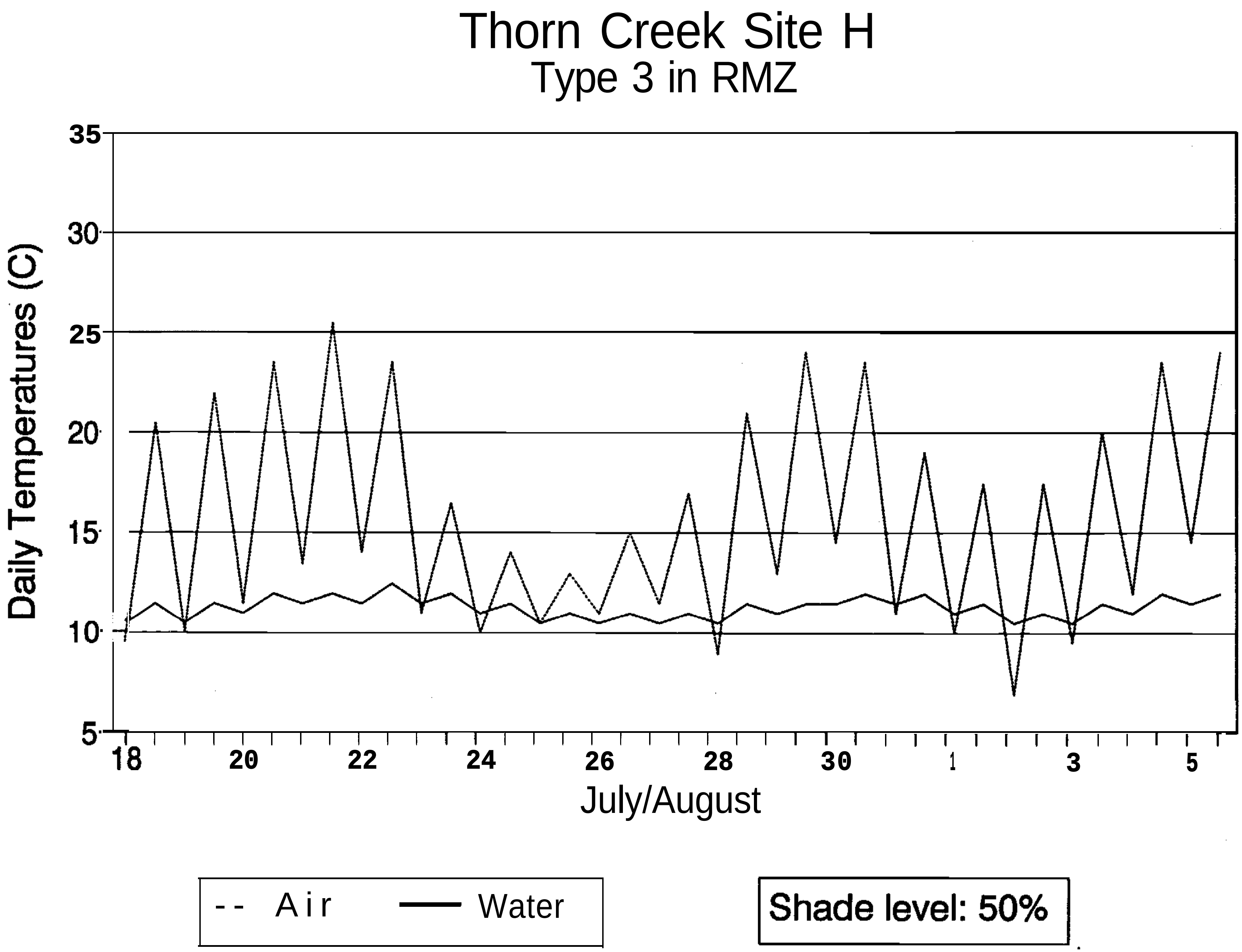
Thorn Creek Site D
Type 3 Lower end canyon forested
Daily Temperatures (C)
35
30
25
20
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
Air
Water
Shade level: 90%

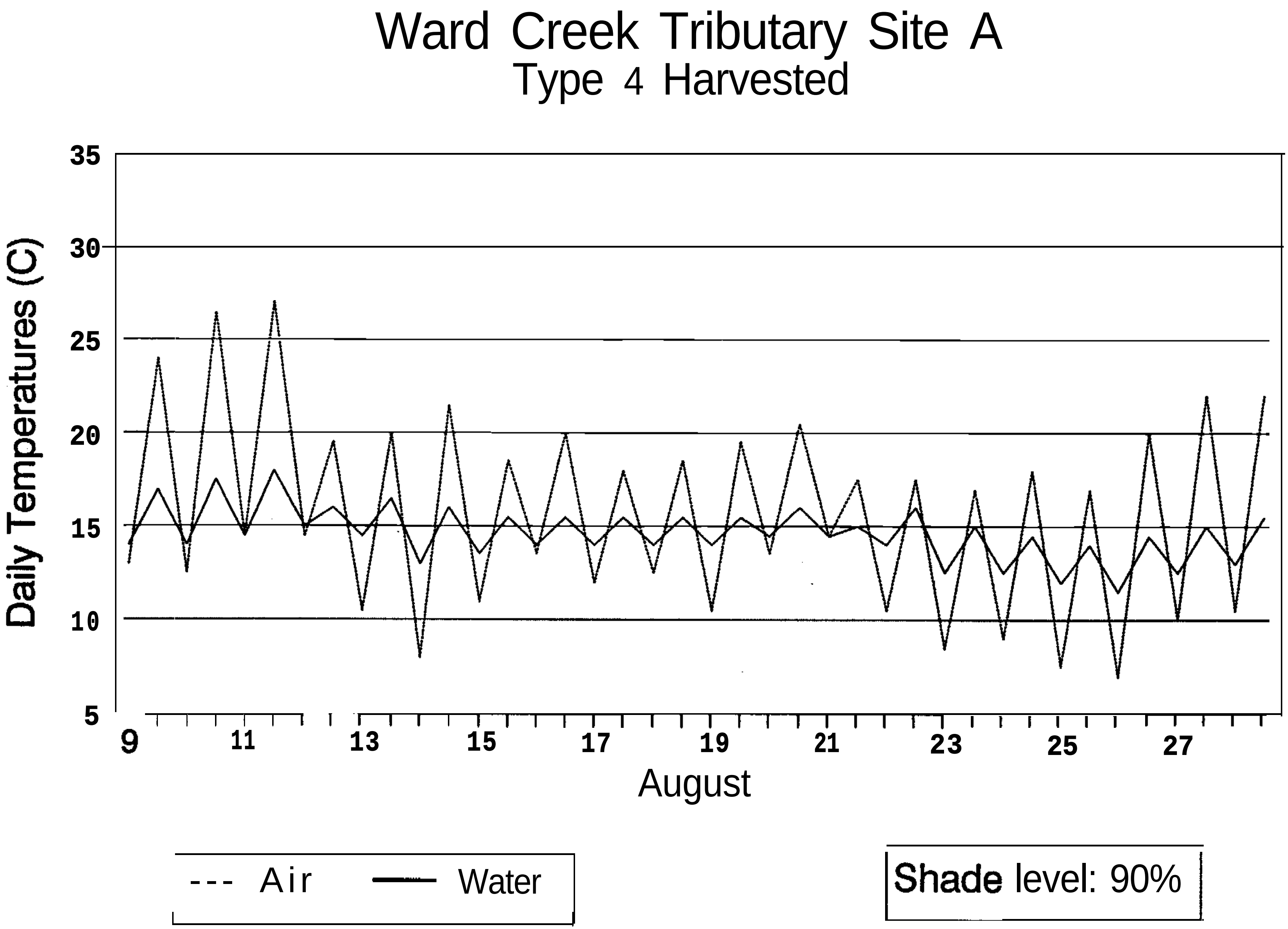

Thorn Creek Site E
Type 4 Harvested tributary
Daily Temperatures (C)
35
30
25
20
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
Air
Water
Shade level: 20%

Thorn Creek Site F
Type 3 in RMZ

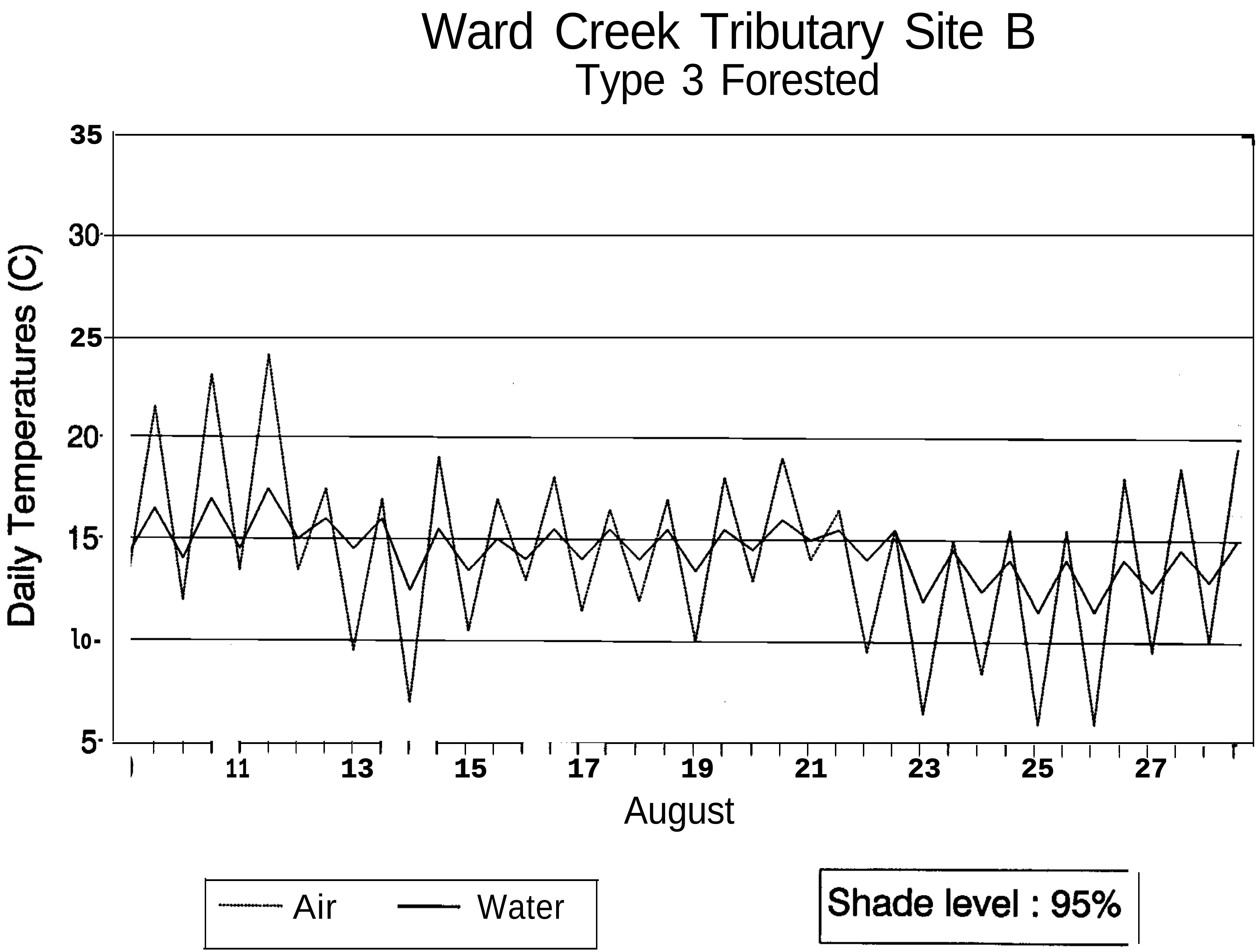



Thorn Creek Site G
Type 3 in RMZ
Daily Temperatures (C)
35
30
25
20
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
Air
Water
Shade level: 60%

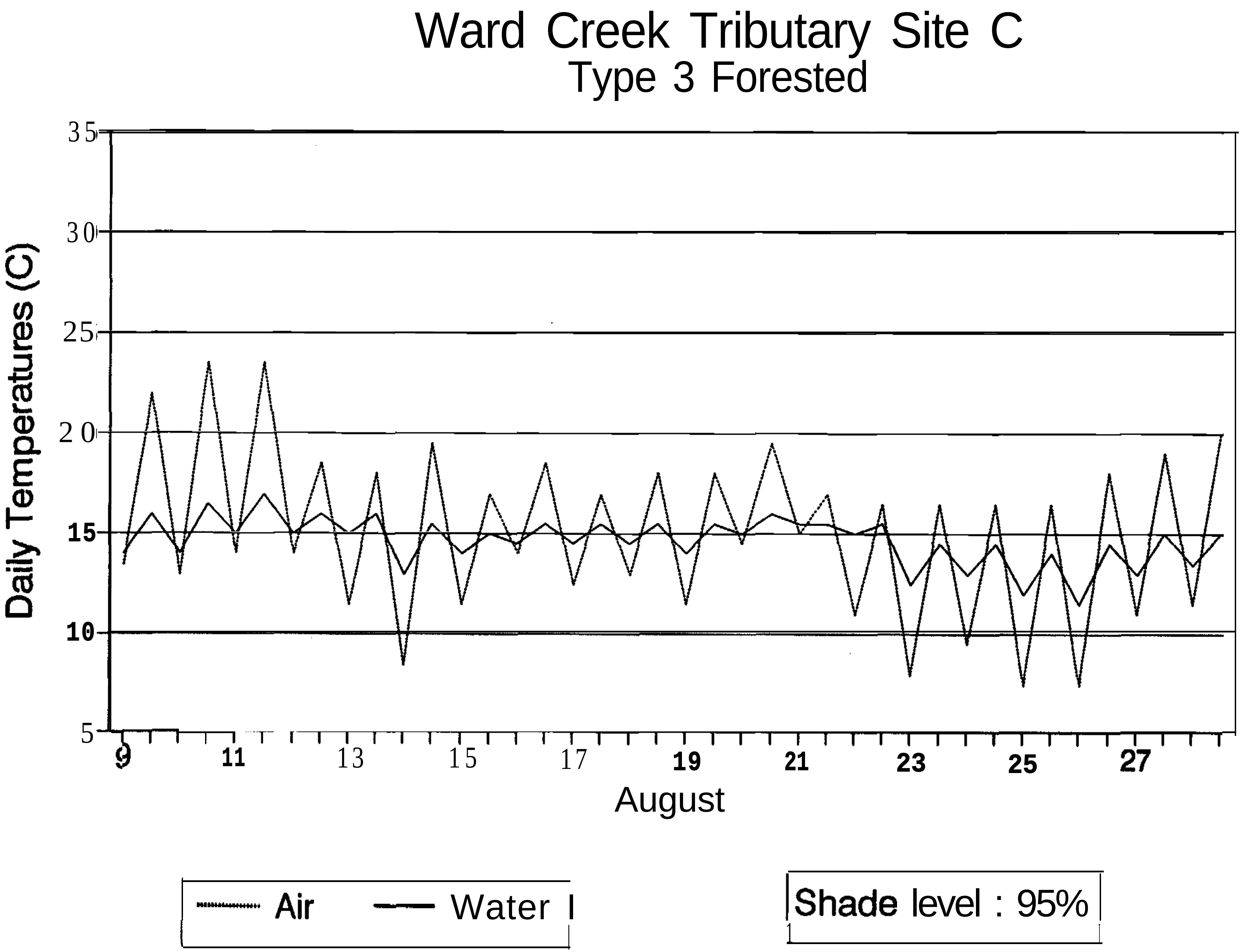

Thorn Creek Site H
Type 3 in RMZ
Daily Temperatures (C)
35
30
25
20
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
-- Air
Water
Shade level: 50%

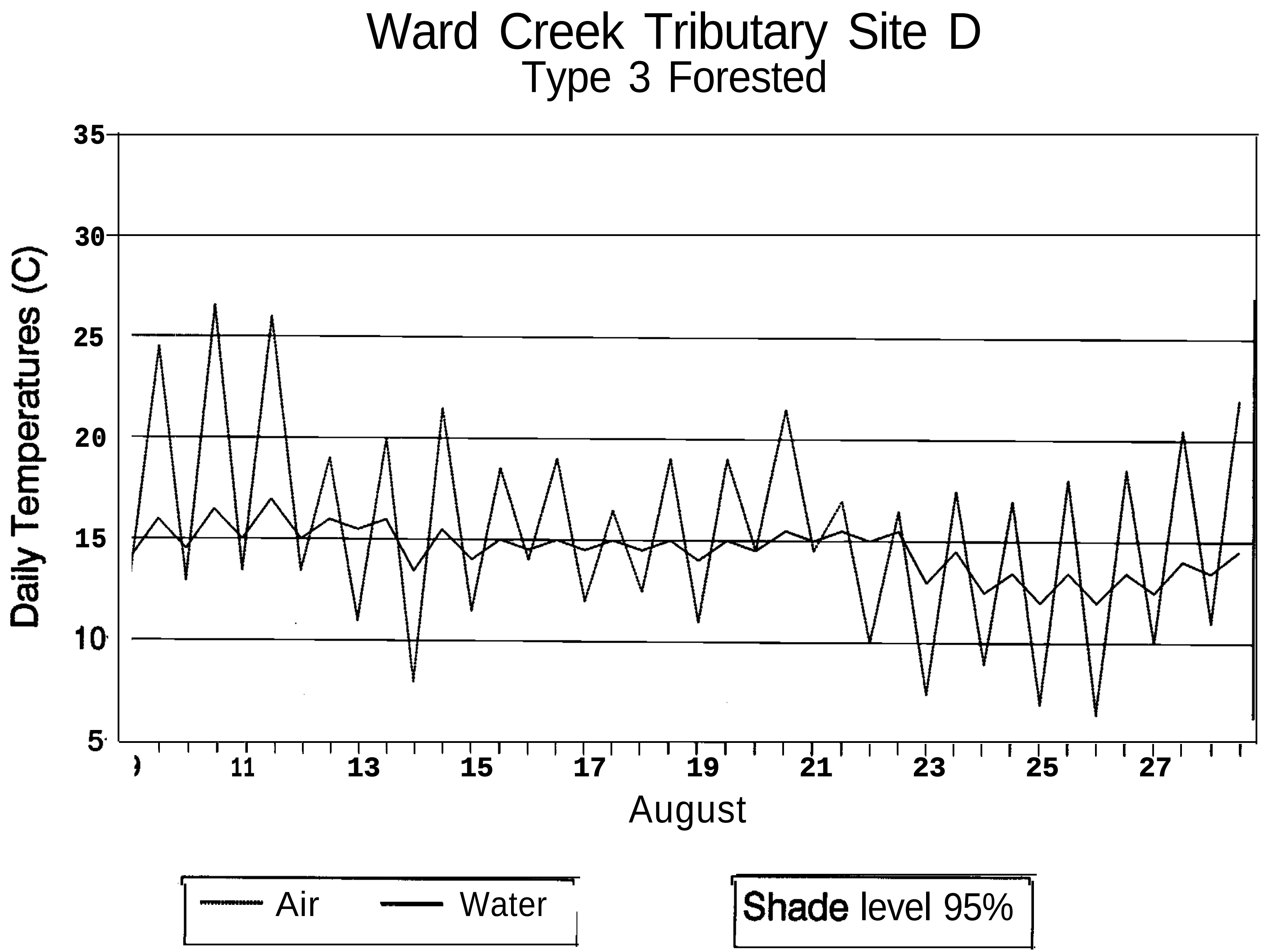


Ward Creek Tributary Site A
Type 4 Harvested
Daily Temperatures (C)
35
30
25
20
15
10
5
9
11
13
15
17
19
21
23
25
27
August
--- Air
Water
Shade level: 90%



Ward Creek Tributary Site B
Type 3 Forested
Daily Temperatures (C)
35
30
25
20
15
10
5
11
13
15
17
19
21
23
25
27
August
Air
Water
Shade level : 95%


Ward Creek Tributary Site C
Type 3 Forested
Daily Temperatures (C)
35
30
25
20
15
10
5
9
11
13
15
17
19
21
23
25
27
August
Air
Water
Shade level : 95%



Ward Creek Tributary Site D
Type 3 Forested
Daily Temperatures (C)
35
30
25
20
15
10
5
11
13
15
17
19
21
23
25
27
August
Air
Water
Shade level 95%

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SUMMER TEMPERATURE PATTERNS IN HEADWATER STREAMS OF THE OREGON COAST RANGE[1]

Liz Dent, Danielle Vick, Kyle Abraham, Stephen Schoenholtz, and Sherri Johnson[2]

ABSTRACT: Cool summertime stream temperature is an important component of high quality aquatic habitat in Oregon coastal streams. Within the Oregon Coast Range, small headwater streams make up a majority of the stream network; yet, little information is available on temperature patterns and the longitudinal variability for these streams. In this paper we describe preharvest spatial and temporal patterns in summer stream temperature for small streams of the Oregon Coast Range in forests managed for timber production. We also explore relationships between stream and riparian attributes and observed stream temperature conditions and patterns. Summer stream temperature, channel, and riparian data were collected on 36 headwater streams in 2002, 2003, and 2004. Mean stream temperatures were consistent among summers and generally warmed in a downstream direction. However, longitudinal trends in maximum temperatures were more variable. At the reach scale of 0.5-1.7 km, maximum temperatures increased in 17 streams, decreased in seven streams and did not change in three reaches. At the subreach scale (0.1-1.5 km), maximum temperatures increased in 28 subreaches, decreased in 14, and did not change in 12 subreaches. Models of increasing temperature in a downstream direction may oversimplify fine-scale patterns in small streams. Stream and riparian attributes that correlated with observed temperature patterns included cover, channel substrate, channel gradient, instream wood jam volume, riparian stand density, and geology type. Longitudinal patterns of stream temperature are an important consideration for background characterization of water quality. Studies attempting to evaluate stream temperature response to timber harvest or other modifications should quantify variability in longitudinal patterns of stream temperature prior to logging.

(KEY TERMS: stream temperature; water quality; shade; cover; riparian forest; rivers/streams; headwater streams.)

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INTRODUCTION

Small headwaters streams make up the majority of the stream network, generate most of the streamflow (MacDonald and Coe, 2007), and provide unique habitats for biological assemblages (Richardson and Danehy, 2007). These small streams contribute to valuable habitat for multiple salmonid species in coastal Oregon watersheds. Population viability for

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many of these species is in question (Nelson *et al.*, 1991). Among other habitat needs, these fish require cool stream temperatures in the summer. Increases in stream temperature at certain life stages can cause stress and/or mortality (Beschta *et al.*, 1987).

It is generally accepted that stream temperature tends to increase in a downstream direction. The rates of change and relationships between basin size and stream temperature patterns have been noted for larger streams and are predicted to increase in a downstream direction (Lewis *et al.*, 1999; Caissie, 2006). However, some studies have observed considerable variability in longitudinal stream temperature patterns, in larger rivers (Torgerson *et al.*, 1999), smaller streams (Johnson, 2004), or side channels (Ebersole *et al.*, 2003). For smaller streams, longitudinal patterns could be highly variable in response to a variety of instream, microclimatic, and geologic processes (Poole and Berman, 2001).

Stream temperature is a function of multiple energy transfer processes including direct solar radiation, longwave radiation, conduction, convection, and evaporation. Of these factors, direct solar radiation is the primary contributor to daily maximum summer stream temperature (Brown and Krygier, 1970; Sinokrot and Stefan, 1993; Johnson, 2004). Therefore, maintaining shade is an effective tool for reducing stream temperature heat flux (Johnson, 2004) during the summer months when maximum stream temperatures are observed.

Riparian forests provide a wide range of structures and functions including but not limited to diverse vegetation types and layered stand structure, snags, downed wood, large wood recruitment to streams, bank stability, nutrient cycling, and shade. Historical forest management that did not require retaining trees along streams resulted in significant reductions in shade and associated increases in stream temperature (Levno and Rothacher, 1967; Brown and Krygier, 1970; Murray *et al.*, 2000). Presently, retention of riparian trees is required along all fish-bearing streams in Oregon during timber harvest (OFPA, 2004) to maintain shade over streams as well as other riparian functions that maintain and protect aquatic habitat. Riparian restrictions around small streams have the potential to be especially costly (Adams *et al.*, 2002). It is important to evaluate stream temperature responses to forest management practices, given the importance of timber harvest to the Oregon economy, the significance of this region to salmonid conservation, and the prevalence of small streams in landscapes.

Geology and channel substrate also have important influences on spatial and temporal stream temperature trends in small streams (Poole and Berman, 2001). Johnson (2004) found that bedrock reaches had wide daily summer stream temperate fluctuations with relatively high maximum and low minimum temperatures. Stream reaches with gravel bottoms and subsurface flows had a much narrower range of daily fluctuations with lower maximums and higher minimums. Ground-water upwellings have potentially greater impacts in headwaters than in downstream reaches (Adams and Sullivan, 1989). Other factors that have been shown to correlate with stream temperature include stream depth (Adams and Sullivan, 1989) and streamflow (Beschta and Taylor, 1988).

In this paper, we describe preharvest spatial and temporal patterns in summer stream temperature for small streams in managed forests in the Oregon Coast Range. We also explore potential sources of variability in summer stream temperature conditions and patterns. The results presented herein are part of a long-term study designed to evaluate effects of forest management on temperature patterns of small streams.

METHODS

Study Area

Stream temperature was studied in 2002, 2003, and 2004 on 36 streams in the Oregon Coast Range. This region is characterized by steep slopes, highly dissected terrain, and sharp ridges with elevations that range from 450 to 750 m for main ridges with a maximum of 1,249 m at Marys Peak. Geology types of the Oregon Coast Range are predominantly layered sandstones and mudstones formed from uplifted ocean sediments that were deposited 60 to 40 million years ago. There are also many basalt intrusions in the north such as those in the vicinity of the Tillamook, Alsea, and Columbia River basins. The study area is influenced by maritime northwest climate patterns with cool, wet winters and mild, dry summers. Maximum air temperatures during study years were 19.0°C, 19.5°C, and 19.9°C from July to September 2002, 2003, and 2004, respectively (OCS, 2006). Rainfall was highly variable in all years and ranged from 2 to 60 mm, 2 to 20 mm, and 1 to 27 mm from July to September in 2002, 2003, and 2004, respectively.

Stream reaches selected for this study are in areas with harvest-regenerated or fire-regenerated forests between 50 and 70 years old (Figure 1). The stream reaches are on managed State of Oregon forests or privately owned industrial forests. In general, Oregon coastal riparian areas are hardwood-dominated, conifer-dominated, or conifer-hardwood mixed and

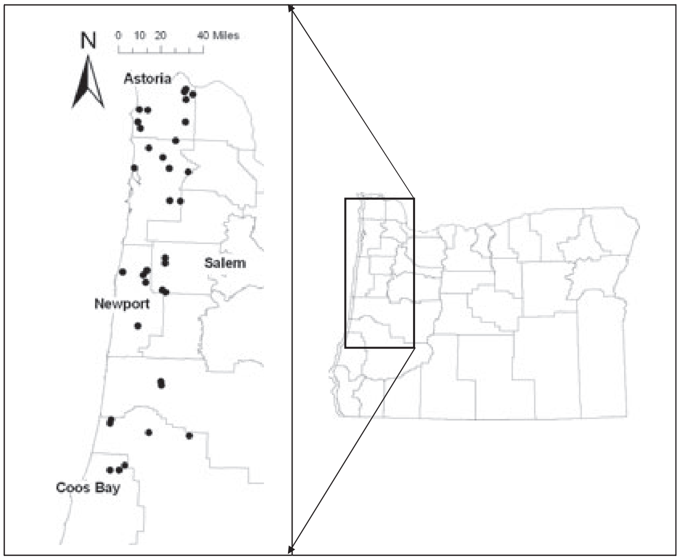

FIGURE 1. Locations of 36 Headwaters Stream Reaches in the Oregon Coast Range.

typically include shrub-dominated openings (Spies *et al.*, 2002). The most common conifer species for this study area is Douglas-fir (*Pseudotsuga menzeisii*) and the most common hardwood species is red alder (*Alnus rubra*). In general, conifer densities increase with increasing distance from stream, whereas hardwoods have not shown clear trends with distance from stream (Pabst and Spies, 1999; Spies *et al.*, 2002). Species composition and structure of riparian vegetation can be influenced by the same disturbances associated with upland stands such as fire, insect and disease, and windthrow. In addition, floods and debris flows have strong influences on riparian characteristics in this region. In general, riparian stands along high-gradient, headwater streams tend to be dominated by conifers. Exceptions include areas disturbed by landslides and debris torrents where red alder, salmonberry (*Rubus spectabilis*), and other deciduous vegetation are dominant (Pabst and Spies, 1999).

Study Design

Stream temperature, channel, and riparian data were collected on 36 stream reaches (defined as the entire length of stream being studied, encompassing two subreaches) as part of a long-term study that utilizes a before-after-control-impact (BACI) approach to examine harvest effects on stream temperature and riparian structure. The design targeted fish-bearing headwater streams classified as small or medium in the Oregon Forest Practices Act (OFPA, 2004). This paper focuses on the pretreatment period: 2002, 2003, and 2004. Because stream reaches were added and the timing of harvest varied, the preharvest sample sizes are 21, 36, and 19, for 2002, 2003, and 2004, respectively.

Because of BACI-related design constraints, a random sample was not practical. We asked all industrial private and state forest managers in the Oregon Coast Range to provide a list of stream reaches that would be harvested within a specific time frame and also met other criteria or constraints (Table 1). An initial list of 130 stream reaches was reduced to the final 36 and includes all stream reaches that met design constraints. Disturbances from beaver activities and debris-torrents, although common in the Oregon Coast Range, were avoided because such disturbances can overwhelm temperature patterns that otherwise could be influenced by harvesting in the posttreatment stage of this project. The final set of stream reaches, while not a random sample, is likely to represent conditions in 50-70-year-old forests, primarily managed for timber production, with small streams that lack recent debris torrent or beaver disturbance, on state and industrial private forest ownership in the Oregon Coast Range.

The majority (77%) of coastal forests in Oregon is under private (68%) or state (9%) ownership and managed for timber production (Spies *et al.*, 2002). Findings from this study are most applicable to streams in mid-successional forests (50-70-year-old conifer), which also make up the majority (82%) of Oregon state and private forests (Spies *et al.*, 2002). These sites do not represent, nor are they intended to represent unmanaged, old growth, or late-successional forest conditions and associated stream temperature patterns. Given that only 5-11% of the Oregon Coast Range is currently estimated to be in old growth or late-successional forest (Wimberly *et al.*, 2000), this study of stream reaches in mid-successional forests has relevance to regional conditions.

TABLE 1. Criteria Used to Select Stream Reaches for Evaluation of Summer Temperature Patterns of Headwater Streams in the Oregon Coast Range.

Site Selection Criteria
Ability to collect at least two years of pretreatment and seven years of posttreatment data
Fish-bearing streams
Minimum subreach lengths of 300 m
Streams must have an upstream "control" subreach that remains unharvested for duration of study
Estimated mean annual streamflow < 280 l/s
No major changes in channel and valley morphology, streamflow, or riparian attributes within streams reaches
No recent impacts from debris torrents
No active beaver ponds and ideally no large abandoned beaver ponds

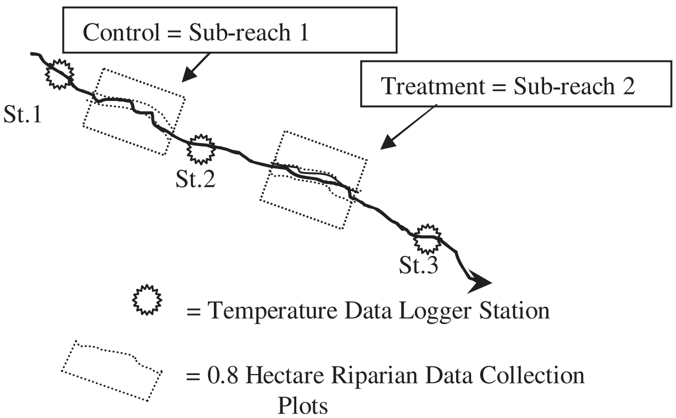

FIGURE 2. Schematic of Stream Reach (full length of stream being studied between Stations 1 and 3) Layout, Probe, and Riparian Plot Locations for 36 Headwater Streams in the Oregon Coast Range. "Subreach 1" (stream length between Stations 1 and 2) will remain as the control reach. "Subreach 2" (stream length between Stations 2 and 3) will become the treatment reach for the longer term study evaluating effects of harvesting on stream temperature. Canopy and channel data were collected at 60-m intervals in both subreaches.

Stream reach lengths varied from 525 to 1,768 m, with a mean of 932 m. Two subreaches (defined as a subsection of the study reach) were established on each stream reach (Figure 2). Subreach 1 will remain unharvested for the life of the study and serves as the "control" reach. Subreach 2, is immediately downstream of Subreach 1 and will eventually serve as the "treatment" reach after harvest. While the goal of the design was to have subreach lengths of ≥300 m, final subreach lengths varied from 137 to 1,494 m with a mean of 466 m. Factors which dictated final subreach lengths included future harvest unit boundaries in Subreach 2, large changes in valley or channel characteristics, or tributary inputs and junctions.

Stream Temperature and Flow Measures

Summer stream temperatures were recorded hourly between June and September 2002, 2003, and 2004 with continuously recording temperature data loggers (Optic Stowaway and Water Temp Pro, Onset Computer Corporation, Bourne, Massachusetts) at three stations in each reach. Predeployment and postdeployment accuracy checks were conducted using cold-water submersion and an NIST thermometer (Dunham *et al.*, 2005). Temperature stations were established at upstream and downstream boundaries of Subreaches 1 and 2 (Figure 2). Station locations were based on boundaries of future harvest units such that Station 1 would be approximately 300 m upstream of the future harvest unit, Station 2 at the upstream end of the harvest unit boundary, and Station 3 at the downstream end of the harvest unit boundary. Streamflow was calculated from measurements of velocity and cross-sectional areas at Station 3 in June, July, August, or September.

Channel Attributes

The following data were collected at measurement stations spaced 60 m apart throughout each subreach, following methods described in Lazorchak *et al.* (1998). Forest and shrub canopy cover was measured with a hand-held densiometer in each of four directions (upstream, left, right, and downstream) in the middle of the channel. Hemispherical photography was used to measure shade. A camera, with a "fish-eye" lens, was leveled at 1 m above the water surface and oriented to the north. Fish-eye photos were processed into electronic format and analyzed with Hemiview Software™ to calculate the amount of solar energy intercepted by canopy cover. Wetted width (wetted surface) and bankfull width (at the estimated average annual high water mark) were measured using a surveyor's rod or tape measure. Flood-prone width is the length measured at the elevation of two-times the bankfull height between flow-confining topographic features (Rosgen, 1994). It was measured using a surveyor's rod or tape measure. Channel gradient was measured using a clinometer. Substrate was characterized with a visual estimate of the percent of channel bed composed of each of six size classes of material (bedrock, boulder, cobble, gravel, sand, or fines). All instream wood jams in both subreaches were measured. A wood jam was defined as numerous pieces of wood functioning as a unit and piled together such that an individual wood tally was inaccurate. The length (L), width (W), and height (H) of each wood jam was measured and multiplied ($L \times W \times H$) to provide an estimate of wood jam volume.

Riparian-Structure Attributes

Riparian attributes were measured in permanent rectangular plots (0.8 ha), 152 m long (parallel to stream) by 52 m wide (horizontal distance from stream) centered within each subreach, one on each side of the stream, for a total of four plots per stream reach (Figure 2). The plot width was based on riparian buffers widths (52 m) that will be used when sites are harvested. Plot length was chosen to represent heterogeneous riparian forest conditions in a cost-effective manner. In heterogeneous forests, large plots or multiple small plots are needed to accurately describe stand structure (Husch *et al.*,1972). We opted for fewer large plots to control costs associated with establishing the plot itself. The species and distance from stream were recorded for every tree with a diameter at breast height (DBH) ≥14 cm.

Analytical Methods

Stream Temperature Metrics. The daily mean, maximum, and minimum stream temperature for each station were derived from hourly data recorded between July 15th and August 30th in 2002, 2003, and 2004. Diurnal fluctuation and maximum seven-day moving mean of the daily maximum (7DAYMAX) were calculated from the daily statistics. Diurnal fluctuation is the daily maximum minus the daily minimum. The 7DAYMAX is used by the Oregon Department of Environmental Quality (ODEQ) as a metric for evaluating if streams meet Oregon water quality standards for temperature (ODEQ, 2006). The 7DAYMAX is calculated using a running average of daily maximum stream temperatures for a seven-day period, then repeating the calculation after dropping the first day and adding the eighth day of record. This is repeated for the entire period of record for each station yielding a seven-day moving mean of daily maximum for each day, the warmest of which is the 7DAYMAX for the season. We identified the 7DAYMAX for each season at Station 3 for each stream reach. The date when the 7DAYMAX occurred at Station 3 was then used to select the corresponding temperature metrics for Stations 1 and 2 to be used for within-reach comparisons.

The ODEQ establishes two numeric standards for fish bearing headwater streams in the Oregon Coast Range (ODEQ, 2006). Streams that provide salmonid spawning habitat are expected to have 7DAYMAXs ≤ 16°C, whereas streams that provide salmonid migration habitat must have 7DAYMAXs ≤ 18°C. We calculated 7DAYMAX between July 15th and August 30th, in 2002, 2003, and 2004 and evaluated it against the appropriate DEQ standard.

Longitudinal Patterns. Streams were designated as having a "warming" pattern if the 7DAYMAX was warmer at the downstream Station 3 relative to the upstream Station 1 or a "cooling" pattern if the 7DAYMAX was cooler at the downstream Station 3 relative to the upstream Station 1. A "no-change" designation was defined as ±0.2°C between Stations 1 and 3, which reflects the factory-established accuracy of temperature probes used for this research.

To account for differences in subreach lengths, we calculated a normalized rate of change in 7DAYMAX per 300 m. Differences between 7DAYMAX at the downstream and upstream stations were divided by the distance between stations and multiplied by 300 m (change in °C/300 m).

Statistical Analyses. We used SAS Version 9.1 (SAS Institute Inc., Cary, North Carolina) for all statistical analyses. Stream temperatures at each sampling location are influenced by upstream channel- and riparian-zone attributes. Therefore, a paired *t*-test for dependent samples was used to evaluate differences in mean channel and riparian attributes between Subreaches 1 and 2. A paired *t*-test for dependent samples was also used to evaluate differences in average of the daily mean, minimum, maximum, and 7DAYMAX stream temperatures between stations. A Pearson correlation analysis was conducted to examine potential sources of observed variability in stream temperature. This analysis was performed on data from 2003 because that year had the greatest sample size and most complete record of stream temperatures.

RESULTS

Stream Channel and Riparian Characteristics

Twenty-three stream reaches were in sedimentary and 13 were in igneous geologic types. Stream reaches were steep, shallow, narrow, confined, and well shaded, with substrates composed primarily of fines and gravel (Table 2). Stream channel attributes were consistent between subreaches with the exception of gradient ($p = 0.02$), wetted width ($p = 0.001$), and bankfull width ($p = 0.0002$). The upstream subreaches had higher mean gradients, narrower wetted widths, and narrower bankfull widths than the downstream subreaches (Table 2). The stream reaches had low streamflows that varied from a low of 1 l/s to a high of 38 l/s, with a mean of 9 l/s.

Mean conifer basal area increased with distance from stream. The near-stream zones (within 8 m of stream) were dominated by a hardwood overstory stand type with a mean hardwood basal area of 28 m^2/ha as compared with a mean conifer basal area of 14 m^2/ha (Table 3). Conifers were more common beginning at 9-15 m zone from the stream. At 31-52 m from the stream, conifer basal area (36 m^2/ha) was four times that of hardwoods (9 m^2/ha).

TABLE 2. Mean and Standard Deviation of Channel and Riparian Attributes for Subreaches 1 and 2 for 36 Streams in the Oregon Coast Range.

Attribute	Mean (standard deviation)	
	Subreach 1	Subreach 2
Streamflow (l/s)	NA	9.1 (7.7)
Channel gradient (%)*	9.6 (8.9)	6.5 (4.2)
Fines (%)	38 (23)	34 (21)
Gravel (%)	38 (17)	38 (13)
Cobble (%)	18 (13)	19 (12)
Boulder (%)	3 (5)	4 (7)
Bedrock (%)	4 (12)	6 (11)
Thalwag depth (m)	0.2 (0.1)	0.2 (0.1)
Wetted width (m)*	1.7 (0.7)	2.1 (0.8)
Bankfull width (m)*	3.5 (1.1)	4.3 (1.4)
Flood prone width (m)	10.1 (8.8)	12.3 (7.0)
Distance from divide (m)	1551 (805)	2203 (867)
Shade (%)	86 (7)	87 (6)
Cover (%)	93 (4)	93 (4)
Wood jam index (m^3/m)	2 (14)	1(8)
Basal area (m^2/ha)	43 (14)	45 (13)
Trees/ha	870 (252)	914 (301)
Sedimentary geology type	23 sites	
Igneous geologic type	13 sites	

Note: For a given attribute, statistical difference ($\alpha = 0.05$) between Subreaches 1 and 2 is indicated with *.

Range of Observed Stream Temperature Conditions

Stream temperatures among individual reaches in this study were highly variable. During the three summers, daily maximum ranged from 7.3°C to 20.4°C, daily minimum from 6.7°C to 16.2°C, and daily mean from 7.0°C to 17.0°C. Daily diurnal fluctuation in summer varied from 0°C to 9.3°C (Figures 3A, 3B, and 3C). The rate of change in 7DAYMAX/300 m varied from −1.6°C/300 m to +3.6°C/300 m (Figure 4). There were no significant differences in mean rate of change among reaches. When we compared rate of change in 2002 to rate of change in 2003 for only those streams sampled in both years, there was no statistical difference between years.

We observed a narrow range of mean temperature conditions. Mean maximum temperatures observed at all stations over the three-year period varied from 12.2°C to 13.9°C, mean minimums from 11.3°C to 12.7°C, overall mean values varied from 11.7°C to 13.2°C, and mean diurnal fluctuation varied from 0.9°C to 1.3°C. The mean 7DAYMAX ranged from 12.2°C to 13.8°C (Table 4). Thirty percent (5/16) and 10% (2/20) of the stream reaches exceeded the ODEQ 7DAYMAX water quality standard at least one day during one of the summers for the 16°C and 18°C standards, respectively.

TABLE 3. Mean Conifer and Hardwood Basal Area in Riparian Zones With Increasing Distance From Streams (n = 36).

Distance From Stream (m)	Conifer Basal Area (m^2/ha)	Hardwood Basal Area (m^2/ha)
0-8	14	28
9-15	25	13
16-23	29	12
24-30	34	10
31-52	36	9

Note: Plots along both subreaches were averaged for this summary.

Longitudinal Patterns

Statistically significant differences in mean values between Stations 1 and 2 and 1 and 3 were observed in all three years (Table 5). Differences between Stations 2 and 3 were only significant in 2003. The results were consistent in that all statistically significant changes represent an increase in temperature in a downstream direction. However, changes were not observed for all temperature metrics, for all reaches, or for all years.

Longitudinal patterns in 7DAYMAX stream temperatures were more variable at both the reach and subreach scales. This analysis was performed on 27 streams because of missing data on nine streams. Longitudinal stream temperature patterns were variable between subreaches and among streams in 2003. Of 27 streams, some displayed a warming pattern in both subreaches, a cooling pattern in both subreaches (Figures 5 and 6), no-change in both subreaches, or some combination of the three. Overall, 63% of the streams warmed, 26% cooled, and 11% had no-change at the stream reach scale with variable patterns at the subreach scale (Table 6).

Sources of Variability

Correlations between 7DAYMAX temperature and stream attributes showed significant positive correlations for bedrock and negative correlations for fines for Subreach 1. In Subreach 2, gradient, wood jam volume, and riparian stand density were negatively correlated with 7DAYMAX, while sedimentary geology was positively correlated. No attributes were significantly correlated with 7DAYMAX in both subreaches (Table 7).

The rate of change in 7DAYMAX/300 m was positively correlated with mean bedrock in Subreach 1 and negatively correlated with cover. In Subreach 2, however, rate of change in 7DAYMAX/300 m was negatively correlated with mean bedrock and positively correlated with percent fines (Table 7).

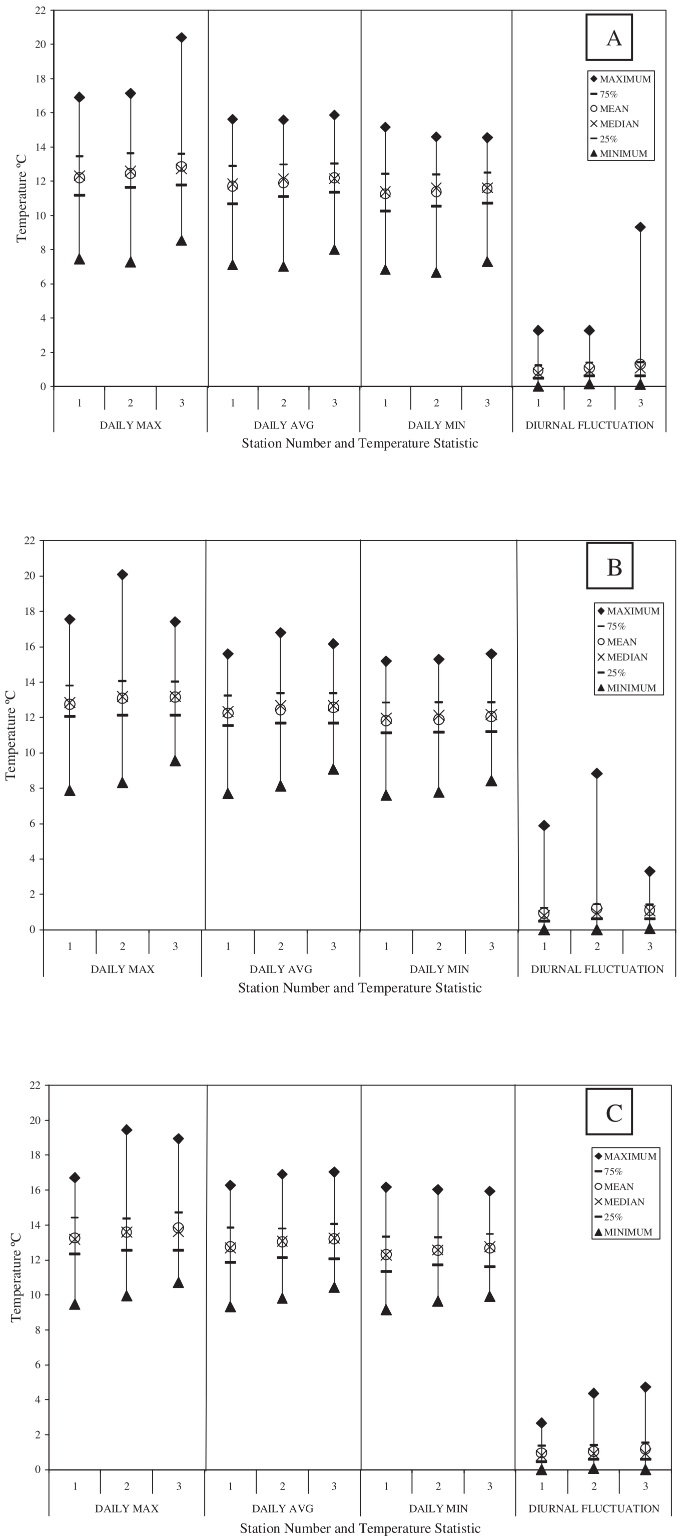

FIGURE 3. Stream Temperature Statistics for (A) 2002, (B) 2003, and (C) 2004 at Stations 1, 2, and 3 (n = 21, 36, and 19 for 2002, 2003, and 2004, respectively) for Headwater Streams in the Oregon Coast Range. Daily statistics were calculated from hourly data collected from 7/15 to 8/30 each year. Observed daily minimums, maximums, 75th and 25th quartiles, mean and medians of the distributions are shown.

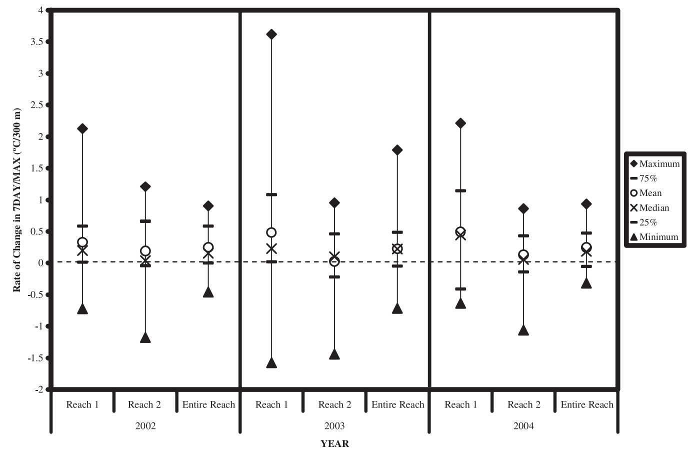

FIGURE 4. Rate of Change in 7DAYMAX/300 m for Subreach 1, Subreach 2, and the Entire Reach for 2002, 2003, and 2004 (n = 21, 36, and 19, respectively) for Headwater Streams in the Oregon Coast Range. The 7DAYMAX and associated rate of change were calculated using daily statistics from hourly data collected from 7/15 to 8/30 each year. The observed daily minimums, maximums, 75th and 25th quartiles, mean and medians of the distributions are shown.

DISCUSSION

We observed a high degree of variability in summertime stream temperature conditions and patterns in these headwater streams. Most notable from this set of streams was the observed variability in longitudinal patterns at small subreach scales. In general mean stream temperature increased in a downstream direction. However, longitudinal patterns for 7DAYMAX temperatures were more complex displaying alternating warming and cooling trends at subreach scales. These findings suggest that a simple model of increasing temperature in a downstream direction does not adequately characterize temperature patterns for many of these small streams. Observed reach-to-reach variability was likely a result of spatially variable instream processes that influence temperature patterns at small reach scales (0.5-2 km in length).

Similar variability in stream temperature patterns is cited by Poole and Berman (2001). Torgerson *et al.* (1999) and Ebersole *et al.* (2003) also found heterogeneous longitudinal patterns of summer stream temperature in northeastern Oregon. In contrast, Brown (1970), Zwieniecki and Newton (1999), and Lewis *et al.* (1999) found predictable patterns of warming in a downstream direction under full canopy cover. While not quantified in this study, possible explanations for observed longitudinal patterns include entrance of cool tributaries and influx of ground water (Beschta *et al.*, 1987; Ebersole *et al.*, 2003). Hewlett and Fortson (1982) determined ground-water input to be

TABLE 4. Mean Values of Temperatures Calculated From Hourly Data Collected From July 15 to August 30.

Year	Station (*n*)	Daily Maximum (°C)	Daily Minimum (°C)	Daily Mean (°C)	Diurnal Fluctuation (°C)	7-Day Maximum (°C)
2002	1 (19)	12.2	11.3	11.7	0.9	12.2
	2 (20)	12.5	11.4	11.9	1.1	12.5
	3 (21)	12.9	11.6	12.2	1.3	12.9
2003	1 (31)	12.8	11.8	12.2	0.9	12.8
	2 (30)	13.1	11.9	12.5	1.2	13.1
	3 (36)	13.2	12.0	12.6	1.1	13.1
2004	1 (19)	13.3	12.3	12.8	1.0	13.3
	2 (18)	13.6	12.6	13.0	1.0	13.6
	3 (19)	13.9	12.7	13.2	1.2	13.8

TABLE 5. Paired *t*-Test Results (for dependent samples) Comparing Mean Stream Temperature Metrics Between Stations.

		Difference in Mean Temperature Between Stations		
Temperature Metric	**Stations Being Compared**	**2002 °C (*p*-value)**	**2003 °C (*p*-value)**	**2004 °C (*p*-value)**
Daily max	1 & 2		0.87 (0.02)	0.08 (0.02)
	2 & 3			
	1 & 3	1.02 (0.03)	0.72 (0.01)	0.03 (0.02)
Daily min	1 & 2		0.53 (0.01)	
	2 & 3		0.30 (0.01)	
	1 & 3		0.51 (<0.01)	0.34 (0.04)
Daily average	1 & 2	0.68 (0.03)	0.41 (0.05)	0.16 (0.05)
	2 & 3			
	1 & 3		0.23 (<0.01)	0.50 (0.01)
7DAYMAX	1 & 2	0.29 (0.05)	0.43 (0.03)	0.42 (0.04)
	2 & 3			
	1 & 3	0.90 (0.02)	0.63 (0.01)	0.73 (0.01)

Note: Statistically significant differences in mean values and *p*-values are provided. All observed changes represent increases between stations.

the primary driver of stream temperature in small streams in the southeastern United States Adams and Sullivan (1989) also argued that ground-water contributions play an important role in temperature patterns. Studies attempting to evaluate stream temperature response to timber harvest should consider the variable longitudinal patterns of stream temperature that can exist prior to disturbance as observed in these study sites.

Streams in this study were consistently well-shaded with high levels of canopy cover. Selection criteria for this study that excluded sites with recent human and natural disturbances such as beaver and debris torrents, in part explain consistently high cover conditions. Such conditions limited the usefulness of cover or shade as a predictor of stream temperature variability prior to logging. Other studies (Levno and Rothacher, 1967; Brown and Krygier, 1970; Beschta and Taylor, 1988; Jackson *et al.*, 2001) of canopy cover prior to logging in the Pacific Northwest have reported similar canopy conditions as observed in this study. Solar radiation is a key driver of midday high stream

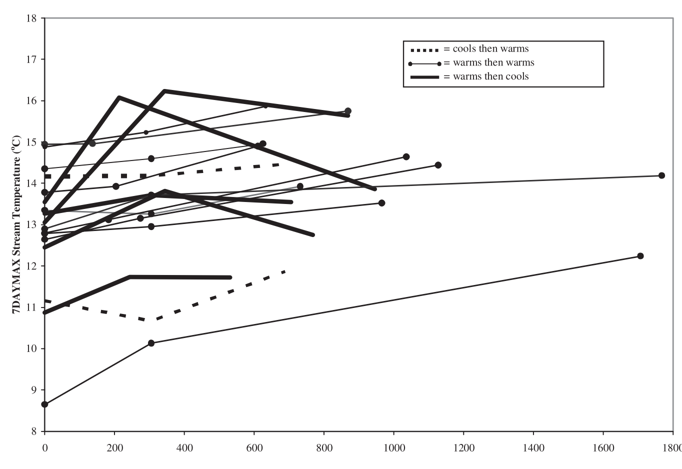

FIGURE 5. 7DAYMAX Temperature *vs.* Distance Between Stations (Station 1 = 0 m) for Streams in the Oregon Coast Range That had an Overall *Warming* Pattern (between Stations 1 and 3) in 2003 (n = 17). Thin solid line represents streams that warmed in both reaches, heavy solid line represents streams that warmed in Subreach 1 but cooled in Subreach 2, and dashed line represents streams that cooled in Subreach 1 but warmed in Subreach 2.

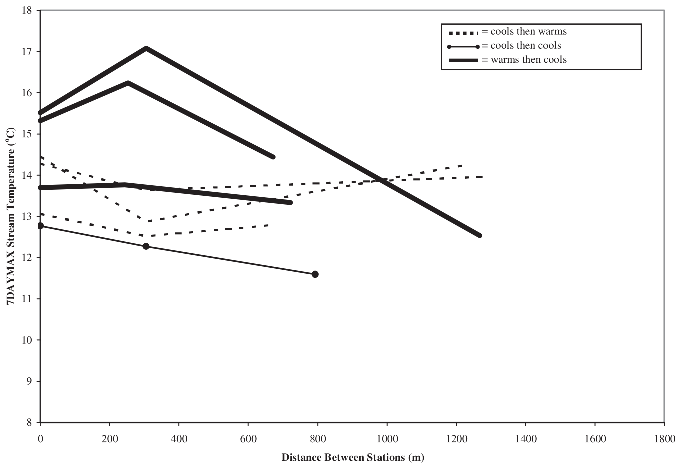

FIGURE 6. 7DAYMAX Temperature *vs.* Distance Between Stations (Station 1 = 0 m) for Streams in the Oregon Coast Range That Had an Overall *Cooling* Pattern (between Stations 1 and 3) in 2003 (n = 7). Thin solid line represents streams that cooled in both reaches, heavy solid line represents streams that warmed in Subreach 1 but cooled in Subreach 2, and dashed line represents streams that cooled in Subreach 1 but warmed in Subreach 2.

temperatures (Beschta and Taylor, 1988; Brown, 1988; Sinokrot and Stefan, 1993) and several studies have established the importance of shade for maintaining stream temperature (Brown, 1970, 1988; Beschta *et al.*, 1987; Lewis *et al.*, 1999; Zwieniecki and Newton, 1999). If future harvest reduces shade, we expect the correlative relationships between shade and stream temperature for these stream reaches to strengthen.

We observed greater extremes in stream temperature and rate of change than reported in other studies (Brown and Krygier, 1970; Amaranthus *et al.*, 1989; Dupuis and Steventon, 1999; Jackson *et al.*, 2001). Higher variability in temperature patterns observed in this study may be a result of our focus on small streams, regional differences, and our larger sample size. Small streams may be more susceptible to temperature variations as a result of low flow volumes and interactions with ground water and substrate. A large sample size may have increased the likelihood of capturing a greater range in conditions.

Channel substrates, specifically the percent fines, percent bedrock, and geologic type were correlated with stream temperature and rate of change with alternating positive and negative relationships by subreach. Johnson (2004) found that streams dominated by bedrock tended to have wide daily summer stream temperate fluctuations with relatively high maximum and low minimum temperatures. Ebersole *et al.* (2003) described cool water in streams as associated with substrate characteristics and localized conditions. Cool temperatures may be responding to conductive heat exchange with the substrate, whereby the slightly warmer stream water is losing heat to the still seasonally cool substrate (Brown, 1988). This hypothesis corresponds to the findings of Sinokrot and Stefan (1993), who found that conduction among shallow, small streams, and the streambed should be considered in heat budget estimates. While similarly variable results have been reported in other research, it is possible that alternating positive and negative correlations between temperature and substrate in this study may reflect over-simplified substrate measures that are inadequate to explain complex cooling and heating processes that result from surface water/channel interactions.

CONCLUSIONS

This study provided several observations with important implications for management and research

TABLE 6. Number and Percent of Streams With Cooling, Warming, or No-Change Patterns in 2003 for 7DAYMAX at the Stream Reach (Stations 1-3) and Subreach Scales for 27 Headwater Streams in the Oregon Coast Range.

Site Level Pattern (percent of sites)	Number of Sites	Subreach 1 Pattern	Subreach 2 Pattern	Percent of Sites With Subreach Pattern
Overall warming pattern between Stations 1 and 3 (63%)	6	Warms	Warms	22
	5	No change	Warms	19
	3	Warms	Cools	11
	2	Warms	No change	7
	1	Cools	Warms	4
Overall cooling pattern between Stations 1 and 3 (26%)	3	Cools	Warms	11
	2	Warms	Cools	7
	1	No change	Cools	4
	1	Cools	Cools	4
No-change between Stations 1 and 3 (11%)	2	No change	Cools	7
	1	No change	No change	4

Note: No-change was defined as ±0.2°C based on the accuracy of temperature probes.

TABLE 7. Pearson Correlation Results Relating 2003 7DAYMAX at Stations 2 and 3 to Upstream Attributes for Subreaches 1 and 2, Respectively, for Headwater Streams in the Oregon Coast Range.

	7DAYMAX (°C)		Rate of Change (°C/300 m)	
Channel or Riparian Parameter (*n* = 25 except when shown)	**Subreach 1 *r* (*p*-value)**	**Subreach 2 *r* (*p*-value)**	**Subreach 1 *r* (*p*-value)**	**Subreach 2 *r* (*p*-value)**
Distance from divide (30)	0.31 (0.09)	0.32 (0.06)	0.00 (0.99)	0.01 (0.95)
Mean % bedrock	0.49 (0.01)*	−0.14 (0.45)	0.43 (0.05)*	−0.52 (0.01)*
Mean % gravel	−0.07 (0.75)	−0.24 (0.18)	−0.11 (0.61)	−0.11 (0.58)
Mean % cobble	0.14 (0.50)	−0.17 (0.36)	−0.28 (0.21)	−0.07 (0.72)
Mean % boulder	0.31 (0.13)	−0.01 (0.97)	0.22 (0.33)	0.00 (0.98)
Mean %fines	−0.40 (0.05)*	0.31 (0.08)	−0.07 (0.77)	0.40 (0.04)*
Mean wetted width	0.24 (0.25)	0.10 (0.60)	0.04 (0.87)	0.19 (0.35)
Mean bankfull width	0.26 (0.21)	−0.04 (0.84)	0.12 (0.59)	−0.10 (0.65)
Mean flood-prone width	0.11 (0.61)	0.23 (0.21)	−0.07 (0.75)	0.24 (0.24)
Mean max depth	−0.09 (0.68)	0.14 (0.44)	−0.13 (0.58)	0.15 (0.46)
Mean % gradient	−0.25 (0.23)	−0.48 (0.01)*	−0.13 (0.57)	−0.12 (0.56)
Mean % cover	−0.03 (0.90)	0.23 (0.21)	−0.54 (0.01)*	−0.18 (0.39)
Mean % shade (27)	−0.17 (0.38)	0.05 (0.76)	−0.31 (0.14)	−0.07 (0.73)
Wood jam volume (34)	−0.19 (0.33)	−0.38 (0.02)*	−0.17 (0.46)	0.20 (0.29)
Mean basal area/ha (28)	−0.12 (0.53)	−0.01 (0.95)	−0.04 (0.86)	0.25 (0.21)
Mean no. of trees/ha (28)	−0.12 (0.53)	−0.36 (0.04)*	−0.17 (0.42)	0.10 (0.61)
Sedimentary geology	0.18 (0.36)	0.45 (0.01)*	−0.18 (0.37)	0.17 (0.37)

Notes: Rate of change in 7DAYMAX/300 m in Subreaches 1 and 2 was likewise compared with Subreaches 1 and 2, respectively.
*Statistically significant correlation (α = 0.05).

on small streams in similar ecological settings as the Oregon Coast Range. Findings highlight the complexity of processes influencing stream temperature at small reach scales in the stream reaches we studied. We intentionally selected small streams that had similar forest management and disturbance histories and channel characteristics which were reflected in narrow ranges of shade and channel conditions. Nevertheless, we observed a wide range of stream temperature conditions and spatial patterns prior to harvest.

Under current forest management, shade is provided by maintaining riparian buffer zones in part to prevent adverse impacts of harvest operations on stream temperature. This is appropriate as greater canopy cover can be a significant predictor of cooler stream temperatures. However, the inherent complexity in small streams observed in this study indicates that additional processes may determine stream temperature conditions and patterns when shade and canopy cover are consistently high. Given the potential influence of substrate and streamflow on temperature patterns in small streams, future studies should consider precise measures of substrate, streamflow, and/or hyporheic exchange. An examination of ground-water-surface water interactions in small streams may explain if this interaction has a modifying affect on harvest response. Given the observed variability in temperature patterns and correlations between temperature and stream characteristics, postharvest evaluations will need to account for inherent variability observed prior to harvest.

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LITERATURE CITED

Adams, D.M., R.R. Schillinger, G. Latta, and A. Van Nalts, 2002. Timber Harvest Projections for Private Land in Western Oregon. Research Contribution 37, Forest Research Laboratory, Oregon State University, Corvallis, Oregon, 44 pp.

Adams, T.N. and K. Sullivan, 1989. The Physics of Forest Stream Heating: A Simple Model. Weyerhaeuser Research Project, Project No. 044-5002/89/1.

Amaranthus, M., H. Jubas, and D. Arthur, 1989. Stream Shading, Summer Streamflow, and Maximum Water Temperature Following Intense Wildfire in Headwater Streams. USDA Forest Service Gen. Tech. Rep., PSW-109, pp. 75-79.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra, 1987. Stream Temperature and Aquatic Habitat: Fisheries and Forestry Interactions. *In*: Streamside Management: Forestry and Fishery Interactions. Chap. 6, pp. 191-232.

Beschta, R.L. and R.L. Taylor, 1988. Stream Temperature Increases and Land Use in a Forested Oregon Watershed. Water Resources Bulletin 24:19-25.

Brown, G.W., 1970. Predicting the Effect of Clearcutting on Stream Temperature. Journal of Soil and Water Conservation 25:11-13.

Brown, G.W., 1988. Forest and Water Quality. OSU Bookstores, Inc., Memorial Union, Oregon State University, Corvallis, Oregon.

Brown, G.W. and J.T. Krygier, 1970. Effects of Clear-Cutting on Stream Temperature. Water Resources Research 6:1133-1139.

Caissie, D., 2006. The Thermal Regime of Rivers: A Review. Freshwater Biology 51:1389-1406.

Dunham, J., G. Chandler, B. Rieman, and D. Martin, 2005. Measuring Stream Temperature With Digital Data Loggers: A User's Guide. Gen. Tech. Rep. RMRS-GTR-150WWW. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, 15 pp.

Dupuis, L. and D. Steventon, 1999. Riparian Management and the Tailed Frog in Northern Coastal Forests. Forest Ecology and Management 124:35-43.

Ebersole, J.L., W.J. Liss, and C.A. Frissell, 2003. Cold Water Patches in Warm Streams: Physiochemical Characteristics and the Influence of Shading. Journal of the American Water Resources Association 39(2):355-368.

Hewlett, J.D. and J.C. Fortson, 1982. Stream Temperature Under an Inadequate Buffer Strip in the Southeast Piedmont. Water Resources Bulletin 18(6):983-988.

Husch, B., C.I. Miller, and T.W. Beers, 1972. Forest Mensuration. John Wiley and Sons, Inc., ISBN 0 471 06834-9, 410 pp.

Jackson, C.R., C.A. Sturm, and J.M. Ward, 2001. Timber Harvest Impacts on Small Headwater Stream Channels in the Coast Ranges of Washington. Journal of the American Water Resources Association 37(6):1533-1549.

Johnson, S.L., 2004. Factors Influencing Stream Temperatures in Small Streams: Substrate and a Shading Experiment. Canadian Journal of Fisheries and Aquatic Sciences 61:93-923.

Lazorchak, J.M., D.J. Klemm, and D.V. Peck (Editors), 1998. Environmental Monitoring and Assessment Program-Surface Waters: Field Operations and Methods for Measuring the Ecological Condition of Wadeable Streams. Section 7. EPA/620/R-94/004F.US Environmental Protection Agency, Washington, D.C.

Levno, A. and J. Rothacher, 1967. Increases in Maximum Stream Temperatures After Logging in Old-Growth Douglas-fir Watersheds. USDA Forest Service Research Note PNW-65. PNW Forest and Range Experiment Station, Portland, Oregon. 12 pp.

Lewis, T.E., D.W. Lamphear, D.R. McCanne, A.S. Webb, J.P. Krieter, and W.D. Conroy, 1999. Executive Summary: Regional Assessment of Stream Temperatures Across Northern California and Their Relationship to Various Landscape-Level and Site-Specific Attributes. Forest Science Project. Humboldt State University Foundation, Arcata, California, 14 pp.

MacDonald, L.H. and D. Coe, 2007. Influence of Headwater Streams on Downstream Reaches in Forested Areas. Forest Science 53(2):148-168.

Murray, G.L.D., R.L. Edmonds, and J.L. Marra, 2000. Influence of Partial Harvesting on Stream Temperatures, Chemistry, and Turbidity in Forests on the Western Olympic Peninsula, Washington. Northwest Science 74:151-164.

Nelson, W., J.E. Williams, and J.A. Lichatowich, 1991. Pacific Salmon at the Crossroads: Stocks at Risk From California, Oregon, Idaho, and Washington. Fisheries 16(2):4-21.

OCS (Oregon Climate Service), 2006. Zone 1 Climate Data Archives 1931 – Present: Station 356032. http://www.ocs.orst.edu/pub_ftp/climate_data/temp/temp6032.dat, *accessed* July 10, 2006.

ODEQ (Oregon Department of Environmental Quality), 2006. Oregon Department of Environmental Quality Water Quality Standards: Beneficial Uses, Policies, and Criteria for Oregon. OAR, Division 41 (340-041-0028 (b) and (c)). Oregon Department of Environmental Quality, Portland.

OFPA (Oregon Forests Practices Act), 2004. Water Protection Rules: Riparian Management Areas and Protection Measures for Significant Wetlands. Chapter 629, Division 635 and 645. Oregon Department of Forestry, Salem, Oregon.

Pabst, R.J. and T.A. Spies, 1999. Structure and Composition of Unmanaged Riparian Forests in the Coastal Mountains of Oregon, USA. Canadian Journal of Forest Research 29(10):1557-1573.

Poole, G.C. and C.H. Berman, 2001. An Ecological Perspective on In-Stream Temperature: Natural Heat Dynamics and Mechanisms of Human-Caused Thermal Degradation. Environmental Management 27:787-802.

Richardson, J.S. and R.J. Danehy, 2007. Synthesis of the Ecology of Headwater Streams and Their Riparian Zones in Temperate Forests. Forest Science 53(2):131-147.

Rosgen, D.L., 1994. A Classification of Natural Rivers. Catena 22:169-199.

Sinokrot, B.A. and H.G. Stefan, 1993. Stream Temperature Dynamics: Measurements and Modeling. Water Resources Research 29:2299-2312.

Spies, T.A., D.E. Hibbs, J.L. Ohmann, G.H. Reeves, R.J. Pabst, F.J. Swanson, C. Whitlock, J.A. Jones, B.C. Wemple, L.A. Parendes, and B.A. Shrader, 2002. The Ecological Basis of Forest Ecosystem Management in the Oregon Coast Range. *In*: Forest and Stream Management in the Oregon Coast Range, S.D. Hobbs, J.P. Hayes, R.L. Johnson, G.H. Reeeves, T.A. Spies, J.C. Tappeiner, II, and G.E. Wells (Editors). Oregon State University Press, Corvallis, Oregon, pp. 31-67.

Torgerson, C.E., D.M. Price, H.W. Li, and B.A. McIntosh, 1999. Multiscale Thermal Refugia and Stream Habitat Associations of Chinook Salmon in Northeastern Oregon. Ecological Applications 9:301-319.

Wimberly, C.M., T.A. Spies, C.J. Long, and C. Whitlock, 2000. Simulating Historical Variability in the Amount of old Forests in the Oregon Coast Range. Conservation Biology 14(1):167-180.

Zwieniecki, M.A. and M. Newton, 1999. Influence of Streamside Cover and Stream Features on Temperature Trends in Forested Streams of Western Oregon. Western Journal of Applied Forestry 14:106-113.

AN ABSTRACT OF THE THESIS OF

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Title: Examining Effectiveness of Oregon's Forest Practice Rules for Maintaining Warm-Season Maximum Stream Temperature Patterns in the Oregon Coast Range

Abstract approved:

Stephen H. Schoenholtz

Stream temperature, as an important component of stream ecosystems, can be affected by forest harvesting through removal of riparian shade and changes in hydrology. Riparian Management Areas (RMAs), as implemented through the current Oregon Forest Practice Rules, are designed, in part, to maintain stream temperature following forest harvesting. However, effectiveness of RMAs in achieving this outcome is uncertain. The objective of this research was to examine effectiveness of RMAs, as outlined by the current Oregon Forest Practices Act and the Northwest State Forests Management Plan, in maintaining warm-season temperature patterns of streamwater. Twenty-two headwater streams, on either private- or state-owned forestlands in the Oregon Coast Range that encompassed a range of RMA widths and harvest prescriptions, were evaluated for effectiveness of RMAs on stream temperature. A Before-After-Control-Impact/Intervention design was used, and each stream had an upstream control and a downstream treatment reach. Temperature probes were placed 1) at the top of the control reach, 2) at the boundary between the control and treatment reaches, and 3) at the bottom of the treatment reach from June to September for four years starting in 2002. All but one stream have at least two years of pre-

harvest temperature data, and one year of post-harvest temperature data. Selected stream and riparian characteristics were collected every 60 m within the control and treatment reaches once prior to and once following harvest. I hypothesized that RMAs would be effective if pre-harvest warm-season maximum temperature patterns were maintained following harvest treatments. Comparisons of temperature patterns between control and treatment reaches both pre- and post-harvest indicate that my hypothesis should be rejected because warm-season maximum temperature patterns were not maintained when mean values in treatment reaches across all study streams were considered. Difference in temperature gradients between control and treatment reaches averaged 0.6°C, based on two years of pre-harvest and one year of post-harvest data. This indicates that more warming or less cooling occurred in treatment reaches than occurred in control reaches when pre-harvest and post-harvest periods were compared, suggesting that current RMAs for small- and medium fish-bearing streams of the Oregon Coast Range are not effective for maintenance of warm-season maximum temperature patterns.

Examining Effectiveness of Oregon's Forest Practice Rules for Maintaining Warm-Season Maximum Stream Temperature Patterns in the Oregon Coast Range

by
Jennifer Marie Fleuret

A THESIS

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Master of Science thesis of Jennifer Marie Fleuret presented on May 12, 2006.

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Jennifer Marie Fleuret, Author

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Examining Effectiveness of Oregon's Forest Practice Rules for Maintaining Warm-Season Maximum Stream Temperature Patterns in the Oregon Coast Range

Chapter I

Introduction

1.1. Introduction

Stream temperature is an important component of a stream ecosystem that can be influenced by timber harvesting through alteration of heat and energy delivery. Many factors influence stream temperature, including hyporheic exchange, solar radiation, shade, air temperature, channel substrate, discharge, and wind speed (Poole and Berman 2001). Removal of riparian canopy and shade through forest harvest has been documented to increase stream temperature (e.g. Johnson and Jones 2000, Story et al. 2003) to levels that are detrimental for some aquatic species (Beschta et al. 1987). Effects of increased stream temperature on fish and other aquatic organisms are well-documented (e.g. Beschta et al 1987, Newbold et al. 1980). Studies detailing impacts on freshwater fish occurred as early as the 1920s (e.g. Titcomb 1926). Increased stream temperature can result in reduced concentrations of dissolved oxygen, which can lead to changes in metabolic rates, spawning success, and disease incidence (Beschta et al. 1987). Increased stream temperature can also result in increased biomass of both periphyton and certain macroinvertebrates, which can increase the productivity of the system (Boothroyd et al. 2004, Newbold et al. 1980).

Many studies have examined the role that riparian vegetation plays by influencing stream temperature through obstruction of insolation. For example, solar radiation can account for more than 95% of the heat input during summer in Oregon Coast Range streams (Brown 1970). Implementation of Riparian Management Areas (RMAs) can reduce the potential for increased temperatures following harvest by retaining riparian vegetation. Although required by law in some states, effectiveness of specific RMAs in maintaining stream temperature patterns is uncertain. Assessing effectiveness of RMAs can be difficult, considering the many factors that influence stream temperature, and the difficulty in obtaining a large sample size. However, my research is designed specifically to determine effectiveness of Oregon's rules for RMAs in maintaining warm-season maximum temperature patterns in streams following harvest.

1.2. Literature Review

1.2.1. Factors Affecting Stream Temperature

Many factors contribute to heating and cooling processes in streams, including incoming solar radiation, hyporheic exchange, discharge, channel substrate composition, convection, and conduction (Poole and Berman 2001). Atmospheric and stream heat exchanges occur in several ways, including inputs of heat through short- and longwave radiation, loss of heat through longwave radiation and evaporation, and heat convection exchanges of energy across the air-water interface (Sinokrot and Stefan 1993). A general formula for heat gains and losses into and out of a stream follows:

$$\Delta H = N + T + B + E + S \qquad [1]$$

where ΔH is change in temperature, N is net radiation, T is heat added or lost by tributary and groundwater inflows, B is heat exchange between the water and streambed (conduction), E is heat exchange from evaporation or condensation, and S is heat exchange between the air and stream surface (convection) (Hewlett and Fortson 1982). These values may be positive (indicating heat gain) or negative (indicating heat loss), and are influenced by various factors, including riparian shade, upland vegetation, precipitation, air temperature, wind speed, solar angle, cloud cover, humidity, groundwater temperature, and tributary temperature and inflows (Poole and Berman 2001). Although conduction, evaporation, and convection are important processes, their relative contributions to stream heating are small when compared to the heat contributed by solar radiation (Brown 1970, Sinokrot and Stefan 1993, Johnson 2004).

The temperature of phreatic groundwater is thought to be the origin of surface water temperature, and the temperature of surface water has been generalized to increase (moves towards atmospheric temperature) as it flows downstream from its source (Vannote et al. 1980). Changes in stream temperature are moderated by the presence of insulating and buffering processes (Poole and Berman 2001).

Insulating processes affect the rate of heat delivery into and out of a stream, and include channel width and riparian vegetation structure, encompassing proximity to the channel, height, and density (Poole and Berman 2001). Channel width determines the surface area of the stream, with a wider stream having a larger surface area available for heat exchange than a narrow stream. Smaller volumes of water will also heat more quickly than streams with a greater volume of water (Moore and Miner 1997).

Buffering processes may contribute to heating and cooling processes by releasing and storing heat (Poole and Berman 2001). Hyporheic flow is probably the most important modifier of stream temperature, and the hyporheic zone is an ecotone between the surface and groundwater through which significant exchanges of water, nutrients, and organic matter occur (Boulton et al. 1998). The magnitude of hyporheic flow is affected by channel morphology, streambed heterogeneity, streamflow variability, as well as groundwater and tributary inflows and outflows (Poole and Berman 2001). Heat exchange with the hyporheic zone was found to have a cooling effect during the daytime in streams in British Columbia, and this effect accounted for more than 25% of the net radiation input into the stream (Moore et al. 2005a).

Thermal heterogeneity within streams comes from a number of sources including the interaction of surface-, hyporheic-, and deep groundwater flow. This interaction and resultant heterogeneity helps create thermal refugia for aquatic organisms. Solar radiation contributes to thermal stratification, and removal of shade can change the presence and location of cold water patches (Ebersole et al. 2003). Additionally, there are longitudinal and seasonal patterns of thermal heterogeneity, which are influenced by lateral and vertical hyporheic exchange, as well as channel substrate, discharge, and riparian vegetation. Groundwater inflows also function to moderate maximum temperatures and dampen diurnal changes (Danehy et al. 2005).

Effects of channel substrate on stream temperature are largely unstudied, and are thought to be relatively minor by some researchers and relatively important by others. For example, bedrock has been postulated to both increase and buffer temperature (Johnson 2004, Brown 1969), and it is possible that effects of bedrock and alluvial substrates are more important in affecting stream temperature than are generally recognized. Heat transfer between water and substrate is much faster than between water and air, and if hyporheic exchange is occurring, a potentially large amount of water is in contact with substrates. Direct solar radiation may heat up substrates during the day, resulting in the conduction of heat to streamwater during the night (Johnson and Jones 2000). Sinokrot and Stefan (1993) also suggest that streambeds can act as an energy sink during the day and a source at night, but that as streams increase in size, streambed heat conduction becomes less important. Also, smaller inputs of solar radiation (such as in heavily shaded streams) allow streambed heat conduction to play a relatively greater role in moderating stream temperature (Story et al. 2003).

There is evidence that upland microclimate influences stream temperature. Upland soil water temperatures were closer to stream temperatures than nearby riparian zone soil water temperature after a harvest in western Washington, which suggests that these streams receive a significant portion of their water from upland preferential flowpaths (Brosofske et al. 1997). Air temperature, as well as relative humidity, cloud cover, and wind speed, also possibly influence streamwater temperature in streams of western Oregon (Zwieniecki and Newton 1999).

Air temperature has been used to predict water temperature. The correlation between air temperature and water temperature tends to decrease with increasing spatial distance between air and stream temperature measurements, and accurate estimation depends on the time lag between air and stream temperature (Stefan and Preud'homme 1993). Additionally, length of the time lag was found to be dependent on stream size, with smaller streams having smaller time lags, and prediction of stream temperature from air temperature was more accurate with smaller streams in Mississippi (Stefan and Preud'homme 1993). Danehy et al. (2005) found that inclusion of maximum air temperature in their model for streams in Idaho and Eastern Oregon improved its predictive capability for maximum stream temperature. Increases in stream temperature were also positively associated with maximum air temperatures for streams in British Columbia (Moore et al. 2005a).

A variable that has not always been quantified in past research of stream temperature is stream discharge and the role it plays in stream temperature dynamics. It is well known that smaller streams are more likely to be influenced by changes in riparian vegetation and thus solar input (e.g. Beschta et al. 1987). Less energy is required to heat a smaller volume of water than a larger volume of water, and thus streams with smaller discharges are likely to be more sensitive to changes in heat input (Moore and Miner 1997). Brown (1970) postulated a formula that has been used to determine stream temperature changes following a clearcut:

$$\Delta T = \frac{A*N}{Q} *0.000267 \qquad [2]$$

where ΔT is change in temperature (°F), A is surface area in square feet, N is solar load per unit area, and Q is discharge in cubic feet per second. Any change in stream temperature, according to this relationship, is dependent on stream surface area, amount of solar radiation reaching the stream, and discharge. Notably, a smaller discharge will result in a greater potential increase in temperature. Hetrick et al. (1998) found that stream temperature changed more in response to changes in streamflow than to percentage of shade in two small Alaskan streams. Because of the many cloudy days observed in the study area, solar radiation was not predominantly factored in stream temperature change. Although discharge was most important, the authors do not discount the value of shade, and note that canopy cover helped to lower the magnitude of changes in stream temperature. Moore et al. (2005a) found that higher discharges in streams in British Columbia also correlated with lower temperatures.

In the review by Tabbachi et al. (1998), they note that formation of pools caused by the presence of large wood and other obstructions such as boulders can also impact temperature by providing localized areas of deeper and cooler water. Temperature in pools can also be stratified, with differences of up to 2°C found in some pools in streams in British Columbia (Moore et al. 2005a).

Basin elevation was found to be the most important predictor of stream temperature in second- to fourth-order streams of Idaho and Wyoming, but width and watershed aspect had very little influence on stream temperature (Isaak and Hubert 2001). The authors concluded that a wider stream has a greater ability to dissipate heat because of the larger volume of water, and therefore greater width results in slower changes to stream temperature. Increases in stream temperature have also occurred with a decrease in hydraulic gradient as found in five streams in New Brunswick; however, the reduction in gradient corresponded with an increase in solar radiation input (Bourque and Pomeroy 2001).

Models have been developed to predict stream temperature in response to several factors. The Stream Network Temperature Model (SNTEMP) was developed to predict stream temperature changes as water flows downstream (Bartholow 2000). Although both this model and Brown's equation [eqn 2] have proven to be relatively effective in predicting mean daily stream temperature, the importance of variables within the models differs. Brown's equation [eqn 2] focuses on the importance of solar radiation and discharge (Brown 1970), whereas the SNTEMP assumes water temperature is most sensitive to air temperature (Bartholow 2000).

There have been suggestions that each stream has its own particular temperature pattern or "signature" which reflects its individual environment and flow pattern (e.g. Zwieniecki and Newton 1999). This signature is likely to be influenced by several factors, including tributary inflows, pool location, substrate, and stream channel morphology (Zwieniecki and Newton 1999). Although generalizations have been made about increases in stream temperature as the stream flows downstream (e.g. Zwieniecki and Newton 1999, Sullivan and Adams 1989, Vannote et al. 1980), it is likely that stream temperature dynamics are more complex, with increases and decreases in temperature within a reach likely to occur. Smith (2004) found that streams in the Oregon Coast Range warmed, cooled, or had components of both warming and cooling as they traveled in a downstream direction. Furthermore, although she found that canopy cover was the most consistent predictor for stream temperature (R^2 = 0.49), 51% of stream temperature variability was left unexplained. Moore et al. (2005a) found that streams in their study in British Columbia also had warming, cooling, and intermediate temperature patterns.

Although many factors contribute to temperature, rarely does one factor independently influence stream temperature, and the relative importance of each factor can change both spatially and temporally (Danehy et al. 2005).

1.2.2. Stream Temperature and Aquatic Organisms

Forested headwater streams usually represent the majority of a drainage network, and provide a significant habitat for many organisms (Peterson et al. 2001). The natural flow regime (*sensu* Poff et al. 1997) maintains that organisms are specifically adapted to survive in a particular stream environment, and changes in this environment can either positively or negatively influence their survival. Most species have an optimum temperature range, and changes in stream temperature regimes can change dominance of species as well as stream community composition (Beschta et al. 1987).

Warmer water holds less oxygen than cooler water, which can result in increased stress and disease incidence among aquatic organisms. Metabolic rates of fish and other aquatic organisms are controlled by stream temperature (Beschta et al. 1987), and higher temperatures can lead to increased metabolism, thus influencing the productivity of the system. Changes in productivity can change the trophic status of the ecosystem, among other things, and modify the distribution of resources (Melody and Richardson 2004). Increased stream temperature can lead to changes in fish embryo development and timing of life history events, such as migration and spawning cues. Additionally, increased temperature can impede migration and facilitate the invasion of warm water species which can displace native species (Beschta et al. 1987).

Removal of vegetation has been documented to change the shading and rate of litter inputs into small streams, which can impact the benthos and limit secondary production and thus food availability (Melody and Richardson 2004). However, increased macroinvertebrate density has also been recorded as a result of algal blooms from increased light inputs; however, this generally corresponds with a reduction in biodiversity (Baillie et al. 2005).

Holtby (1988) studied the effects of logging on Coho salmon (*Oncorhynchus kisutch*) in British Columbia, and found that increases in stream temperature led to earlier emergence of salmon fry, as well as a longer summer growing season. This resulted in larger fingerlings, as well as improvement in winter survival, which increased yearling populations. However, yearling smolt migration also occurred earlier, which may have led to a reduced population of two-year-old smolts (Holtby 1988).

1.2.3. Riparian Management Areas and Stream Temperature

Riparian management areas are designed to protect water quality from non-point source pollutants, which come from a variety of dispersed sources. They have been used to maintain stream temperature, reduce sediment input, reduce nutrient input, and retain a riparian environment. They are also designed to provide large wood and organic matter to mountain streams (Osborne and Kovacic 1993). Width requirements for RMAs vary across the country, but mean RMA width for lakes, rivers, and streams in Canada and the United States ranges from 15 to 30 m. For small perennial streams, the average RMA width is 22 m (Lee et al. 2004).

Riparian management areas are used in forestry to separate a waterbody from an upland harvest in order to reduce disturbance to the waterbody and to maintain a riparian habitat (USEPA 2006). Recently, increased RMA retention has been attributed to objectives to maintain riparian corridors and protect riparian ecosystems (Lee et al. 2004). Guidelines for RMAs are increasingly site-specific and complex when compared to historical RMA directives, requiring an increased understanding of riparian dynamics (Lee et al. 2004). Guidelines for RMAs depend on a particular state's rules as well as a landowner's management objectives; however, the United States Environmental Protection Agency's (USEPA) guidelines stipulate that an RMA width of 11 to 15 m is generally recommended for an RMA to be effective (http://www.epa.gov/owow/nps/forestrymgmt/).

Stability of RMAs can be impacted by blowdown, insects, disease, and logging activities, and some researchers have recommended site-specific designs for RMAs (Steinblums et al. 1984). Based on regressions developed to predict stability, RMA design should take into account anticipated RMA width, pre-harvest RMA basal area, and the dominant slope of both the riparian and harvest areas (Steinblums et al. 1984).

Recommended width of an RMA on state or private lands in Oregon depends on several factors, but is determined primarily based on location within Oregon. Width also depends on whether the stream is fish-bearing (Type F), non-fish-bearing (Type N), or is considered a domestic water source for use within homes and businesses (Type D). Finally, riparian buffer width depends on size of the stream: whether it is small (<0.06 cms), medium (0.06 – 0.28 cms), or large (>0.28 cms) (Table 1.1). (Logan 2002).

Table 1.1. Stream classification and size of required riparian management areas (RMAs) for private land in the Oregon Coast Range (adapted from Logan 2002).

Size	Type[2]	RMA width (m)
Small	F	15
(<0.06 cms)[1]	N	0
	D	6
Medium	F	21
(0.06-0.28 cms)	N	15
	D	15
Large	F	30.5
(>0.28 cms)	N	21
	D	21

[1]cms: discharge units of m^3sec^{-1}. [2] F: fish-bearing; N: non-fish-bearing; D: domestic water source

There are also specific basal area retention requirements within the RMA (known as standard targets in the Oregon Forest Practice Rules) depending on the type of harvest, as well as stream classification. Minimum levels of basal area must be retained, the majority of which is required to be conifer. Limited harvesting may take place within the RMA, particularly if there is more basal area in the RMA than the standard target or if the stream or riparian area is in need of restoration. If a landowner successfully restores these areas, he or she may harvest within the RMA to a level known as the active management target, a basal area retention below the standard target (Logan 2002).

State forests have different requirements for widths of RMAs. State RMAs are required to have four zones: aquatic, stream bank, inner RMA, and outer RMA. Regardless of the type and size of the stream, the entire RMA should be at least 52 m in width. However, requirements for basal area retention depend on the type of harvest as well as size and type of stream (see Northwest Oregon State Forests Management Plan, Appendix J, 2001).

Effectiveness of RMAs has been studied previously in other regions. In Alaskan headwater streams, sensitive fish species preferred pools with some cover (preferably large-wood cover), and streams that were exposed directly to clearcut harvesting had fewer pools and less large organic debris, and therefore less favorable habitat. However, streams that had intact RMAs maintained pool area, and blowdown from the RMA frequently added to the volume of organic debris (Heifetz et al.1986).

Nitschke's (2005) meta-analysis that compared wildfire effects on stream temperature to effects from clearcut harvesting suggested that clearcuts can have similar effects on stream temperature as wildfire. The difference in temperature between the wildfire and clearcut sites was not statistically significant, indicating that changes in temperature following intense wildfires were similar to changes in temperature following harvesting. However, mean temperature within streams with RMAs was significantly lower than wildfire sites, indicating that RMAs and intact riparian areas can help to moderate stream temperature following a disturbance.

1.2.4 Influence of Solar Radiation and Shade

Although not all studies have identified insolation as a primary driver of stream temperature, solar radiation has been documented to account for over 95% of heat input into a stream in the summer at midday in the Oregon Coast Range (Brown 1970). In their recent review of stream temperature literature, Moore et al. (2005b) conclude that shade is the key factor in controlling stream temperature, particularly in forested regions.

There is some disagreement on how effective shade is in moderating stream temperature (e.g. Larson and Larson 1996, Beschta 1997). However, most studies that examine shade agree that it plays a dominant role. An increase of 6ºC was found when riparian canopy was removed from Pacific Northwest headwater streams, and greater canopy retention helped to maintain stream temperatures (MacDonald et al. 2003). The authors also found that temperature increased in the first three years following harvest, and only decreased in the fourth year when understory vegetation began to shade the channel. Holtby (1988) reported that increases of over 3˚C occurred when 41% of a watershed in British Columbia was clearcut. Increases of 6-8ºC also occurred when canopy was removed in the Western Cascades of Oregon, and maximum temperatures corresponded with maximum inputs of solar radiation (Johnson and Jones 2000). Levno and Rothacher (1967) found that clearcutting harvests in the Oregon Cascades increased maximum stream temperature by 4˚F, but when the streambed was scoured by a winter storm that removed remaining riparian vegetation, maximum temperatures increased up to 12˚F. Additionally, following slash burning along the same channel, stream temperatures increased by an additional 8˚F (Levno and Rothacher 1969). In streams in British Columbia studied by Danehy et al. (2005) the maximum stream temperature increased with increasing insolation, and models which included solar radiation were better at predicting maximum stream temperature. Moore et al. (2005a) reported that maximum daily water temperatures increased up to 5˚C following harvest in Idaho and Eastern Oregon in the summer, and that although treatment effects were variable, this reflected the variation in solar radiation availability.

Greene (1950) concluded that shading was the controlling factor of stream temperature when an open-canopy stream in North Carolina was found to be, on average, 11.5˚F warmer than a nearby forested stream.

Variation in temperature along a stream reach has been correlated to the presence of intact RMAs, and blockage of direct insolation was determined to be of primary importance in influencing temperature in Southern Ontario streams (Barton et al. 1985). Smith (2004) found that canopy cover was the most influential factor controlling summertime stream temperatures in the Oregon Coast Range, suggesting that energy input from solar radiation was the dominant form of heat contribution to these streams. Slash covering a stream channel and therefore blocking solar radiation was thought to contribute to the lack of temperature change in Washington Coast Range streams following harvest (Jackson et al. 2001).

A commercial clearcut and a harvest that received herbicide in Pennsylvania both resulted in increases in temperature when compared to a forested control (Lynch et al. 1984). Although both treatments resulted in increases, the harvest receiving herbicide (which removed residual low lying cover) showed increases of up to 9˚C. Minimum temperatures were also significantly increased during the daytime, but decreased during the night, which was attributed to increased radiational cooling (Lynch et al. 1984). Temperature increases following logging were shown to occur as early as February at a site in Pennsylvania, and continue into November (Rishel et al. 1982).

A study using both SNTEMP and measured stream temperatures indicated that a wooded canopy provided the most shade for streams, as compared to RMAs dominated by grass and shrub cover in Minnesota. Also, it was found that shade significantly moderated both modeled and measured maximum stream temperatures for streams in Minnesota (Blann and Nerbonne 2002).

Conflicting evidence exists regarding the downstream recovery time of stream temperature after it is heated by exposure to solar radiation through the removal of canopy (e.g. Johnson 2004, Beschta et al. 1987). Some studies suggest that water returns to pre-disturbance trajectories downstream of a disturbance (e.g. Zwieniecki and Newton 1999), and other studies have stated that although shade can prevent stream heating, it does not cause decreases in stream temperature (Brown 1970). Bourque and Pomeroy (2001) found that temperatures in streams in New Brunswick increased when forest cover was removed and a greater amount of solar radiation was able to reach the stream. Temperatures also did not decrease downstream, illustrating that effects of temperature increase are not necessarily mediated when canopy is restored downstream. Greene (1950) stated that when an open-canopy stream cooled after traveling through a shaded reach in North Carolina that canopy cover was responsible for the cooling, but Beschta et al. (1987) maintain that streams do not cool unless there is a source of colder water. Meehan (1970) suggests that shade is a necessity for cooling streams and for maintenance of cool streamwater. Story et al. (2003) state that inflow of groundwater is a prerequisite for downstream cooling of streams flowing through clearcuts, and Holtby (1988) suggests that temperatures are not likely to return to pre-harvest levels below clearcuts unless riparian vegetation is restored. Riparian canopy closure influences the amount of solar radiation that reaches the stream, and therefore the quantity of shade that covers the stream is a driving factor for moderating stream temperature. The distinction should be made that shade does not, in itself, produce cooling but rather mediates delivery of solar radiation into a stream (Larson and Larson 1996).

Long-term effects of shade removal on stream temperature have also been documented. Ten to 15 years after a harvest on the Olympic Peninsula of Washington, significant increases in temperature were still found in water flowing through a harvested unit compared to an undisturbed stream nearby (Murray et al. 2000). Also, Johnson and Jones (2000) found that it took 15 years for stream temperatures to return to pre-disturbance levels in the Oregon Cascades, and coincided with return of the canopy. Holtby (1988) suggests that because riparian revegetation in British Columbia can take as long as 15 to 30 years, effects of logging on stream temperature could persist for at least that length of time.

1.3. Rationale

This research is part of a larger, ongoing study supported by the Oregon Department of Forestry (ODF). Goals of the ODF study are multiple, and include understanding factors that influence stream temperature and determining if RMAs as outlined by the Forest Practices Act and the Northwest State Forests Management Plan are effective in maintaining stream temperature patterns in Oregon Coast Range streams (Riparian Function and Stream Temperature Study Approach 2003). Knowing more about effectiveness of current RMA guidelines in maintaining stream temperature patterns will provide information for the ODF to either modify or maintain existing guidelines. Stream temperature, as an important component of a stream ecosystem, is influenced by many factors; however, solar radiation appears to be the most influential factor. Harvesting has potential to remove important shade which absorbs and deflects solar radiation, and stream temperature has been shown to increase substantially when this shade is removed. Riparian management areas are commonly used in conjunction with forest harvests to help moderate riparian vegetation removal, but their effectiveness and stability is still uncertain. Information about stream temperature and RMA effectiveness is scarce, and in order to protect these stream systems adequately, managers and policy makers should be informed as to effectiveness of the current rules.

1.4. Objective and Hypothesis

The objective of this study is to determine effectiveness of RMAs in maintaining warm-season maximum stream temperature patterns following harvest. Prior to harvest, these streams were found to have individual warming and cooling patterns (Smith 2004), and the degree to which these patterns are maintained after forest harvesting will be used to determine effectiveness of RMAs. I hypothesize that effective RMAs will be characterized by maintenance of pre-harvest warm-season maximum stream temperature patterns following forest harvesting.

Chapter II

Methods

2.1 Site Descriptions

Twenty two streams in the Oregon Coast Range, ranging from Astoria to Coos Bay (Figure 2.1), were selected for this study, and were chosen based on criteria developed by the ODF for a larger, ongoing study of riparian vegetation function and stream temperature. The streams were located on either private- or state-owned forestlands. Streams included in this study were selected for uniformity in channel morphology and riparian characteristics, and were classified as either small- or medium fish-bearing streams (Table 1.1). Additionally, streams with recent beaver activity, debris torrents, or dams were excluded from the study.

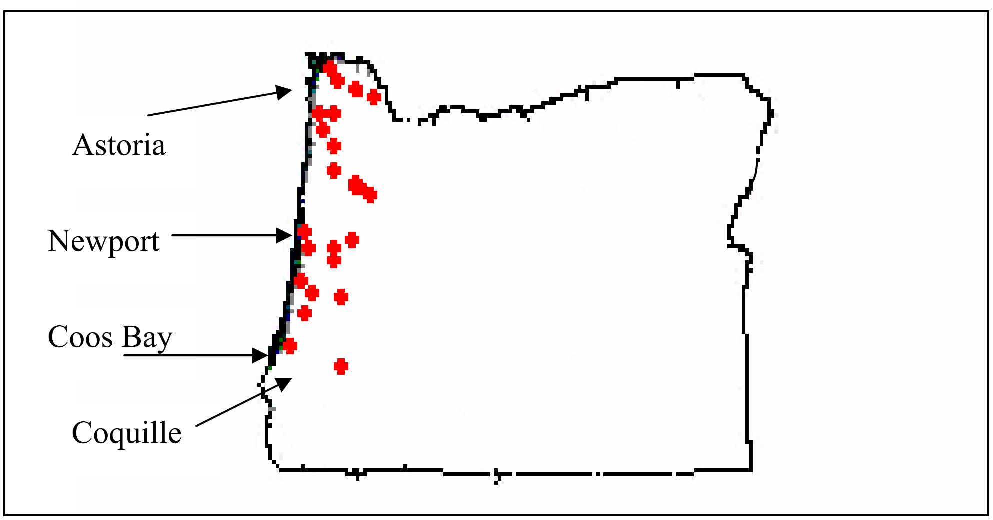


Figure 2.1. Location of 22 Oregon Coast Range headwater streams for temperature monitoring.

Composition of the channel substrate of the streams included silts, cobbles, boulders, and bedrock. The watersheds are dominated by red alder (*Alnus rubra*) and Douglas-fir (*Pseudotsuga menziesii*), with salmonberry (*Rubus spectabilis*) and devil's club (*Echinopanax horridum*) present in the majority of the riparian zones. Mean annual precipitation along the Coast Range is dominated by rainfall and is approximately 2,000 mm (http://www.ocs.orst.edu/allzone/allzone5.html).

2.2. Study Design

A Before-After-Control-Impact/Intervention (BACI) design was used in this study, with each stream assigned both an upstream control reach (not to be harvested for the study's duration) ≥213 m, and a downstream treatment reach (to be harvested at least two years after initiation of the study) ≥300 m (Figure 2.2). All but one of the 22 streams has at least two years of pre-treatment temperature data and one year of post-treatment temperature data, and channel characteristics were collected once prior to and once following harvest. Landowners harvested according to Oregon's Forest Practice Rules, which allows limited harvesting within the RMA, and riparian buffers ranged in width from 6 to 60 m on each side of the stream. Clearcut harvests occurred on one or both sides of the stream, and some harvests were one- or two-sided partial cuts.

2.3. Data Collection in the Field

Channel characterization data were collected every 60 m within the control and treatment reaches, and included canopy cover, gradient, wetted width, maximum depth, bankfull width, floodprone width, and channel substrate. Large wood pieces and wood jams were also tallied between each 60 m station (Table 2.1). Two additional variables (aspect and geology) were identified from Smith (2004). Geology at each site was classified as either igneous or sedimentary, and aspect ranged from North, Northeast, East, Southeast, South, Southwest, West, to Northwest.

Temperature data loggers (Onset © Stowaways or Hobos, accuracy ± 0.2°C) were placed at 1) the top of the upstream control (referred to as 'upstream control'), 2) the interface between the control and the treatment reaches (referred to as 'downstream control'), and 3) the bottom of the treatment reach (referred to as 'treatment') (Figure 2.2), and were anchored to a heavy rock with surgical tubing to avoid loss during high flows. Temperature probes were in place from June through September, for up to three seasons (2002, 2003, and 2004) prior to harvest and for at least one June-through-September season (2004 and/or 2005) following harvest (Table 2.2). Probes recorded hourly maximum and minimum temperatures in °C.

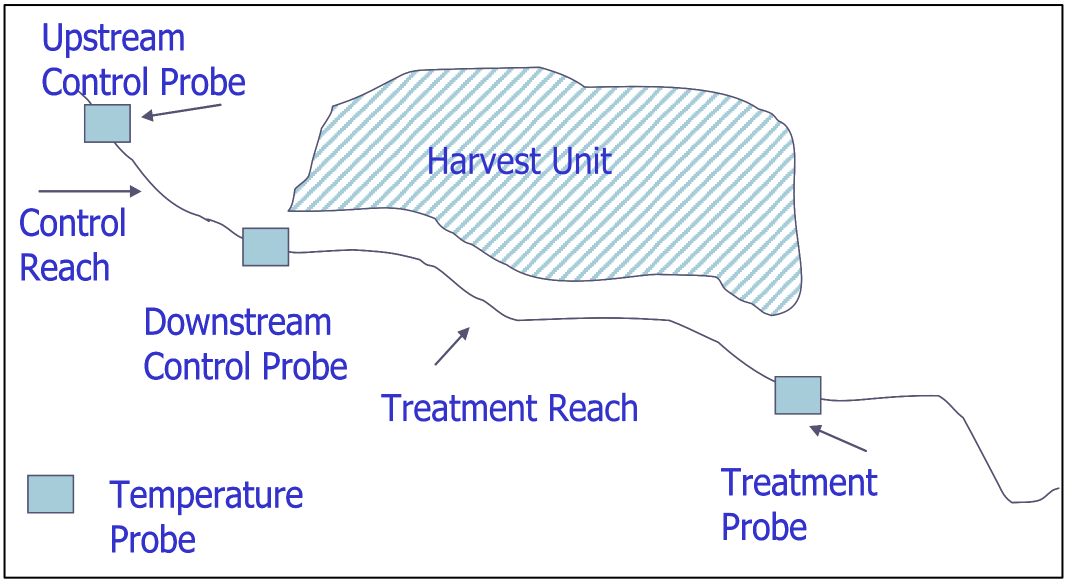


Figure 2.2. Location of control reach, treatment reach, and temperature probes used to determine effectiveness of riparian management areas in the Oregon Coast Range.

Table 2.1. Channel characterization variables collected every 60 m within the control and treatment reaches of 22 Oregon Coast Range headwater streams. (Adapted from Smith 2004).

Variable	**Description**
Shade	A hemispherical photograph was taken at each 60-m station at 0.9 m above the water surface. The camera was positioned facing north, and produces a 180 and 360 degree view of the canopy. Percent shade is calculated from the digitized photograph.
Gradient	Gradient was measured from one pool to the next pool upstream from each 60-m station using a clinometer.
Wetted width	The width of the wetted surface of the channel was measured. Mid-channel bars that were above the water surface were subtracted from the total width of the channel.
Maximum depth	The depth of the stream at the deepest point in the channel cross section.
Bankfull depth	The height of the wetted channel at the average annual peak flow was estimated, and the width of the channel at this point was measured.
Floodprone width	Twice the bankfull height was obtained at the deepest part of the channel. The tape measure was then extended to either side of the channel at this height until an incline was reached that would impede water flow. If greater than 20 m, the width was estimated.
Substrate	Substrate estimates of the relative percentages of bedrock, boulder, cobble, gravel, fines. Bedrock: solid rock Boulder: detached rock sized between a car and a basketball Cobble: sized between a basketball and a golf ball Gravel: sized between a golf ball and a ladybug Fines: substrate smaller than a ladybug
Large Wood	Large wood both within bankfull and between bankfull and 1.8 m above bankfull was tallied between each 60-m station. Large wood was considered anything with a small end diameter of at least 15 cm, and a length of at least 1.8 m. Number, height, width, and length of wood jams (a collection of wood pieces too great to count) was also tallied between each 60-m station.

Table 2.2. Number of Oregon Coast Range headwater streams evaluated for this study and their pre- and post-harvest years.

Number of streams	2002	2003	2004	2005
8	Pre-harvest	Pre-harvest	Post-harvest	Post-harvest
7	Pre-harvest	Pre-harvest	Pre-harvest	Post-harvest
6		Pre-harvest	Pre-harvest	Post-harvest
1			Pre-harvest	Post-harvest

2.4 Data Analysis

All statistical analyses were completed using SAS version 9.1 (SAS Institute Inc. 1989). Statistical significance was based on $\alpha = 0.05$.

2.4.1. Channel Characteristics

Differences between pre-harvest and post-harvest channel characteristics in the control and treatment reaches were determined by subtracting the pre-harvest values from the post-harvest values measured at each 60-m station. The number of wood pieces and volumes of wood jams were standardized to numbers per 300 m of channel length. Means and standard deviations of these differences for the control and treatment reaches of each stream were calculated. A two-sided t-test was used to determine if the changes between pre- and post-harvest channel characteristics in the control reach were significantly different from the changes in the treatment reach.

2.4.2. Climate Characteristics

Daily temperatures and total monthly precipitation for the years 2002-2005 in May-August for Oregon Climate Service Stations 350328 (Astoria), 356032 (Newport), and 351836 (Coquille) were obtained from the Oregon Climate Service (http://www.ocs.orst.edu/allzone/allzone5.html). These stations represent northern, central, and southern portions, respectively, of the distribution of study streams (Figure 2.1). Daily temperatures were averaged to produce monthly means and standard deviations. Both temperature and precipitation data were graphed.

2.4.3. Stream Temperature

Maximum daily stream temperatures for the period of July 15th to August 31st were calculated. These dates were chosen because peak streamwater temperatures occur in the Oregon Coast Range during this period, and for this study this period will be defined as the 'warm season' (Smith 2004). Using each day's maximum temperature, the 7-day moving mean of the daily maximum (7DMMDMax) was computed for July 15th to August 31st. It is calculated for each day by taking the maximum daily temperatures for the three preceding days, the maximum daily temperature for that day, and the maximum daily temperatures for the three following days, and averaging these values. Differences in 7DMMDMax between probes (i.e. Downstream Control – Upstream Control (referred to as 'control'), and Treatment – Downstream Control (referred to as 'treatment')) were then calculated to reduce spatial correlation and filter out the confounding effect of climate differences among years.

These differences were then averaged for each reach, and were standardized to be the mean difference per 300 m. This value is referred to as the ‘temperature gradient’.

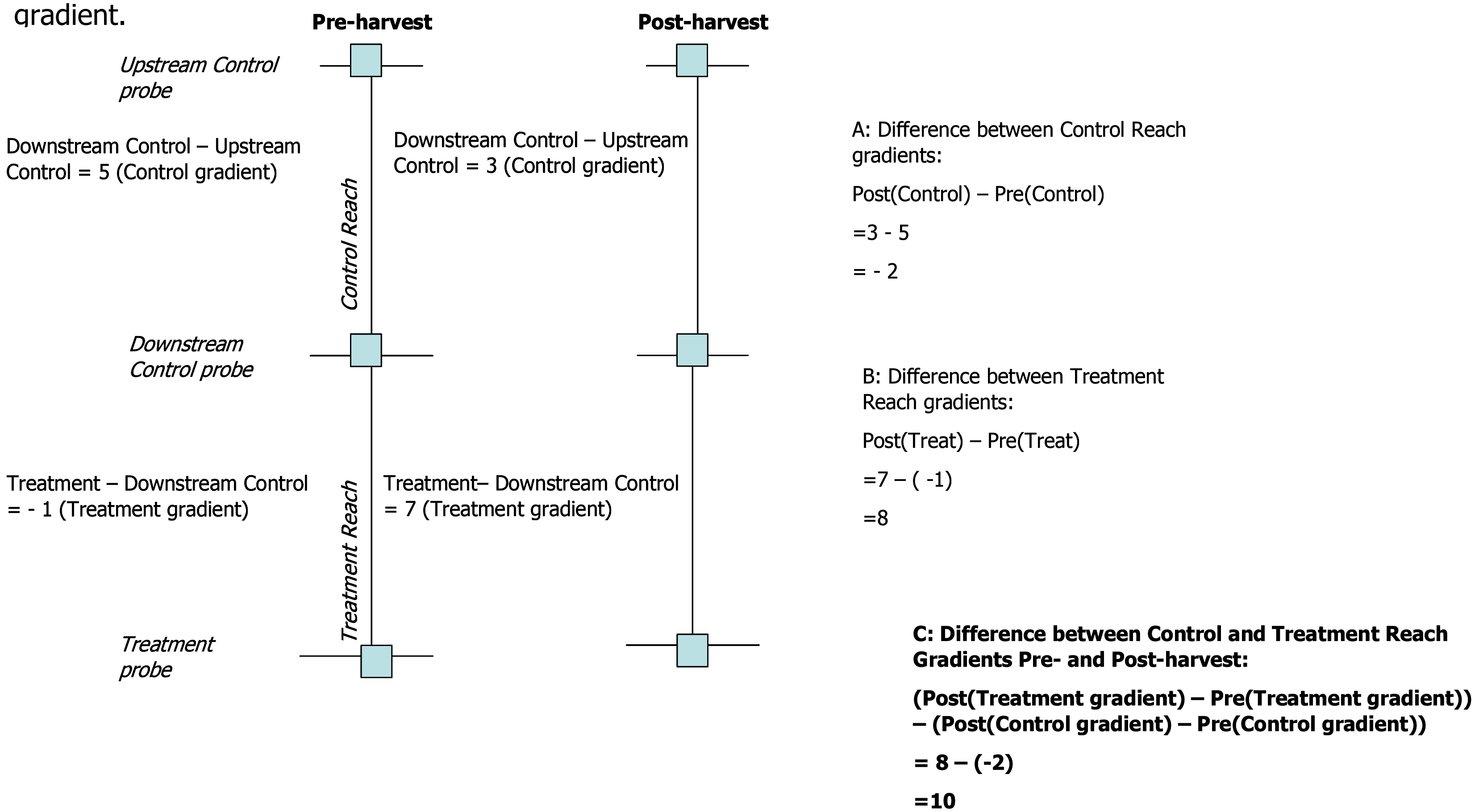
2.4.3.1. Warm-Season Maximum Stream Temperature Characteristics

The mean temperature gradient for the control and treatment reaches for each pre-harvest year (2002, 2003, and/or 2004) and each post-harvest year (2004 or 2005) and the standard deviation of the means were calculated.

2.4.3.2. Change in Warm-Season Maximum Stream Temperature Characteristics

In order to determine if there were statistically significant differences in the mean warm-season temperature gradient between years and between reaches within streams, a repeated measures analysis of variance (RMANOVA) was completed. The RMANOVA was conducted using one year pre-harvest data (2003 or 2004) and one year post-harvest data (2004 or 2005), as well as two years pre-harvest data (2002/2003 or 2003/2004) and one year post-harvest data (2004 or 2005) to determine if the RMAs maintained pre-harvest warm-season temperature patterns. A RMANOVA was also conducted between two pre-harvest years (2002 vs. 2003, or 2003 vs. 2004) to see if there were significant differences between years and reaches prior to any treatment. Estimates of the mean temperature gradients in the control reach and treatment reach pre- and post-harvest were obtained, as well as the differences in each reach pre- and post-harvest. Additionally, the pre-harvest difference in the mean temperature gradient between the control and treatment reaches was compared to the post-harvest difference between the control and treatment reaches (Figure 2.3).

Figure 2.3. Schematic and example of how estimates of changes in temperature gradients were obtained. ‘Control’ and ‘Treatment’ refer to temperature gradient/300m in the respective reach. Negative value indicates decrease in reach temperature gradient characterized by cooling or less warming; positive value indicates an increase in temperature gradient.



2.4.3.3. Relationships between Warm-Season Maximum Stream Temperature Gradient and Channel Characteristics

Simple linear regression was used to determine the presence of significant relationships between temperature gradient and channel characteristics. Explanatory variables were the mean of each of the channel characteristics measured at 60-m intervals within a particular reach, and the response variable was the temperature gradient for each corresponding reach. Explanatory variables with the highest significance ($p < 0.05$) and the higher R^2 values were considered the best predictors for temperature gradient. Relationships that were considered for each reach among the 22 controls and each reach among the 22 treatments had only one explanatory variable, because the sample size ($n = 22$ for control reaches, $n = 22$ for treatment reaches) was not large enough to accommodate two-variable selections.

Exploration of two-variable models was accomplished by treating each reach (control and treatment) in each stream as a separate statistical unit, which increased the sample size to 44.

2.4.3.4. Warm-Season Stream Temperature Patterns of Individual Streams

The 7DMMDMax occurring each day between July 15th and August 31st for the downstream control and treatment probes was obtained. The relationship between the downstream control and treatment probes for these values on each stream was visually assessed for all pre-harvest and post-harvest years. Additionally, 95% confidence intervals for predicted pre-harvest temperatures were determined.

The metric used by the ODF and Oregon Department of Environmental Quality (ODEQ) to determine if a water body has exceeded the temperature standard is the maximum 7DMMDMax, or the maximum mean temperature for the warmest week of the season (Max7Day). This value for each probe was obtained for each stream in each year, as well as the date on which it occurred.

Chapter III

Results

3.1 Stream Channel Characteristics

3.1.1 Shade Characteristics

Prior to treatment, shade in control reaches ranged from 72 to 96%, with a mean of 85% (±8). In the year following harvest, shade in control reaches ranged from 83 to 99%, with a mean of 89% (±5) (Figure 3.1A). Shade in treatment reaches prior to harvest ranged from 70 to 95%, with a mean of 86% (± 7). Following harvest, shade in treatment reaches ranged from 51 to 99%, with a mean of 79% (±13) (Figure 3.1B).

In control reaches, percent shade increased by a mean of 3% (± 8) in the year following harvest, whereas in the treatment reaches, percent shade decreased by a mean of 6% (±10). The change in percent shade in control reaches was significantly different than the change in treatment reaches (p-value=0.0021) when pre-harvest and post-harvest means were compared (Figure 3.1C).

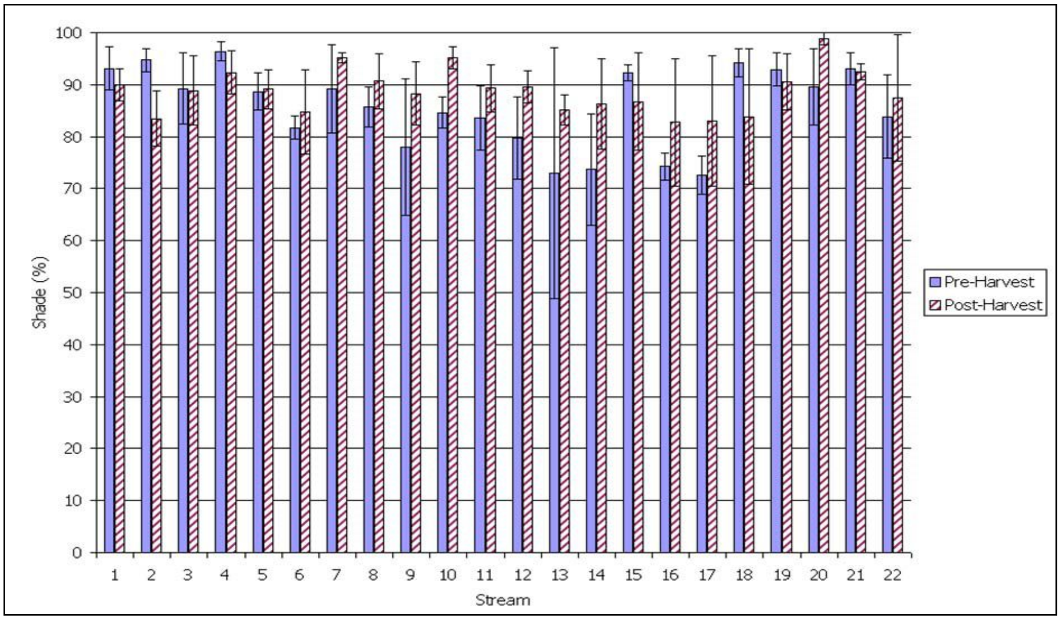


Figure 3.1A. Percent shade in control reaches pre- and post-harvest in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

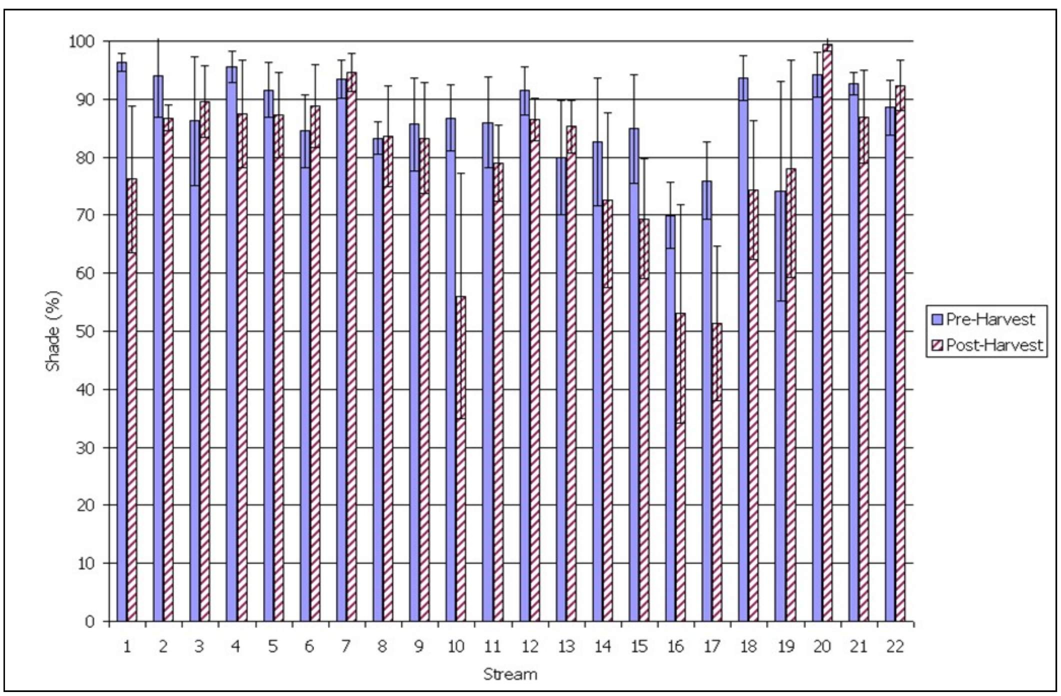


Figure 3.1B. Percent shade in treatment reaches pre- and post-harvest in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

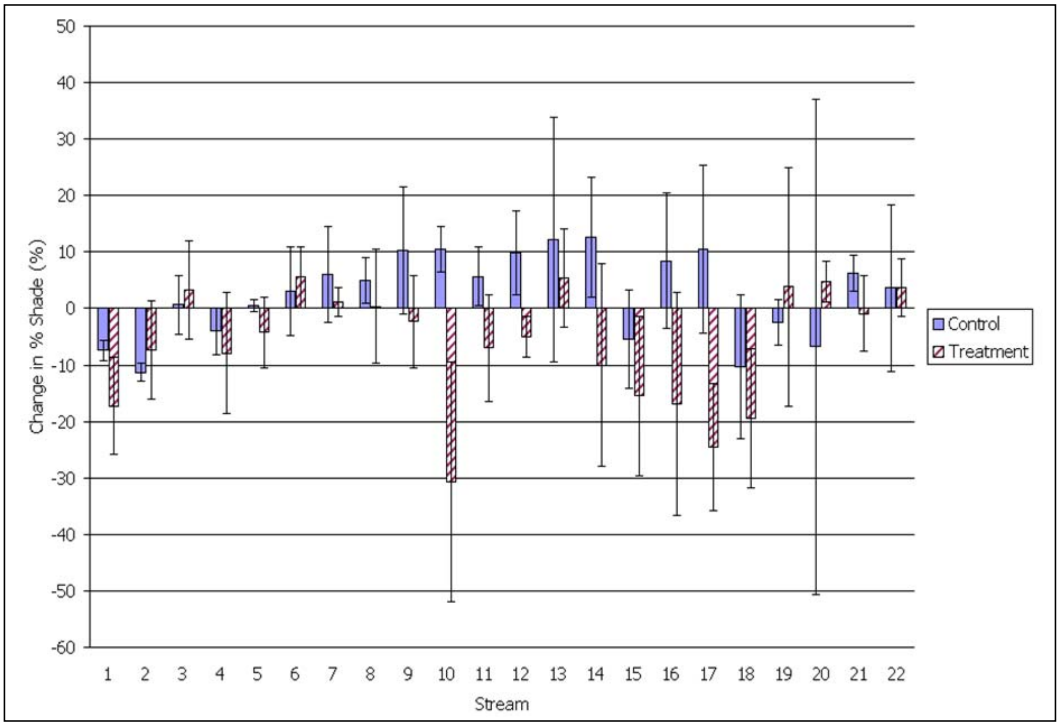


Figure 3.1C. Change in percent shade in control and treatment reaches following harvest in 22 Oregon Coast Range headwater streams. Error bars represent on standard deviation of the mean.

3.1.2. Stream Channel Morphology

Following harvest, stream gradient in the control and treatment reaches was 0.5% (± 1) and 1.3% (±1) lower, respectively, than gradients observed prior to harvest (Figure 3.2A).Wetted width in control and treatment reaches increased following harvest by 0.6 m (± 0.7) and 0.5 m (± 0.9), respectively (Figure 3.2B). Maximum streamwater depth in the control and treatment reaches increased 0.03 m (± 0.07) and 0.05 m (±0.07) following harvest, respectively (Figure 3.2C). Bankfull width in control reaches increased by 0.1 m (± 0.7) following harvest, and in treatment reaches decreased by 0.1 m (±1) (Figure 3.2D). Floodprone width in control reaches increased following harvest by 1.6 m (±5) and in the treatment reach by 2.0 m (±4) (Figure 3.2E). These changes in stream gradient, wetted width, maximum depth, bankfull width, and floodprone width in the control reach following harvest were not significantly different than changes in the treatment reach (p-values= 0.44, 0.33, 0.42, 0.81, respectively).

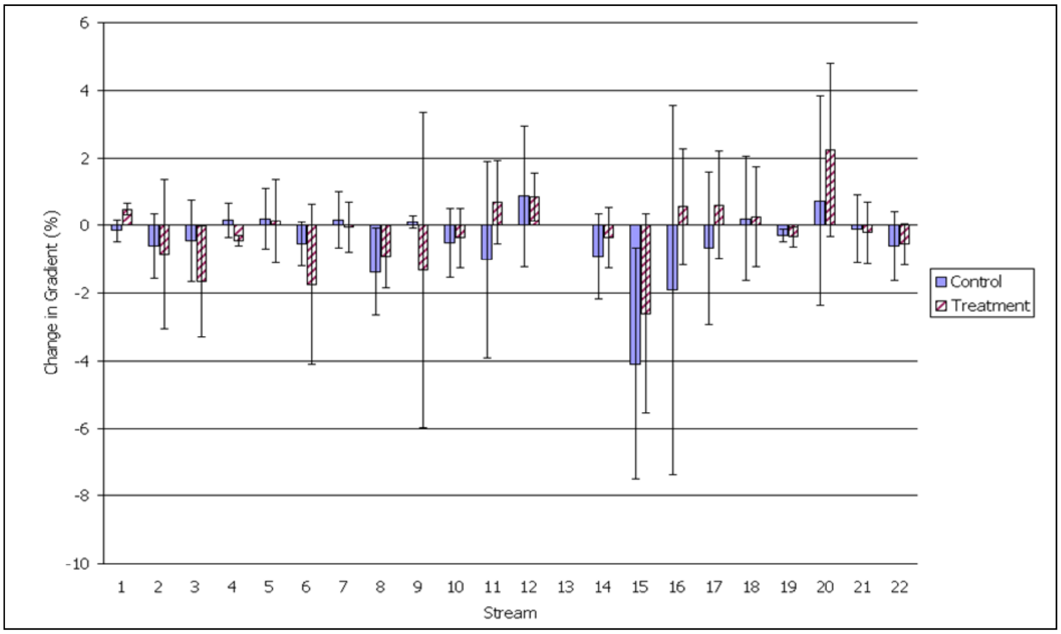


Figure 3.2A. Mean change in gradient in control and treatment reaches following harvest in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

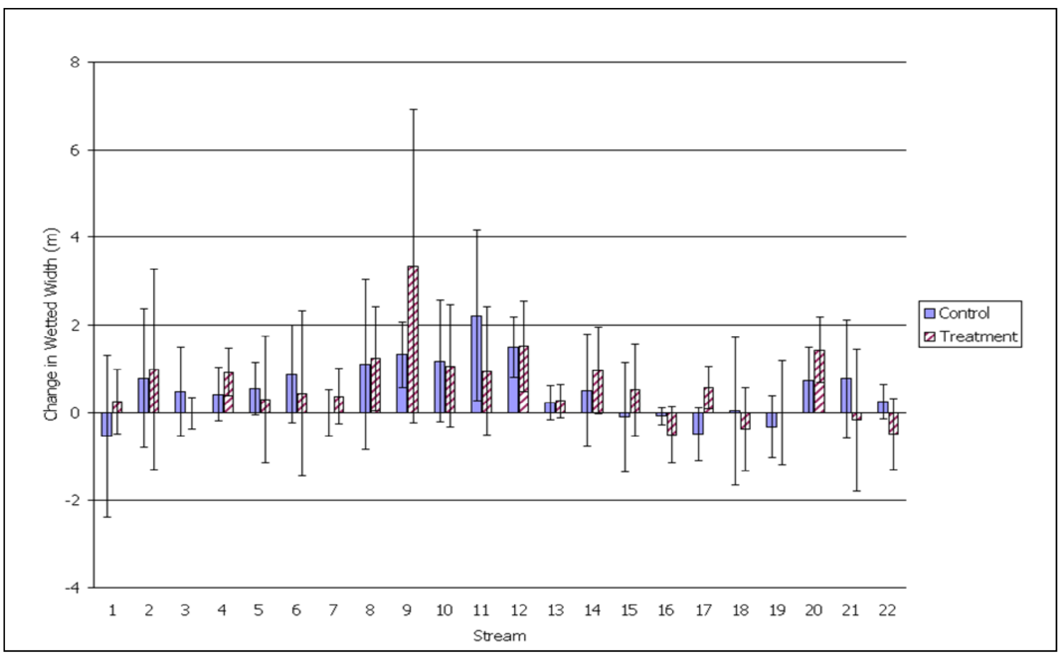


Figure 3.2B. Mean change in wetted width in control and treatment reaches following harvest in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

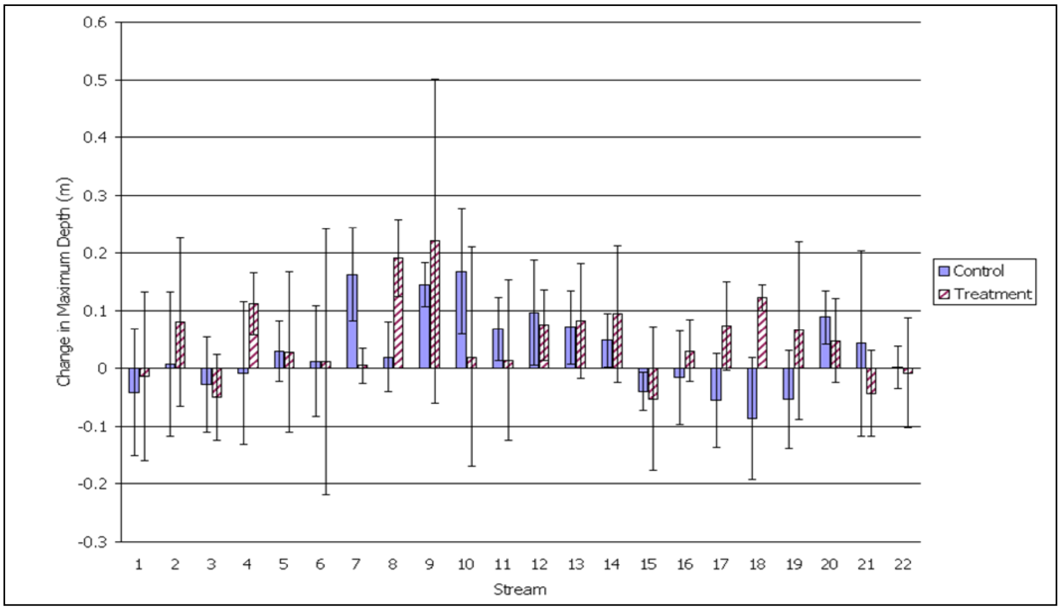


Figure 3.2C. Mean change in maximum depth in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

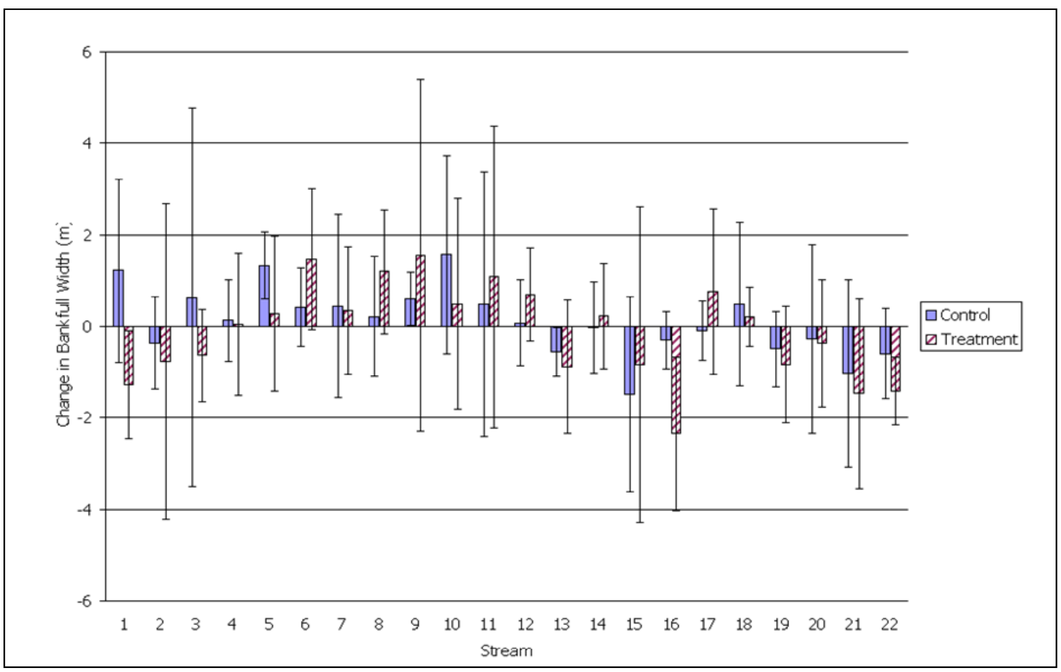


Figure 3.2D. Mean change in bankfull width in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

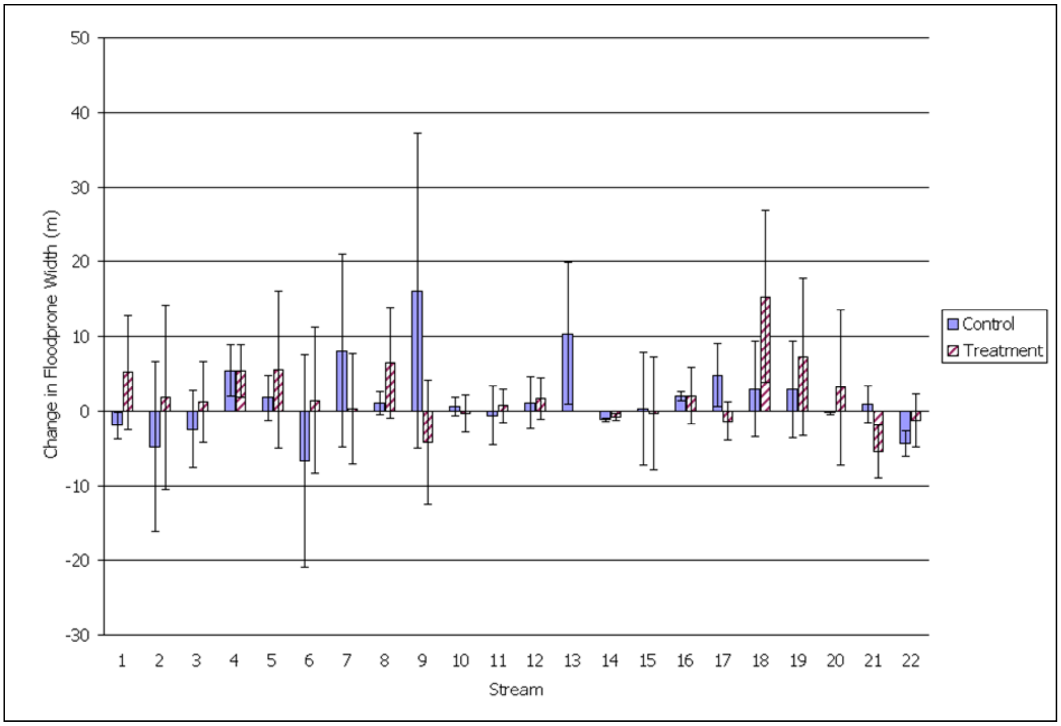


Figure 3.2E. Mean change in floodprone width for control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

3.1.3. Channel Substrate Characteristics

Percent bedrock in control and treatment reaches increased following harvest by 3% (±8) and 2% (±5), respectively (Figure 3.3A). Percent boulder increased in control and treatment reaches following harvest by 9% (±10) and 8% (±9), respectively (Figure 3.3B). Percent cobble increased in control and treatment reaches following harvest by 16% (±15) and 15% (±16), respectively (Figure 3.3C). Percent gravel decreased in control and treatment reaches following harvest by 11 (±16) and 5% (±19), respectively (Figure 3.3D). Percent fines decreased in control and treatment reaches following harvest by 18% (±18) and 14% (±22), respectively (Figure 3.3E). Change in bedrock, boulder, cobble, gravel, and fines in treatment reaches following harvest was not significantly different than change in control reaches (p-values=0.45, 0.81, 0.92, 0.25, 0.57, respectively).

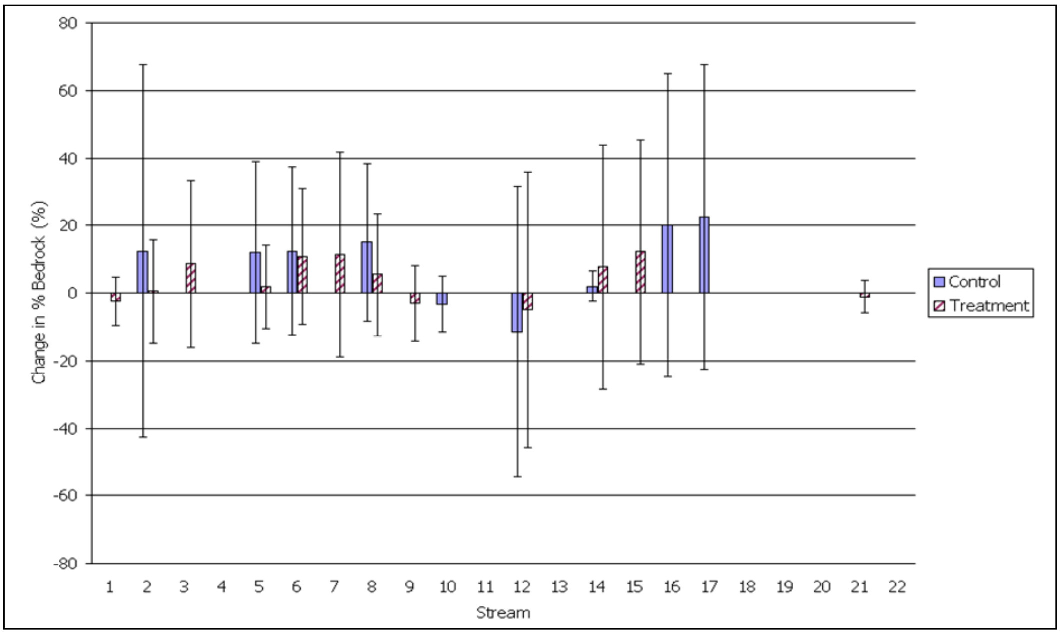


Figure 3.3A. Mean change in percent bedrock in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

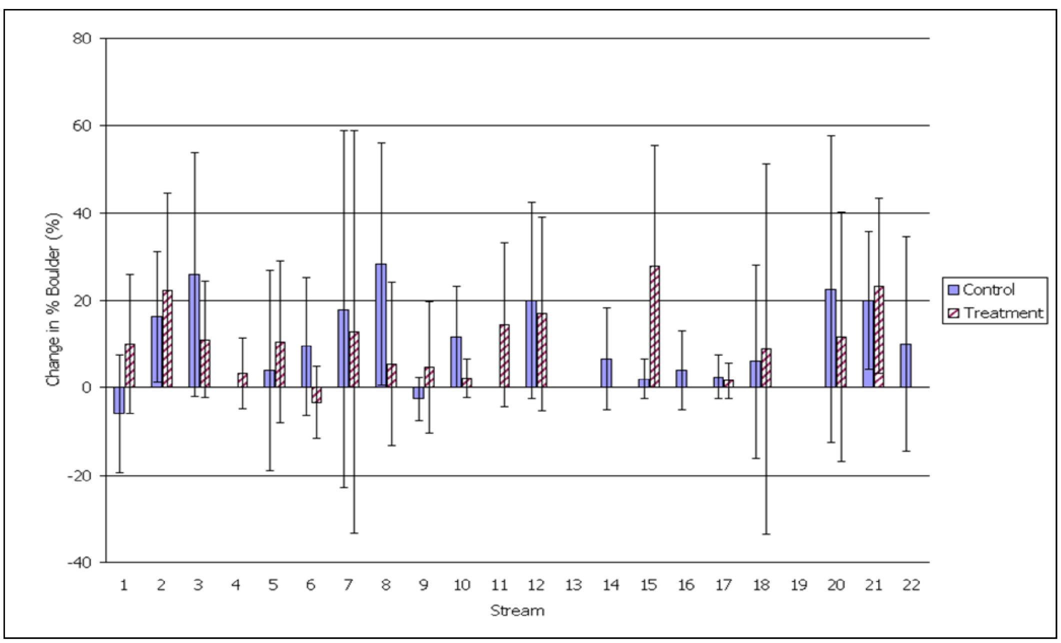


Figure 3.3B. Mean change in percent boulder in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

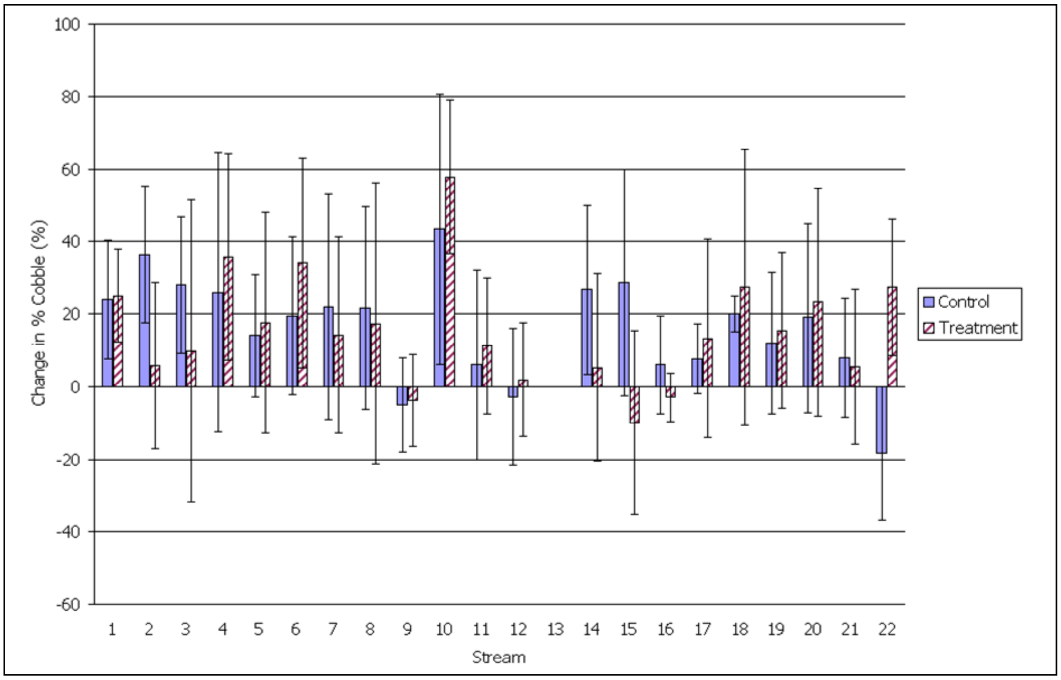


Figure 3.3C. Mean change in percent cobble in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

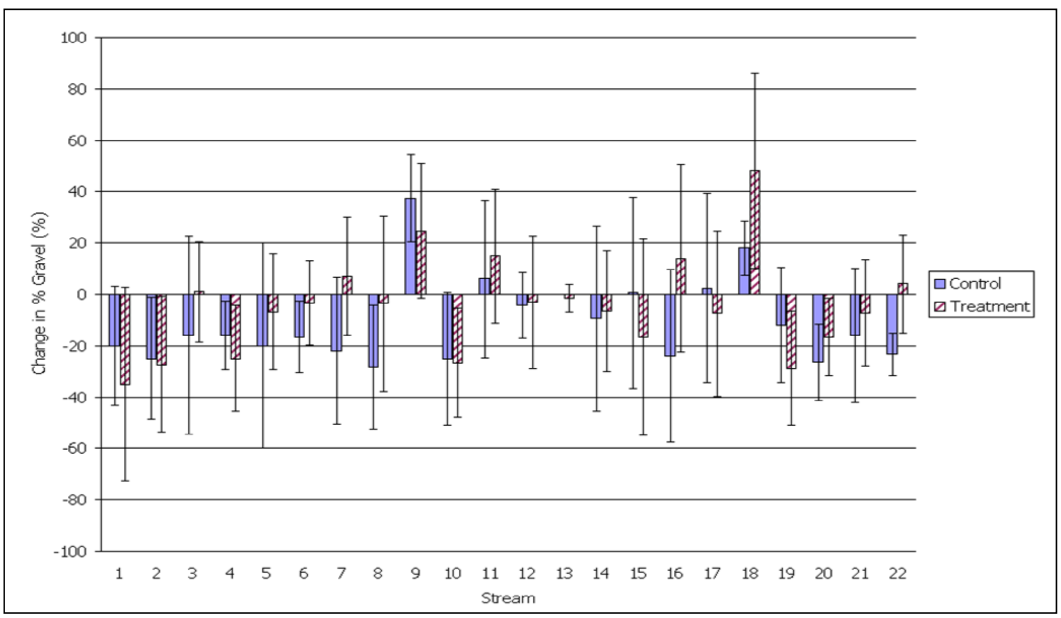


Figure 3.3D. Mean change in percent gravel in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

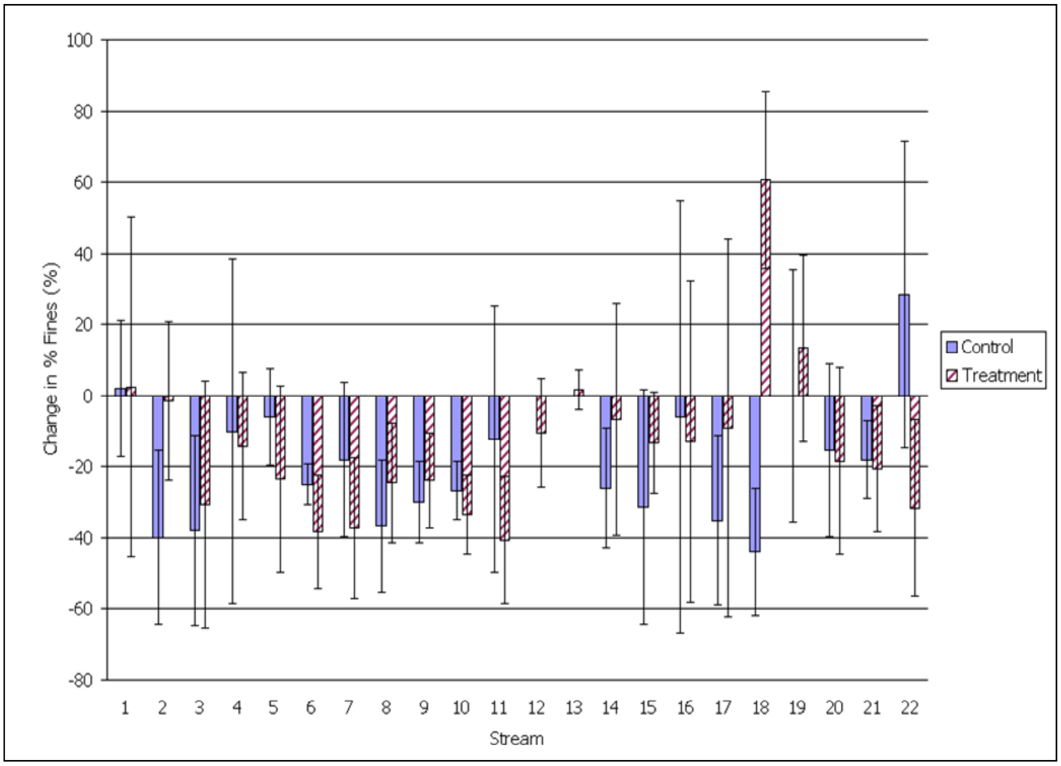


Figure 3.3E. Mean change in percent fines in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

3.1.4. Large Wood Characteristics

Number of wood pieces per 300 m within the bankfull depth in control reaches decreased by a mean of 2 (± 5) following the harvest year, and increased in treatment reaches by a mean of 0.5 (± 5) (Figure 3.4A). Number of wood pieces per 300 m between the bankfull depth and 1.8 m above bankfull depth in control reaches increased by 1 (± 5), and increased in treatment reaches by 3 pieces (± 4) (Figure 3.4B). Volume of wood jams per 300 m in control reaches decreased by a mean of 18 m^3 (±98) following harvest, and in treatment reaches decreased by a mean of 14 m^3 (±34) (Figure 3.4C). Changes in wood pieces both within and above bankfull depth, and changes in wood jam volume in treatment reaches following harvest were not significantly different than changes in control reaches (p-values=0.18, 0.24, 0.87, respectively).

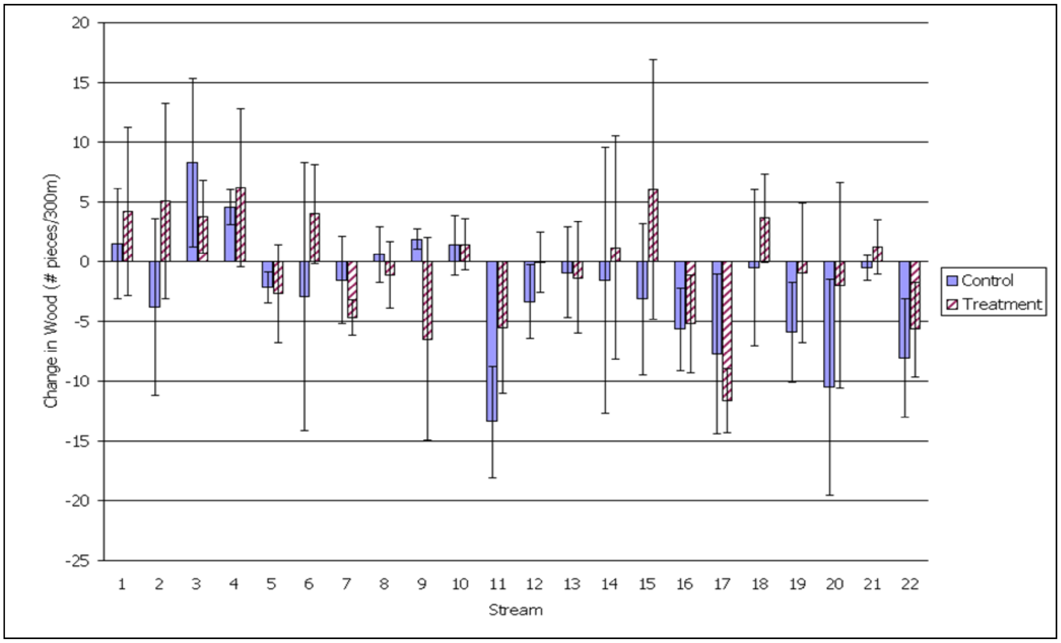


Figure 3.4A. Mean change in number of wood pieces per 300 m within the bankfull width following harvest in control and treatment reaches in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

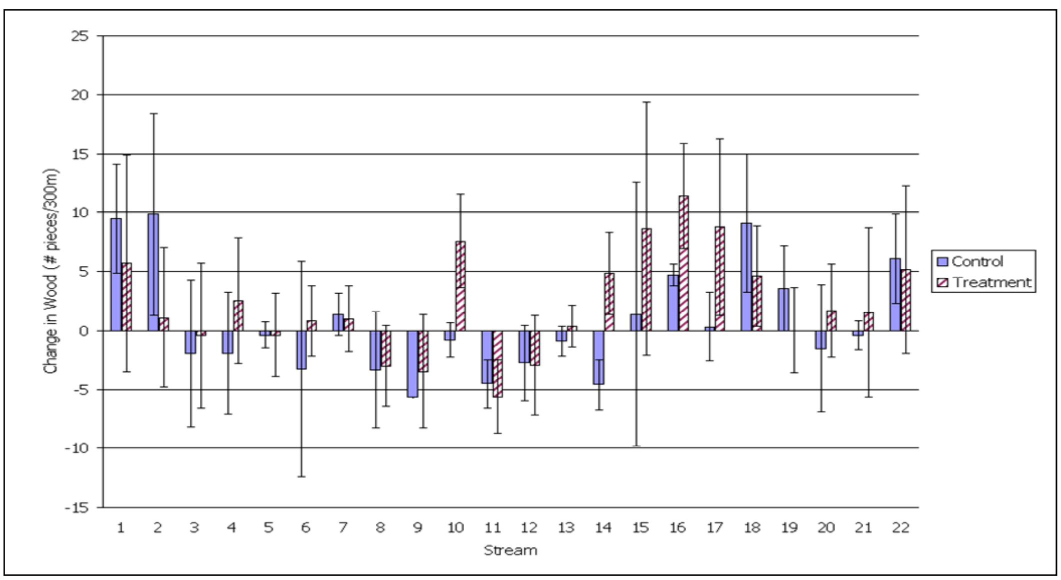


Figure 3.4B. Mean change in number of wood pieces per 300 m within the bankfull width and 1.8 m above bankfull width following harvest in control and treatment reaches of 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

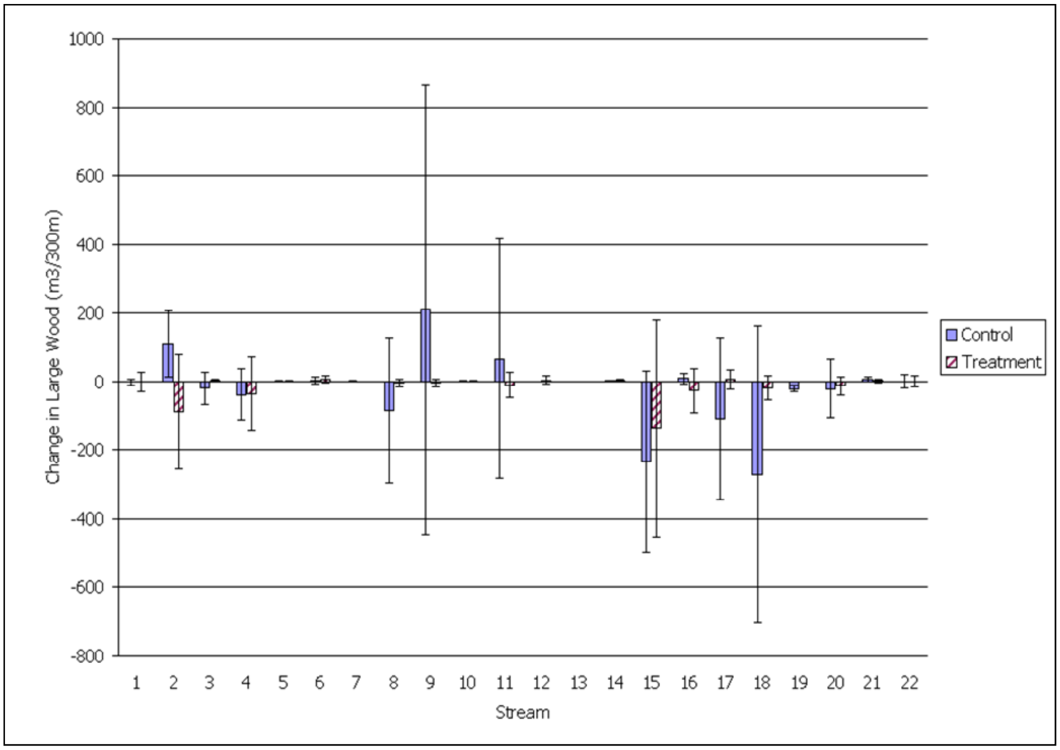


Figure 3.4C. Mean change in wood jam volume (m^3) per 300 m following harvest in control and treatment reaches in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

3.2. Climate Characteristics

3.2.1. Mean Monthly Air Temperature for 2002-2005

Mean monthly air temperature range among the four years between May and August of this study in Astoria was 12.2 to 16.3˚C (±0.9) in 2002, 12.9 to 16.6˚C (±0.4) in 2003, 15.3 to 17.7 (±0.4) in 2004, and 13.4 to 16.8˚C (±0.8) in 2005 (Figure 3.5A). Mean monthly air temperature range among the four years in Newport was 13.5 to 14.8˚C (±0.7) in 2002, 13.7 to 15.6˚C (±0.5) in 2003, 12.9 to 16.1˚C (±0.4) in 2004, and 13.9 to 15.6˚C (±0.9) in 2005 (Figure 3.5B). Mean monthly air temperature range among the four years in Coquille was 12.2 to 16.7˚C (±1.0) in 2002, 14.1 to 16.7˚C (±0.3) in 2003, 14.3 to 18.5˚C (±0.45) in 2004, and 14.1 to 17.3˚C (±1.1) in 2005 (Figure 3.5C).

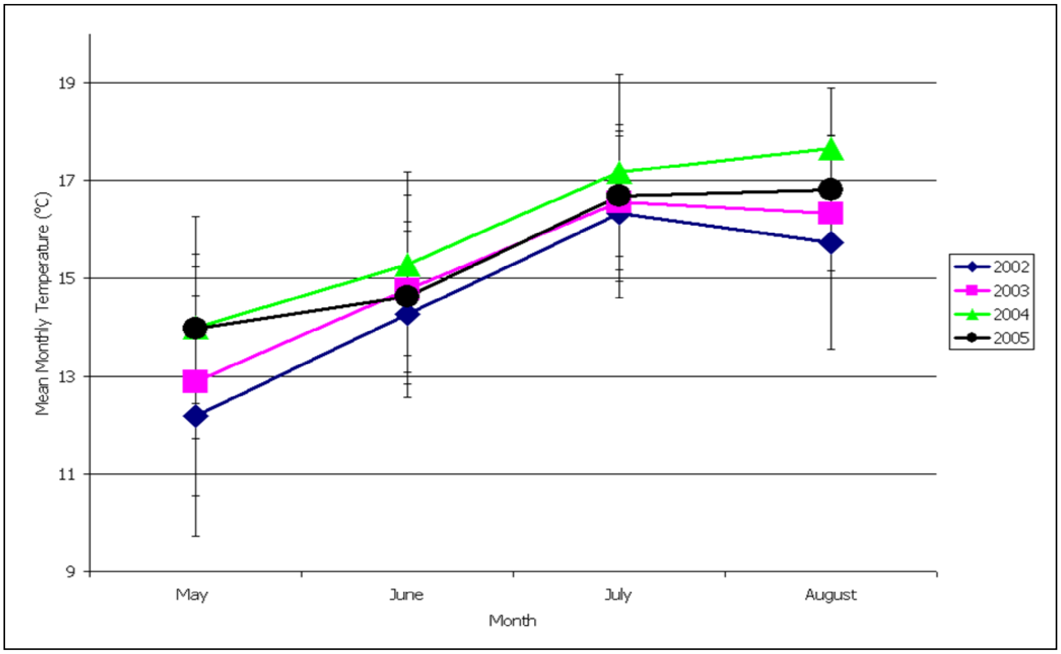


Figure 3.5A. Mean monthly air temperature for Oregon Climate Service Station #350328 (Astoria) for 2002 to 2005. Error bars represent one standard deviation of the mean.

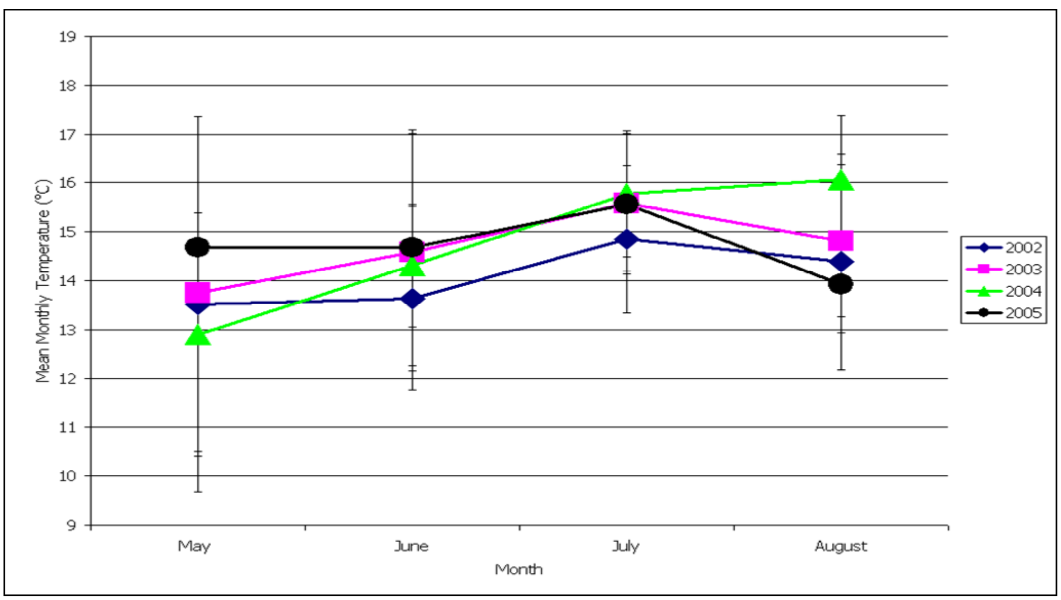


Figure 3.5B. Mean monthly air temperature for Oregon Climate Service Station #356032 (Newport) for 2002 to 2005. Error bars represent one standard deviation of the mean.

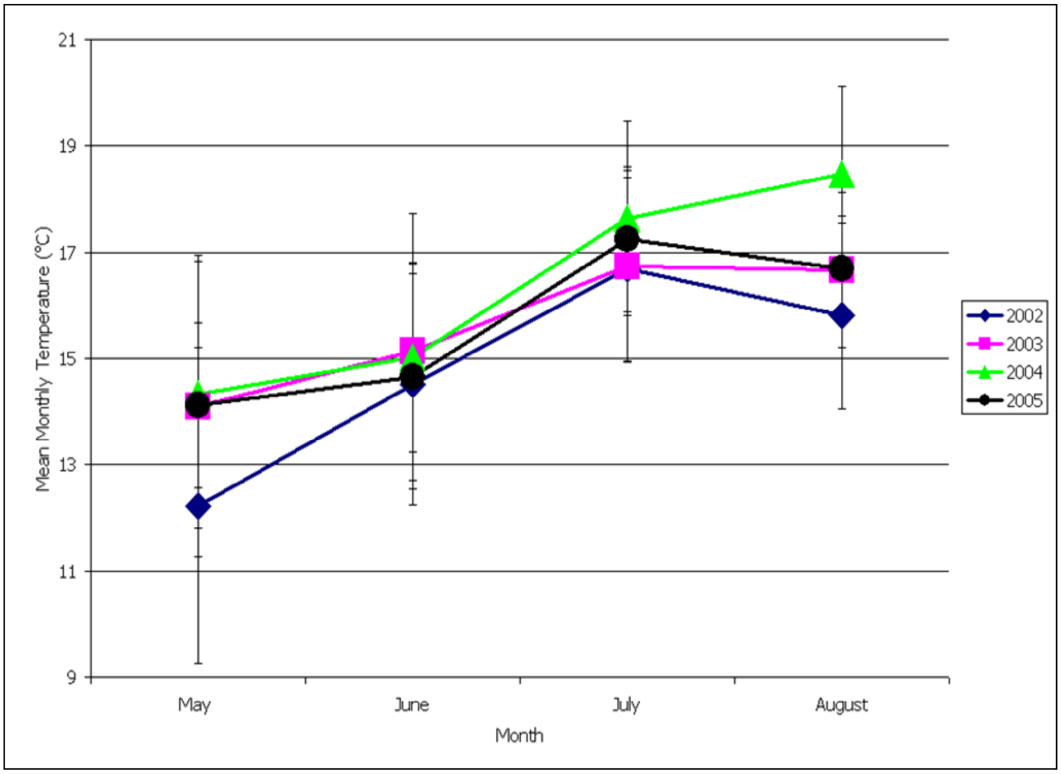


Figure 3.5C. Mean monthly air temperature for Oregon Climate Service Station #351836 (Coquille) for 2002 to 2005. Error bars represent one standard deviation of the mean.

3.2.2. Total Monthly Precipitation

Total monthly precipitation between May and August for Astoria in 2002, 2003, 2004, and 2005 ranged from 0.8 mm in August to 58.9 mm in June, 2.5 mm in August to 55.3 mm in May, 3.8 mm in July to 100.8 mm in August, and 6.4 mm in August to 138.7 mm in May, respectively (Figure 3.6A). Total monthly precipitation for Newport in 2002, 2003, 2004, and 2005 ranged from 2.5 mm in August to 60 mm in June, 2 mm in August to 33.8 mm in May, 0.5 mm in July to 81.8 mm in August, and 1.5 mm in August to 130.6 mm in June, respectively (Figure 3.6B). Total monthly precipitation for Coquille in 2002, 2003, 2004, and 2005 ranged from 0.8 mm in July to 24.9 mm in June, 0 mm in July to 42.9 mm in May, 0.25 mm in July to 51.3 mm in May, and 0 mm in August to 159 mm in May, respectively (Figure 3.6C).

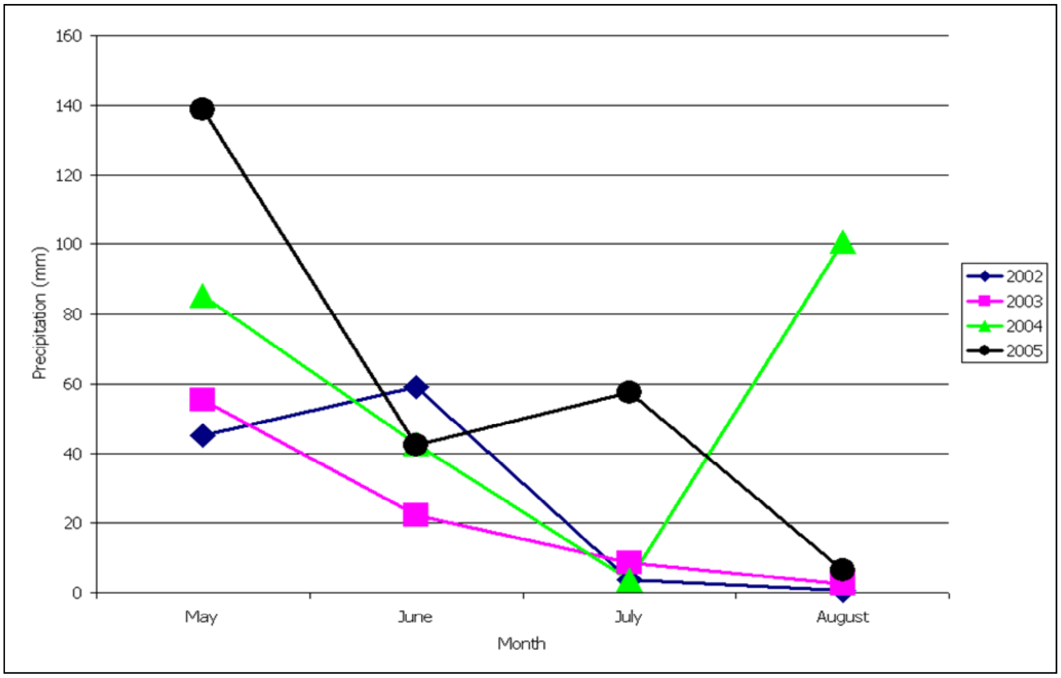


Figure 3.6A. Total monthly precipitation for Oregon Climate Service Station #350328 (Astoria) for 2002 to 2005.

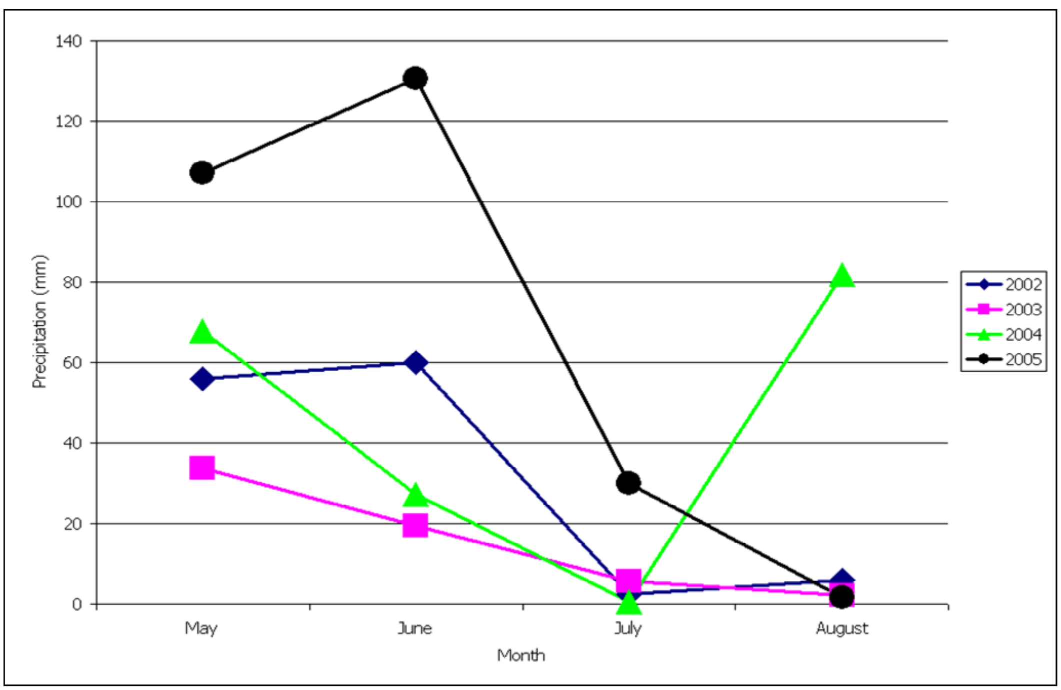


Figure 3.6B. Total monthly precipitation for Oregon Climate Service Station #356032 (Newport) for 2002 to 2005.

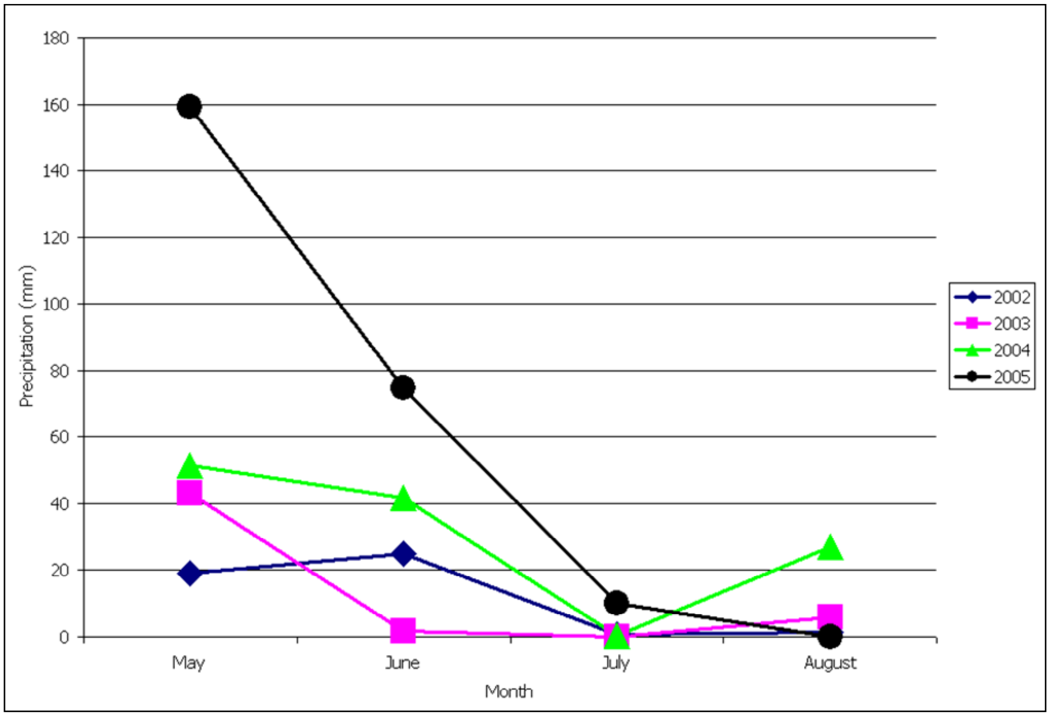


Figure 3.6C. Total monthly precipitation for Oregon Climate Service Station #351836 (Coquille) for 2002 to 2005.

3.3. Warm-Season Stream Temperature Characteristics

3.3.1. Warm-Season Stream Temperature Gradients

Warm-season temperature gradient in the control reaches in pre-harvest year 2002 averaged 0.4°C (±0.7), and in the treatment reaches averaged 0.1°C (± 0.4) (Figure 3.7A). Warm-season temperature gradient in the control reaches in pre-harvest year 2003 averaged 0.6°C (±1), and in the treatment reaches averaged -0.1°C (± 1) (Figure 3.7B). Warm-season temperature gradient in the control reaches in 2004 (for those streams that remained unharvested) averaged 0.3°C (±0.6), and in the treatment reaches averaged 0.0°C (±0.4) (Figure 3.7C).

Following harvest, streams treated in 2004 had a mean warm-season temperature gradient of 0.4°C (± 0.7) in control reaches, and 0.3°C (± 0.6) in treatment reaches (Figure 3.7D). Streams treated in 2005 had a mean warm-season temperature gradient of 0.3°C (±0.6) in the control reach, and 0.4°C (±0.9) in the treatment reach (Figure 3.7E).

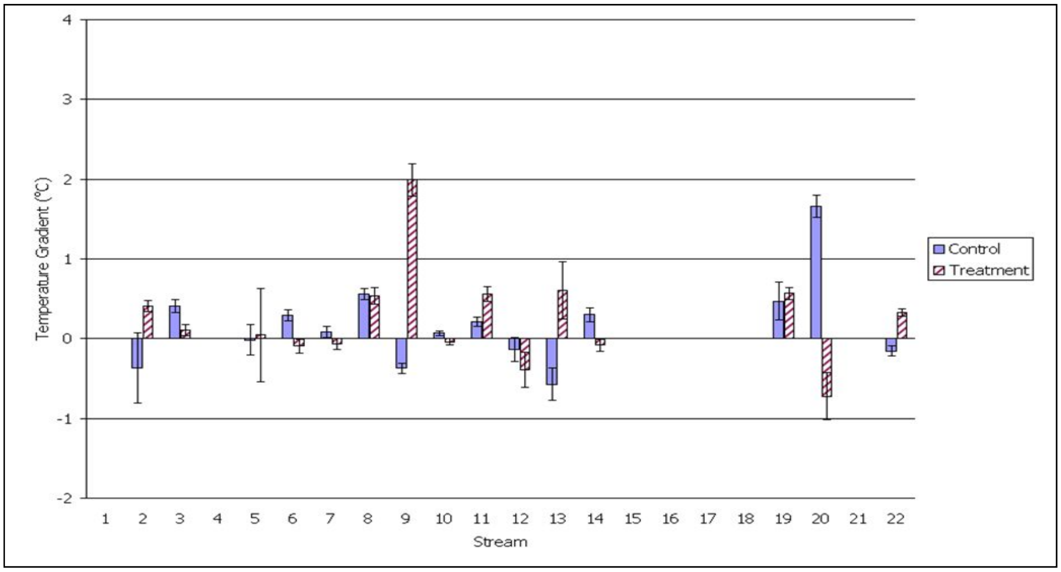


Figure 3.7A. Mean warm-season temperature gradient in the control and treatment reaches of Oregon Coast Range headwater streams in pre-harvest year 2002. Missing values indicate streams that were not yet installed with temperature probes. Error bars represent one standard deviation of the mean (n=48 days, July 15th to August 31st).

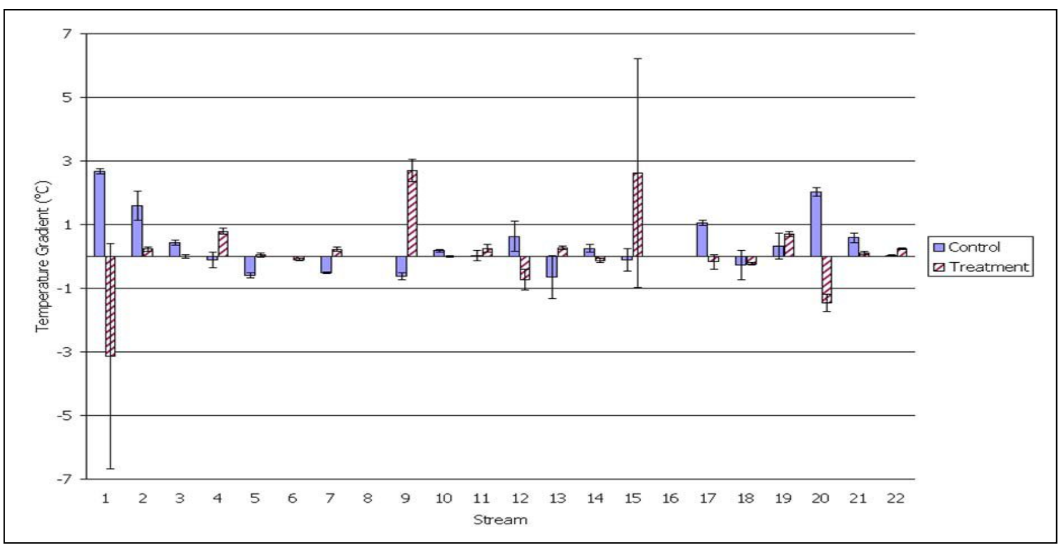


Figure 3.7B. Mean warm-season temperature gradient in the control and treatment reaches for Oregon Coast Range headwater streams in pre-harvest year 2003. Stream #8 and #16 missing data because of missing temperature probes. Error bars represent one standard deviation from the mean (n=48 days, July 15th to August 31st). Note change in scale from Figure 3.7A.

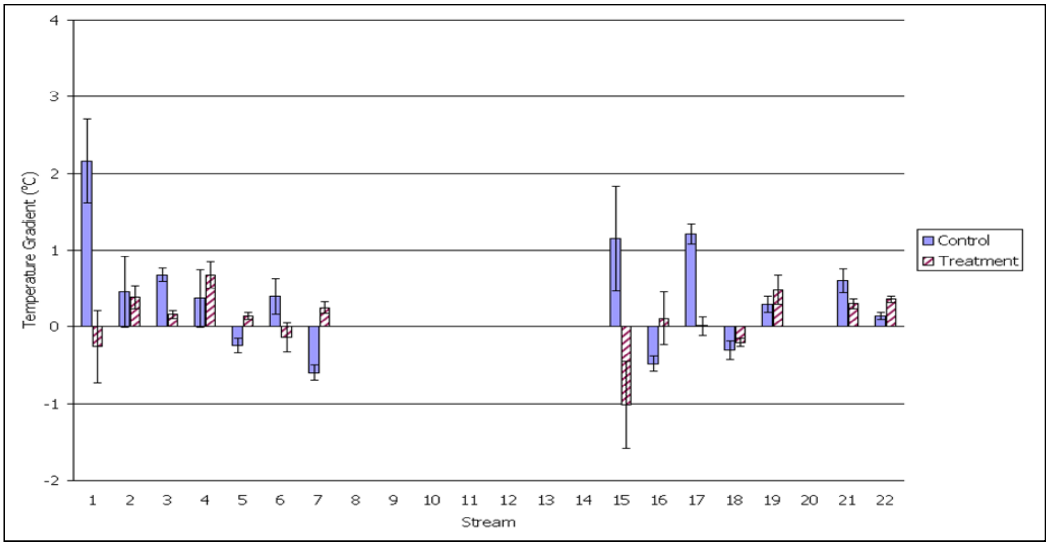


Figure 3.7C. Mean warm-season temperature gradient in the control and treatment reaches for Oregon Coast Range headwater streams in pre-harvest year 2004. Missing data indicate streams that were harvested in 2004. Error bars represent one standard deviation of the mean (n=48 days, July 15th to August 31st).

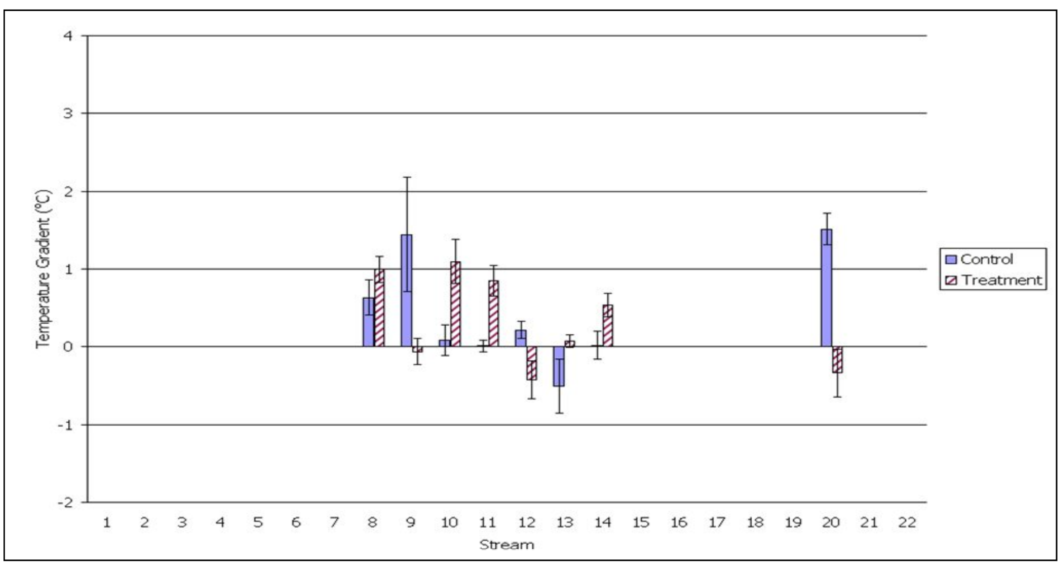


Figure 3.7D. Mean warm-season temperature gradient in 2004 following harvest for the control and treatment reaches for Oregon Coast Range headwater streams. Missing data indicate streams harvested in 2005. Error bars represent one standard deviation of the mean (n=48 days, July 15th to August 31st).

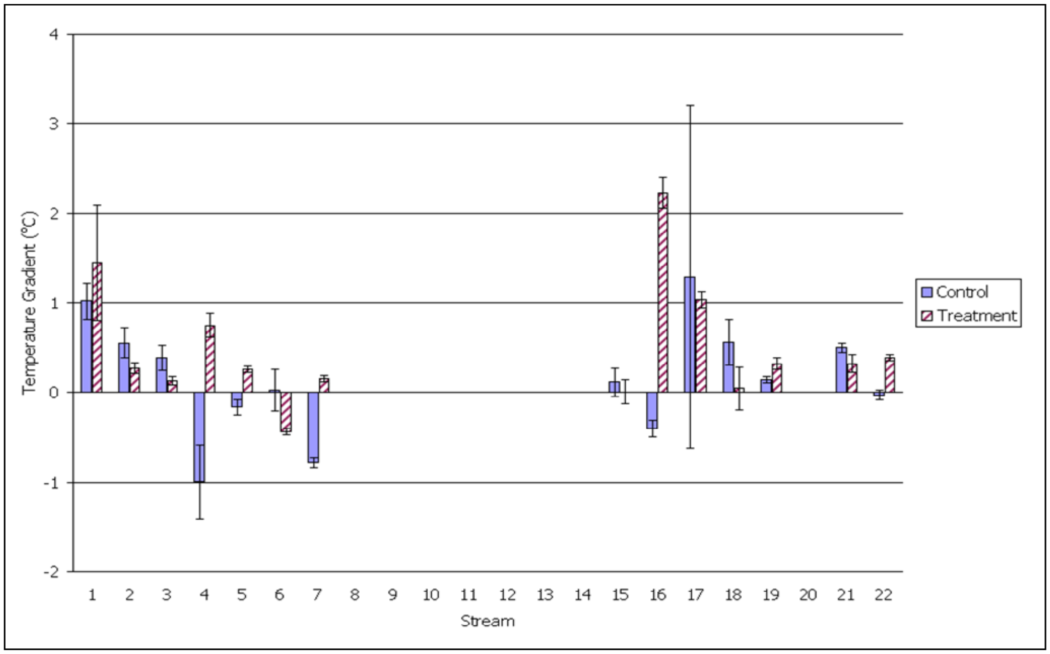


Figure 3.7E. Mean warm-season temperature gradient in 2005 following harvest for the control and treatment reaches for Oregon Coast Range headwater streams. Missing data indicate streams harvested in 2004. Error bars represent one standard deviation of the mean (n=48 days, July 15th to August 31st).

Warm-season temperature gradients in the two pre-harvest years were variable. In control reaches during July 15th to August 31st of the first pre-harvest year, the mean temperature gradient was 0.4˚C, a change significantly greater than zero (p-value=0.02, S.E.=0.18) (Figure 3.8). Mean temperature gradient was 0.1˚C (p-value=0.71, S.E.=0.17) in the treatment reaches during July 15th to August 31st in the first pre-harvest year. During the same sampling period in the second pre-harvest year, mean temperature gradient in the control reaches was 0.4˚C (p-value=0.01, S.E.=0.17) and mean temperature gradient in treatment reaches was 0.0˚C (p-value=0.85, S.E.=0.17) (Figure 3.8).

Mean warm-season temperature gradient in control reaches in the first pre-harvest year was the same (0.0˚C) as that observed in the second pre-harvest year (p-value=0.95, S.E.=0.21) (Table 3.1). Mean temperature gradient in treatment reaches in the first pre-harvest year was 0.1˚C lower than that observed in the second pre-harvest year (Table 3.1). This difference was not statistically significant (p-value=0.55, S.E.=0.21). Difference in temperature gradients between the control and treatment reaches in the first-pre harvest year was 0.1˚C less than that observed in the second pre-harvest year, but was not significantly different (p-value=0.65, S.E.=0.30) (Table 3.1).

Post-harvest mean warm-season temperature gradient in control reaches, combining all streams using two pre-harvest years (either 2002 & 2003, or 2003 & 2004), was 0.3˚C (p-value=0.13, S.E.=0.17), and in treatment reaches using one-year-post-harvest data (either 2004 or 2005) was 0.4˚C (p-value=0.01, S.E.=0.17) (Figure 3.8).

Mean warm-season temperature gradient in the control reaches following harvest was cooler by 0.2˚C than that observed pre-harvest, but this change was not significant (p-value=0.30, S.E.=0.17). However, mean temperature gradient in treatment reaches was 0.4°C warmer than observed prior to harvesting. This increase was significant (p-value=0.02, S.E.=0.17) (Table 3.2). The resulting mean difference in warm-season temperature gradient between treatment and control reaches following harvest was 0.6°C greater than that observed prior to harvest, which is also a significant increase (p-value 0.01, S.E. 0.24), indicating that, on average, a statistically significant increase in warming occurred in the treatment reaches following harvest (Table 3.2).

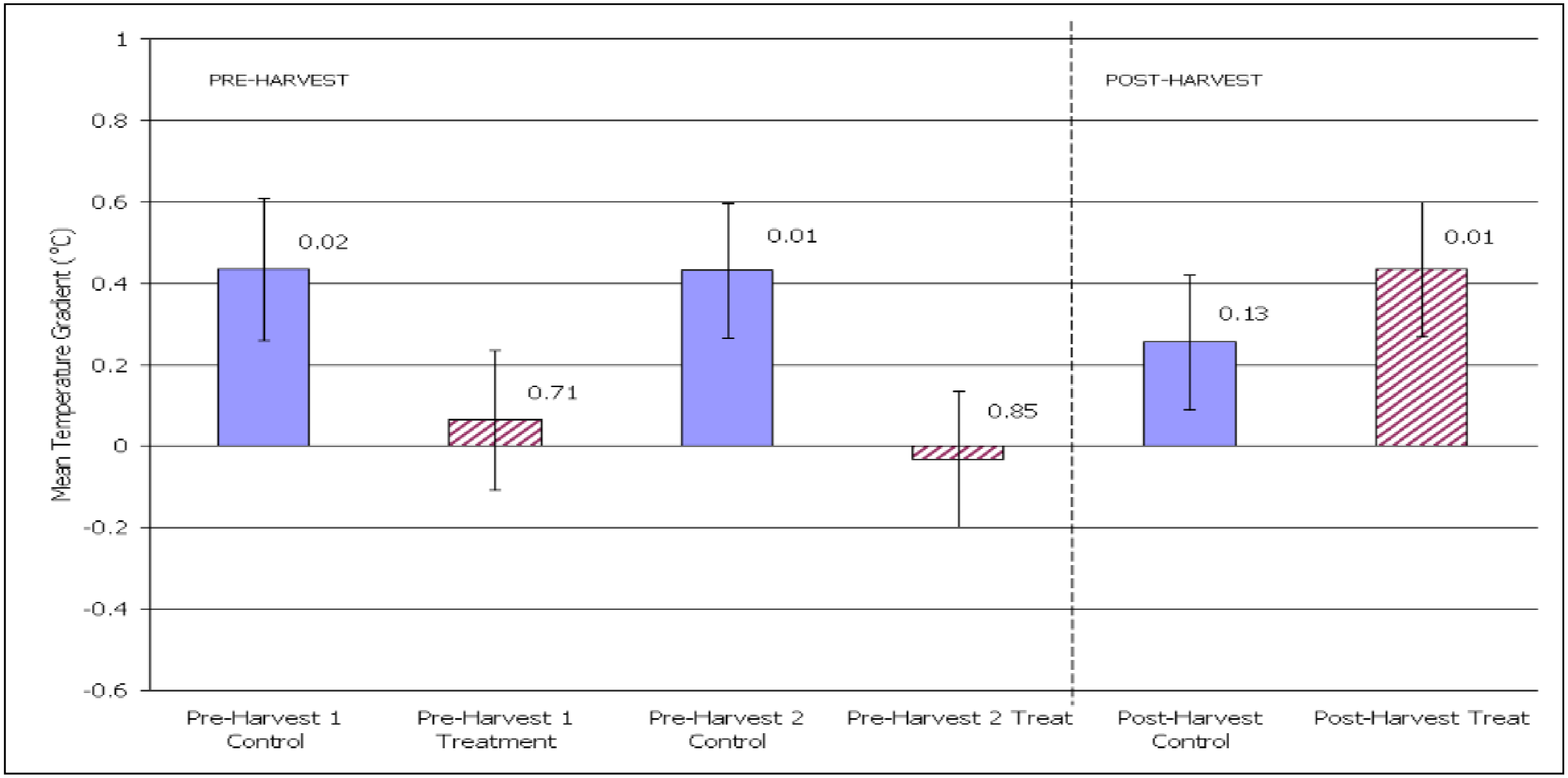


Figure 3.8. Mean warm-season temperature gradient/300 m for 22 streams in the Oregon Coast Range using two years pre- harvest and one year post-harvest data for the mean 7-day moving mean of the daily maximum (7DMMDMax) between July 15th and August 31st (2002-2005). Error bars represent one standard error of the mean and p-values are indicated. Significance level is 0.05, testing if temperature gradient is significantly different

Table 3.1. Changes in warm-season mean temperature gradient among 22 streams in the Oregon Coast Range between two pre-harvest years.

	Estimate (°C)	Standard Error	P-value
A[1]	0.0	0.21	0.95
B	0.1	0.21	0.55
C	-0.1	0.30	0.65

[1]Value A: Post(Control) – Pre(Control). Value B: Post (Treatment) – Pre(Treatment). Value C: (Post (Treatment) – Pre(Treatment)) – (Post(Control) – Pre(Control)).

Table 3.2. Changes in warm-season mean temperature gradient among 22 streams in the Oregon Coast Range comparing two years pre-harvest with one year post-harvest.

	Estimate (°C)	Standard Error	P-value
A[1]	-0.2	0.17	0.30
B	0.4	0.17	0.02
C	0.6	0.24	0.01

[1]Value A: Post(Control) – Pre(Control). Value B: Post (Treatment) – Pre(Treatment). Value C: (Post (Treatment) – Pre(Treatment)) – (Post(Control) – Pre(Control)).

3.3.2. Relationships Between Channel Characteristics and Warm-Season Stream Temperature Gradient

Percentage of channel substrate comprised of gravel was the strongest predictor of mean warm-season temperature gradient in control reaches (p-value = 0.01, Pearson correlation coefficient = 0.54, R^2 = 0.30) followed by geologic substrate and percentage of the channel substrate comprised of boulder (Table 3.3). However, shade was the strongest predictor of mean warm-season temperature gradient in treatment reaches (p-value = 0.00, Pearson correlation coefficient = -0.69, R^2 = 0.46) followed by number of large wood pieces between bankfull width and 1.8 m above bankfull width (Table 3.4). Relationships between shade and mean changes in temperature gradient for control and treatment reaches following harvest show a strong linear correlation within treatment reaches and no relationship within control reaches (Figure 3.9).

Table 3.3. Relationships between selected stream channel characteristics and mean temperature gradient in control reaches of 22 Oregon Coast Range headwater streams. Variables in bold are significant at alpha = 0.05.

Variable	Pearson Correlation Coefficient	p-value	R^2
Gravel	**0.54**	**0.01**	**0.29**
Geology	**-0.39**	**0.03**	**0.21**
Boulder	**0.45**	**0.04**	**0.20**
Gradient	0.40	0.10	0.13
Fines	-0.27	0.22	0.07
Wood Jam Volume	0.22	0.32	0.05
Maximum Depth	0.22	0.33	0.05
Shade	0.16	0.49	0.02
Wetted Width	0.14	0.53	0.02
Bankfull Width	0.13	0.57	0.02
Cobble	-0.08	0.71	0.01
High Wood	0.08	0.73	0.01
Bedrock	0.07	0.78	0.00
Low Wood	0.07	0.77	0.00
Aspect	0.05	0.82	0.00
Floodprone Width	0.01	0.95	0.00

Table 3.4. Relationships between selected channel characteristics and mean temperature gradient in treatment reaches of 22 Oregon Coast Range headwater streams. Variables in bold are significant at alpha = 0.05.

Variable	Pearson Correlation Coefficient	p-value	R^2
Shade	**-0.69**	**≤0.01**	**0.46**
High Wood	**0.44**	**0.04**	**0.20**
Boulder	-0.42	0.05	0.17
Fine	0.40	0.07	0.16
Bankfull Width	-0.33	0.14	0.11
Wetted Width	-0.32	0.15	0.10
Maximum Depth	-0.25	0.27	0.06
Floodprone Width	-0.23	0.31	0.05
Cobble	-0.20	0.38	0.04
Aspect	0.18	0.42	0.03
Bedrock	-0.15	0.49	0.02
Gravel	-0.08	0.71	0.01
Wood Jam Volume	-0.08	0.71	0.01
Gradient	-0.06	0.79	0.00
Low Wood	-0.06	0.81	0.00
Geology	0.03	0.89	0.00

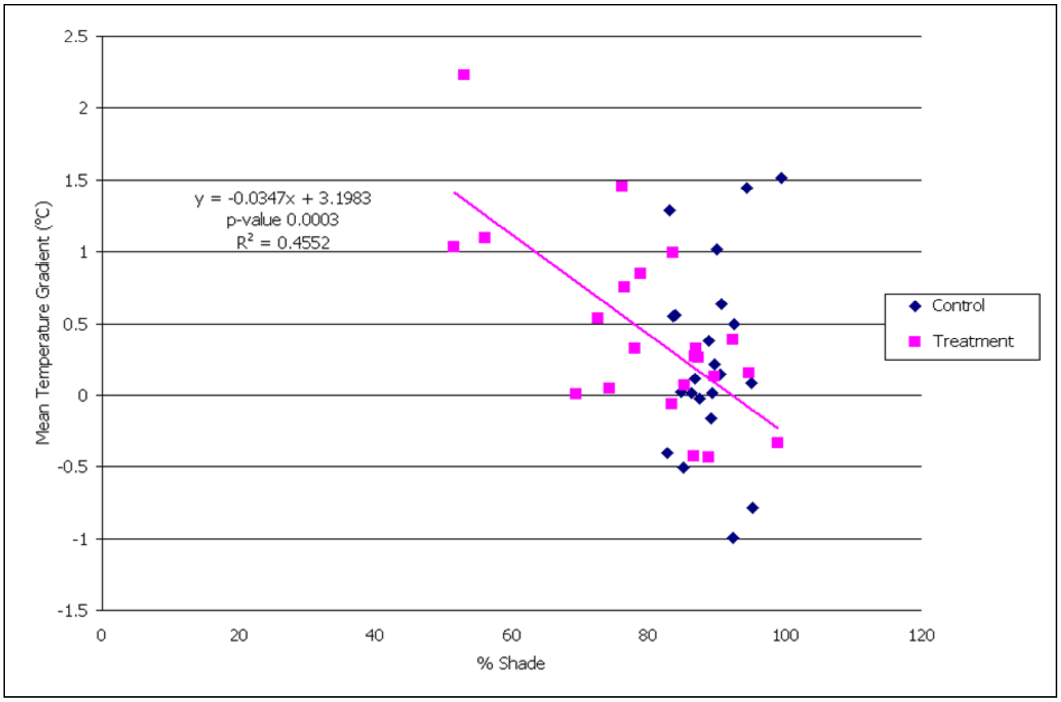


Figure 3.9. Relationship between percent shade and temperature gradient in control and treatment reaches in the summer following harvest of 22 Oregon Coast Range headwater streams. Trend line and equation are provided for relationships between shade and temperature gradient in treatment reaches.

If each reach (control and treatment) in each stream is treated as a separate statistical unit (n = 44), then the two-variable model using shade and channel gravel content is the strongest predictor (p-value = 0.04, adjusted R^2 = 0.27) for mean temperature gradient (Table 3.5). Shade alone is the second best predictor (p-value = ≤0.01, Pearson Correlation Coefficient=-0.43, R^2 = 0.19) for stream temperature gradient using a sample size of 44 reaches (control and treatment reaches in each stream) (Table 3.6).

Table 3.5. Relationships between selected pairs of channel characteristics and mean temperature gradient in both treatment and control reaches following harvest for 22 Oregon Coast Range streams (n=44). Variables in bold are significant at alpha = 0.05.

Variables	P-value	Adjusted R^2
Shade+gravel	**0.04**	**0.27**
Shade+gradient	0.17	0.23
Shade+boulder	0.28	0.21
Shade+geology	0.11	0.20
Shade+floodprone width	0.49	0.20
Shade+cobble	0.56	0.20
Shade+maximum depth	0.64	0.19
Shade+fine	0.73	0.19
Shade+bankfull width	0.80	0.19
Shade+aspect	0.85	0.19
Shade+wetted width	0.87	0.19
Shade+bedrock	0.87	0.19
Shade+jam volume	0.45	0.16
Shade+high wood	0.59	0.16
Shade+low wood	0.65	0.16

Table 3.6. Relationships between selected channel characteristics and mean temperature gradient in control and treatment reaches following harvest for 22 Oregon Coast Range streams (n=44). Variables in bold are significant at alpha = 0.05.

Variable	Pearson Correlation Coefficient	P value	R^2
Shade	**-0.44**	**≤0.01**	**0.19**
High Wood	0.26	0.09	0.07
Gravel	0.22	0.15	0.05
Geology	-0.20	0.89	0.04
Gradient	0.15	0.34	0.02
Cobble	-0.11	0.46	0.01
Aspect	0.11	0.46	0.01
Bankfull Width	-0.10	0.52	0.01
Floodprone Width	-0.09	0.56	0.01
Wood Jam Volume	0.09	0.58	0.01
Wetted Width	-0.07	0.67	0.00
Fines	0.05	0.73	0.00
Bedrock	-0.04	0.78	0.00
Maximum Depth	0.03	0.84	0.00
Low Wood	0.00	0.96	0.00
Boulder	0.00	0.97	0.00

3.4. Warm-Season Temperature Patterns of Individual Streams

3.4.1. Cooling Pattern Following Harvest

Following harvest, one stream had 7DMMDMax temperatures between July 15th and August 31st lower than predicted with a 95% confidence interval based on pre-harvest relationships (Figure 3.10).

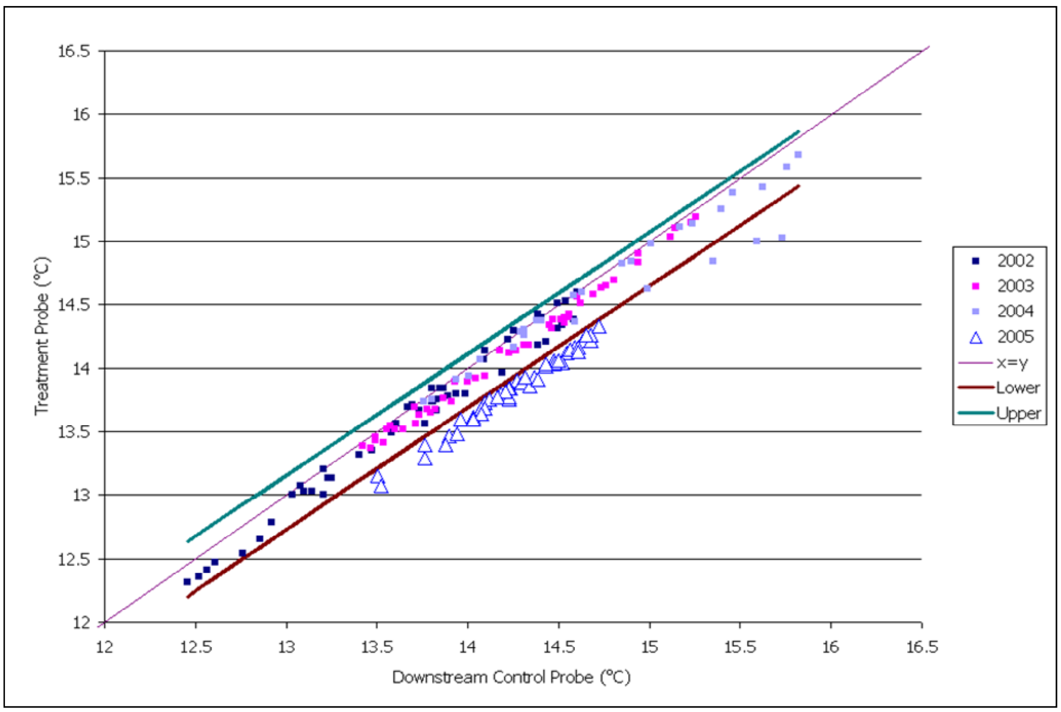


Figure 3.10. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #6 in pre-harvest (2002, 2003, 2004) and post-harvest year (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

3.4.2. No Change in Warm-Season Temperature Pattern Following Harvest

Following harvest, nine streams had observed 7DMMDMax temperatures between July 15th and August 31st within the 95% confidence interval predicted by pre-harvest temperature relationships between control and treatment reaches (Figures 3.11A to 3.11I).

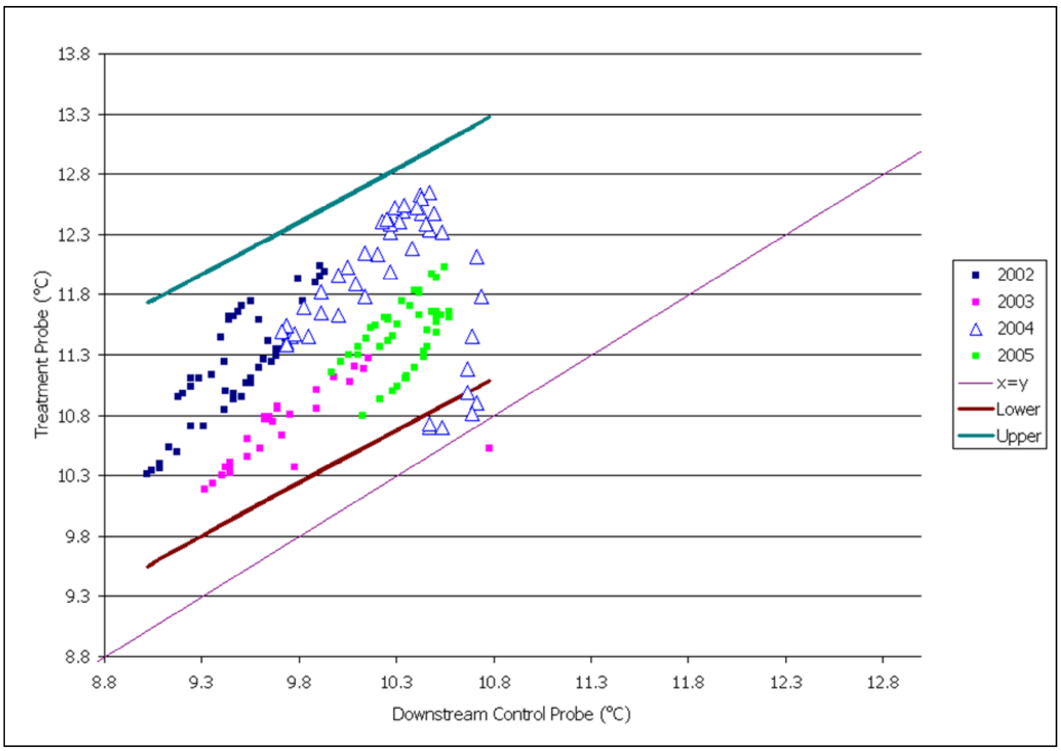


Figure 3.11A. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #2 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

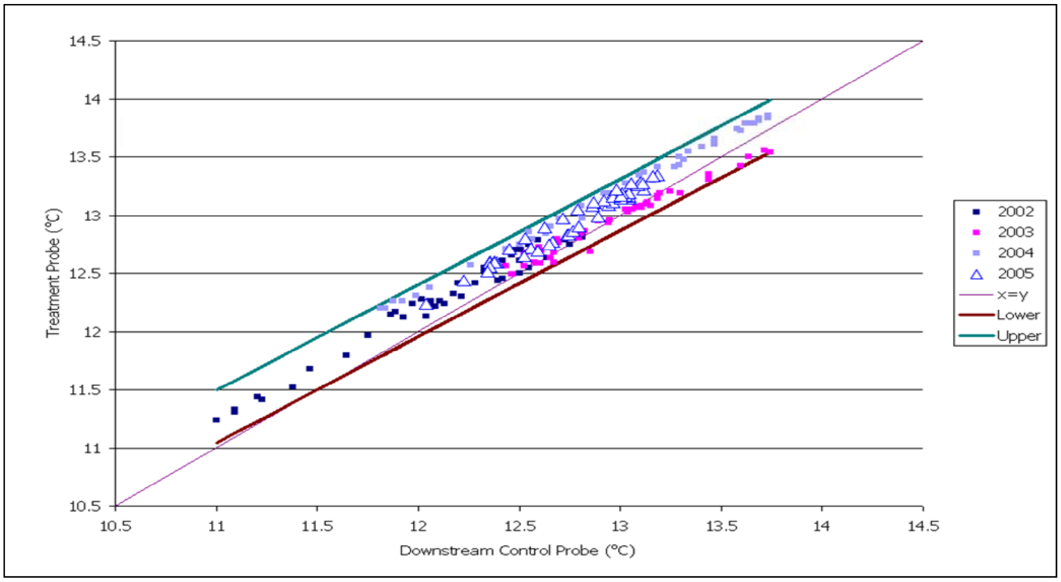


Figure 3.11B. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #3 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

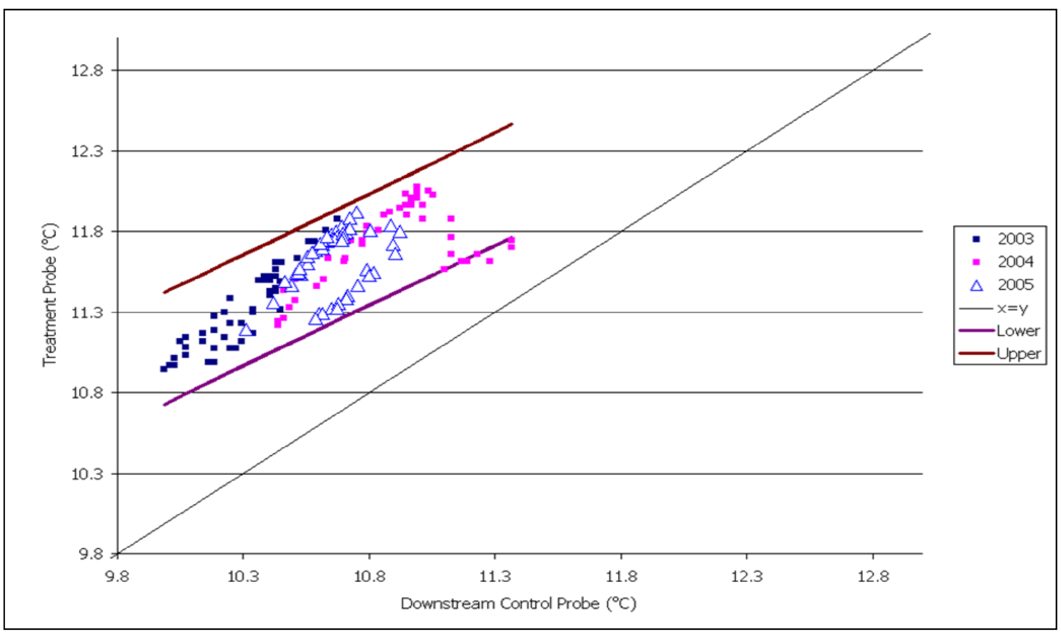


Figure 3.11C. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #4 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

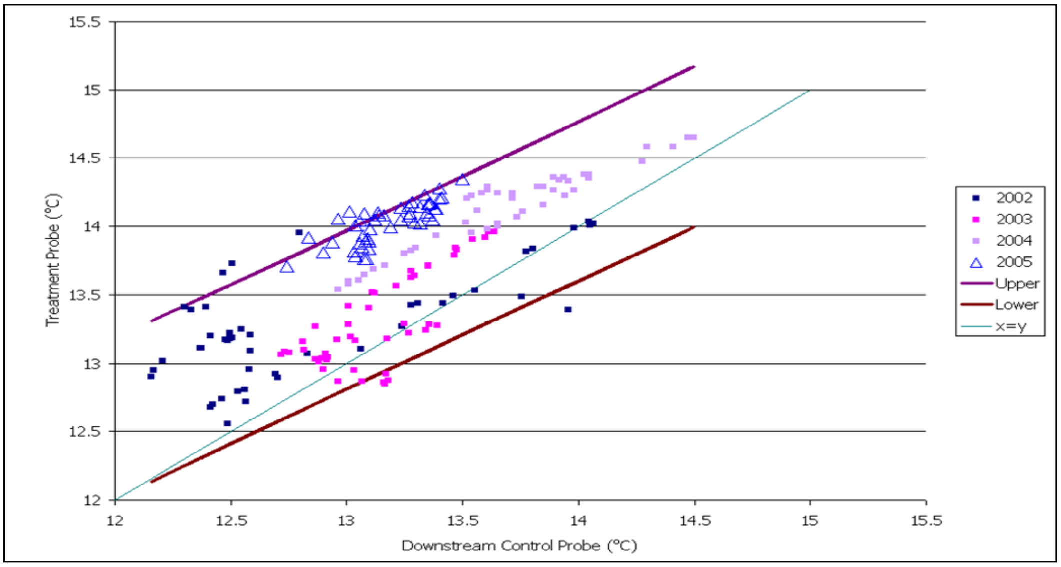


Figure 3.11D. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #5 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

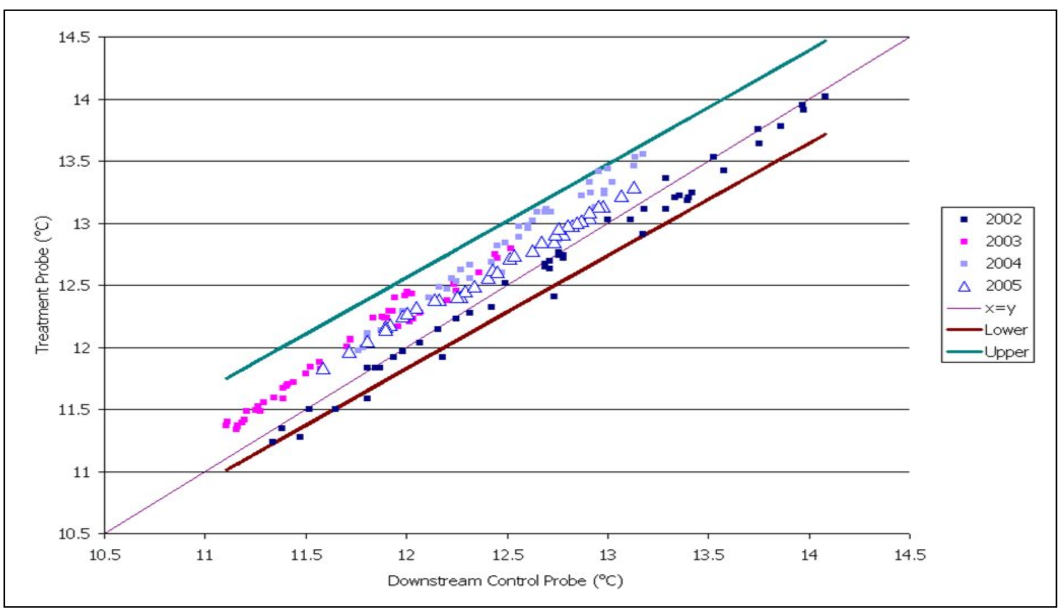


Figure 3.11E. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #7 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

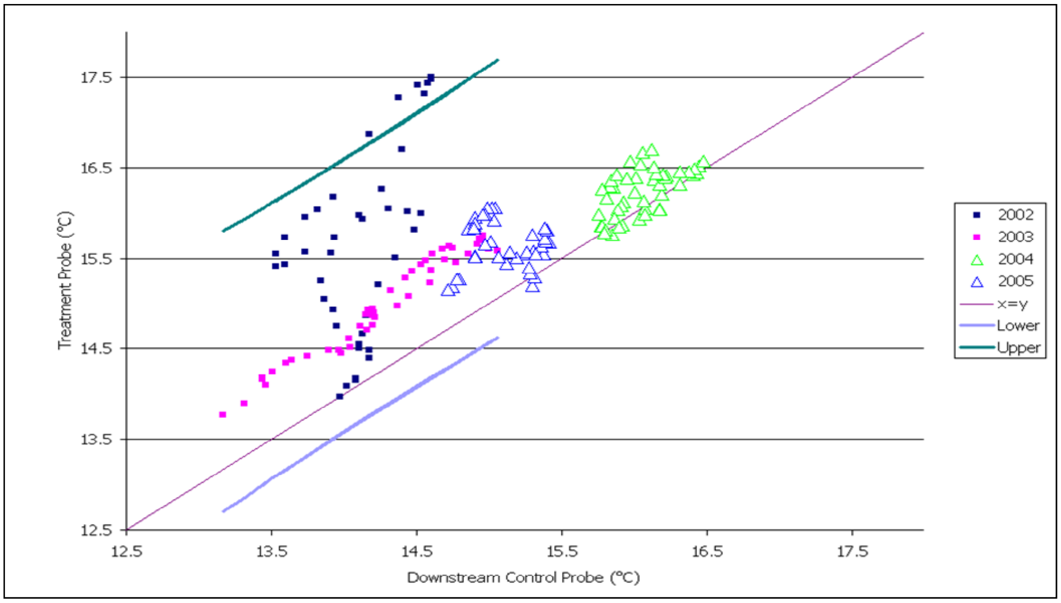


Figure 3.11F. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #13 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

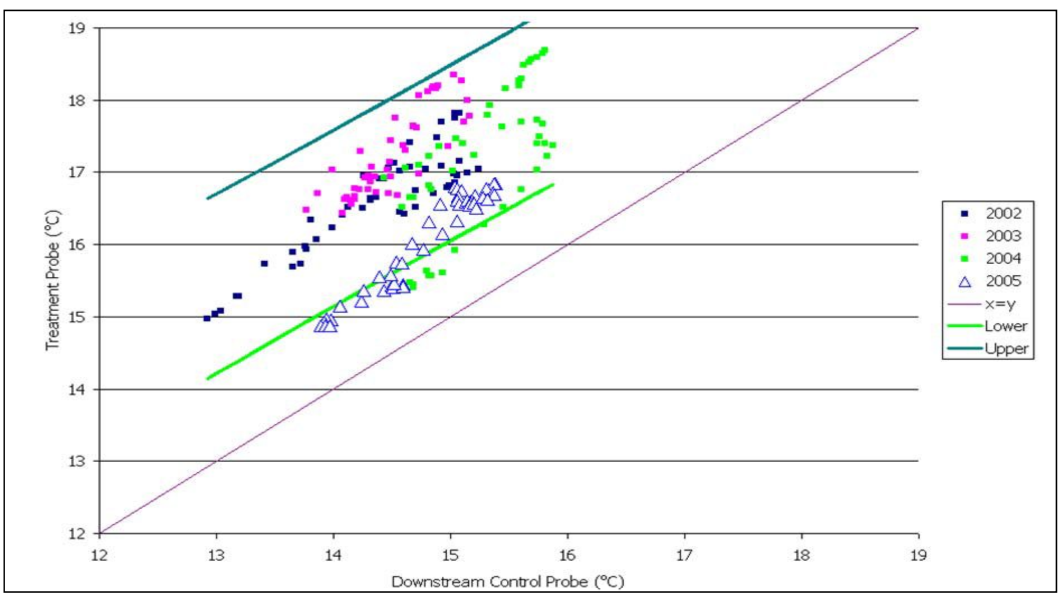


Figure 3.11G. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #19 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

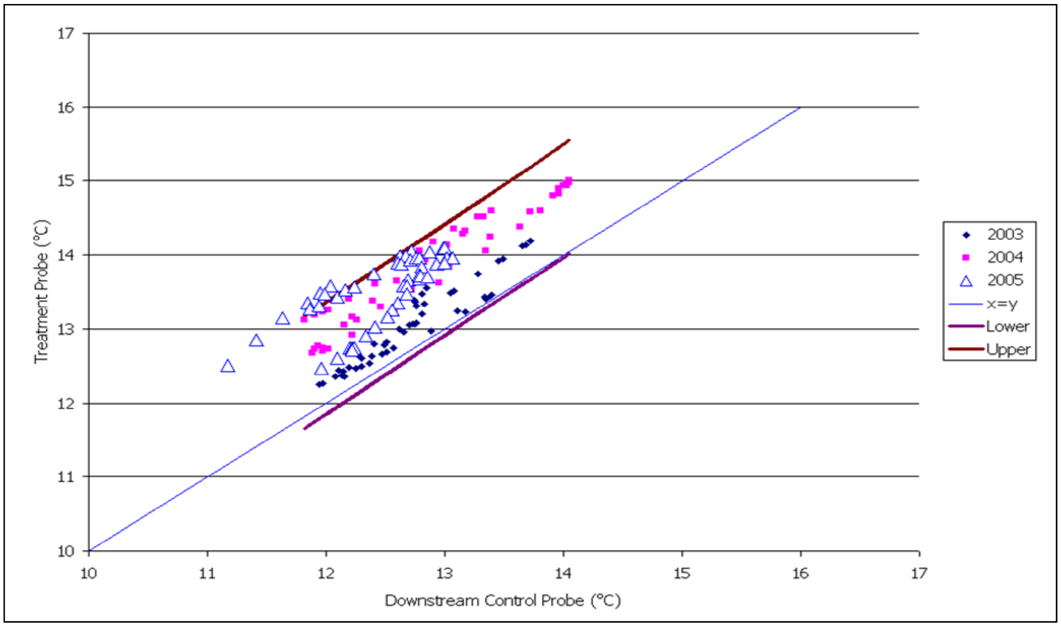


Figure 3.11H. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #21 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

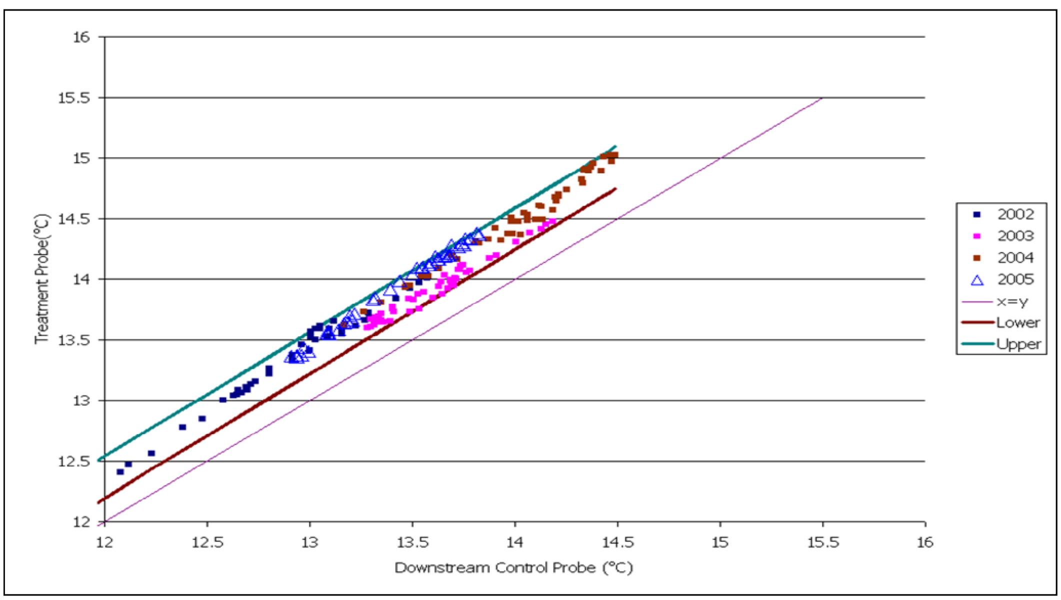


Figure 3.11I. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #22 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

3.4.3. Warm-Season Warming Pattern Following Harvest

Following harvest, 12 streams had warmer 7DMMDMax temperatures between July 15th and August 31st in the treatment reach than predicted from pre-harvest temperature relationships between control and treatment reaches (Figures 3.12A to 3.12L).

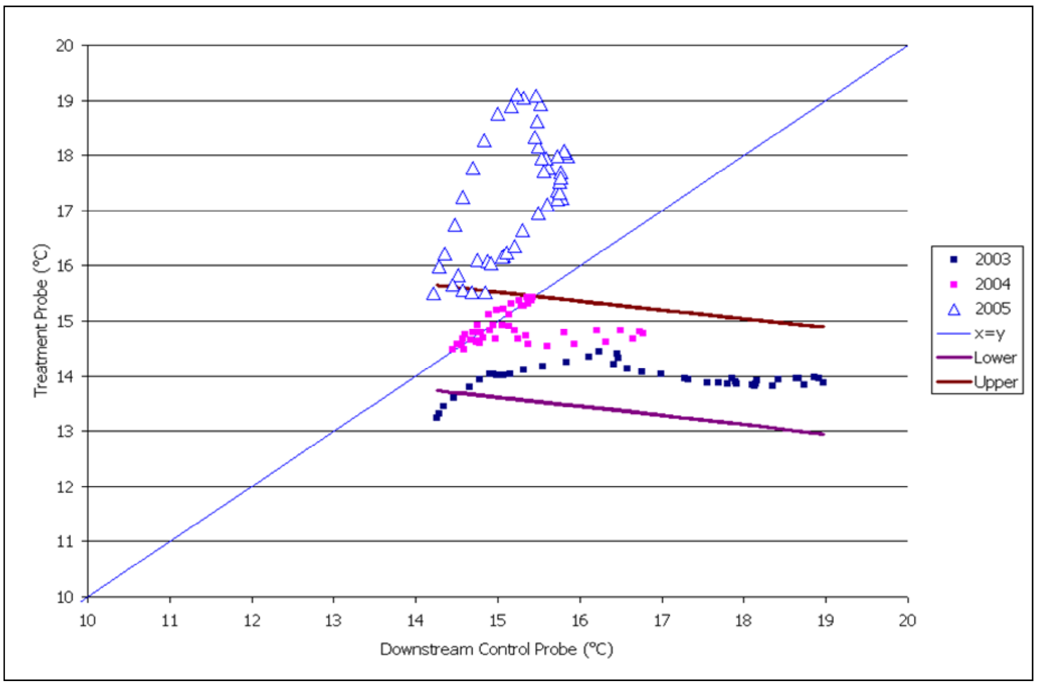


Figure 3.12A. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #1 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

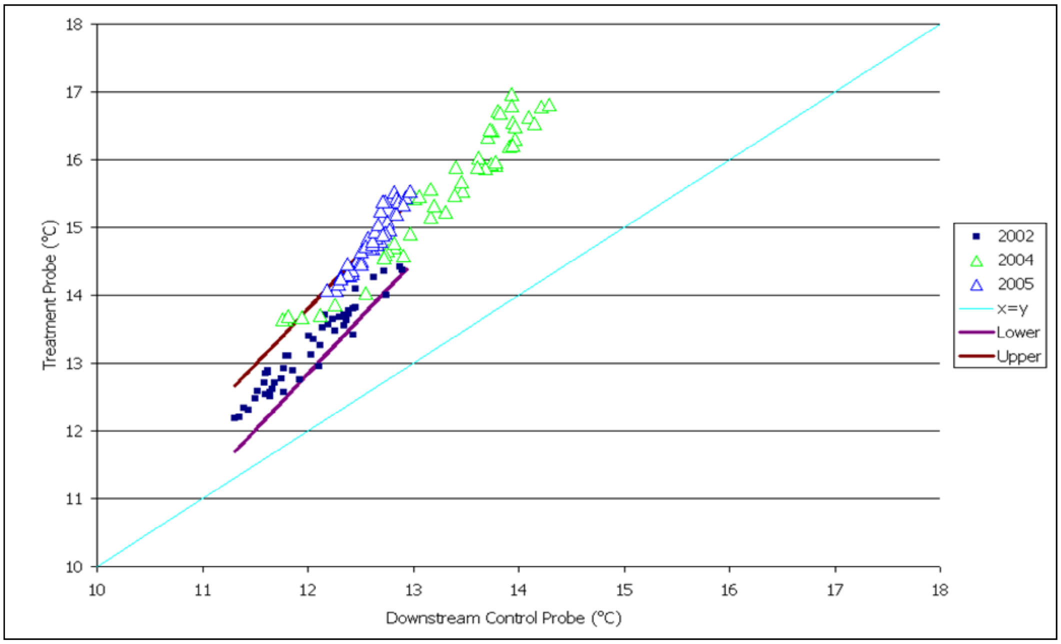


Figure 3.12B. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #8 in pre-harvest (2002) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

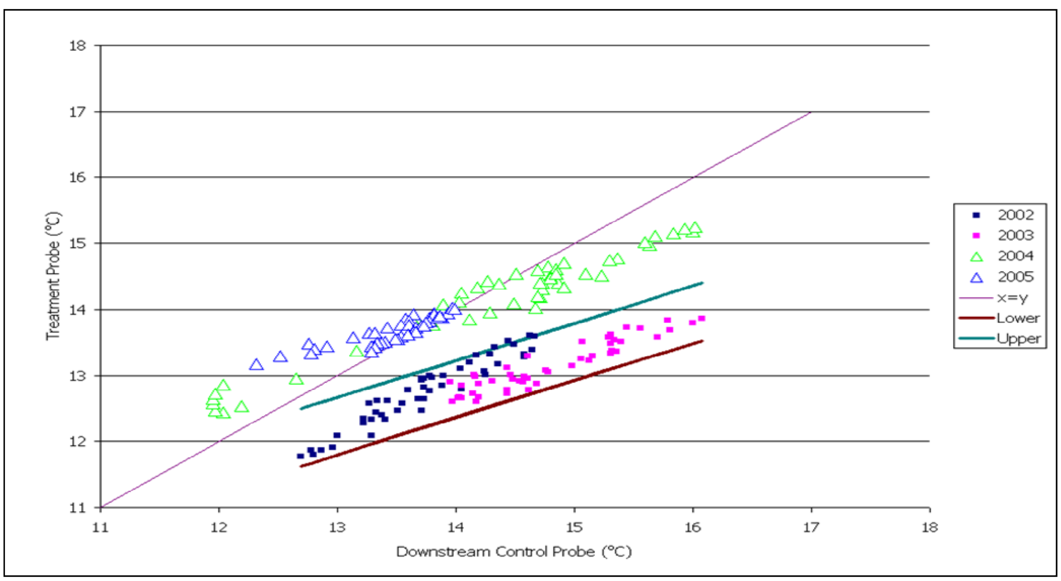


Figure 3.12C. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #9 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

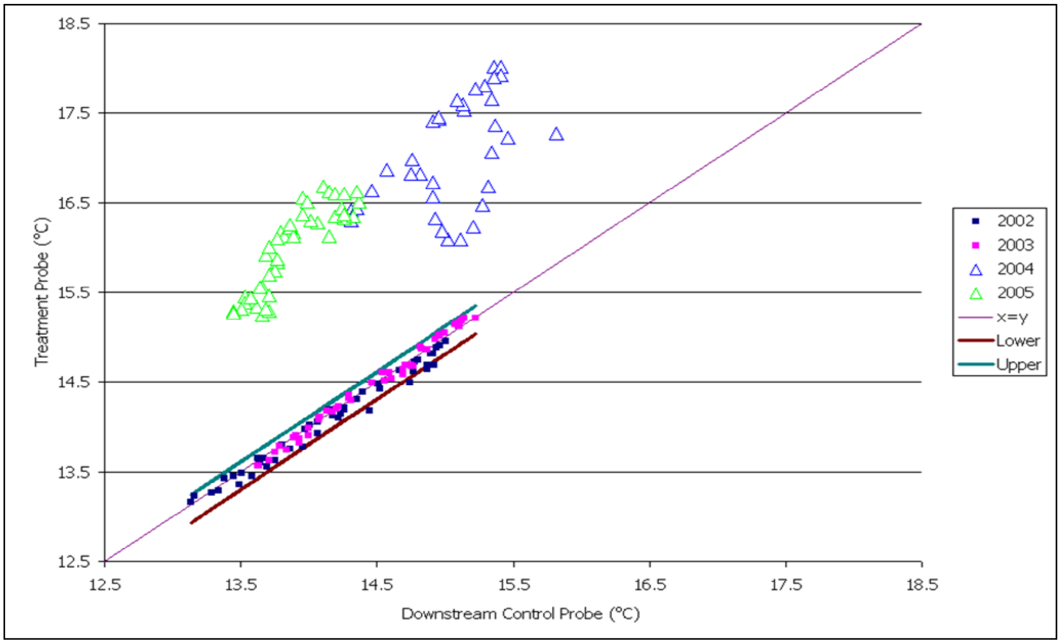


Figure 3.12D. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #10 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

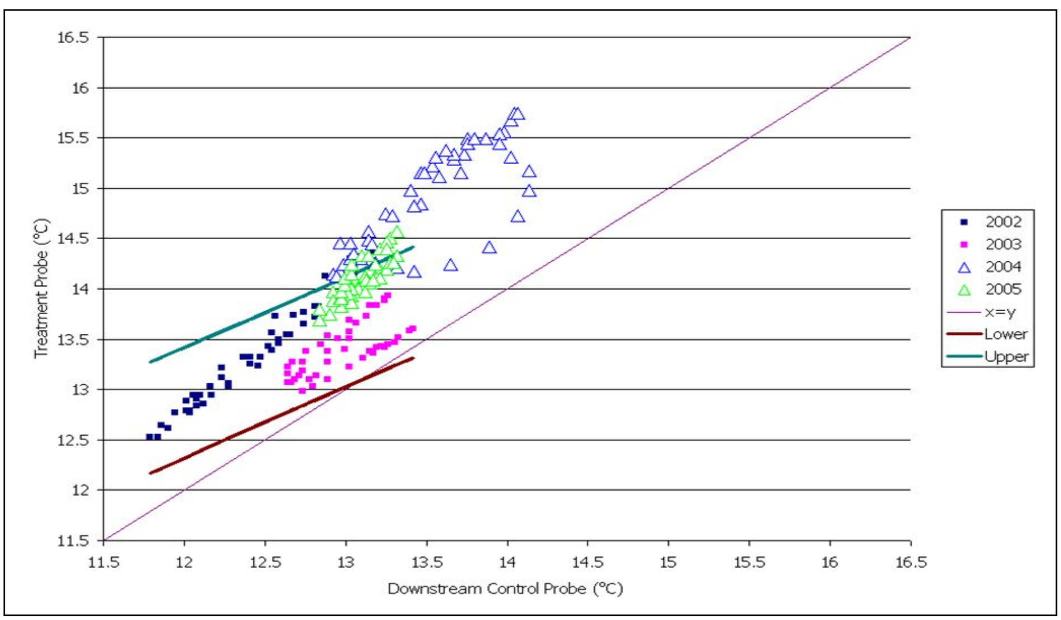


Figure 3.12E. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #11 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

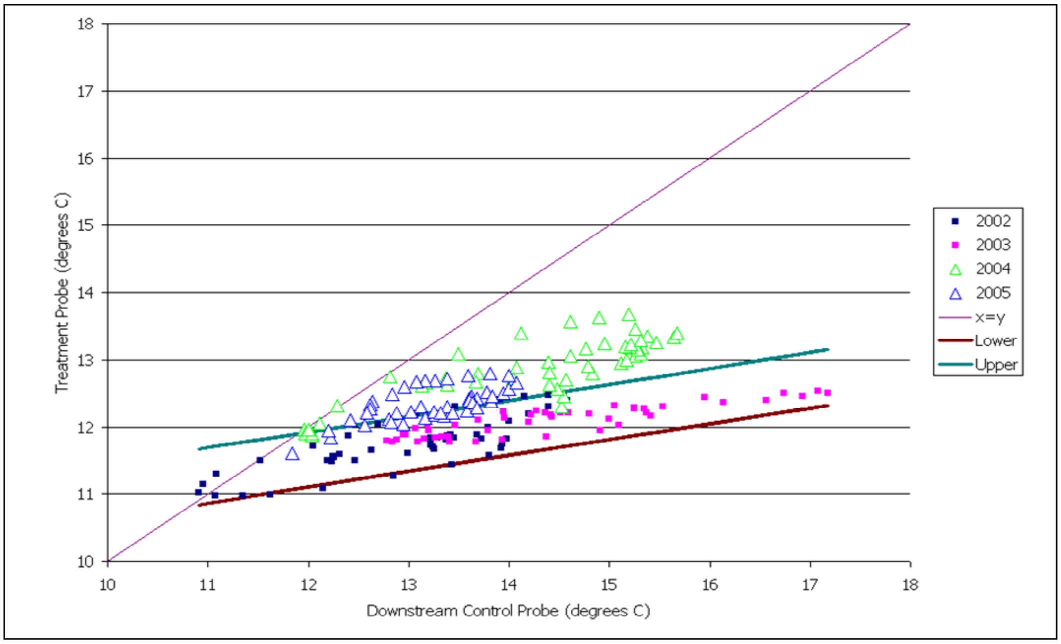


Figure 3.12F. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #12 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence intervals based on pre-harvest temperatures.

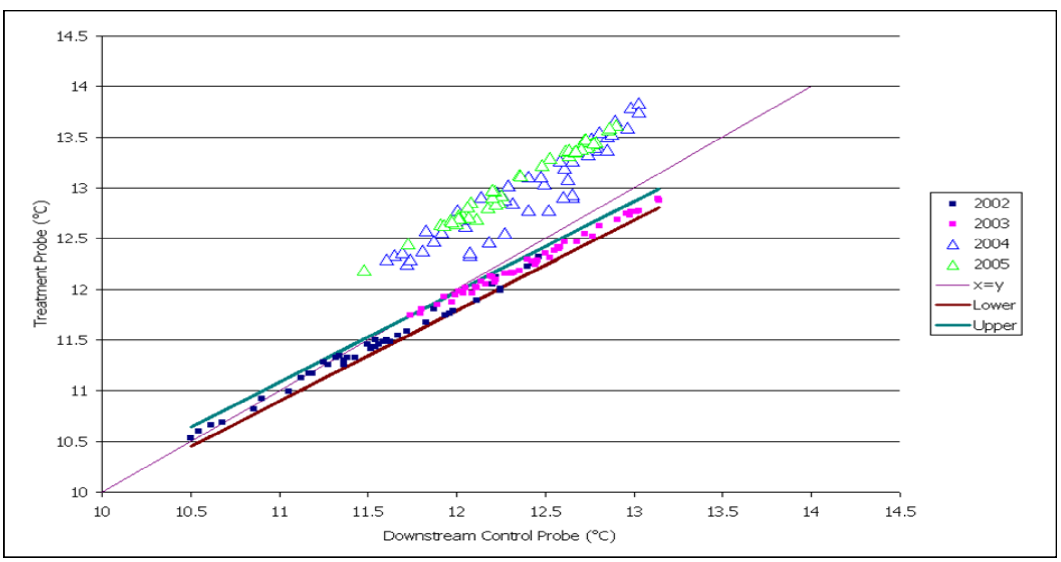


Figure 3.12G. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #14 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

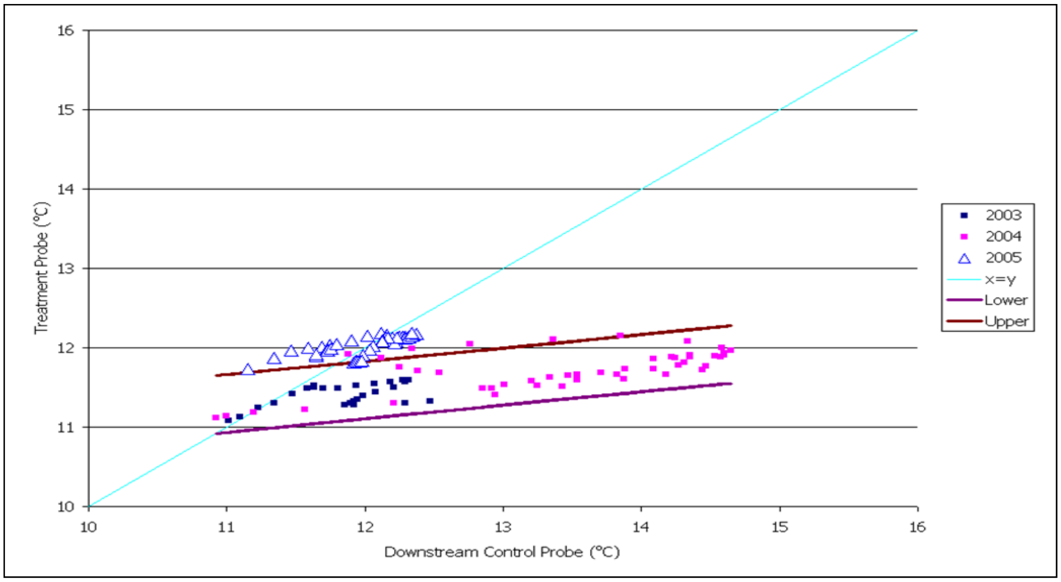


Figure 3.12H. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #15 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

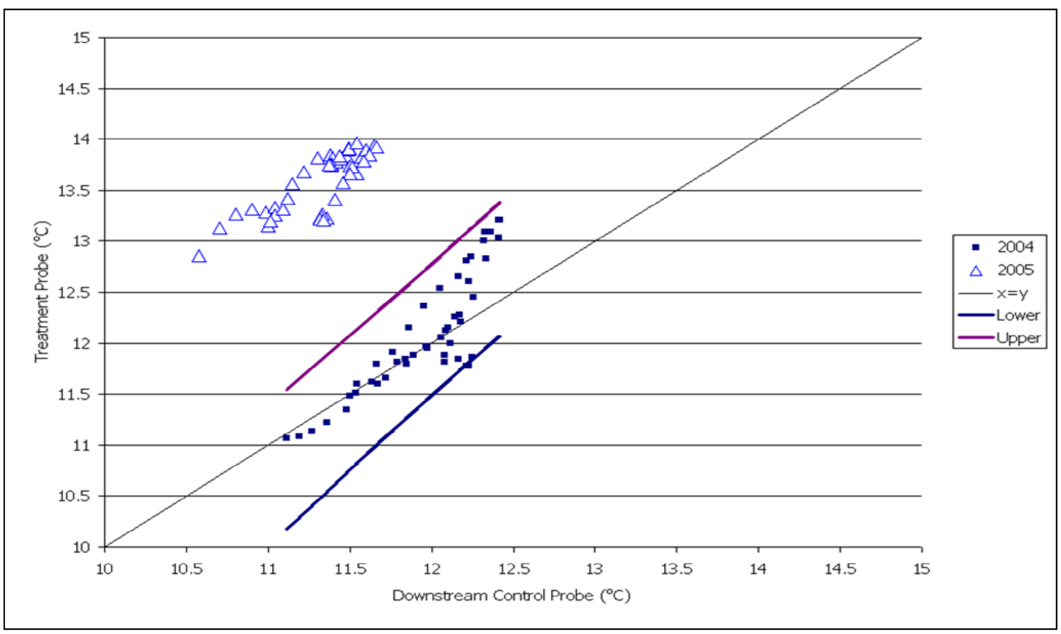


Figure 3.12I Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #16 in pre-harvest (2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

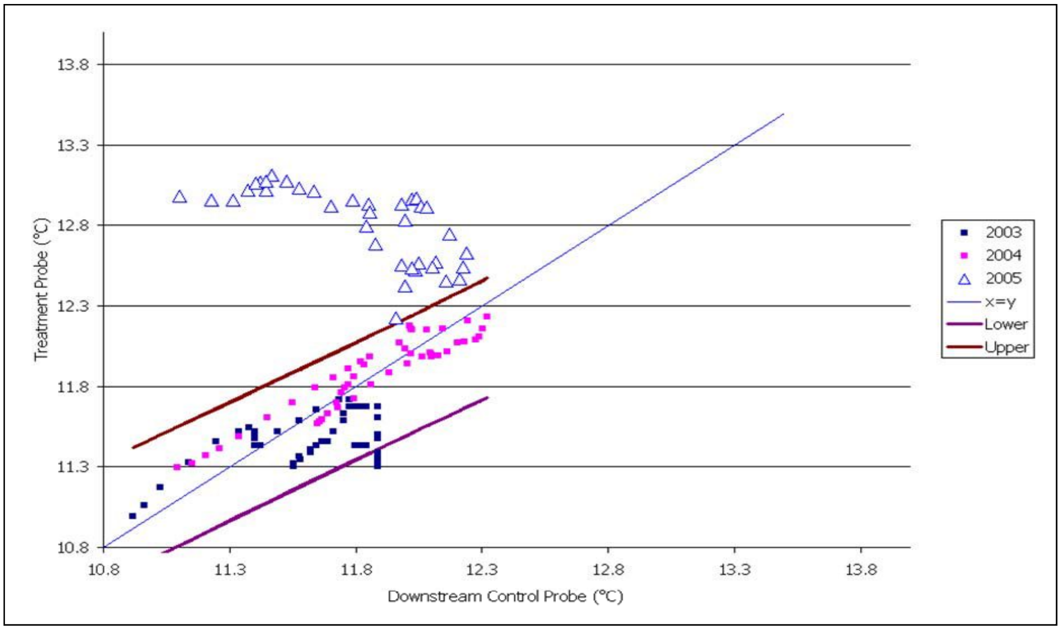


Figure 3.12J. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #17 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

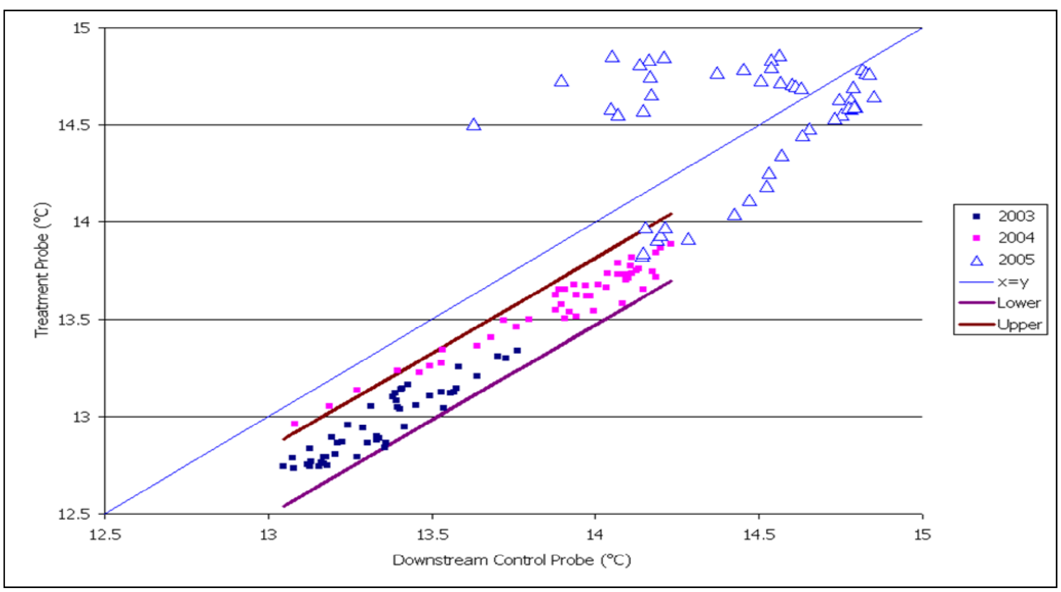


Figure 3.13K. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #18 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

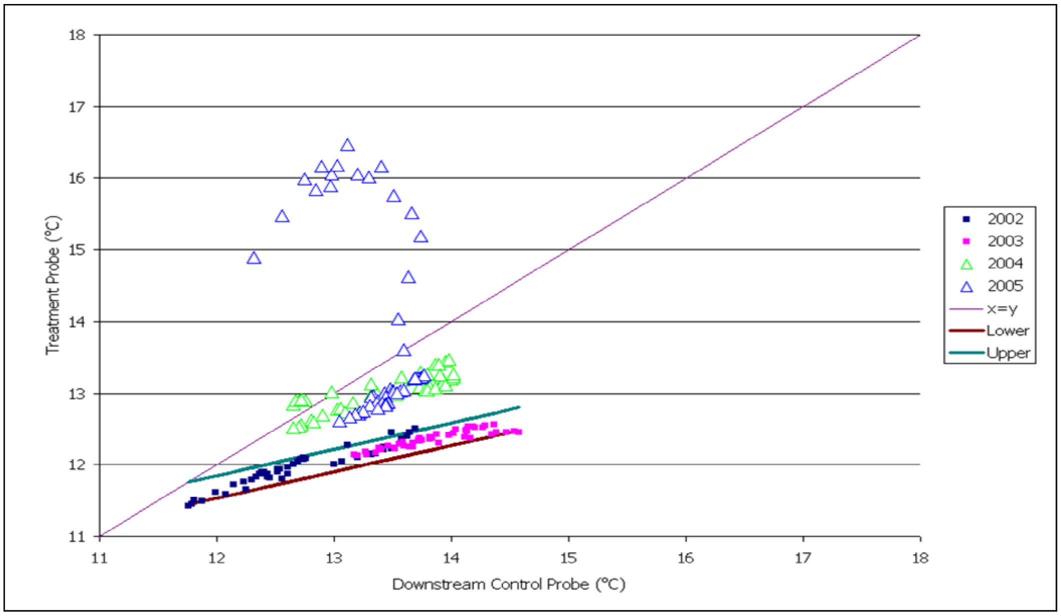


Figure 3.13L. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #20 pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

3.4.4. Maximum Temperatures of Individual Streams

The maximum 7-day moving mean of the daily maximum (Max7Day) is the metric used by the ODEQ to determine if a waterbody has exceeded water quality temperature standards. Prior to harvest, the Max7Day at the upstream control, downstream control, and treatment probes ranged from 10.4 to 15.8°C, 9.9 to 19.0°C, and 11.3 to 18.3°C, respectively. After harvest, the upstream control, downstream control, and treatment probes ranged from 10.2 to 17.0°C, 10.6 to 16.5°C, and 11.9 to 19.1°C, respectively (Table. 3.7). The Max7Day occurred on a variety of dates between July 15th and August 31st, depending on individual streams and year of measurement (Table 3.8).

Table 3.7. Max7Day values (˚C) for 22 Oregon Coast Range headwater streams between July 15th and August 31st. Values in bold indicate first year after harvest. * indicates missing temperature probes; blanks indicate streams not yet installed with probes.

	2002			2003			2004			2005		
Stream	Probe 1[1]	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3
1				15.3	19.0	14.4	15.8	16.8	15.4	**14.9**	**15.9**	**19.1**
2	10.4	9.9	12.0	10.8	10.8	11.3	11.0	10.7	12.6	**10.2**	**10.6**	**12.0**
3	12.5	12.8	12.9	13.3	13.7	13.6	13.0	13.7	13.9	**12.7**	**13.2**	**13.3**
4				11.2	10.7	11.9	11.5	11.4	12.1	**12.5**	**10.9**	**11.9**
5	14.4	14.1	14.0	14.3	13.6	14.0	14.9	14.5	14.7	**13.8**	**13.5**	**14.3**
6	14.4	14.6	14.6	*	15.3	15.2	15.5	15.8	15.7	**14.8**	**14.7**	**14.3**
7	14.0	14.1	14.0	13.1	12.5	12.8	13.8	13.2	13.6	**14.0**	**13.1**	**13.3**
8	12.2	12.9	14.4	12.9	*	14.9	**13.3**	**14.3**	**17.0**	12.5	13.0	15.5
9	13.2	14.7	13.6	13.6	16.1	13.9	**14.3**	**16.0**	**15.2**	13.2	14.0	14.0
10	14.9	15.0	15.0	15.1	15.2	15.2	**15.3**	**15.8**	**18.6**	14.1	14.4	16.7
11	13.0	13.2	14.4	13.3	13.4	13.9	**14.2**	**14.1**	**15.7**	13.4	13.3	14.6
12	14.6	14.6	12.5	15.5	17.2	12.5	**15.3**	**15.7**	**13.7**	14.5	14.1	12.8
13	15.0	14.6	17.5	15.6	15.1	15.7	**17.0**	**16.5**	**16.7**	16.8	16.3	16.1
14	12.3	12.5	12.3	13.0	13.1	12.9	**13.0**	**13.0**	**13.8**	12.9	12.9	13.6
15				12.8	12.5	11.6	13.4	14.6	12.2	**12.4**	**12.4**	**12.2**
16							12.9	12.4	13.2	**12.2**	**11.7**	**14.0**
17				11.2	11.9	11.7	11.4	12.3	12.2	**11.0**	**12.2**	**13.1**
18				14.2	13.8	13.3	14.6	14.2	13.9	**14.5**	**14.9**	**14.9**
19	14.6	15.2	17.8	15.9	15.2	18.3	15.5	15.9	18.7	**15.2**	**15.4**	**16.8**
20	12.0	13.7	12.5	12.4	14.6	12.6	**12.4**	**14.0**	**13.5**	15.6	13.8	16.5
21				12.9	13.7	14.2	13.3	14.0	15.0	**12.5**	**13.1**	**14.1**
22	13.8	13.6	14.0	14.2	14.2	14.5	14.3	14.5	15.0	**13.8**	**13.8**	**14.4**

[1]Probe 1: Upstream Control, Probe 2: Downstream Control, Probe 3: Treatment Probe.

Table 3.8. Date on which the Max7Day occurred for 22 Oregon Coast Range streams. Values in bold indicate first year after harvest. * indicates missing temperature probe; blanks indicate streams not yet installed with probes.

	2002			2003			2004			2005		
Stream	Probe 1[1]	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3
1				24-Jul	16-Aug	31-Jul	27-Jul	19-Aug	26-Jul	**7-Aug**	**5-Aug**	**19-Aug**
2	30-Aug	14-Aug	15-Aug	31-Aug	11-Aug	30-Jul	25-Aug	23-Aug	25-Jul	**26-Jul**	**28-Jul**	**16-Aug**
3	14-Aug	14-Aug	15-Aug	30-Jul	30-Jul	31-Jul	17-Aug	17-Aug	18-Aug	**17-Aug**	**16-Aug**	**16-Aug**
4				30-Jul	29-Jul	30-Jul	25-Aug	27-Aug	25-Jul	**6-Aug**	**17-Aug**	**28-Jul**
5	14-Aug	14-Aug	13-Aug	10-Aug	10-Aug	10-Aug	24-Jul	24-Jul	24-Jul	**29-Jul**	**29-Jul**	**29-Jul**
6	23-Jul	23-Jul	23-Jul	*	24-Jul	24-Jul	25-Jul	25-Jul	25-Jul	**21-Jul**	**16-Aug**	**16-Aug**
7	23-Jul	23-Jul	23-Jul	24-Jul	24-Jul	24-Jul	24-Jul	24-Jul	24-Jul	**24-Jul**	**24-Jul**	**24-Jul**
8	14-Aug	15-Aug	14-Aug	30-Jul	*	30-Jul	**25-Jul**	**25-Jul**	**18-Aug**	2-Aug	28-Aug	28-Aug
9	23-Jul	23-Jul	24-Jul	24-Jul	24-Jul	25-Jul	**25-Jul**	**25-Jul**	**25-Jul**	14-Aug	14-Aug	13-Aug
10	22-Jul	22-Jul	22-Jul	15-Jul	15-Jul	15-Jul	**19-Jul**	**28-Jul**	**20-Jul**	20-Jul	20-Jul	24-Aug
11	15-Aug	15-Aug	15-Aug	11-Aug	24-Jul	11-Aug	**24-Jul**	**21-Aug**	**25-Jul**	28-Aug	2-Aug	28-Aug
12	23-Jul	23-Jul	25-Jul	24-Jul	24-Jul	25-Jul	**26-Jul**	**26-Jul**	**19-Aug**	28-Jul	16-Aug	18-Aug
13	29-Aug	13-Aug	13-Aug	15-Jul	15-Jul	19-Jul	**23-Jul**	**23-Jul**	**19-Aug**	16-Jul	16-Jul	22-Aug
14	14-Aug	14-Aug	14-Aug	27-Aug	25-Jul	24-Jul	**17-Aug**	**18-Aug**	**18-Aug**	16-Aug	6-Aug	6-Aug
15				30-Jul	12-Aug	31-Jul	24-Jul	19-Aug	22-Aug	**16-Aug**	**16-Aug**	**29-Jul**
16							18-Aug	18-Aug	18-Aug	**16-Aug**	**17-Aug**	**13-Aug**
17				31-Aug	31-Aug	31-Jul	22-Aug	22-Aug	22-Aug	**16-Aug**	**19-Aug**	**13-Aug**
18				30-Jul	25-Jul	25-Jul	26-Jul	26-Jul	26-Jul	**5-Aug**	**11-Aug**	**28-Jul**
19	14-Aug	23-Jul	14-Aug	27-Jul	31-Jul	28-Jul	27-Jul	17-Aug	27-Jul	**6-Aug**	**6-Aug**	**6-Aug**
20	14-Aug	15-Aug	15-Aug	24-Jul	28-Aug	24-Jul	**19-Aug**	**19-Aug**	**25-Jul**	28-Jul	6-Aug	20-Jul
21				25-Jul	25-Jul	25-Jul	17-Aug	17-Aug	17-Aug	**17-Aug**	**17-Aug**	**6-Aug**
22	15-Aug	15-Aug	14-Aug	25-Jul	25-Jul	25-Jul	20-Aug	19-Aug	19-Aug	**7-Aug**	**16-Aug**	**17-Aug**

[1]Probe: Upstream Control, Probe 2: Downstream Control, Probe 3: Treatment Probe.

Chapter IV

Discussion

4.1. Channel Characteristics

Following harvest, there were non-significant increases and decreases in the various measured channel characteristics. Shade was the only riparian characteristic to decrease significantly by 6% in treatment reaches compared to control reaches from pre- to post-harvest periods. Decreases in riparian canopy cover following harvest around streams with riparian buffers have been documented in a number of studies (e.g. Zwieniecki and Newton 1999, Dignan and Bren 2003). The significant reduction in percent shade in my study is unlikely to be entirely a result of either sampling error or even natural variability because of the accuracy of hemispherical photography in measuring percent canopy cover (Ringold et al. 2003, Kelley and Krueger 2005).

Both wetted width and maximum depth showed a tendency to increase following harvest, however differences between the control and treatment reaches were not significant. Boothroyd et al. (2004) found significant increases in channel width following harvest, which they attributed to reduced evapotranspiration and interception, thus leading to increases in streamflow. However, because two different field crews measured channel characteristics in the pre- and post-harvest years in my study, the slight, non-significant increases in wetted width and maximum depth are more likely caused by differences in sampling technique. The mean increase in floodprone width in both the control and treatment reaches is likely a reflection of the increase found in maximum depth and thus bankfull depth, because floodprone width is based on these measurements. The decrease in channel gradient in both the control and treatment reaches following harvest was not significantly different, and is again most likely a result of differences in sampling technique.

Small increases in percent bedrock, boulders, and cobbles comprising streambed substrate following harvest were not significantly different between the control and treatment reaches. Johnson and Jones (2000) and Levno and Rothacher (1967) noted that debris-flow scour contributed to increased bedrock exposure in the Oregon Cascades. It is possible that debris flows could have occurred in the winter prior to harvest and contributed to the increased bedrock exposure, as well as the increases in percent boulder observed in my study. However, it is more likely that these differences are a result of the subjectivity of measurements by different sampling crews.

Percentages of both gravels and fines in streambeds decreased following harvest, but neither of these changes were statistically significant between the control and treatment reaches. Some studies have found increases in fine sediments following harvest (e.g. Ward et al. 2001, Grant and Wolff 1991, Beschta 1978) from increased erosion and runoff. The small decreases in gravels and fines in the streams in my study are, again, probably more likely a result of differences in field crews.

4.2. Warm-Season Stream Temperature Patterns

4.2.1. Pre-Harvest Warm-Season Stream Temperature Patterns

The majority of studies of stream temperature in forested headwater catchments have focused on either paired watersheds, or in-depth analyses of one or a few streams (e.g. Hewlett and Fortson 1982, Feller 1981, Hetrick et al. 1998). Few studies have examined more than ten streams (Sullivan and Adams 1989, Zwieniecki and Newton 1999, Jackson et al. 2001, Smith 2004). Previous studies have also focused on various measures of stream temperature, including (1) instantaneous values of maximum temperature before and after harvest (Feller 1981), (2) average changes in maximum and minimum temperatures (Hewlett and Fortson 1982), and (3) change between maximum pre- and post-treatment temperatures (Swift and Messer 1971). My study used the differences in 7DMMDMax between upstream and downstream temperature probes between July 15th and August 31st to filter out climatic fluctuations, as well as ensuring that the warmest period of the year for Oregon Coast Range headwater streams was used. My study is unique because of its larger sample size which allowed for BACI analysis and use of statistical analyses based on a large sample of headwater streams.

Among the twenty two streams in my study, the magnitude of cooling and warming differed among pre-harvest years, as well as within streams. Mean warm-season temperature gradient in control reaches was 0.4°C in each of the first and second pre-harvest years. In treatment reaches for the first pre-harvest year, the warm-season temperature gradient averaged 0.1°C, and in the second pre-harvest year the warm-season temperature gradient averaged 0.0°C. In the first pre-harvest year, nine streams warmed and six streams cooled in the control reach, with one stream indicating no warming or cooling pattern. In the treatment reach, nine streams warmed and seven streams cooled prior to harvest (Figure 3.7A). In the second pre-harvest year, 11 streams warmed and seven streams cooled in the control reach, with two exhibiting neither cooling nor warming. In the treatment reach, 10 streams warmed and seven cooled, with one exhibiting no cooling or warming (Figure 3.7B). Prior to treatment, 14 streams maintained patterns of consistent warming or cooling across all years within reaches, and, of those 14, only four streams indicated patterns of warming in a downstream direction across all years through both control and treatment reaches. Eight streams had inconsistent warming or cooling between reaches, as well as across years.

The River Continuum Concept (RCC) predicts that stream temperature increases as streams flow toward valley bottoms (Vannote et al. 1980). Zwieniecki and Newton (1999) found that in streams they studied in the Oregon Coast Range, temperatures tended to increase from the ridgeline to the confluence, although there was some variability. Johnson (2004) found increases of 4-5˚C over a 200 m bedrock reach in the Oregon Cascades. However, the warming trend predicted by the RCC was not always observed in my study. Prior to any disturbance, some streams heated with distance from the divide, some streams cooled, and some cooled in the control reach and warmed in the treatment, and some warmed in the control reach and cooled in the treatment reach. Moore et al. (2005a) also found that streams they studied in British Columbia had differential areas of cooling and warming, and that they followed no specific trend in downstream warming. Danehy et al. (2005) found general increases in temperature downstream in Idaho and Eastern Oregon, but also found small decreases caused by local stream factors, such as groundwater inflows.

4.2.2. Post-Harvest Warm-Season Stream Temperature Patterns

Following harvest, warm-season stream temperature gradients in control reaches were similar to what they had been prior to harvest.

However, warm-season stream temperature gradients in treatment reaches increased, indicating that an increased level of warming was taking place that had not occurred prior to harvest. As noted in Table 3.2, temperature gradients in the treatment reach increased by a mean of 0.4°C following harvest when compared with two years of pre-harvest data. Control reaches, conversely, decreased by 0.2°C when compared to data from two years prior to harvest. In control reaches following harvest, 16 streams exhibited warming trends and six streams indicated cooling trends. In treatment reaches, 18 streams warmed and four cooled following harvest.

Increases in stream temperature following harvest are common (e.g., Levno and Rothacher 1967, MacDonald et al. 2003, Beschta and Taylor 1988). Harr and Fredriksen (1988) reported increases of 2-3°C in streamwater temperature following harvest in Western Oregon. Moore et al. (2005a) found increases of up to 5°C in streams following clearcut harvesting in British Columbia, and Holtby (1988) found increases of greater than 3°C following harvest of 41% of a watershed in another study in British Columbia. Swift and Messer (1971) reported increases of up to 12°C following complete clearcuts adjacent to streams in the Appalachian Mountains. Baillie et al. (2005) observed increases of up to 5.6°C following harvest near streams in New Zealand. Maximum mean monthly stream temperatures increased up to 7°C in the summer in a clearcut watershed in Wales (Stott and Marks 2000). However, no studies have examined the change in temperature from upstream to downstream in a control and treatment reach both before and after harvest in numbers of streams approaching that used in my study.

4.2.3. Effectiveness of Riparian Management Areas

I hypothesized that RMAs implemented through current Oregon RMA guidelines on private and state lands would be effective if pre-harvest, warm-season maximum-temperature patterns were maintained following harvest treatments. Comparisons of temperature patterns between control and treatment reaches both pre- and post-harvest indicate that my hypothesis should be rejected because warm-season maximum- temperature patterns were not maintained when mean values across all study streams were considered. Difference in warm-season temperature gradients between control and treatment reaches averaged 0.6˚C, based on two years of pre-harvest and one year of post-harvest data. This indicates that more warming or less cooling occurred in treatment reaches than occurred in control reaches during July to August when pre-harvest and post-harvest periods were compared.

Zwieniecki and Newton (1999) reported that when canopy cover was reduced to 78% in the Oregon Coast Range, mean stream temperature increased by 1.09˚C. Johnson and Jones (2000) found that removal of riparian cover in the Oregon Cascade Range corresponded to increases in both maximum and minimum stream temperatures, and that maximum temperatures occurred at the time of maximum solar input. Furthermore, they found that stream temperature returned to pre-disturbance levels 15 years following harvest, which coincided with return of canopy coverage. Johnson (2004) found that artificially shading a section of stream in Oregon's Cascade Range reduced the amount of solar radiation reaching the stream surface, and highlighted the importance of shade in influencing daily maximum stream temperatures.

Following partial harvesting in the Olympic Peninsula of Washington, stream temperatures were found to increase by up to 3˚C compared to unharvested controls, and this was linked to a corresponding reduction in shade cover (Murray et al. 2000). MacDonald et al. (2003) found that when limited riparian vegetation was retained in riparian areas in British Columbia, stream temperatures increased by nearly 6˚C compared to pre-harvest levels. Moreover, temperatures in streams that had high retention of riparian vegetation had statistically insignificant increases of less than 1˚C following harvest (MacDonald et al. 2003).

Studies in other parts of the country have found that removal of canopy corresponded with increases in stream temperature. Burton and Likens (1973) found heating of 4-5˚C following strip cutting in the Hubbard Brook Experimental Forest in New Hampshire, which they concluded occurred as a result of reduced shade and increased exposure of the stream to solar radiation. In Pennsylvania, stream temperatures of up to 32˚C were recorded in a clearcut receiving herbicide treatment, which also had mean temperatures 9˚C higher than in a corresponding control stream. The herbicide effectively removed any lower vegetation from shading the stream, and increases in temperature were attributed to a 450-m-long opening in the canopy which allowed increased exposure to solar radiation. Additionally, a buffered stream in the same study had post-harvest temperatures only slightly higher than in the corresponding control, and temperatures lower than in the clearcut which received herbicide treatment (Rishel et al. 1982, Lynch et al. 1984).

In a study that clearfelled 100% of a catchment in New Zealand, including riparian vegetation, Baillie et al. (2005) found that monthly maximum temperatures three years following harvest had increased up to 5˚C compared to an unharvested reference stream. They found that harvesting the riparian zone increased instream light levels by up to 90%, the remainder of the shade being provided by steep banks and regenerating vegetation. Dignan and Bren (2003) found that following harvest in Australia, there were detectable increases in light penetration to the stream, which illustrated the potential for increased exposure to solar radiation.

One study in particular, however, found limited increases in stream temperature, as well as decreases, following clearcut harvesting in seven streams in Washington's Coast Range (Jackson et al. 2001). The authors attributed this to the large-scale deposition of slash and woody debris into and near the stream, which effectively shaded the water and prevented penetration of solar radiation (Jackson et al. 2001).

Considered by many to be the most important factor influencing temperature in small headwater streams (e.g. Beschta 1997, Brown 1969), solar radiation and the role that riparian vegetation plays in moderating its influence is a key consideration for maintenance of pre-harvest stream temperature patterns. Significant reductions in percent shade and significant increases in temperature gradients following harvest found in my study support the importance of shade in moderating changes in stream temperature.

Recommendations for an effective riparian buffer strip vary. Some stipulate that site-specific designs should be completed prior to harvest (e.g. Steinblums et al. 1984), and others suggest that riparian buffer widths of 30 m are sufficient to supply shade levels similar to that of old-growth forests (Beschta et al. 1987). However, riparian buffers have been considered effective for maintaining stream temperature if similar levels of shade are retained regardless of width. Boothroyd et al. (2004) found that temperature in harvested streams with no riparian buffers in New Zealand were up to 2˚C higher than both pre-harvest sites and harvested streams that retained buffers. The vegetative structure of post-harvest buffers was predominantly the same as pre-harvest, and cover values were generally similar. Additionally, they found that light levels in the streams with buffers were substantially lower than in harvested streams with no riparian buffer (Boothroyd et al. 2004). In their review of RMA literature, Broadmeadow and Nisbet (2004) note that although it is not possible to specify definitive widths, buffers of 5- to 30- m width have been found to be 50 to 75% effective in maintaining several aquatic functions, including shade production. Also, they recommend that the riparian buffer should mimic the state of the riparian area and aquatic zone prior to harvest. Brazier and Brown (1973) found that temperature was poorly correlated with both RMA timber volume and width in streams in western Oregon, but that designing buffers to maintain shade rather than volume could be more effective in maintaining stream temperature.

Barton et al. (1985) found no correlation between riparian buffer width and maximum stream temperature in Southern Ontario streams, which could suggest that as long as sufficient shade is maintained buffer width may be irrelevant. Bourque and Pomeroy (2001) also found that there was no clear relationship between riparian buffer width and stream warming in New Brunswick, and particularly noted that a stream with 60-m-wide buffers had consistently higher temperatures than a stream with a 30-m buffer.

Dignan and Bren (2003) found distinct changes in light penetration in the riparian zone following upslope harvest in Australia, but suggest that buffers of 70- to 100-m would be sufficient to maintain the pre-harvest light environment. The network model of Blann et al. (2002)

suggests that riparian buffers that provided at least 50% shade were adequate for mediating maximum stream temperatures.

4.2.4. Relationships Between Warm-Season Stream Temperature Gradients and Channel Characteristics

4.2.4.1 Control Reach

Percentage of gravel in the streambed was the most significant predictor for warm-season stream temperature gradients in the control reach following harvest, accounting for approximately 29% of the variation in temperature gradients. A higher percentage of gravel in the control reach corresponded to higher mean temperature gradients, which implies that warmer temperatures correspond to greater percentages of gravel. This suggests that hyporheic flow and transient storage could be playing a role in moderating stream temperature in the control reach of these streams. Edwards (1998) suggests that considerable alluvial porosity in the Pacific North Coastal region allows for high flow velocities within large interstitial spaces in the streambed, which can contribute to the formation of hyporheic environments. Valett et al. (1996) also found that greater hydraulic conductivities resulted in greater exchanges between surface and subsurface water. Morrice et al. (1997) reported that increased alluvial grain size corresponded with higher hydraulic conductivities, creating more of a potential for hyporheic exchange. However, they found that residence time in the hyporheic zone also decreased with increasing hydraulic conductivity, and therefore reduced contact time with cooler water. Stream reaches with increased gravel percentages found in my study could be associated with increased hydraulic conductivity, and therefore shorter residence times with less hyporheic interaction.

Streambed heat conduction may also be playing a relatively important role in the observed temperature gradients in control reaches where shade is at consistently high levels. Johnson and Jones (2004) suggest that conduction from the streambed into the water may be more important than is generally recognized, and that after solar radiation inputs, streambed conduction may be the most important contributor to stream temperature. Sinokrot and Stefan (1993) reported that streambeds can act as energy sinks during the day and sources at night, which contributes to stream heating at night. Also, they concluded that streambeds composed of rocks, as opposed to very fine sediments, are better conductors of heat.

Geologic parent material (i.e. sedimentary sandstone versus igneous basalt) was also a strong predictor of warm-season stream temperature in the control reach, explaining 21% of the variation in temperature gradients. Streams dominated by basalt parent geology tended to have higher temperature gradients, therefore warming more through the control reach, than streams dominated by sedimentary bedrock. Parent geology was noted to contribute to the size of channel substrate particles in the Pacific Northwest (Edwards 1998), which can influence both the magnitude of hyporheic exchange as well as streambed conduction. Wroblicky et al. (1998) found that streams with sedimentary sandstone parent geology in New Mexico had smaller hyporheic cross-sectional areas, which implies less volume was available for hyporheic exchange. Valett et al. (1996) also found less hydraulic exchange in sandstone-dominated catchments in New Mexico, which is opposite to the findings in my study. Although more warming appeared to have occurred in the basalt streams than the sedimentary streams in my study, it could be related to subsurface flow. However, a definitive conclusion cannot be drawn. Johnson (2004) reported that a section of a reach in the Oregon Cascades that had a higher percentage of bedrock also had higher maximum temperatures, and concluded this was caused by greater streambed conduction. In my study, streams with basalt geology tended to have higher percentages of bedrock, which could explain the higher temperature gradients observed in the igneous-dominated control reaches of these streams.

In a case with small inputs of solar radiation the importance of streambed conduction in small streams of Mississippi and Minnesota was highlighted (Sinokrot and Stefan 1993). The control reach in most of the streams in my study was heavily forested, with shade values averaging 89%. This high level of shading is similar to levels observed in old-growth Douglas-fir forests (Beschta et al. 1987) and the canopy likely reflects or absorbs the majority of incoming solar radiation. With inputs of solar radiation into the stream at such low levels, the relative influence of other moderators of stream temperature, such as streambed gravel or geology, may be easier to observe.

4.2.4.2. Treatment Reach

Shade was the most significant predictor for warm-season stream temperature gradient in treatment reaches following harvest, indicating that a shift in the relative importance of stream temperature factors occurred between the unharvested control and harvested treatment reaches. As shade decreased, warm-season stream temperature gradient increased. Shade accounted for almost 46% of the temperature variability in the treatment reaches of these streams, which corresponds to the value that Smith (2004) found when she examined these streams prior to harvest (49%).

Solar radiation has been documented by a number of studies (Brown 1970, Beschta et al. 1987, Moore et al. 2005a, Danehy et al. 2005) as being the strongest driver of stream temperature, and the change in temperature predictors from bedrock in the heavily shaded control to shade in the treatment reach in the same stream as found in this study reinforces this concept. If canopy cover is reduced following harvest, then it is likely that larger areas of the streams will be directly exposed to solar radiation, which may account for the observed increases in temperature. In the review by Poole and Berman (2001), they note shade as being one of the more important factors for insulating stream temperature from changes in the rate of heat input into and/or out of a stream. The regression model of Danehy et al. (2005) based on streams in Idaho and Northeast Oregon similarly found solar radiation to be the best predictor for stream temperature, and as inputs of solar radiation increased, so did stream temperature. Smith (2004) in studying the same streams used in my study prior to harvest found shade to be the best predictor for the 7DMMDMax in both the control and treatment reaches. This may have not been seen in my study because of the difference in temperature metrics by Smith (2004). Using the SNTEMP model, Bartholow (2000) found that small reductions in shade cover resulted in the largest increases in maximum daily stream temperature compared to other variables in the model.

Number of wood pieces between bankfull width and 1.8 m above bankfull width was also a significant predictor for warm-season stream temperature gradient in the treatment reach. Number of wood pieces was correlated positively with temperature gradient, indicating that the temperature gradient was higher with more pieces of wood above bankfull width. It is possible that following harvest, blowdown in the riparian buffer occurred, which could have reduced the quantity and quality of shade remaining in the RMA. Steinblums et al. (1984) note that in western Oregon, the majority of damage to riparian buffers is caused by windthrow, which allows greater penetration of solar radiation into the stream. Although windthrow was not specifically examined in my study, it is possible that streams with a greater proportion of the riparian buffer damaged by windthrow heated up more following treatment. The moderating influence provided by canopy cover over streams was reduced following a harvest in British Columbia when the majority of protective vegetation was lost because of windthrow (MacDonald et al. 2003).

4.2.5. Warm-Season Temperature Patterns of Individual Streams

Of the twelve streams in my study that exhibited increased values of 7DMMDMax between July 15th and August 31st following treatment, all but two had reductions in percent shade. In particular, some of the streams with the larger increases in temperature similarly had the largest reductions in percent shade. For example, prior to harvest, the 7DMMDMax temperatures in the control reach were similar to those in the treatment reach in Stream #10. However, during the same summer period in two post-harvest years, 7DMMDMax temperatures in the treatment reach were greater than those observed in the control reach. This corresponded to a decrease in shade of more than 30%. This was also observed in Stream #17, where following harvest, increases in the 7DMMDMax occurred along with a 25% decrease in shade within the treatment reach. Lynch et al. (1984) found that streams in Pennsylvania that had been clearcut and herbicided were up to 9˚C warmer than nearby control streams as well as nearby commercial harvests with riparian buffers. The herbicided clearcuts also exceeded water quality standards more often (Lynch et al. 1984). Bourque and Pomeroy (2001) concluded that the increase in temperature in their study in New Brunswick varied based on several factors, including the amount of forested area in the catchment, and that temperature increases were generally dependent on the amount of solar radiation reaching the stream. Hetrick et al. (1998) found that in sections of streams in southeastern Alaska with open canopy, significantly more solar radiation was able to reach the stream and thus influence temperature. Harr and Fredriksen (1988) found that annual maximum stream temperature increased by up to 3˚C following clearcut harvesting alongside a stream in western Oregon. In addition, they noted that stream temperatures appeared to be returning to pre-harvest levels within three years of harvest, which corresponded to regrowth of riparian vegetation that provided shade.

Nine of the streams in this study had either very little or no change in the 7DMMDMax following harvest. Of these nine, six retained shade at a level similar to pre-harvest, or actually increased in shade, possibly through increases in streamside vegetation. Streams with greater canopy cover are less likely to increase in temperature (Brown 1969, Beschta et al. 1987), and as the canopy was maintained in these streams at levels corresponding to pre-harvest, large changes in temperature would be unexpected. These results correspond to those found by Hetrick et al. (1998) that in closed canopy sections of streams in southeastern Alaska, less solar radiation was able to reach the stream surface and influence stream heating than in open sections of the stream. Also, decreases in monthly mean temperature maxima of up to 5˚C were observed in a forested stream in Scotland when compared to non-forested moorland, which was attributed to the blocking of solar radiation by the forested canopy (Webb and Crisp 2006). However, decreases in shade in my study occurred at two of the streams with no significant corresponding increase in temperature. The moderating influence of groundwater and hyporheic flow on stream temperature has been described in some studies (e.g. Poole and Berman 2001, Story et al. 2003). Story et al. (2003) found that cooling generally occurred only when the surface water interacted with groundwater sources in streams in British Columbia, and that high rates of cooling were also associated with greater transient storage. Influence of groundwater and hyporheic water could explain the lack of a significant increase in the 7DMMDMax in these two streams, despite the reduction in shade.

Of the twelve streams that heated following harvest, all of which had riparian buffers, nine had clearcut harvesting on both sides, two had clearcut harvesting on one side, and one had a partial cut on one side. The majority of the streams that had little-to-no change following harvest had either a clearcut harvest on one side, or were subjected to partial cuts. Additionally, streams that retained the smallest levels of shade were also the streams that were clearcut on both sides.

Prior to harvest, the 7DMMDMax for Stream #6 in the control reach was similar to that in the treatment reach. However, following harvest the 7DMMDMax for the treatment reach decreased significantly outside of the 95% confidence interval. The amount of shade in both the control and treatment reach appears to have increased following harvest, and there was also between 85 and 90% shade both before and after the harvest year. The observed cooling could be related to the increase in stream shading, as was observed by Johnson (2004) following artificial shading of a stream reach in the Cascades of Oregon, in which cooling of 2-4°C was observed. Cooling could also have occurred from decreased evapotranspiration and interception, and increased subsurface flow from the harvest upslope (Hewlett and Helvey 1970), which could result in increased discharge in the stream.

4.2.6. Maximum Temperatures of Individual Streams

The ODF currently uses the maximum mean temperature for the warmest week of the year (Max7Day) as a standard for evaluating water quality. The water quality standard for stream temperature in core cold water habitat in the Oregon Coast Range is a Max7Day of 16°C (http://www.deq.state.or.us/wq/wqrules/wqrules.htm). Four of the streams observed in this study exceeded this temperature standard prior to any treatments. Following harvest, these four streams as well as three additional streams exceeded the water quality temperature standard at least once between July 15th and August 31st following harvest. That the streams, prior to any harvest, were already exceeding the maximum water quality temperature standard indicates that meeting current standards in some streams may not be physically possible. It is interesting to note that following harvest, only three additional streams exceeded the state's water quality temperature standard, and that the highest observed Max7Day for all streams following harvest was 19.1°C, found at a Treatment probe. This occurred on a stream that had a Max7Day of 19°C the previous year which occurred at the Downstream Control probe. Again, this demonstrates the inherent variability within these small headwater streams. Ice (2004) suggests that streamwater temperature guidelines not be based only on biologically beneficial or physically attainable temperatures, but should also rely on identification of natural stream temperature patterns. Also, use of physical models in determining what is generally expected in the area being studied before implementation of standards could be helpful for setting more achievable standards.

Johnson and Jones (2000) found that increased daily temperature maxima occurred earlier in the season following harvest than had been observed prior to harvest. They also noted that timing of stream temperature maxima coincided with timing of maximum solar radiative inputs. In my study, only one stream had a Max7Day temperature occur earlier in the year at the Treatment probe than observed prior to harvest. Stream #11 had a Max7Day occur at the Treatment probe on August 15^{th} in the first pre-harvest year, and on August 11^{th} in the second pre-harvest year. Following harvest, the Max7Day occurred on 25^{th} July. However, in the second post-harvest year, the Max7Day occurred on August 28^{th}. Other studies have also found that the timing of stream temperature maxima occurs earlier in the year following harvest than that observed prior to harvest (e.g. Rishel et al. 1982). However, that does not appear to have occurred in my study. Although no definitive conclusions can be drawn, changes in the date of the Max7Day may be caused by the natural variability within the streams as well as likely variations in groundwater influences, and year-to-year climatic variation.

Chapter V

Conclusions and Management Implications

The inherent variability of warm-season maximum temperature in heavily shaded headwater streams of the Oregon Coast Range has been reported previously (Smith 2004). However, few studies have examined impacts of forest harvesting on temperature in the context of natural variability, instead focusing on maximum daily, monthly, or seasonal temperatures. My study helps provide further information on the natural variability of warm-season stream temperature, as well as harvest impacts on stream temperature patterns within the context of this natural variability. Effectiveness of RMAs as outlined by Oregon's current Forest Practice Rules was based on maintenance of warm-season maximum stream temperature patterns following harvest in the presence of RMAs. Pre-harvest warm-season maximum temperature patterns were not consistently maintained in the studied streams following harvest. This suggests that current RMAs for small- and medium fish-bearing streams of the Oregon Coast Range are not effective for maintenance of warm-season temperature patterns.

Many of the streams in my study subjected to significant reductions in shade also had significant increases in warm-season stream temperature. Streams that were characterized by greater retention of shade also had little or no change in warm-season temperature patterns following harvest. Thus, RMAs that maintained shade at levels similar to pre-harvest conditions appear to be more effective in maintaining pre-harvest warm-season temperature patterns. This suggests that RMA design might be improved if percentages of shade present prior to harvest were taken into account and attempts to maintain this shade following harvest were emphasized.

This study also reinforced the concept that solar radiation is one of the most important factors driving stream temperature, at least among the variables examined in this study, and shade covering stream channels functions to moderate its influence. In the heavily shaded control reaches observed in this study, shade was not an important component in predicting temperature prior to harvesting. However, in the treatment reaches following harvest shade was the most important predictor, indicating a shift in the relative importance of temperature drivers from channel substrate to shade. When more solar radiation was able to reach the treatment reaches of these streams, the role that shade played in absorbing or reflecting it became more apparent. This should continue to be an important consideration for RMA design.

Setting a water quality standard is a necessary step for identifying anti-degradation measures. However, some streams in my study exceeded the standard of 16°C for a maximum seven-day mean (Max7Day) prior to forest harvesting, and with no upstream disturbance, which indicates that inherent variability should be taken into consideration when water quality standards are set. If undisturbed, heavily forested headwater streams cannot meet the water quality standard, it is unlikely that in their disturbed state the water quality standard will be met.

One of the key strengths of this study was the presence of both pre- and post-treatment data, as well as the ability to compare upstream (control) and downstream (treatment) reaches of each stream. Few studies have had a comprehensive BACI design, and the uniqueness of this allowed for different analyses than have been undertaken in other studies. However, more intensive sampling of channel characteristics would have been useful in my study, particularly for shade measurements. Also, temperature in small streams has been shown to fluctuate over very small spatial and temporal scales. If this study is repeated, installation of more temperature probes along each reach may prove useful in increasing precision of temperature gradients and temperature changes within each reach. Discharge is also a factor that influences stream temperature, particularly warm-season stream temperatures. Measurement of discharge through either dilution gauging or some other means would likely help to explain more of the temperature variability found in these streams.

There are many challenges associated with site-specific RMA designs, as well as generalized recommendations for width of RMAs. Temperature variability in small headwater streams is well known, and not all the processes that contribute to stream temperature are well understood. However, my study helps to reinforce the role of solar radiation and shade as being important for stream temperature, and RMAs that retain sufficient shade are likely to be the most effective for maintaining warm-season stream temperature patterns in the Oregon Coast Range. Improved understanding of all factors that contribute to stream temperature would help to clarify inherent variability observed in this study, as well as leading to more effective design of RMAs.

BIBLIOGRAPHY

Baillie, B.R., K.J. Collier, and J. Nagels. 2005. Effects of forest harvesting and woody debris removal on two Northland streams, New Zealand. New Zealand Journal of Marine and Freshwater Research 39: 1-15.

Barton, D.R., W.D. Taylor, and R.M. Biette. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. North American Journal of Fisheries Management 5: 364-378.

Bartholow, J.M. 2000. Estimating cumulative effects of clearcutting on stream temperatures. Rivers 7(4): 284-297.

Beschta, R.L. 1978. Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range. Water Resources Research 14(6): 1011-1016.

Beschta, R.L., R.E. Bilby, G.W. Brown, L.B. Holtby, and T.D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. In: Streamside Management: Forestry and Fishery Interactions, E.O. Salo and T.W. Cundy (Eds). University of Washington, Institute of Forest Resources, Contribution No. 57, Seattle, Washington, pp. 191-232.

Beschta, R.L. 1997. Riparian shade and stream temperature: An alternative perspective. Rangelands 19 (2): 25-28.

Beschta, R.L. and R.L. Taylor. 1988. Stream temperature increases and land use in a forested Oregon watershed. Water Resources Bulletin 24(1): 19-25.

Blann, K., J.F. Nerbonne, and B. Vonderacek. 2002. Relationship of riparian buffer type to water temperature in the Driftless Area ecoregion of Minnesota. North American Journal of Fisheries Management 22: 441-451.

Boothroyd, I.K.G., J.M. Quinn, E.R.L. Langer, K.J. Costley, and G. Steward. 2004. Riparian buffers mitigate effects of pine plantation logging on New Zealand streams 1. Riparian vegetation structure, stream geomorphology and periphyton. Forest Ecology and Management 194: 199-213.

Boulton, A.J., S. Findlay, P. Marmonier, E.H. Stanley, and H.M. Valett. 1998. The functional significance of the hyporheic zone in streams and rivers. Annual Review of Ecology and Systematics 29: 59-81.

Bourque, P.A., and J.H. Pomeroy. 2001. Effects of forest harvesting on summer stream temperatures in New Brunswick, Canada: an inter-catchment, multiple year comparison. Hydrology and Earth System Sciences 5(4): 599-613.

Brazier, J.R. and G.W. Brown. 1973. Buffer strips for stream temperature control. Research Paper 15, For. Res. Lab. Oregon State University, Corvallis. 9p.

Broadmeadow, S., and T.R. Nisbet. 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practices. Hydrology and Earth System Sciences 8(3): 286-305.

Brosofske, K.D., J. Chen, R.J.Naiman, and J.F. Franklin. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecological Applications 7(4): 1188-1200.

Brown, G.W. 1969. Predicting temperatures of small streams. Water Resources Research 5: 68-75.

Brown, G.W. 1970. Predicting the effect of clearcutting on stream temperature. Journal of Soil and Water Conservation 25: 11-13.

Burton, T.M. and G.E. Likens. 1973. The effect of strip cutting on stream temperatures in the Hubbard Brook Experimental Forest, New Hampshire. Bioscience 23(7): 433-435.

Danehy, R.J., C.G. Colson, K.B. Parrett, and S.D. Duke. 2005. Patterns and sources of thermal heterogeneity in small mountain streams within a forested setting. Forest Ecology and Management 208: 287-302.

Dignan, P., and L. Bren. 2003. A study of the effect of logging on the understorey light environment in riparian buffer strips in a south-east Australian forest. Forest Ecology and Management 172: 161-172.

Ebersole, J.L., W.J. Liss, and C.A. Frissell. 2003. Cold water patches in warm streams: physicochemical characteristics and the influence of shading. Journal of the American Water Resources Association 39(2): 355-368.

Edwards, R.T. 1998. The Hyporheic Zone. In: River Ecology and Management: Lessons from the Pacific Coastal Ecoregion, R.J. Naiman and R.E. Bilby (Eds). Springer New York, pp. 399-427.

Feller, M.C. 1981. Effects of clearcutting and slash burning on stream temperature in southwestern British Columbia. Water Resources Bulletin 17(5): 863-867.

Greene, G.E. 1950. Land use and trout streams. Journal of Soil and Water Conservation 5(3): 125-126.

Grant, G.E. and A.L. Wolff. 1991. Long term patterns of sediment transport after timber harvest, Western Cascade Mountains, Oregon, USA. Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation. Proceedings of the Vienna Symposium. IAHS publication No. 203.

Harr, R.D., and R.L. Fredriksen. 1988. Water quality after logging small watersheds within the Bull Run watershed, Oregon. Water Resources Bulletin 24(5): 1103-1111.

Heifetz, J., M.L. Murray, and K.V. Koski. 1986. Effects of logging on winter habitat of juvenile salmonids in Alaskan streams. North American Journal of Fisheries Management 6:52-58.

Hetrick, N.J., M.A. Brusven, W.R. Meehan, and T.C. Bjornn. 1998. Changes in solar input, water temperature, periphyton accumulation and allochthonous input and storage after canopy removal along two small salmon streams in Southeast Alaska. Transactions of the American Fisheries Society 127(6): 859-875.

Hewlett, J.D., and J.C. Fortson. 1982. Stream temperature under an inadequate buffer strip in the southeast piedmont. Water Resources Bulletin 18(6): 983-988.

Hewlett and Helvey. 1970. Effects of forest clear-felling on the storm hydrograph. Water Resources Research 6(3): 768-782.

Holtby, L.B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the Coho salmon (Oncorhynchus kisutch). Canadian Journal of Fisheries and Aquatic Sciences 45(3): 502-515.

Ice, G.G., J. Light, and M. Reiter. 2004. Use of natural temperature patterns to identify achievable stream temperature criteria for forest streams. Western Journal of Applied Forestry 19(4): 252-259.

Isaak, D.J. and W.A. Hubert. 2001. A hypothesis about factors that affect maximum summer stream temperatures across montane landscapes. Journal of the American Water Resources Association 37(2): 351-365.

Jackson, C.R., C.A. Sturm, and J.M. Ward. 2001. Timber harvest impacts on small headwater stream channels in the Coast Ranges of Washington. Journal of the American Water Resources Association 37(6): 1533-1549.

Johnson, S.L. 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. Canadian Journal of Fisheries and Aquatic Sciences 61: 913-923.

Johnson, S.L. and J.A. Jones. 2000. Stream temperature response to forest harvest and debris flows in western Cascades, Oregon. Canadian Journal of Fisheries and Aquatic Sciences 57: 30-39.

Kelley, C.E. and W.C. Krueger. 2005. Canopy cover and shade determinations in riparian zones. Journal of the American Water Resources Association 41(1): 37-46.

Larson, L.L. and S.L. Larson. 1996. Riparian shade and stream temperature: a perspective. Rangelands 18(4): 149-152.

Lee, P., C. Smith, and S. Boutin. 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. Journal of Environmental Management 70: 165-180.

Levno, A. and J. Rothacher. 1967. Increases in maximum stream temperature after logging in old-growth Douglas fir watersheds. Pacific Northwest and Range Exp. Sta. USDA Forest Service Res. Note PNW-65, 12 pp.

Levno, A. and J. Rothacher. 1969. Increases in maximum stream temperature after slash burning in a small experimental watershed. Pacific Northwest and Range Exp. Sta. USDA Forest Service Res. Note PNW-110, 7pp.

Logan, R. 2002. Oregon's Forest Protection Laws: An illustrated manual. Oregon Forest Resources Institute, Portland, OR.

Lynch, J.A., G.B. Rishel, and E.S. Corbett. 1984. Thermal alteration of streams draining clearcut watersheds: quantifications and biological implications. Hydrobiologia 111:161-169.

MacDonald, J.S., E.A. MacIssac, and H.E. Herunter. 2003. The effect of variable-retention riparian buffer zones on water temperatures in small headwater streams in sub-boreal forest ecosystems of British Columbia. Canadian Journal of Forest Research 33: 1371-1382.

Meehan W. R. 1970. Some effects of shade cover on stream temperature in southeast Alaska. U.S. Forest Service Research Note PNW-113.

Melody, K.J. and J. S. Richardson. 2004. Responses of invertebrates and algae of a boreal coniferous forest stream to experimental manipulation of leaf litter inputs and shading. Hydrobiologia 519: 197-206.

Moore, J.A., and J.R. Miner. 1997. Stream temperatures: some basic considerations. Oregon State University Extension Service, Oregon State University, Corvallis, OR. 97339.

Moore, R.D., P. Sutherland, and A. Dhakal. 2005a. Thermal regime of a headwater stream within a clearcut, coastal British Columbia, Canada. Hydrological Processes 19: 2591-1608.

Moore, R.D., D.L. Spittlehouse, and A. Story. 2005b. Riparian microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resources Association 41(4): 813-834.

Morrice, J.A., H.M. Valett, C.N. Dahm, and M.E. Campana. 1997. Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams. Hydrological Processes 11: 253-267.

Murray, G.L.D., R.L. Edmonds, and J.L. Marra. 2000. Influence of partial harvesting on stream temperatures, chemistry, and turbidity in forests on the Western Olympic Peninsula, Washington. Northwest Science 74(2): 151-164.

Nitschke, C.R. 2005. Does forest harvesting emulate fire disturbance? A comparison of effects on selected attributes in coniferous-dominated headwater systems. Forest Ecology and Management 214: 305-319.

Newbold, J.D., D.C. Erman, and K.B. Roby. 1980. Effects of logging on macroinvertebrates in streams with and without buffer strips. Canadian Journal of Fisheries and Aquatic Sciences 37(7): 1076-1085.

Oregon Department of Forestry. 2003. Riparian Function and Stream Temperature: effectivness of Oregon Departmet of Forestry's protection rules and strategies. Oregon Department of Forestry, Salem, OR.

Osborne, L.L. and D.A. Kovacik. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29: 243-258.

Peterson, B.J. 2001. Stream processes alter the amount and form of nitrogen exported from small watersheds. Science 292: 86–90.

Poff, N.L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime. Bioscience 47(11): 769-784.

Poole, G.C. and C.H. Berman. 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. Environment Management 27(6): 787-802.

Ringold, P.L., J.V. Sickle, K. Rasar, and J. Schacher. 2003. Use of hemispheric imagery for estimating stream solar exposure. Journal of the American Water Resources Association 39(6): 1373-1384.

Rishel, G.B., J.A. Lynch, and E.S. Corbett. 1982. Seasonal stream temperature changes following forest harvesting. Journal of Environmental Quality 11(1): 112-116.

Sinokret, B.A., and H.G. Stefan. 1993. Stream temperature dynamics: measurements and modeling. Water Resources Research 29: 2299-2312.

Smith, D.D. 2004. Contributions of riparian vegetation and stream morphology to headwater stream temperature patterns in the Oregon Coast Range. M.S. Thesis. Department of Forest Engineering, Oregon State Universtiy, Corvallis, Oregon, 97339.

Stefan, H.G., and E.B. Preud'homme. 1993. Stream temperature esimation from air temperature. Water Resources Bulletin 29(1): 27-45.

Steinblums, I.J., H.A. Froehlich, and J.K. Lyons. 1984. Designing stable buffer strips for stream protection. Journal of Forestry 82: 49-52.

Story, A., R.D. Moore, and J.S. MacDonald. 2003. Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology. Canadian Journal of Forest Research 33: 1382-1396.

Stott, T. and S. Marks. 2000. Effects of plantation forest clearfelling on stream tempreatures in the Plynlimon experimental catchments, Mid-Wales. Hydrology and Earth System Sciences 4(1): 95-104.

Swift, L.W. and J.B. Messer. 1971. Forest cuttings raise temperatures of small streams in the southern Appalachians. Journal of Soil and Water Conservation 26(3): 111-115.

Sullivan, K., and T.N. Adams. 1989. The physics of stream heating 2) An analysis of temperature patterns in stream environments based on physical principles and field data. Weyerhaeuser Research Report Project No. 044-5002/89/2.

Tabacchi E., D.L. Correll, G. Pinay, A.-M. Planty-Tabacchi, and R.C. Wissmar. 1998. Development, maintenance and role of riparian vegetation in the river landscape. Freshwater Biology 40:497–516.

Titcomb, J.W. 1926. Forests in relation to freshwater fishes. Transactions of the American Fisheries Society 56(1): 122-129.

Valett, H.M., J.A. Morrice, C.N. Dahm, and M.E. Campana. 1996. Parent lithology, surface-groundwater exhange, and nitrate retention in headwater streams. Limnology and Oceanography 41(2): 333-345.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37: 130-137.

Ward, J.M. and C.R. Jackson. 2004. Sediment trapping within forestry streamside management zones, Georgia piedmont, USA. Journal of the American Water Resources Association 40(6): 1421-1431.

Webb, B.W. and D.T. Crisp. 2006. Afforestation and stream temperature in a temperate maritime environment. Hydrological Processes 20: 51-66.

Wroblicky, G.J., M.E. Campana, H.M. Valett, C.N. Dahm. 1998. Seasonal variation in surface-subsurface water exchange and lateral hyporheic area of two stream-aquifer systems. Water Resources Research Vol. 34 (3): 317-328.

Zwieniecki, M.A., and M. Newton. 1999. Influence of streamside cover and stream features on temperature trends in forested streams of western Oregon. Western Journal of Applied Forestry 14(2): 106-113.

APPENDIX

Table 1. Means and standard deviations of selected channel characteristics for control reaches of 22 Oregon Coast Range streams.

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank-full Width (m)	Post-Harvest Bank-full Width (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
1	2.80 (2.39)[1]	1.20 (1.60)	1.52 (0.46)	0.88 (0.05)	0.09 (0.03)	0.05 (0.05)	3.29 (1.00)	4.23 (0.98)	8.13 (2.33)	1.29 (0.30)
2	17.50 (7.51)	15.50 (4.80)	1.69 (0.52)	2.48 (1.16)	0.47 (0.14)	0.48 (0.25)	4.23 (1.29)	3.86 (0.96)	13.11 (11.64)	1.18 (0.29)
3	14.67 (2.16)	12.60 (5.85)	1.77 (0.54)	2.20 (0.80)	0.19 (0.06)	0.17 (0.08)	3.61 (1.10)	4.53 (3.23)	6.26 (5.15)	1.38 (0.99)
4	2.50 (1.22)	2.40 (1.67)	1.42 (0.43)	1.82 (0.34)	0.13 (0.04)	0.12 (0.07)	3.37 (1.03)	3.70 (0.88)	6.51 (1.67)	1.13 (0.27)
5	13.33 (9.46)	14.80 (8.17)	1.52 (0.46)	2.06 (0.57)	0.09 (0.03)	0.12 (0.04)	2.14 (0.65)	3.33 (0.54)	6.54 (1.10)	1.02 (0.16)
6	5.40 (2.70)	4.00 (3.65)	3.84 (1.17)	5.19 (1.20)	0.15 (0.05)	0.18 (0.03)	5.82 (1.78)	6.78 (1.81)	17.78 (9.68)	2.07 (0.55)
7	4.00 (1.41)	4.60 (1.52)	1.66 (0.51)	1.65 (0.22)	0.15 (0.05)	0.14 (0.08)	2.94 (0.90)	3.70 (1.84)	8.64 (3.17)	1.13 (0.56)
8	15.17 (8.68)	10.67 (8.07)	2.18 (0.67)	3.29 (1.81)	0.22 (0.07)	0.24 (0.08)	4.32 (1.32)	4.53 (1.89)	8.03 (4.94)	1.38 (0.58)

[1]Numbers in parentheses indicate one standard deviation of the mean.

Table 1 Continued

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank-full Width (m)	Post-Harvest Bank-full Width (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
9	1.75 (0.50)	2.00 (1.00)	3.13 (0.95)	4.45 (0.33)	0.11 (0.03)	0.25 (0.08)	5.18 (1.58)	5.79 (0.89)	10.67 (6.47)	1.76 (0.27)
10	7.00 (2.37)	5.33 (2.50)	1.89 (0.57)	3.06 (1.51)	0.14 (0.04)	0.31 (0.10)	2.92 (0.89)	3.96 (2.35)	5.32 (3.32)	1.21 (0.72)
11	14.33 (11.08)	11.00 (3.35)	1.74 (0.53)	3.96 (1.71)	0.07 (0.02)	0.14 (0.03)	3.97 (1.21)	4.46 (1.91)	9.65 (5.23)	1.36 (0.58)
12	6.33 (5.89)	11.00 (2.45)	1.45 (0.44)	2.95 (0.69)	0.11 (0.03)	0.21 (0.08)	4.27 (1.30)	4.34 (0.58)	7.32 (1.61)	1.32 (0.18)
13	1.00 (0.00)	1.00 (0.00)	0.97 (0.29)	1.17 (0.34)	0.11 (0.03)	0.17 (0.09)	3.15 (0.96)	2.41 (0.64)	53.35 (2.16)	0.73 (0.20)
14	12.00 (4.85)	9.00 (2.65)	1.48 (0.45)	1.99 (1.01)	0.09 (0.03)	0.13 (0.03)	3.04 (0.93)	3.02 (1.42)	5.08 (5.23)	0.92 (0.43)
15	28.67 (7.55)	16.00 (8.33)	1.17 (0.36)	1.03 (0.80)	0.10 (0.03)	0.04 (0.03)	4.22 (1.29)	2.98 (0.67)	9.53 (4.01)	0.91 (0.20)
16	18.20 (15.82)	16.00 (6.30)	0.58 (0.18)	0.43 (0.53)	0.07 (0.02)	0.05 (0.04)	1.62 (0.49)	1.37 (0.95)	6.81 (0.77)	0.42 (0.29)
17	14.40 (13.32)	14.75 (9.93)	1.16 (0.35)	0.66 (0.46)	0.18 (0.06)	0.14 (0.10)	1.65 (0.50)	1.26 (0.71)	3.76 (2.25)	0.38 (0.22)

Table 1 Continued

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank full Width (m)	Post-Harvest Bank full Width (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
18	12.17 (5.91)	14.20 (5.00)	1.95 (0.59)	2.10 (1.20)	0.24 (0.07)	0.15 (0.09)	2.59 (0.79)	3.04 (1.35)	6.10 (1.52)	0.93 (0.41)
19	2.00 (0.63)	1.00 (0.00)	2.21 (0.67)	1.81 (0.78)	0.21 (0.06)	0.16 (0.09)	3.49 (1.06)	3.05 (0.76)	8.10 (2.30)	0.93 (0.23)
20	21.00 (10.20)	27.20 (9.28)	0.87 (0.27)	1.63 (0.27)	0.06 (0.02)	0.15 (0.05)	3.17 (0.97)	2.77 (0.53)	4.57 (0.91)	0.85 (0.16)
21	7.83 (2.99)	8.20 (2.43)	3.53 (1.08)	4.28 (1.73)	0.18 (0.05)	0.25 (0.13)	7.25 (2.21)	6.17 (1.78)	13.31 (5.48)	1.88 (0.54)
22	7.50 (4.51)	5.50 (2.35)	0.87 (0.26)	1.11 (0.66)	0.06 (0.06)	0.07 (0.02)	2.82 (0.86)	2.22 (0.74)	7.66 (1.60)	0.68 (0.22)

Table 2. Means and standard deviations of channel substrate characteristics in control reaches of 22 Oregon Coast Range Streams.

Site	Pre-Harvest Bedrock (%)	Post-Harvest Bedrock (%)	Pre-Harvest Boulder (%)	Post-Harvest Boulder (%)	Pre-Harvest Cobble (%)	Post-Harvest Cobble (%)	Pre-Harvest Gravel (%)	Post-Harvest Gravel (%)	Pre-Harvest Fines (%)	Post-Harvest Fines (%)
1	0	0	6 (13)	0	20 (12)	44 (6)	64 (25)	44 (8)	10 (14)	12 (12)
2	10 (20)[1]	23 (45)	0	16 (15)	10 (20)	46 (34)	40 (8)	15 (17)	40 (25)	0
3	0	0	3 (8)	30 (31)	10 (11)	40 (26)	42 (22)	26 (17)	45 (24)	4 (8)
4	0	0	0	0	7 (10)	34 (34)	52 (23)	30 (21)	42 (26)	36 (44)
5	0	12 (25)	5 (12)	10 (13)	25 (20)	44 (21)	52 (24)	34 (24)	18 (24)	4 (8)
6	0	13 (22)	4 (9)	15 (16)	20 (12)	40 (19)	50 (16)	33 (11)	26 (6)	0
7	0	0	5 (12)	24 (37)	18 (18)	40 (37)	38 (26)	24 (23)	38 (28)	12 (20)
8	0	45 (7)	0	34 (27)	15 (18)	44 (27)	45 (14)	25 (17)	40 (21)	10 (0)
9	0	0	10 (20)	30 (0)	10 (12)	10 (0)	50 (35)	88 (19)	30 (12)	0
10	3 (8)	0	0	18 (10)	28 (17)	72 (28)	42 (17)	20 (17)	27 (8)	0
11	0	0	0	0	20 (22)	39 (8)	40 (25)	46 (11)	40 (19)	42 (10)
12	57 (50)	87 (12)	8 (13)	38 (26)	18 (20)	18 (8)	15 (16)	20 (10)	0	0
13	0	0	0	0	0	0	0	0	100 (0)	100 (0)
14	0	10 (0)	10 (14)	21 (10)	12 (16)	39 (21)	42 (16)	33 (23)	36 (25)	25 (21)
15	0	0	0	2 (4)	28 (24)	45 (33)	38 (30)	31 (19)	33 (25)	23 (28)
16	0	25 (45)	0	5 (9)	0	8 (13)	40 (26)	20 (22)	60 (26)	43 (45)
17	0	23 (40)	0	3 (5)	0	8 (10)	28 (19)	30 (42)	72 (19)	38 (39)

[1]Numbers in parentheses indicate one standard deviation of the mean.

Table 2 Continued

Site	Pre-Harvest Bedrock (%)	Post-Harvest Bedrock (%)	Pre-Harvest Boulder (%)	Post-Harvest Boulder (%)	Pre-Harvest Cobble (%)	Post-Harvest Cobble (%)	Pre-Harvest Gravel (%)	Post-Harvest Gravel (%)	Pre-Harvest Fines (%)	Post-Harvest Fines (%)
18	0	0	17 (32)	22 (40)	3 (8)	24 (24)	33 (45)	42 (30)	47 (52)	12 (17)
19	0	0	0	0	5 (12)	12 (18)	25 (22)	14 (17)	70 (24)	74 (34)
20	0	0	0	57 (33)	7 (10)	29 (15)	38 (13)	39 (9)	55 (12)	39 (33)
21	17 (41)	0	8 (20)	30 (19)	20 (17)	32 (21)	42 (25)	34 (21)	17 (14)	2 (4)
22	0	0	0	10 (25)	18 (18)	0	52 (20)	28 (20)	30 (28)	58 (30)

Table 3. Total number of wood pieces and wood jam volume in control reaches of 22 Oregon Coast Range streams. Low wood is below bankfull depth; high wood is between bankfull depth and 1.8 m above bankfull depth.

Site	Pre-Harvest Low Wood (#)	Post-Harvest Low Wood (#)	Pre-Harvest HighWood (#)	Post-Harvest HighWood (#)	Pre-Harvest Wood Jams (m^3)	Post-Harvest Wood Jams (m^3)
1	43	32	30	63	3	23
2	67	56	25	54	0	330
3	54	95	58	44	10	8
4	50	67	62	33	143	204
5	19	8	10	6	0	0
6	25	32	23	22	4	47
7	27	19	24	26	0	0
8	40	43	49	21	63	208
9	27	32	24	1	31	945
10	30	36	16	9	0	4
11	116	49	74	22	70	1035
12	21	4	23	7	0	0
13	20	18	7	2	0	0
14	16	76	36	15	0	5
15	25	85	90	96	315	708
16	83	52	31	49	0	34
17	96	41	36	27	100	69
18	87	71	55	85	282	439

Table 3 Continued

Site	Pre-Harvest Low Wood (#)	Post-Harvest Low Wood (#)	Pre-Harvest High Wood (#)	Post-Harvest High Wood (#)	Pre-Harvest Wood Jams (m^3)	Post-Harvest Wood Jams (m^3)
19	59	30	46	41	2	0
20	99	54	81	27	18	68
21	3	8	14	18	3	31
22	74	33	19	49	7	89

Table 4. Means and standard deviations of selected channel characteristics for treatment reaches of 22 Oregon Coast Range streams.

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank full Width (m)	Post-Harvest Bank full Depth (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
1	2.00 (0.71)[1]	3.43 (0.38)	1.34 (0.96)	0.93 (0.61)	0.11 (0.05)	0.09 (0.13)	4.20 (1.01)	3.24 (0.59)	1.28 (0.39)	10.57 (9.43)
2	13.19 (7.51)	14.31 (10.13)	3.09 (1.61)	3.56 (2.22)	0.23 (0.13)	0.24 (0.14)	8.26 (3.25)	6.18 (2.12)	2.52 (0.77)	14.12 (9.79)
3	9.46 (6.24)	9.14 (2.57)	2.03 (0.89)	1.87 (0.63)	0.22 (0.06)	0.13 (0.09)	3.63 (0.98)	2.87 (1.10)	1.11 (0.34)	5.30 (3.83)
4	3.17 (1.17)	2.50 (0.82)	1.66 (0.41)	2.25 (0.67)	0.12 (0.08)	0.12 (0.05)	3.72 (1.23)	3.28 (0.98)	1.13 (0.35)	11.09 (4.85)
5	7.38 (5.41)	7.94 (7.31)	2.07 (0.58)	2.36 (1.39)	0.17 (0.10)	0.19 (0.11)	3.62 (0.89)	3.92 (1.76)	1.10 (0.34)	12.90 (14.44)
6	6.90 (7.62)	1.40 (0.45)	3.93 (1.36)	4.17 (1.53)	0.21 (0.15)	0.21 (0.10)	5.53 (2.88)	6.48 (1.85)	1.69 (0.51)	16.83 (9.08)
7	5.50 (1.87)	5.14 (2.07)	1.20 (0.53)	1.58 (0.36)	0.11 (0.05)	0.14 (0.02)	2.77 (0.91)	2.93 (1.21)	0.85 (0.26)	12.83 (6.80)
8	6.73 (2.97)	3.83 (1.71)	2.23 (0.41)	3.50 (1.05)	0.23 (0.16)	0.20 (0.07)	4.97 (1.27)	6.29 (1.56)	1.52 (0.46)	12.55 (6.93)

[1]Numbers in parentheses indicate one standard deviation of the mean.

Table 4 Continued

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank full Width (m)	Post-Harvest Bank full Depth (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
9	3.15 (3.67)	4.38 (6.92)	2.99 (1.74)	6.33 (3.33)	0.18 (0.19)	0.40 (0.28)	7.10 (2.73)	8.66 (3.31)	2.17 (0.66)	19.23 (6.45)
10	4.33 (2.35)	3.11 (1.27)	2.74 (0.87)	3.80 (1.00)	0.18 (0.12)	0.20 (0.06)	3.88 (0.71)	5.00 (1.14)	1.18 (0.36)	10.32 (4.88)
11	8.00 (3.93)	10.25 (5.65)	2.25 (1.19)	3.20 (1.55)	0.17 (0.11)	0.18 (0.04)	3.96 (0.86)	5.05 (3.21)	1.21 (0.37)	8.89 (4.29)
12	5.81 (3.29)	8.56 (2.53)	1.85 (1.00)	3.36 (1.04)	0.10 (0.08)	0.18 (0.09)	4.69 (1.25)	5.39 (1.71)	1.43 (0.44)	10.19 (2.34)
13	1.00 (0.00)	1.00 (0)	1.55 (0.60)	1.81 (0.58)	0.13 (0.10)	0.21 (0.15)	3.88 (0.71)	3.00 (0.77)	1.18 (0.36)	32.71 (37.96)
14	6.50 (3.62)	5.33 (1.21)	1.81 (0.56)	2.78 (1.20)	0.08 (0.08)	0.18 (0.06)	3.28 (1.84)	3.51 (1.64)	1.00 (0.31)	7.11 (4.09)
15	22.50 (9.34)	14.22 (6.53)	1.54 (0.97)	1.59 (1.02)	0.14 (0.18)	0.07 (0.05)	4.19 (3.71)	2.95 (0.81)	1.28 (0.39)	9.00 (5.85)
16	9.20 (3.63)	9.83 (3.78)	1.71 (0.92)	1.32 (0.35)	0.12 (0.06)	0.12 (0.07)	3.78 (1.58)	1.49 (0.61)	1.15 (0.35)	9.75 (5.60)
17	8.00 (2.45)	8.67 (4.53)	0.88 (0.39)	1.32 (0.38)	0.08 (0.04)	0.14 (0.07)	2.23 (1.10)	2.94 (1.17)	0.68 (0.21)	9.71 (5.59)

Table 4 Continued

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank full Width (m)	Post-Harvest Bank full Depth (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
18	4.13 (2.17)	5.11 (5.21)	2.30 (0.69)	1.88 (0.61)	0.16 (0.08)	0.13 (0.02)	3.39 (0.91)	3.56 (0.84)	1.03 (0.32)	19.23 (9.77)
19	2.10 (0.97)	1.00 (0)	2.18 (0.91)	2.13 (1.03)	0.13 (0.10)	0.18 (0.15)	4.08 (1.31)	3.17 (1.44)	1.24 (0.38)	10.29 (8.57)
20	4.60 (2.07)	14.63 (13.46)	1.35 (1.03)	2.28 (1.50)	0.08 (0.06)	0.13 (0.03)	4.44 (2.44)	3.44 (1.96)	1.35 (0.41)	6.55 (7.39)
21	6.65 (2.62)	5.71 (2.38)	3.27 (1.16)	3.22 (1.63)	0.19 (0.10)	0.14 (0.07)	6.43 (2.39)	5.08 (2.16)	1.96 (0.60)	8.42 (2.17)
22	4.83 (1.72)	3.00 (1.55)	1.48 (0.83)	0.99 (0.28)	0.09 (0.06)	0.09 (0.05)	3.09 (0.80)	1.67 (0.49)	0.94 (0.29)	3.19 (0.89)

Table 5. Means and standard deviations of channel substrate characteristics for treatment reaches of 22 Oregon Coast Range streams.

Site	Pre-Harvest Bedrock (%)	Post-Harvest Bedrock (%)	Pre-Harvest Boulder (%)	Post-Harvest Boulder (%)	Pre-Harvest Cobble (%)	Post-Harvest Cobble (%)	Pre-Harvest Gravel (%)	Post-Harvest Gravel (%)	Pre-Harvest Fines (%)	Post-Harvest Fines (%)
1	17 (37)[1]	0	0	16 (15)	12 (15)	34 (17)	52 (32)	23 (22)	19 (23)	27 (33)
2	6 (15)	10 (25)	13 (18)	27 (26)	24 (13)	33 (23)	48 (19)	22 (24)	10 (13)	8 (16)
3	0	10 (27)	0	13 (14)	24 (21)	38 (20)	35 (19)	33 (10)	42 (27)	6 (23)
4	0	0	0	3 (0)	12 (20)	44 (31)	53 (26)	38 (24)	35 (12)	14 (13)
5	9 (26)	11 (21)	0	11 (19)	17 (15)	34 (20)	41 (24)	34 (19)	33 (22)	11 (15)
6	0	3 (22)	4 (9)	0	22 (15)	62 (21)	30 (7)	31 (14)	44 (9)	4 (9)
7	0	11 (33)	12 (29)	23 (27)	23 (19)	37 (27)	32 (23)	34 (18)	33 (5)	3 (8)
8	0	60 (0)	8 (12)	21 (17)	23 (15)	47 (32)	32 (21)	27 (22)	37 (20)	30 (21)
9	3 (11)	0	8 (16)	53 (42)	6 (13)	15 (7)	61 (17)	93 (18)	24 (13)	0
10	0	0	0	10 (0)	23 (11)	81 (15)	41 (12)	19 (15)	36 (7)	20 (0)
11	0	0	0	29 (17)	9 (13)	40 (18)	41 (15)	56 (32)	50 (13)	15 (7)
12	41 (48)	73 (30)	4 (10)	38 (20)	21 (20)	34 (14)	23 (19)	39 (20)	11 (15)	0
13	0	0	0	0	0	0	3 (8)	0	97 (8)	100 (0)
14	13 (33)	42 (15)	0	0	18 (10)	35 (11)	38 (20)	32 (10)	30 (9)	47 (25)
15	0	11 (33)	0	26 (28)	43 (33)	38 (26)	40 (32)	23 (25)	18 (13)	2 (7)
16	0	0	0	0	4 (9)	1 (2)	24 (15)	32 (33)	72 (22)	66 (35)
17	0	0	0	2 (5)	8 (11)	20 (29)	30 (22)	23 (22)	62 (30)	54 (40)

[1]Numbers in parentheses indicate one standard deviation of the mean.

Table 5 Continued

Site	Pre-Harvest Bedrock (%)	Post-Harvest Bedrock (%)	Pre-Harvest Boulder (%)	Post-Harvest Boulder (%)	Pre-Harvest Cobble (%)	Post-Harvest Cobble (%)	Pre-Harvest Gravel (%)	Post-Harvest Gravel (%)	Pre-Harvest Fines (%)	Post-Harvest Fines (%)
18	0	0	13 (18)	36 (41)	38 (29)	38 (26)	30 (27)	25 (18)	20 (26)	0
19	0	0	0	0	0	18 (21)	52 (25)	23 (18)	48 (27)	60 (35)
20	0	0	0	50 (0)	26 (9)	54 (27)	36 (11)	22 (14)	38 (15)	32 (15)
21	1 (5)	5.88	8 (15)	30 (18)	29 (9)	33 (18)	40 (14)	31 (17)	22 (17)	1 (2)
22	0	0.00	0	0	3 (8)	31 (21)	38 (17)	43 (9)	58 (15)	27 (16)

Table 6. Total number of wood pieces and wood jam volume in treatment reaches of 22 Oregon Coast Range streams. Low wood is below bankfull depth; high wood is between bankfull depth and 1.8 m above bankfull depth.

Site	Pre-Harvest Low Wood (#)	Post-Harvest Low Wood (#)	Pre-Harvest High Wood (#)	Post-Harvest High Wood (#)	Pre-Harvest Wood Jams (m^3)	Post-Harvest Wood Jams (m^3)
1	17	32	29	63	5	23
2	31	56	27	54	220	330
3	57	95	49	44	0	8
4	38	67	43	33	37	204
5	33	8	21	6	1	0
6	35	32	34	22	0	47
7	58	19	38	26	0	0
8	34	43	35	21	4	208
9	51	32	40	1	5	945
10	17	36	10	9	0	4
11	72	49	50	22	10	1035
12	13	4	23	7	0	0
13	31	18	11	2	0	0
14	17	76	26	15	0	5
15	63	85	49	96	256	708
16	75	52	26	49	19	34
17	103	41	26	27	6	69

Table 6 Continued

Site	Pre-Harvest Low Wood (#)	Post-Harvest Low Wood (#)	Pre-Harvest High Wood (#)	Post-Harvest High Wood (#)	Pre-Harvest Wood Jams (m^3)	Post-Harvest Wood Jams (m^3)
18	21	71	19	85	17	439
19	45	30	31	41	0	0
20	59	54	49	27	18	68
21	23	8	50	18	5	31
22	55	33	23	49	7	89

Table 7. Individual site conditions for 22 Oregon Coast Range headwater streams. CC = clearcut, PC = partial cut.

Site	Name	Location	Owner	Harvest Beyond RMA	Pre-Harvest Data Collection	Post-Harvest Data Collection	Control Length (m)	Treatment Length (m)
1	Argue Creek	T21S, R8W, S6	Roseburg Forest Products	2 sided CC	2003-2004	2005	253	418
2	Cook East	T2N, R8W, S14&15	State Forest	1 sided CC	2002-2004	2005	183	1261
3	Wolf's Foot	T1N, R7W, S7&8	State Forest	1 sided CC	2002-2004	2005	305	401
4	Bale Bound	T10S, R8W, S1	State Forest	1 sided PC	2003-2004	2005	305	384
5	Smith Creek	T1N, R10W, S17	Simpson Timber Company	2 sided CC	2002-2004	2005	305	976
6	Nettle Meyer	T5N, R6W, S20	State Forest	1 sided PC	2002-2004	2005	232	293
7	West Creek Combo	T7N, R6W, S 1, 11, 12&14	State Forest	1 sided PC	2002-2004	2005	305	366
8	Big South Fork	T6N, R9W, S28&29	Weyerhaeuser	2 sided CC	2002-2003	2004-2005	305	671

Table 7 Continued

Site	Name	Location	Owner	Harvest Beyond RMA	Pre-Harvest Data Collection	Post-Harvest Data Collection	Control Length (m)	Treatment Length (m)
9	Ice Box	T4N, R10W, S10	Weyerhaeuser	2 sided CC	2002-2003	2004-2005	213	793
10	Shangrila	T6N, R10W, S26,27,34&35	Weyerhaeuser	2 sided CC	2002-2003	2004-2005	305	549
11	Section 27 Center	T5N, R10W, S27	Weyerhaeuser	2 sided CC	2002-2003	2004-2005	305	488
12	Toad Creek	T3N, R7W, S3	Longview Fibre Company	1 sided CC	2002-2003	2004-2005	305	963
13	Siletz River Trib.	T8S, R11W, S26	Boise	2 sided CC	2002-2003	2004-2005	168	793
14	Upper Mary's River	T10S, R7W, S5	Starker Forests	2 sided CC	2002-2003	2004-2005	244	327
15	East Fork Buck Creek	T8S, R9W, S33	Plum Creek	2 sided CC	2003-2004	2005	305	488
16	Elk Creek North	T8S, R9W, S14	Plum Creek	2 sided CC	2003-2004	2005	305	305

Table 7 Continued

Site	Name	Location	Owner	Harvest Beyond RMA	Pre-Harvest Data Collection	Post-Harvest Data Collection	Control Length (m)	Treatment Length (m)
17	Elk Creek South	T8S, R9W, S14	Plum Creek	2 sided CC	2003-2004	2005	244	287
18	West Fork Silver Creek	T24S, R11W, S12&13	Weyerhaeuser	1 sided CC	2003-2004	2005	244	477
19	Knapp Knob	T17S, R7W, S18	State Forest	1 sided PC	2002-2004	2005	305	1178
20	Eck Creek	T3N, R9W, S28&33	State Forest	1 sided PC	2002-2003	2004-2005	274	305
21	Cezanne	T1N, R6W, S22, 23&27	State Forest	2 sided PC	2003-2004	2005	976	976
22	North Nelson	T17S, R7W, S6	State Forest	1 sided PC	2002-2004	2005	305	393

Table 8. Mean warm-season (July 15th – August 31st) maximum temperature gradients and standard deviations for 22 Oregon Coast Range streams. Missing values indicate streams not installed with temperature probes; * indicates probe loss; bold indicates post-harvest value.

	2002		2003		2004		2005	
Site	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment
1			2.7 (0.1)	-3.1 (3.6)	2.2 (0.6)	-0.3 (0.5)	**1.0 (0.2)**	**1.4 (0.6)**
2	-0.4 (0.4)[1]	0.4 (0.1)	1.6 (0.5)	0.2 (0.1)	0.5 (0.5)	0.4 (0.2)	**0.6 (0.2)**	**0.3 (0.1)**
3	0.4 (0.1)	0.1 (0.1)	0.4 (0.1)	0.0	0.7 (0.1)	0.2 (0.1)	**0.4 (0.1)**	**0.1 (0.0)**
4			-0.1 (0.2)	0.8 (0.1)	0.4 (0.4)	0.7 (0.2)	**-1.0 (0.4)**	**0.8 (0.1)**
5	0.0	0.0	-0.6 (0.1)	0.1 (0.1)	-0.2 (0.1)	0.1 (0.0)	**-0.2 (0.1)**	**0.3 (0.0)**
6	0.3 (0.2)	-0.1 (0.1)		-0.1 (0.0)	0.4 (0.2)	-0.1 (0.2)	**0.0**	**-0.4 (0.0)**
7	0.1 (0.1)	-0.1 (0.1)	-0.5 (0.0)	0.2 (0.1)	-0.6 (0.1)	0.2 (0.0)	**-0.8 (0.1)**	**0.2 (0.0)**
8	0.6 (0.1)	0.5 (0.1)	*	*	**0.6 (0.2)**	**1.0 (0.2)**	**0.4 (0.1)**	**1.0 (0.1)**
9	-0.4 (0.1)	2.0 (0.2)	-0.6 (0.1)	2.7 (0.4)	**1.4 (0.7)**	**-0.1 (0.2)**	**1.1 (01)**	**0.1 (0.1)**
10	0.1 (0.0)	0.0	0.2 (0.0)	0.0	**0.1 (0.2)**	**1.1 (0.3)**	**0.2 (0.1)**	**1.2 (0.2)**
11	0.2 (0.1)	0.6 (0.1)	0.0	0.3 (0.1)	**0.0**	**0.8 (0.2)**	**-0.1 (0.0)**	**0.6 (0.1)**
12	-0.1 (0.2)	-0.4 (0.2)	0.6 (0.5)	-0.7 (0.3)	**0.2 (0.1)**	**-0.4 (0.2)**	**-0.3 (0.3)**	**-0.3 (0.1)**
13	-0.6 (0.2)	0.6 (0.4)	-0.7 (0.7)	0.3 (0.1)	**-0.5 (0.3)**	**0.1 (0.1)**	**-0.9 (0.2)**	**0.2 (0.1)**
14	0.3 (0.1)	-0.1 (0.1)	0.3 (0.1)	-0.1 (0.1)	**0.0**	**0.5 (0.2)**	**0.1 (0.1)**	**0.6 (0.0)**
15			-0.1 (0.3)	2.6 (3.6)	1.1 (0.7)	-1.0 (0.6)	**0.1 (0.2)**	**0.0**
16					-0.5 (0.1)	0.1 (0.3)	**-0.4 (0.1)**	**2.2 (0.2)**
17			1.1 (0.1)	-0.2 (0.2)	1.2 (0.1)	0.0	**1.3 (2.0)**	**1.0 (0.1)**

[1]Numbers in parentheses indicate one standard deviation of the mean.

Table 8 Continued

Site	2002 Control	Treatment	2003 Control	Treatment	2004 Control	Treatment	2005 Control	Treatment
18			-0.3 (0.4)	-0.2 (0.0)	-0.3 (0.1)	-0.2 (0.1)	**0.6 (0.2)**	**0.0**
19	0.5 (0.2)	0.6 (0.1)	0.3 (0.4)	0.7 (0.1)	0.3 (0.1)	0.5 (0.2)	**0.1 (0.0)**	**0.3 (0.0)**
20	1.7 (0.1)	-0.7 (0.3)	2.0 (0.1)	-1.5 (0.3)	**1.5 (0.2)**	**-0.3 (0.3)**	**0.2 (1.5)**	**0.6 (1.5)**
21			0.6 (0.2)	0.1 (0.1)	**0.6 (0.2)**	**0.3 (0.1)**	**0.5 (0.0)**	**0.3 (0.1)**
22	-0.2 (0.1)	0.3 (0.0)	0.0 (0.0)	0.2 (0.0)	**0.1 (0.1)**	**0.4 (0.0)**	**0.0**	**0.4 (0.0)**

APPENDIX 12

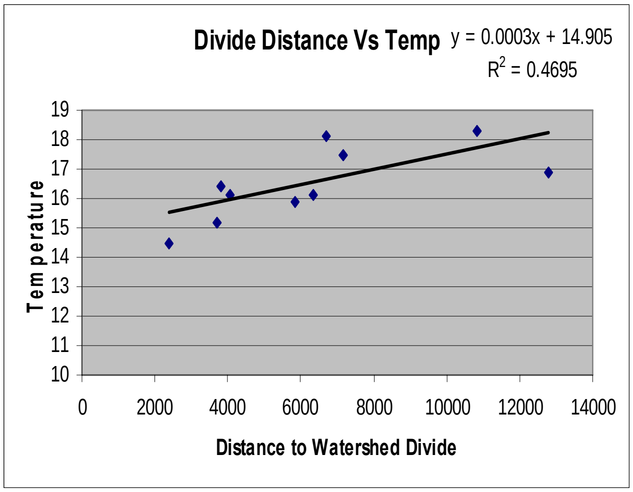
STREAM TEMPERATURE

Background

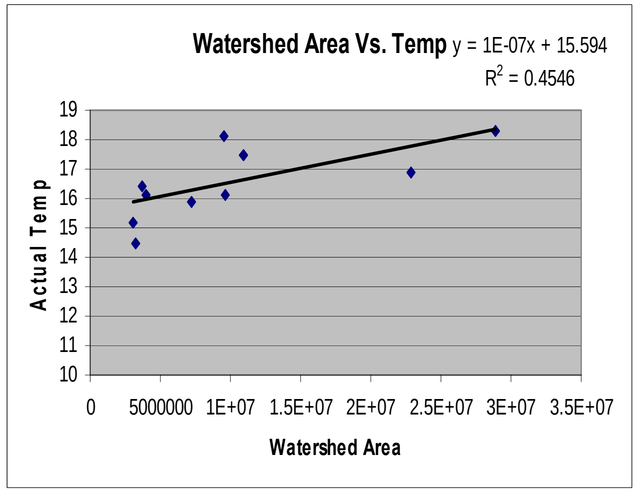
Water temperature is an important habitat parameter potentially influencing reproductive success and survival during all freshwater life stages for coho salmon, steelhead, and many amphibians, aquatic macro-invertebrates, and other organisms (Bjornn and Reiser 1991). Water temperature influences metabolism, behavior, and mortality of fish and other organisms in their environment. Coho salmon tend to be relatively intolerant of elevated summer water temperatures and may therefore be absent from streams that can still support steelhead. Although fish may survive at temperatures near the extremes of the suitable range, growth is reduced at low temperatures because all metabolic processes are slowed and at high temperatures because most or all food energy must be used for maintenance (Bjornn and Reiser 1991).

Stream temperature is influenced by external factors, the internal structure associated with channel morphology, and the riparian zone. The internal factors are reduced vegetative shading (allowing more solar radiation to reach streams), changes in channel morphology, altered streamflows, and heating of unvegetated near-stream soils and alluvial substrates (Poole and Berman in press, Johnson and Jones 2000). The external factors include: topographic shade, upland vegetation, precipitation, air temperature, wind speed, solar angle, cloud cover, relative humidity, phreatic groundwater temperature, tributary temperatures and flow (Poole and Berman 2000). In addition, water temperatures generally increase in a downstream direction even in fully shaded streams (Sullivan et al. 1990). As streams become progressively larger and wider, riparian vegetation shades a progressively smaller proportion of the water surface (Beschta et al. 1987; Spence et al. 1996; Murphy and Meehan 1991). Figure 1 illustrates how stream temperatures in a watershed tend to increase in the downstream direction and increase with increasing watershed area.

Land management activities can influence water temperature by exerting changes on channel characteristics (Table 1). In forested landscapes, incoming solar radiation represents the dominant form of energy input to small and medium size streams during the summer months (Bescheta 1987, Sullivan et al. 1990). Canopy cover is important in reducing direct solar radiation to the channel and can be directly influenced by forest management. Removal of a streamside riparian canopy typically increases solar radiation intensity, summer water temperature, and diurnal temperature fluctuations throughout the year (Chamberlin et al. 1991, Hetrick et al. 1998). Removal of too much canopy can adversely affect growth and survival of rearing salmonids. The more canopy removed, the greater the exposure to solar radiation, which then increases stream temperature.



A



B

Figure 1. Relationship between Divide Distance (meters) and Stream Temperature (ºC) (A) and Watershed Area (meters^2) and Stream Temperature (ºC) (B).

Table 1. Associated Human Influences on Processes that Affect Water Temperature.

PROCESS AFFECTING WATER TEMPERATURE	HUMAN INFLUENCE
Increased phreatic groundwater discharge	Removal of upland vegetation
	Water withdrawals for irrigation / municipal use
Reduced stream flow	Water withdrawals
Hydrology and Channel Morphology	Dams; reduction in peak flows
	Dikes and Levies
	Riparian management; removal of LWD
Changes in channel morphology – wider streams, channel aggradation	Management activities; increased sedimentation
	Dams; removal of peak flows
Riparian canopy cover	Riparian management; influences on shade

(Modified from Poole and Berman 2000.)

Conversely, riparian vegetation also limits light penetration to a stream and may suppress aquatic primary productivity (Murphy and Meehan 1991). Planned openings along cold, closed canopy coastal streams can improve periphyton production, leading to increased aquatic invertebrate abundance and subsequently enhance fish productivity if other habitat requirements are maintained (Murphy and Meehan 1991; Chamberlin et al. 1991; Hetrick et al. 1998). However, cumulative effects of increased water temperature and sediment from numerous disturbances in a watershed can nullify any beneficial effects of increased food production (Murphy and Meehan 1991). Therefore, timber harvesting activities in riparian zones need to be carefully planned if improved salmonid production is desired.

There is uncertainty regarding the optimal riparian buffer to shade a stream, or whether there is any single configuration that is most beneficial or desirable. The relative degree of shading provided by a buffer strip depends on species composition, age of stand, density of vegetation, and sun angle. Spence et al. (1996) concluded buffer widths of approximately 0.75 site potential tree heights are needed to provide full protection of stream shading. FEMAT (1993) reported that nearly all shade to a stream can be maintained by a buffer width equal to approximately 0.8 potential tree height. According to the Record of Decision for FEMAT (FEMAT ROD 1994), a site potential tree equals the average maximum height of the tallest dominant trees (200 years or older) for a given site class. For a coast redwood on Site I or II land, it is likely that a “mature” tree would be at least 250 feet tall.

In a comprehensive review of the FEMAT (1993) standards, CH2M-Hill and Western Watershed Analysts (1999) reported that nearly 80 percent of the cumulative riparian shade effectiveness is reached within approximately 0.5 site-potential tree heights (e.g., for a 250 foot site potential tree, this distance would be 125 feet, 25 feet less than the current width of a Class I WLPZ). Beschta et al. (1987) and Murphy (1995) state that buffer strips with widths of 30 m (approximately 100 feet) or more generally provide the same level of shading as that of an old-growth stand.

The stream temperature at any given point can be taken as an indicator of the cumulative spatial and temporal effects of numerous factors upstream of that point. As discussed above, there are numerous natural and anthropogenic factors that determine stream temperature. Since stream temperature is such a robust cumulative effect indicator, it is an important parameter to measure on an ongoing basis. It is also important to try to understand the state, over space and time, of the determinants of temperature. Stream canopy is one of the most important and most readily measurable of stream temperature determinants. It also is a stream temperature determinant that has been significantly affected by land management activities in the North Coast region since the last half of the 19th century.

Regulatory Setting and Regional Context for Use of the MWAT Criterion for Assessing Impacts

The North Coast Regional Water Quality Control Board (NCRWQCB) is responsible for implementing and regulating water quality control plans for the North Coast Hydrologic Unit Basin Planning Area. The Basin Plan provides a definitive program of actions designed to preserve and enhance water quality and to protect beneficial uses of water. The US EPA and NCRWQCB have identified 22 North Coast water bodies as having beneficial uses impaired by elevated water temperatures (Table 2). These water bodies, with a total watershed area of 8.7 million acres, are listed as temperature impaired under section 303(d) of the federal Clean Water Act.

Table 2. Temperature Impaired Water Bodies and Watershed Area in the North Coast Hydrologic Unit.

Water Body	Watershed Area (acres)	Water Body	Watershed Area (acres)
Big River	115,840	Shasta River	505,542
Eel River (6 units)	2,356,802	Russian River	949,986
Garcia River	73,223	Klamath River (including)	
Gualala River	191,145	*Salmon River*	480,805
Redwood Creek	180,700	*Scott River*	521,086
Ten Mile River	76,800	*South Fork Trinity River*	596,480
Mattole River	189,440	*Upper & Lower Lost River*	1,917,782
Navarro River	201,600		
Mad River	322,200	**TOTAL AREA**	**8,679,431**

The NCRWQCB has listed Big River for temperature and sediment. The Noyo is listed for sediment, but not temperature, although reaches of the Noyo are subject to relatively high water temperature, especially in the main channel. This impairment designation is assigned to streams where established water quality objectives as specified in the Basin Plan are not being met or where beneficial uses are not sufficiently protected. Total Maximum Daily Loads (TMDLs) must be developed for water quality listed streams, as required in Section 303d of the Clean Water Act (CWA). A TMDL is a planning document designed to identify the causes of impairment and establish a framework for restoring watershed impairments. Sediment TMDLs have been developed for both the Noyo and Big River, but a temperature TMDL has not yet been developed for the Big River watershed, nor has a completion date for one been specified.

MWAT Threshold and Criteria for Determining Impairment

Water temperature suitability for anadromous salmonids in the North Coast region can be evaluated using the maximum weekly average temperature (MWAT). MWAT is defined as the highest average of mean daily temperatures over any 7-day period. The MWAT threshold is a measure of the upper temperature recommended for a specific life stage of freshwater fish (Armour 1991). For coho salmon and steelhead, the MWAT threshold is calculated for the late-summer rearing life stage, because water temperatures are generally highest during this stage. Coho salmon are considered to be less tolerant of high water temperatures than steelhead (CDF 1999).

A range of MWAT values has been proposed by different agencies and through independent studies to identify appropriate threshold values (Table 3). For the JDSF EIR, an MWAT value of 16.8°C (62.2°F) was chosen as a threshold of significance to evaluate potential impacts to water temperature that are associated with the proposed project. The National Marine Fisheries Services originally established 16.8°C as an MWAT threshold for coho (NMFS and USFWS 1997). This threshold is supported with recent findings by Welsh et al. (2001), where researchers found juvenile coho present in 18 of 21 tributaries of the Mattole River with MWATs up to 16.7°C (62.1°F). They also found coho in all streams where MWATs were less than 14.5°C (58.1°F). Similarly, Hines and Ambrose (2000) collected water temperature and coho salmon data over a five-year period from 1993 to 1997 at 32 sites in coastal streams of western Mendocino County, including 4 sites in the Noyo and Big River watersheds. Their data showed that the number of days a site exceeded an MWAT of 17.6°C (63.7°F) was one of the most influential variables for predicting coho presence and absence.

Table 3. A range of known MWAT thresholds and standards for salmonids (source: NCRWQCB 2004).

MWAT Thresholds and Standards		
Temperature (C)	**Descriptions**	**Temperature (F)**
26	Upper end of range of acute thresholds (considered lethal to salmonids)	78.8
25		77.0
24	Lower end of range of acute thresholds (considered lethal to salmonids)	75.2
23		73.4
22		71.6
21		69.8
20		68.0
19	Steelhead growth reduced 20% from maximum (Sullivan and others, 2000).MWAT metric USEPA (1977) growth MWAT for rainbow trout	66.2
18	USEPA (1977) growth MWAT for coho	64.4
17	Steelhead growth reduced 10% from maximum. Coho growth reduced 20% from maximum (Sullivan and others, 2000), MWAT metric	62.6
16.8	**NMFS MWAT threshold.**	**62.2**
16.7	Welsh and others (2001) MWAT threshold for coho presence/absence in the Mattole	62.1
16	Oregon Dept. of Environmental Quality Standard for salmonids (equivalent MWAT calculated from 7-day max.)	60.8
15	EPA Region 10 Recommended MWAT. Threshold for Coldwater Salmonid Rearing	59.0
14.8	Coho growth reduced 10% from maximum (Sullivan and others, 2000), MWAT metric	**58.6**
14.6	Upper end of preferred rearing range of coho	58.3
14.3	Washington Dept. of Ecology standard (equivalent MWAT calculated from annual max.)	57.7
14		57.2
13	Upper end of preferred rearing range for steelhead.	55.4

The Recovery Strategy for Coho Salmon (Department of Fish and Game 2004) makes only a generic range-wide recommendation regarding stream temperature. That is, “Identify and implement actions to maintain and restore water temperatures to meet habitat requirements for coho salmon in specific streams,” (recommendation RW-X-B-01).

Logging History and Water Temperature

The stream channels and watersheds within and surrounding JDSF have a long and varied history of logging, railroad, and road construction. Beginning in the 1850s, Big River was used as a log transport route to get logs to the sawmill located near the mouth of the river. The Noyo River has a similar history, although railroad transport was dominant in that drainage (Wurm 1986). In the Noyo River, there is evidence that river transport occurred between the 1860s and the very early 1900s (Marc Jameson, CDF, Fort Bragg, personal communication).

Before the development of railroads in and along coastal waterways, trees were felled and moved to the river channels by use of both hand and animal labor (Napolitano and others 1989). In the Big River drainage, animals, primarily oxen, were used for yarding of logs until 1914 (Jackson 1991). The logs were dragged downhill and dumped into the river. In order to facilitate water transport, the channels were often cleared of logs, stumps, debris, and standing trees that were capable of interfering with transport and resulting in logjams. River transport in Big River continued over a period of nearly 70 years, between 1850 and 1930, using 27 splash dams to facilitate the floating of logs downstream to the mill at the town of Mendocino (Jackson 1991) (Figure 2). South Fork Big River is heavily incised from flushing logs. The dams varied in size and construction methods, but ranged to as tall as 40 feet. Many of the dams were designed to operate in a synchronized fashion to maximize the flow of water in downstream reaches.

The actual process of logging removed most, if not all, of the old-growth trees growing along the streams, which probably resulted in large increases in direct solar radiation striking the channel and coincident substantial increases in water temperature. This effect was accentuated with the development of railroad technology. Railroad grades were constructed immediately adjacent to river channels, and often constructed directly within the channels (Wurm 1986). Along with the railroads, steam yarder technology enabled efficient clearcutting of vast tracts upslope and adjacent to the river and stream system, with logs generally pulled downslope within or adjacent to watercourses along their route to the rail line. This activity created large openings along waterways, in addition to massive erosion into the channels, creating wide, unshaded streambeds with aggradation and elevated water temperature.

Railroad logging was replaced by trucks and tractors, beginning in the 1920s, with the railroads being all but eliminated by the mid-1940s (CDF 2003, Wurm 1986). Early road construction and tractor yarding provided no stream protection. Roads were constructed immediately adjacent to, or within stream channels. Logs were yarded downslope by tractor, often being moved directly within stream channels to reduce the amount of excavation required during the yarding process. Log landings were commonly constructed within tributary channels during this period. All of these activities tended to reduce shade-producing canopy, resulting in elevated water temperature. There are numerous accounts by the Department of Fish and Game of stream damage and elevated water temperature within the Noyo and Big River watersheds (DFG stream survey files, Yountville).

Figure 2. Hells Gate Splash Dam on the South Fork. Photo provided courtesy of the Mendocino Historical Society and the Held Poage Memorial Home and Research Library (from the Collection of Robert Lee).

There were no effective regulations in place to protect stream channels and shade-producing canopy until 1974, with the implementation of the Z'Berg Nejedly Forest Practice Act of 1973. The Forest Practice regulations of the mid-1970s provided for some consideration of stream protection, but it was still possible to substantially reduce shade canopy along fish streams. Streams were defined as natural watercourses--as designated by a solid line or dash and three dots symbol shown on the largest scale USGS maps most recently published, or as corrected in the THP map to reflect conditions on the ground. The Stream Protection Zone (SPZ) was defined as a strip of land along both sides of the watercourse for 100 feet for streams which supported and were used by trout or anadromous fish any time of the year, and 50 feet for any other streams or lakes. Enough trees had to be left so that 50% or more of the shade producing canopy present before timber operations remained after timber operations. Most, if not all of the shade-producing conifers could be removed if the forester could adequately explain how 50% of the shade would be retained.

It was not until 1983 that forest practice rules were enacted that required consideration of key indicator beneficial uses of water (fish, domestic water supplies for Class I watercourses, etc.), and it was not until the mid-1980s that cumulative impacts were expressly considered in the THP process. Protective zones were based on watercourse class and side slopes (0-30%, 30-50%, 50-70%, and >70%). The stream protection rules enacted substantially increased both the consideration of, and protection of, streamside canopy. In 1991, the rules were strengthened again. With the listing of both the Noyo River and Big River as impaired waterbodies, along with the listing of the coho salmon, rules have been substantially strengthened, and streamside canopy considerations have been further elevated. In July 2000, the implementation of the Threatened and Impaired Watersheds Rule Package greatly increased stream protection and post-harvest canopy levels. Proposals to reduce shade-producing canopy adjacent to Class I watercourses within the watercourse protection zone are not often encountered within the assessment area, and the level of shade-producing canopy should be increasing as riparian stands grow.

CDF's Hillslope Monitoring Program report for 1996 through 2001 found that watercourse protection zones retained high levels of post harvest canopy and surface cover (Cafferata and Munn 2002). Mean total canopy exceeded Forest Practice Rule requirements and was approximately 80 percent in the Coast Forest Practice District for both Class I and II watercourses. WLPZ width requirements were generally met, with major Forest Practice Rule departures recorded only about one percent of the time. Modified Completion Report monitoring conducted by CDF Forest Practice Inspectors from 2001 through 2004 similarly revealed that post-harvest total canopy levels were high (281 THPs sampled, 198 with Class I or II WLPZs) (Brandow 2005). Class I and II WLPZ total canopies averaged 83% and 82%, respectively, for the Coast Forest Practice District. These numbers are very similar to those recorded for the earlier Hillslope Monitoring Program. Similar measurement techniques were used by both monitoring efforts. As the streamside forest continues to develop within the assessment area, water temperature should take steady progress toward levels favorable to fish.

Watershed Setting and Regional Context for Stream Temperature

The JDSF ownership covers portions of both the Noyo and Big Rivers (see Map Figure A). The South Fork of the Noyo River (SFNR) and North Fork of the Big River, including Chamberlain and James Creeks, are the primary watersheds that drain the forest. The SFNR is a major tributary to the Noyo River, which drains to the Pacific Ocean at Fort Bragg. The SFNR catchment area at the confluence with the Noyo River drains a 27.32 mi^2 area, which is approximately 35% of the entire Noyo River watershed (113 mi^2). The vast majority of SFNR is owned and managed by JDSF. As such, management activities contribute to the overall water quality conditions in the lower Noyo, below its confluence with SFNR. The SFNR basin is characterized by steep mountainous terrain with confined valleys. The headwaters of the SFNR have more moderate terrain.

The Big River drains a 181 mi^2 watershed, flowing into the Pacific Ocean at the town of Mendocino. The elevation ranges from sea level to 1556 ft and consists of moderate to extremely rugged terrain (Matthews, 2001). Chamberlain and James Creeks are major tributaries to the North Fork of the Big River. The majority of these tributary watersheds are public lands managed by JDSF. The headwaters of the North Fork of Big River are private forest land and reside upstream from the JDSF boundary. Water from the Upper North Fork Big River flows through JDSF, passes through private forest in the Lower North Fork of the Big River, before joining the mainstem of the Big River.

CDF has conducted comprehensive summer water temperature monitoring in streams throughout JDSF since 1993, as well as temperature monitoring in the Caspar Creek watershed since the mid-1960s. Overall, water temperatures in JDSF Class I watercourses are generally in the suitable range for coho salmon and steelhead, with a few exceptions (CDF 1999). The areas of concern that are potentially impacted by JDSF land management are located on the South Fork of the Noyo River and Chamberlain Creek, tributary to the North Fork of Big River.

Stream temperature data are collected widely across the Noyo and Big River watersheds (Figure 3). Stream temperature issues were analyzed using data collected by state agencies (CDF, NCRWCQB, and DFG, and landowners) and supplemented with data from the KRIS Noyo and Big River projects (see http://www.krisweb.com). A summary of the data used in this assessment is provided in Attachment A. While water temperature is of concern for both watersheds, Big River has recorded warmer temperatures, leading to its inclusion on the U.S. EPA's 303(d) list as temperature impaired. The spatial distribution of water temperature was mapped out across the entire assessment area to identify areas of concern that may require more detailed analysis (Figure 3). The thresholds for interpreting water temperature were based on the criteria established by NMFS (1997) and additional criteria that were agreed upon by state agencies under the North Coast Watershed Assessment Program (NCWAP).

Based on these thresholds, Figure 3 identifies several areas that are potentially of concern, including:

- North Fork of the Noyo,
- South Fork of the Noyo (including Parlin Creek),
- North Fork of the Big River (including Chamberlain and James Creek), and
- South Fork of the Big River.

In addition, an emphasis was placed on those watersheds that either deliver water to JDSF (i.e., are up-stream) or are considered receiving waters (i.e., are downstream) from JDSF. Neither the Upper Noyo nor the South Fork of the Big River drain directly to JDSF, and as such, are discussed in less detail. The Mendocino Redwood Company (MRC) watershed analysis reports for the Noyo and Big River watersheds provide a thorough discussion of water temperature for these areas, although limited to that specific ownership. A summary of information from these reports is presented to provide a more comprehensive assessment of water temperature throughout the Noyo and Big River basins.

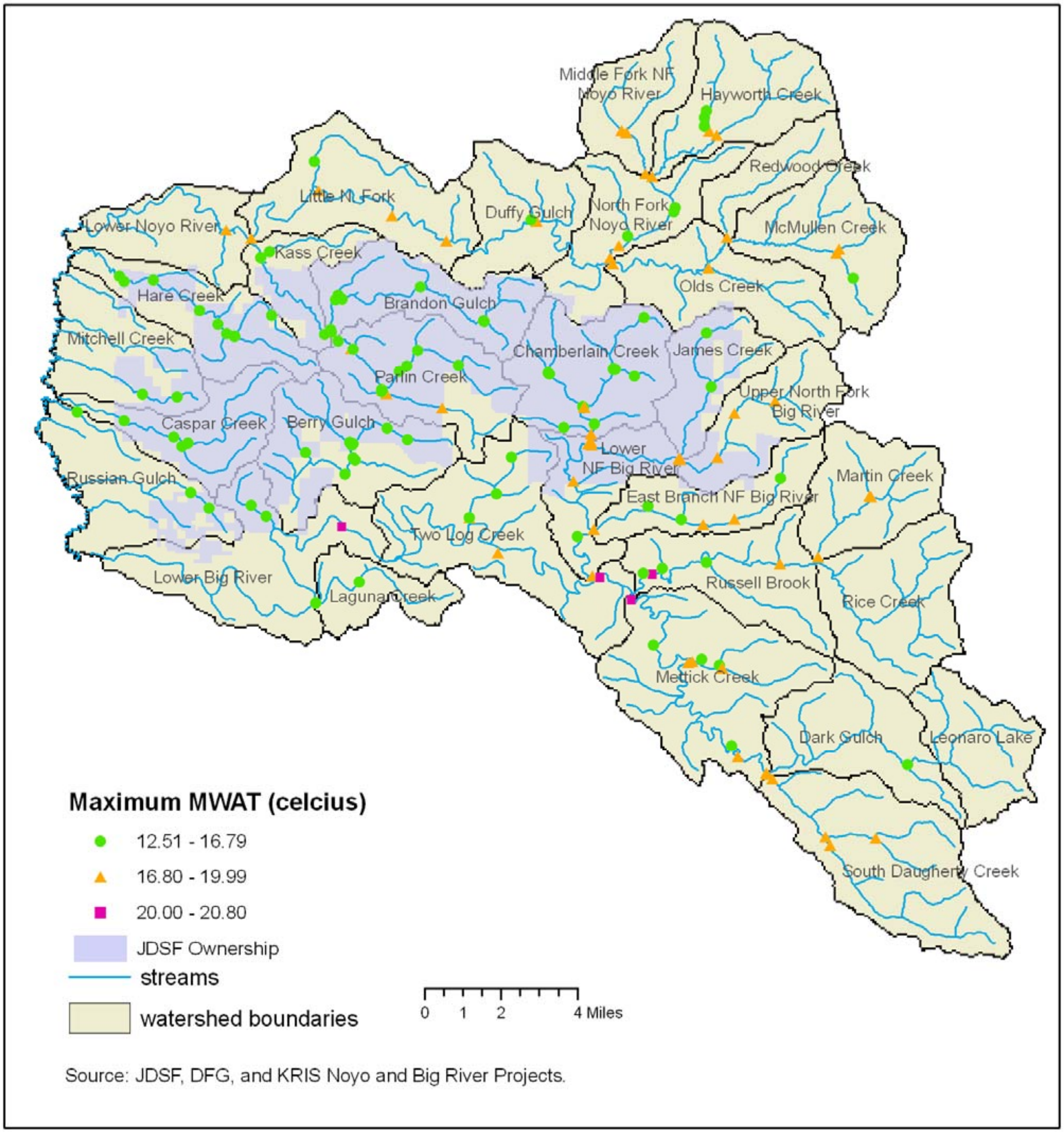


Figure 3. Distribution of Stream Temperatures across the Noyo and Big Rivers Based on the Maximum MWAT Values from 1994-2004.

Noyo River Water Temperature

Water temperatures across the Noyo River are generally desirable and below MWAT thresholds. However, water temperatures increase dramatically in the interior watersheds with the diminishing coastal influence. The warmest stream temperatures are recorded in the headwaters of the North Fork of the Noyo, where summer air temperatures can regularly exceed 100 °F.

A. Upper and Middle Noyo (outside JDSF)

The Upper Noyo consists of the headwaters of the Noyo (27 mi^2) and the North Fork of the Noyo River (25 mi^2). The upper end of the basin is directly west of the city of Willits. The upper mainstem of the Noyo drains a number of tributaries including: Olds Creek, Redwood Creek, McMullen Creek, NF Noyo River, Middle Fork of the NF Noyo River, and Hayworth Creek.

Stream temperature and canopy cover data were collected as part of the Noyo River Watershed Analysis across the MRC ownership in the Upper Noyo. Stream temperature was monitored in the Upper Noyo by Louisiana-Pacific Corp. from 1991 to1997 and MRC in 1999. MRC (2000) reported MWAT values for just 1996 and 1999. Stream temperatures were monitored during the summer months when the water temperatures are highest. Many of the monitoring stations recorded MWAT values that exceed the 16.8°C threshold (Welsh et al. 2001; NMFS and USFWS 1997). In addition, many stations recorded maximum stream temperatures that exceed 20°C. The highest stream temperatures were recorded on Hayworth Creek and along the mainstem of the Upper Noyo. It is presumed that these temperature spikes are associated with extremely warm weather conditions and are not sustained for long periods of time.

Stream temperature in the middle and lower portions of the mainstem Noyo are potentially of concern, although, there is little historic water temperature data available for comparison. Monitoring locations have consistently reported MWAT values that exceed the target threshold of 16.8 °C. Much cooler stream temperatures are reported for tributaries to the Noyo, with MWAT values ranging from 13.2 to 16.3°C (Table 3). Water temperatures for these tributaries have remained below the target threshold despite a history of intensive land management across each of these watersheds.

Table 3. Water Temperature (MWAT) for Tributaries to the Noyo River.

Stream Name	**Percent Harvested** 1986-2004	**Annual Instream Water Temperature (MWAT) (°C) (Target Temperature is ≤ 16.8° C**									
		1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Little North Fork Noyo	80%	13.7	15.1	14.1	15.6	14.1	14.3	13.8	13.9	14.1	14.6
Duffy Gulch	83%				15.4	15.1	14.9	14.8	14.6		14.8
Kass Creek	63%	13.2	14.5	16.3	13.8	13.8	13.6	13.4	13.6	13.6	14.1

B. Water Temperature Data for the South Fork Noyo River (inside JDSF)

The South Fork of the Noyo River (SFNR) is a major tributary to the Noyo River. The SFNR catchment area at the confluence with the Noyo River drains a 27.32 mi^2 area, which is approximately 35% of the entire Noyo River watershed (113 mi^2). The vast majority of SFNR is owned and managed by JDSF. As such, JDSF management activities contribute to the overall water quality conditions in the lower Noyo, below its confluence with SFNR. The SFNR basin is characterized by steep mountainous terrain with confined valleys. The extreme headwaters of the SFNR have more moderate terrain.

The mainstem of the South Fork Noyo flows for approximately 7 miles through JDSF. Stream temperatures are characterized by fluctuations in maximum MWAT values as the river flows from the upstream boundary to the downstream boundary of JDSF (Figure 4). However, data recorded near the downstream boundary of JDSF has shown a noticeable decline for the last three years of record (site 1, Figure 4). For the most recent date (2000), the MWAT value for site number 1 was 16.2 °C. This is contrasted with much warmer readings on the mainstem of the Noyo above the confluence with the South Fork Noyo. Stream temperature data recorded on the middle Noyo (near Grove) have consistently recorded MWAT values at or near 18.6 °C from 1998 to 2003 (figure 1). Below the confluence with the SF Noyo, the water temperatures decline by about 1 °C (site 13, figure 4). Stream temperature data collected at the USGS gaging station along the mainstem of the lower Noyo has recorded an average MWAT value of 17.5 °C from 1998-2003. As such, the South Fork Noyo appears to have a moderate cooling effect on water temperatures in the lower Noyo depending upon the relative flow of the two streams.

Stream temperatures reported by Valentine (1996) provide a baseline for stream temperature along the South Fork Noyo River. The maximum single measurement (not MWAT) water temperatures identified at two monitoring locations were 19.4º C. All stations were below 18º C more than 85% of the time. Among the tributaries to the South Fork Noyo, Parlin Creek recorded the warmest temperatures. Data loggers along the South Fork Noyo, above and below the confluence (Figure 4, site 6 and 8), showed a modest increase in stream temperatures just below Parlin Creek. The degree to which stream temperatures along the South Fork Noyo are elevated by Parlin Creek were not considered significant by Valentine (1996), but were indicative of warming temperatures in lower reaches of Parlin Creek. Temperatures were shown to increase in the downstream direction along Parlin Creek. Valentine (1996) found that conditions did not represent a serious cause for concern with regard to coho salmon.

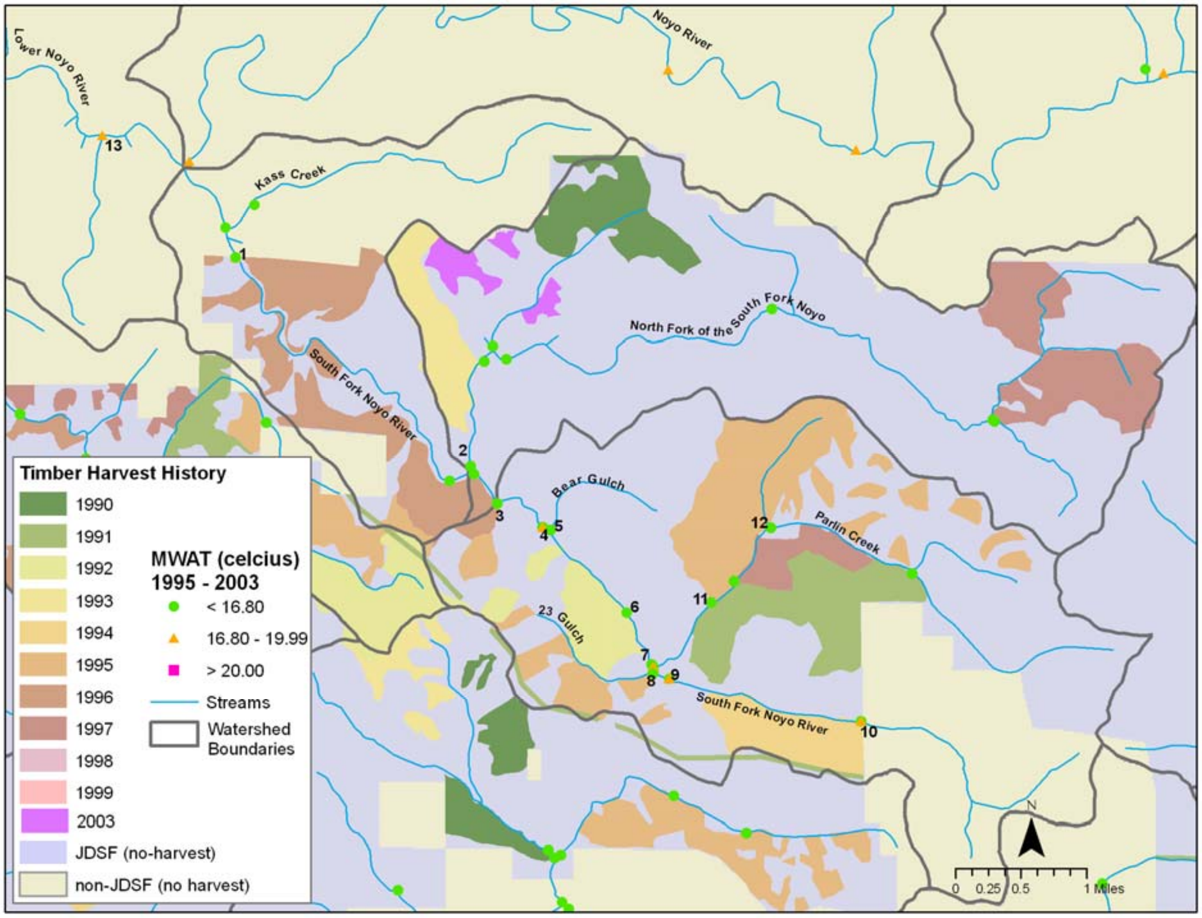
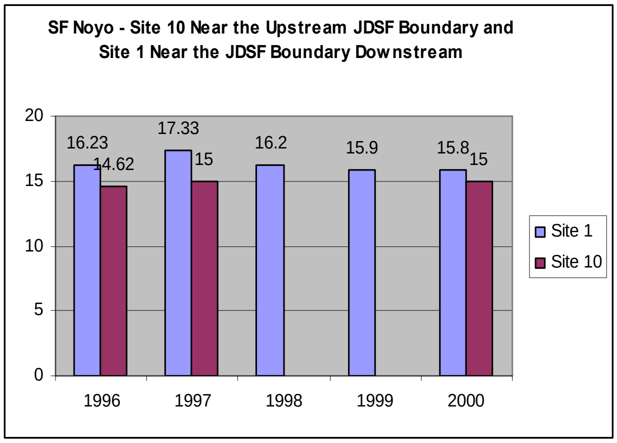


Figure 4. Distribution of Stream Temperatures along the South Fork Noyo River and Parlin Creek. Note: Timber Harvest boundaries ***do not*** reflect harvest restrictions in the WLPZ. There were no timber harvests for 2000–2002.

Stream temperature data following the 1996 study were analyzed to evaluate any changes from previously identified conditions. Treating 1996 as a baseline, data were analyzed post-1996 to determine if there are any trends in water temperature. Stream temperatures remain somewhat higher along the mainstem of the South Fork Noyo, about 0.5^{o} C, as water flows past Parlin Creek, but the trend is flat (Figure 5). This suggests that stream temperatures have been more or less stable since 1996. The area where Parlin Fork meets the South Fork contains a large opening associated with an historic homestead, logging camp, and current conservation camp. The riparian forest zone in this vicinity is relatively narrow. Recent timber harvests in both Parlin Creek and throughout the South Fork of the Noyo since 1996 do not appear to be influencing stream temperature.



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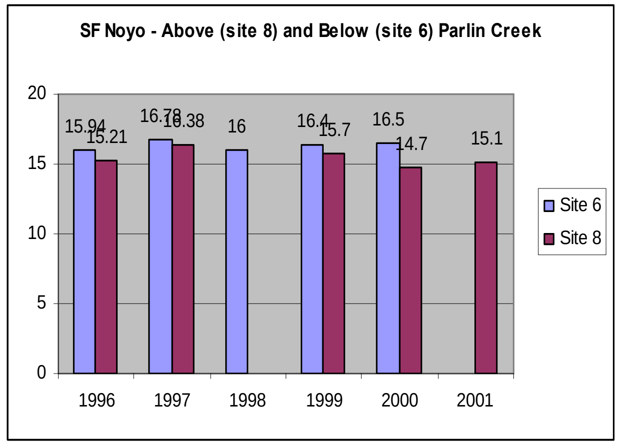

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Figure 5. Trends in MWAT Stream Temperatures (°C) along the South Fork Noyo River. Figure 5A provides a comparison in stream temperature from the upstream boundary of JDSF and the downstream boundary where water flows out of JDSF. Figure 5B provides a comparison of stream temperatures recorded directly above and below Parlin Creek. The water temperature is moderately warmer below Parlin Creek, but there is no dramatic increase or decrease over time.

Big River Water Temperature

The Big River watershed (181 mi^2) is larger than the Noyo, draining to the Pacific Ocean at the town of Mendocino. Most of basin is remote with few towns or incorporated areas. The topography varies from relatively flat marine terraces and estuaries to extremely rugged mountainous terrain. Land use within the watershed has been dominated by timber harvesting, with a substantial area dedicated to range management in the upper reaches. JDSF predominately influences water temperature along the North Fork of the Big River, and to a lesser extent, along the Little North Fork. Water temperature data along the mainstem of Big River consistently exceeds the 16.8°C MWAT threshold (Figure 3). The Big River is listed as temperature impaired per Section 303(d) of the federal Clean Water Act. Thus, management practices that have the potential to elevate stream temperatures are of concern. Water temperature data were assessed by the NCRWQCB staff under the NCWAP watershed assessment program and a summary of the data is provided in Attachment B. However, a more general discussion of water temperature issues is presented here for completeness of known water temperature issues.

A. South Fork of the Big River

The Mendocino Redwoods Company (MRC) has substantial ownership in the South Fork of the Big River. With ownership concentrated in Daugherty Creek, Mettick Creek and Russell Brook. MRC (2003) conducted a watershed analysis on their lands in the Big River basin, including an assessment of stream temperature and canopy cover. The temperature data for most sites were higher than the 16.8°C MWAT threshold for the North Fork of the Big River, with MWATs ranging from 17.4 to 19.7°C, and streamside canopy cover mostly moderate (40% – 70%). Conditions reported on the South Fork of Big River are similar. MWATs ranged from 18 to 18.4°C on the mainstem, with much cooler water recorded along tributaries (12.9 to 15.1°C).

B. North Fork of the Big River

Some of the warmest stream temperatures on JDSF have been recorded along the lower reaches of Chamberlain and James Creek (Figure 6). Chamberlain and James Creek are the eastern most watersheds that are predominately managed by JDSF. As interior watersheds, they can be influenced by very warm air temperatures throughout the summer months. Both watersheds have a history of intensive land management, but have had very little (none on JDSF lands) timber harvesting over the last 20 years. The maximum value for MWAT ranged from 13.8 to 18.9 °C, based on water temperature data collected from 1996 through 2003.

Stream temperatures are very similar at the mouth of James and Chamberlain Creeks. Chamberlain Creek is a larger watershed (7,868 acres) than James Creek (4,459 acres), but both have a similar north-south orientation. Both creeks exhibit a distinct increase in stream temperatures in the downstream direction. Based upon recorded MWAT values, stream temperatures increased by 2.5 °C in the downstream direction on Chamberlain and 3.5°C on James Creek (Figure 7B). Unlike the South Fork Noyo, there has been no timber harvesting in Chamberlain Creek since 1985, and only two recent harvest units in James Creek off of JDSF land. As such, canopy conditions are likely to have improved as a result of canopy development along both channels, where relatively young forest has re-grown to replace the old forest that existed prior to the 1940s and 1950s.

Stream temperature data have been collected at four locations along the North Fork of Big River (Figure 6). Stream temperature appears to be much higher upstream of the JDSF boundary, cooling as it passes through JDSF, and then increasing below the JDSF boundary (NCWAP, 2004, Attachment B). Stream temperature data loggers have recorded higher temperatures at the station above the confluence of James Creek than at downstream locations within JDSF. Stream temperatures do not appear to increase as water flows past the entrances of James and Chamberlain Creeks. Water temperatures recorded on the mainstem of the North Fork of the Big River are consistently higher than water temperatures recorded along the lower reaches of James and Chamberlain Creeks (Figure 7B). The computed MWAT recorded on the North Fork of the Big River upstream of Chamberlain is a full degree (Celsius) higher than the MWAT recorded from the station on Chamberlain Creek just above its confluence with Big River. As such, the conditions within JDSF appear to have a moderating temperature effect upon water flowing into the state forest. As canopy continues to develop adjacent to these stream reaches in the future, the cooling trend is likely to continue and to improve.

The lower portions of the East Branch of the North Fork of the Big River were included in a recent watershed assessment conducted by Mendocino Redwoods Company (MRC, 2003). Streamside canopy cover was mostly high (> 90%) and MWAT values range from 16.3 to 18.4°C along the mainstem. Temperature data on tributaries (Class II watercourses) were limited to one year of data, but all sites recorded MWAT values below 15°C.

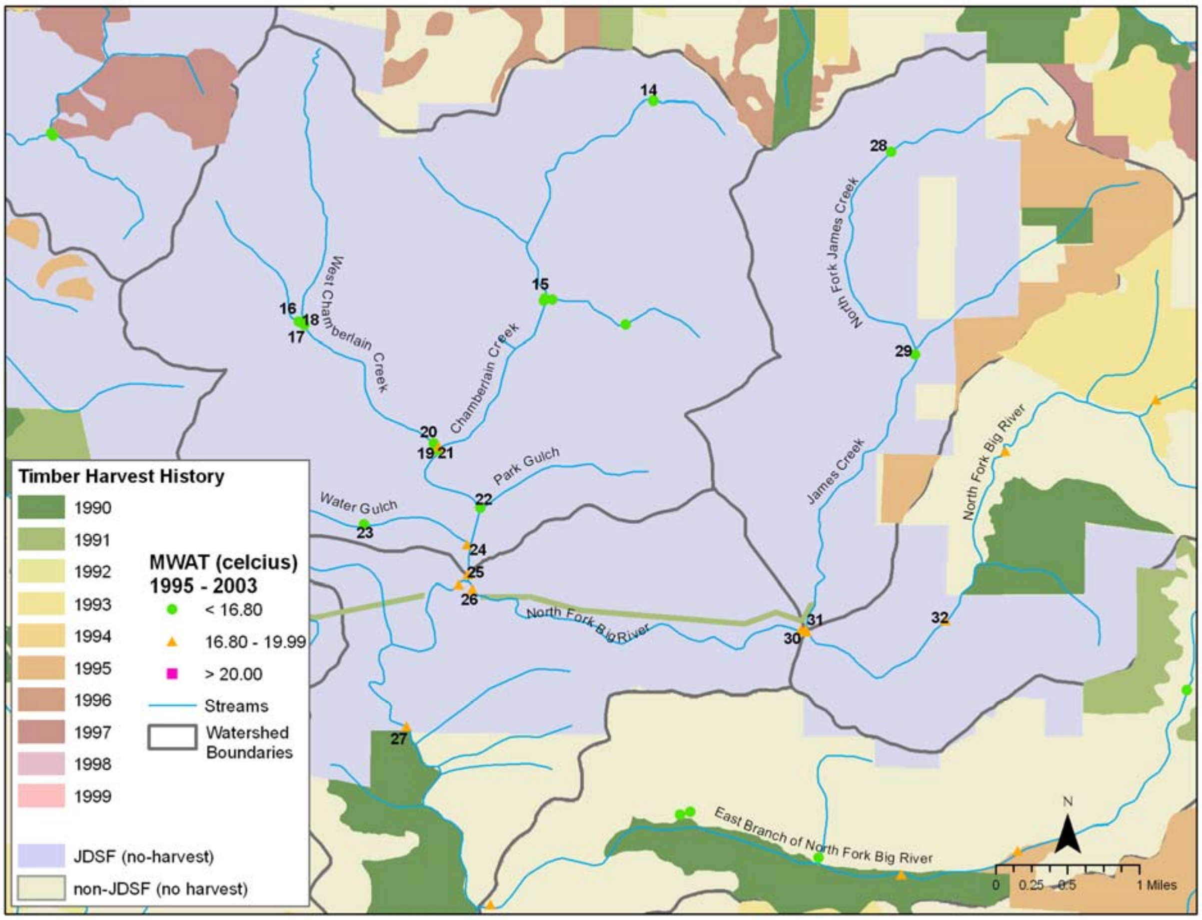
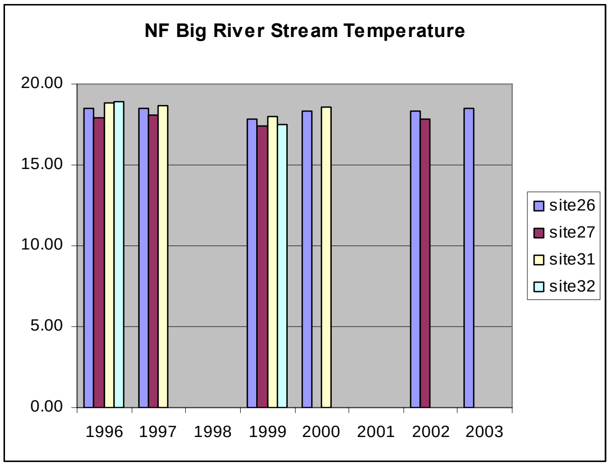


Figure 6. Distribution of Stream Temperatures along the North Fork Big River, Chamberlain and James Creeks. Note: Timber Harvest boundaries ***do not*** reflect harvest restrictions in the WLPZ.



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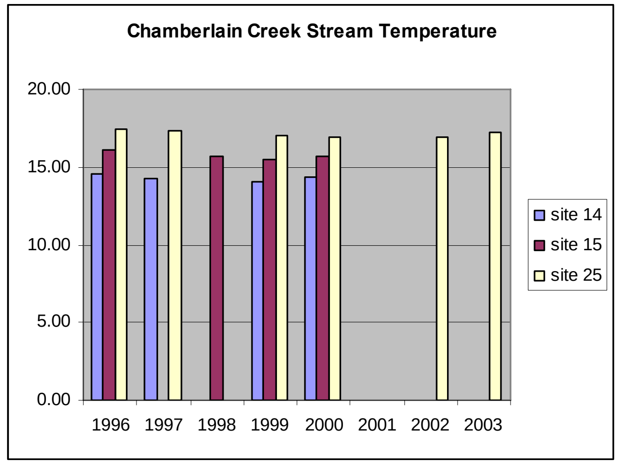

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Figure 7. Stream Temperature (MWAT °C) for North Fork Big River and Chamberlain Creek. Figure 7A. MWAT stream temperatures along the North Fork of the Big River are consistently above the target threshold of 16.8 °C. However, there is not a noticeable increase of stream temperature from the upstream boundary of JDSF (site 32) to the downstream boundary of JDSF (site 27). Figure 7B. From the headwaters to the confluence, MWAT stream temperatures increase in the downstream direction along Chamberlain Creek by as much as 3 °C. This trend is fairly consistent over time, with some indication of a decrease in stream temperature at the furthest downstream station (site 25) recorded in the last 4 years of data collection.

Coastal Watersheds

Management practices on JDSF lands also influence a number of small coastal watersheds that drain directly to the Pacific Ocean. These watersheds include Russian Gulch, Caspar Creek, Jughandle Creek, Mitchell Creek, and Hare Creek. In general, the stream temperatures appear to be in a range that is supportive for salmonids. None of the temperature data for these watersheds has exceeded the 16.8 °C MWAT threshold.

Nearly all of the early temperatures monitoring efforts were in the Caspar Creek watershed. Cafferata (1990) reported pre-management water temperatures in the North Fork and South Fork Caspar Creeks. Most observed summer maximum stream temperatures in 1965 were slightly below 16°C (60°F) with absolute maximums reaching 17°C (62.6°F) at the weirs. In 1988, small uncut tributary basins had maximum temperatures of about 13°C (56°F) with average daily highs about 12°C (54°F). Cafferata (1990) reported approximately a 13% reduction in shading resulting from timber harvesting along a Class II watercourse channel in the North Fork Caspar Creek (note that shading and canopy, while related, are two different measurements; see Berbach et al. 1999). Following clearcut logging of approximately 50% of the North Fork of the Caspar Creek watershed with buffer strips prescribed by the modern Forest

Practice Rules, Nakamoto (1998) concluded that the increase in water temperature was small and the range of temperatures observed within the North Fork was within the tolerable range for coho salmon and steelhead.

Stream Canopy Cover

Streamside canopy densities are relatively high throughout JDSF. Stillwater Sciences estimated canopy cover for streams in or adjacent to JDSF in 1996 (Table 4). This survey emphasized fish bearing streams (Class I). In addition, stream surveys have been conducted by CDFG. Of the 35 stream surveys conducted by CDFG between 1995 and 1997, 25 streams had canopy densities exceeding 90%, 6 streams exceeded 80% and 4 streams were between 60 and 79% (see Map Figure F in Map Figures section).

Table 4. Summary of Streamside Canopy Cover Data for Streams in or adjacent to JDSF. Based on 1996 vegetation conditions, the data are summarized by Planning Watersheds.

	SHADE CATAGORIES (UNITS = MILES)						
PWSNAME	**< 40%**		**40 - 70%**		**70 - 100%**		**Total**
	miles	**percent**	**miles**	**percent**	**miles**	**percent**	**miles**
Berry Gulch	0.87	3.0		0.0	27.73	97.0	28.60
Brandon Gulch		0.0		0.0	24.74	100.0	24.74
Caspar Creek	0.33	1.8		0.0	17.86	98.2	18.20
Chamberlain Creek	0.34	1.1	1.17	3.7	30.22	95.2	31.73
East Branch North Fork Big River	2.17	12.4	0.33	1.9	15.02	85.7	17.52
Hare Creek		0.0		0.0	23.75	100.0	23.75
James Creek		0.0	1.22	7.7	14.55	92.3	15.77
Kass Creek		0.0	0.45	3.2	13.36	96.8	13.81
Laguna Creek		0.0		0.0	0.00	100.0	0.00
Lower North Fork Big River	3.43	17.3	1.25	6.3	15.10	76.3	19.78
Mitchell Creek		0.0		0.0	15.62	100.0	15.62
Mouth of Big River	5.44	15.1	6.04	16.8	24.53	68.1	36.01
Mouth of Noyo River		0.0		0.0	0.01	100.0	0.01
Parlin Creek	1.60	5.3	0.60	2.0	28.06	92.7	30.26
Russian Gulch		0.0		0.0	14.19	100.0	14.19
Two Log Creek	12.67	29.0		0.0	31.01	71.0	43.67
Upper North Fork Big River		0.0		0.0	17.93	100.0	17.93
Grand Total	26.84		11.06		313.70		351.60

Outside JDSF, canopy cover data has been collected as part of the Department of Fish and Game (DFG) stream surveys that were conducted between 1995 and 2003. The information relating streamside canopy cover and forest composition is presented in Attachment C. In summary, the data show that most of the streams that were surveyed meet or exceed the 85% canopy cover target. Stream reaches that do not can be found along the mainstem of the Big River, the mainstem of the Noyo, North Fork of the Big

River, South Fork of the Big River, and some of the major tributaries (i.e., Daughtery Cr., Mettick Cr., and James Cr).

Additional information on canopy cover is contained in watershed assessments that have been conducted by private landowners. Streamside canopy cover data were collected by MRC for their lands in the Noyo River watershed in 1998. Canopy cover were grouped into three classes: high (>70%), moderate (40–70%) and low (0–40%). The canopy closure assessment showed a majority of Class I streams with a high streamside shade classification (58% of total Class I watercourses). However, a significant percentage of the Noyo watershed assessment unit Class I streams have a moderate streamside shade classification (28% of Class I watercourses) and low streamside shade classification (14% of Class I watercourses). Streamside canopy cover data also were collected by MRC for their lands on the Big River to support a watershed assessment conducted in 2000. Canopy cover ranged from 40%-100% across MRC lands in the Big River. In general, canopy cover appears lowest among the mainstem of the larger river channels and is summarized as (MRC 2003):

> Canopy closure over watercourses in the Big River WAU [watershed assessment unit] ranges from poor to good. Big River, North Fork Big River and South Fork Big River have less than ideal canopy cover values but this is to be expected from larger river channels. East Branch North Fork Big River and Two Log Creek are two areas that have good canopy cover. Daugherty Creek is an area which has low canopy cover.

Discussion

In addition to a number of other factors, stream temperatures are affected by varying amounts of canopy cover that are the result of differing intensities of harvest and the natural conditions encountered throughout a watershed. The potential impact of timber harvesting on water temperatures can result from a single action, or the cumulative impact of multiple harvests. The recovery from this impact (i.e., return to a temperature regime associated with pre-harvest conditions) should consider both the upstream and downstream canopy conditions and the time required for full canopy cover to be re-established. Studies have shown that stream temperatures will return to equilibrium conditions within 10 km downstream of the harvest area (Bartholow 2000). Studies in Oregon have shown that canopy cover and water temperatures had fully recovered within 15 years following intensive harvesting within three experimental watersheds, but this is dependent upon the localized canopy and channel conditions, and the type of harvesting conducted. The North Fork Caspar Creek study (Nakamoto 1998) discussed above showed that clearcutting 50 percent of the watershed using buffer strips prescribed by contemporary Forest Practice Rules led to a small increase in water temperature; temperatures remained within the range considered suitable for coho and steelhead.

The previous discussion on the effects of timber harvesting on stream temperatures provides an assessment of current conditions and direct impacts associated with canopy cover. While not as well understood, there are other physical changes besides canopy cover that can have a cumulative influence on stream temperatures. The development of a stream temperature model by Bartholow (2000) provides insight into a range of secondary impacts that may result from timber harvesting and the degree to which they influence stream temperatures. While stream shade was an important factor, explaining 40% of the increase in stream temperature, it was not the only factor. Stream width was an important secondary factor

The model identified effects directly related to stream temperatures that are associated with: meteorology, hydrology, and stream geometry (Figure 8). Changes in meteorology refer to the micro-climate dynamics within a riparian zone. On JDSF, recent studies by Hughes et al (2004) focused on changes in riparian micro-climate as a result of timber harvest. Results have shown distinctive temperature gradients that increase with distance from the stream channel. Hydrologic changes are addressed in a separate section of the EIR, but in summary, findings from Caspar Creek suggest a recovery time of approximately 11 years for changes in peak flow. Changes in stream geometry, channel width and depth, are not well documented across the assessment area. However, historic land management practices are very likely to have altered stream geometry across large portions of the assessment area. Recovery of a more natural stream geometry from these substantial historic impacts will take a long time.

Summary

Water temperatures vary both spatially and temporally across the JDSF EIR assessment area. In general, stream temperatures are highest in some of the larger tributaries towards the interior (i.e., eastern) portions, and along portions of the mainstem Noyo River, the Big River and the North and South Forks of the Big River. Achieving targets for canopy cover will require a period of time sufficient to increase both tree height and canopy density. In addition, stream temperatures in a watershed tend to increase in the downstream direction and increase with increasing watershed area (Figure 1). Water temperature data indicate that stream temperatures along the middle and upper mainstem of the Noyo River remain warm and are consistently warmer than water temperatures measured along the lower reaches of the South Fork Noyo downstream of JDSF. This is undoubtedly due to the fact that the channels are wider, have been subjected to substantial canopy reductions in the past, and trees growing along the margins of the stream are incapable of fully shading the full channel width.

To prevent any future impacts to water temperature from the proposed management plan JDSF will meet or exceed all watercourse protection measures as stated in the FPRs. In addition, JDSF is committed to maintaining a network of monitoring stations that can be used to document trends in water temperature and identify potential impacts on water temperature from forest management. Currently, most streams within JDSF consistently record water temperature that is below the MWAT threshold of 16.8 C. However, Parlin Creek, Chamberlain Creek and James Creek have all recorded MWAT values that exceed this threshold and are areas of potential concern. These areas should be priorities for continued monitoring and canopy development.

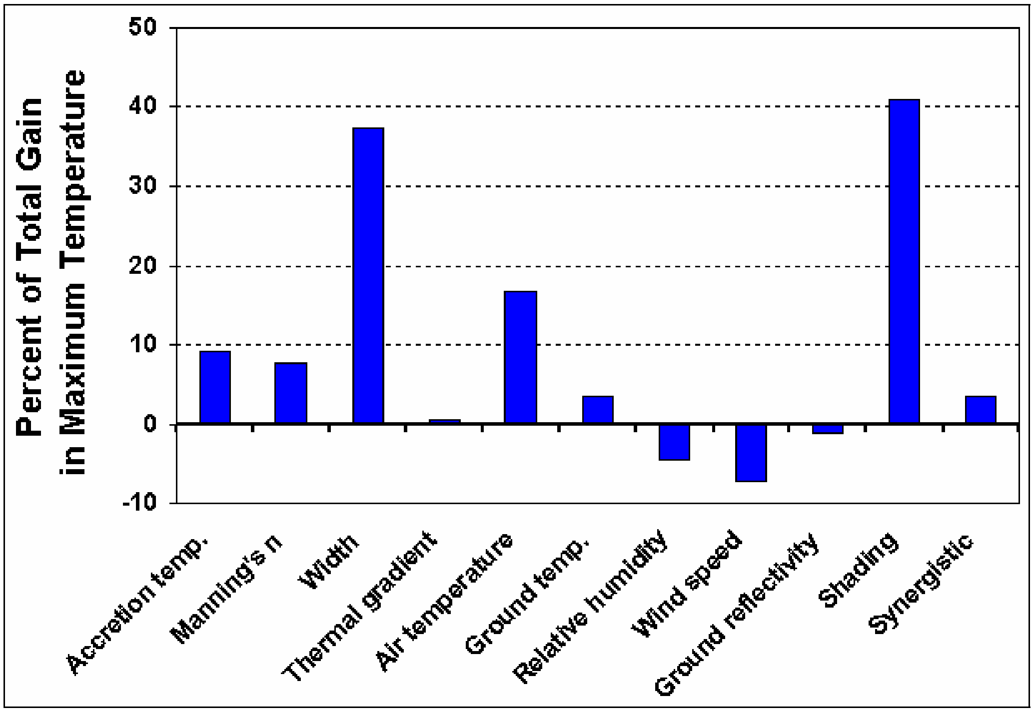

Figure 8. Stream Temperature Model Results. Model shows environmental conditions that are affected by timber harvesting and the relative magnitude of their influence on stream temperatures. Note that values above zero indicate increasing stream temperatures, while values below zero indicate decreasing temperatures (Bartholow, 2000).

References

Armour, C.L. 1991. “Guidance For Evaluating and Recommending Temperature Regimes To Protect Fish: Instream Flow Information Paper 28,” Biological Report 90 (22). Fort Collins: U. S. Fish and Wildlife Service, National Ecology Research Center.

Bartholow, J.M. 2000. Estimating cumulative effects of clearcutting on stream temperatures. Rivers 7(4): 284-297. http://smig.usgs.gov/cgi-bin/SMIG/pageprint?page=features_0902/clearcut_inline.html

Bjornn, T. C. and D. W. Reiser. 1991. “Habitat Requirements of Salmonids in Streams.” American Fisheries Society Special Publication 19: 83-138.

Berbach, M., P. Cafferata, T. Robards, and B. Valentine. 1999. Forest canopy measurements in watercourse and lake protection zones: a literature review. Final Report dated June, 1999. Calif. Dept. of Forestry and Fire Protection. Sacramento, CA. 22 p.

Beschta, R. L., R. E. Bilby, G. W. Brown, L. B. Holtby, and T. D. Hofstra. 1987. “Stream Temperature and Aquatic Habitat: Fisheries and Forestry Interactions.” Streamside Management: Forestry *and Fishery Interactions.* Pages 191-232. Seattle: University of Washington, College of Forest Research.

Brandow, C. 2005. Modified completion report monitoring. PowerPoint presentation for the Board of Forestry and Fire Protection’s Monitoring Study Group meeting held on April 7, 2005, Willits, CA. Final report in preparation.

Brosofske, K.D., J. Chen, R.J. Naiman, and J.F. Franklin. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecological Applications 7(4): 1188-1200. http://research.eeescience.utoledo.edu/lees/pubs/brosofske1997.pdf

Brungs, W.A. and B.R. Jones. 1977. Temperature criteria for freshwater fish: protocol and procedures. EPA-600-3-77-061. Environmental Research Laboratory-Duluth, Office of Research and Development, US Environmental Protection Agency. 136 p.

Cafferata, P.H. 1990. Temperature Regimes of Small Streams Along The Mendocino Coast. Jackson Demonstration State Forest Newsletter, No. 39, October 1990. P. 1-4.

Cafferata, P.H. and J.R. Munn. 2002. Hillslope Monitoring Program: Monitoring Results from 1996 through 2001. California Department of Forestry and Fire Protection, Sacramento. 114 p. Available at http://www.bof.fire.ca.gov/pdfs/ComboDocument_8_.pdf.

California Department of Forestry and Fire Protection, 1999, Draft Habitat Conservation Plan and Sustained Yield Plan for Jackson Demonstration State Forest dated June 1999. Prepared by Stillwater Sciences, Berkeley, California.

Chamberlin, T.W., R.D. Harr, and F.H. Everest. 1991. “Timber Harvesting, Silviculture, and Watershed Processes.” In Influences of Forest and Rangeland Management on Salmonid Fishes *and Their Habitats: American Fisheries Society Special Publication 19*. Pages 181-205 NR: American Fisheries Society.

CH_2M-Hill and Western Watershed Analysts. 1999. FEMAT riparian process effectiveness curves: what is science-based and what is subjective judgment? Final Report prepared for the Oregon Forest Industries Council, Salem Oregon.

Department of Fish and Game. 2004. Recovery Strategy for California Coho Salmon. Species Recovery Strategy 2004-1. February 2004. Report to the California Fish and Game Commission. Sacramento, California. 594p. Available on the Internet at http://www.dfg.ca.gov/nafwb/CohoRecovery/RecoveryStrategy.html

Forest Ecosystem Management Assessment Team (FEMAT). 1993. Forest ecosystem management: an ecological, economic, and social assessment. Report published by the U.S. Department of Agriculture and five other federal agencies, July 1993.

Forest Ecosystem Management Assessment Team Record of Decision (FEMAT ROD). 1994. Record of Decision for amendments to Forest Service and Bureau of Land Management documents within the range of the northern spotted owl. U.S. Government Printing Office for the U.S. Department of Agriculture, Forest Service and Bureau of Land Management. April 1994.

Hetrick, N. J., et al. 1998. “Changes In Solar Input, Water Temperature, Periphyton Accumulation, and Allochthonous Input and Storage After Canopy Removal Along Two Small Salmon Streams In Southeast Alaska” *Transactions of American Fisheries Society 127(6): 859-875*. NR: American Fisheries Society.

Hines, D. and J. Ambrose. 2000. Evaluation of stream temperatures based on observations of juvenile coho salmon in northern California streams. Georgia-Pacific West, Inc., Fort Bragg, California. Unpublished Report. 30 p. http://www.krisweb.com/biblio/gen_afs_hinesetal_xxxx.pdf

Hughes, T., Macedo, R. and B. Valentine, 2004. Air temperature of stream-sides in the North Coast Redwood Region 2001-2003. Redwood Region Forest Science Symposium, Rohnert Park, CA.

Johnson, S.L. and J.A. Jones. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Can. J. Fish. Aquat. Sci. 57(Suppl. 2): 30–39.

Mendocino Redwood Company Co., LLC, 2003. Watershed Analysis for Mendocino Redwood Company’s Ownership in the Big River Watershed.

Mendocino Redwood Company Co., LLC, 2000. Noyo River Watershed Analysis.

Murphy, M.L. 1995. Forestry impacts on freshwater habitat of anadromous salmonids in the Pacific Northwest and Alaska—requirements of protection and restoration. NOAA Coastal Ocean Program Decision Analysis Series No. 7. NOAA Coastal Ocean Office, Silver Spring, MD. 156 p.

Murphy, M. L., and W. R. Meehan. 1991. "Stream Ecosystems," Influences of Forest and Rangeland Management On Salmonid Fishes and Their Habitats: .American Fisheries Society Special Publication 19: 17-46.NR: American Fisheries Society.
Nakamoto, R.. 1998. Effects of timber harvest on aquatic vertebrates and habitat in the North Fork Caspar Creek. *In:* Ziemer, R.R., technical coordinator. Proceedings of the conference on coastal watersheds: the Caspar Creek story, 1998 May 6; Ukiah, CA. General Tech. Rep. PSW GTR-168. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; p. 87-95.

NMFS and USFWS (National Marine Fisheries Service and U.S. Fish and Wildlife Service). 1997. Aquatic properly functioning condition matrix. NMFS, Southwest Region, Northern California Area Office, Santa Rosa, and USFWS, Arcata, California.

North Coast Regional Quality Control Board. 2004 (preliminary draft). Big River Water Quality Assessment. Report compiled for the North Coast Watershed Assessment Program. North Coast Regional Quality Control Board, Santa Rosa. Draft utilized with permission of R. Klamt, Chief of Timber Harvest Division, North Coast Regional Water Quality Control Board.

Poole, G. C. and C. H. Berman. 2000. Pathways of human influence on water temperature dynamics in stream channels. Environmental Management.

Spence, B.C., G.A. Lomnicky, R.M. Hughes, and R.P. Novitzki. 1996. An Ecosystem Approach To Salmonid Conservation. TR-4501-96-6057. Corvallis: Mantech Environmental Research Services Corp.

Steinblums, I.J., H.A. Froehlich, and J.K. Lyons. 1984. Designing stable buffer strips for stream protection. Journal of Forestry 82 (1):49-52.

Sullivan, K., et al. 1990. Evaluation of Prediction Models and Characterization of Stream Temperature Regimes In Washington. Timber/Fish/Wildlife Rep. No. TFW-WQ3-90-006. Olympia: Washington Dept. Nat. Resources.

Valentine, B.E. 1996. Stream Temperatures on Jackson Demonstration State Forest, Mendocino County, California During Summer of 1995. Draft Report. Santa Rosa: CDF, Coast-Cascade Region.

Welsh, H. H., G. R. Hodgson, B. K. Harvey, and M. E. Roche. 2001. "Distribution of Juvenile Coho Salmon In Relation To Water Temperatures In Tributaries of The Mattole River, California," North American Journal of Fisheries Management. 21:464-470.

CDF. 2003. Assessment of Land Use in the Big River Watershed. Draft Report, North Coast Watershed Assessment Program, Sacramento, CA.

Jackson, W.F. 1991. Big River Was Dammed. FMMC Books, Mendocino, CA.

Napolitano, M., F. Jackson, and P. Cafferata. 1989. A history of logging in the Caspar Creek basin. Jackson Demonstration State Forest Newsletter, No. 33, April 1989. p. 4-7. http://www.fs.fed.us/psw/publications/4351/JDSF89.pdf

Wurm, T. 1986. Mallets on the Mendocino Coast: Caspar Lumber Company railroads and steamships. Glendale: Trans-Anglo Books. 34 p.

Attachment A

Stream Temperature Data Summary

PLANNING WATERSHEDS	Site	Avg	Max	Min	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
BIG RIVER HEADWATERS																	
Martin Creek	FSP_5219	18.4	18.6	18.3	0.0	0.0	0.0	0.0	0.0	0.0	18.6	18.3	0.0	0.0	0.0	0.0	0.0
	FSP_5235	16.0	17.3	14.7	0.0	0.0	0.0	0.0	0.0	0.0	17.3	14.7	0.0	0.0	0.0	0.0	0.0
	FSP_5240	17.4	17.8	17.0	0.0	0.0	0.0	0.0	0.0	0.0	17.0	17.8	0.0	0.0	0.0	0.0	0.0
Russel Brook	MRC_T74-01	19.5	20.1	19.0	0.0	20.1	19.0	19.0	0.0	0.0	0.0	0.0	0.0	19.3	19.9	19.4	0.0
	MRC_T74-02	15.8	16.6	14.9	0.0	0.0	0.0	15.2	16.6	0.0	0.0	0.0	0.0	16.0	14.9	15.7	16.6
	MRC_T74-03	18.4	19.0	16.0	0.0	0.0	0.0	18.8	16.0	0.0	0.0	0.0	18.8	0.0	18.8	19.0	18.9
	MRC_T74-20	14.2	14.2	14.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.2	0.0	0.0
	MRC_T74-21	14.7	14.7	14.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.7	0.0	0.0
NORTH FORK BIG RIVER																	
Upper North Fork Big River	JDSF_3201	18.2	18.9	17.5	0.0	0.0	0.0	0.0	0.0	18.9	0.0	0.0	17.5	0.0	0.0	0.0	0.0
	JDSF_3202	18.5	18.9	18.0	0.0	0.0	0.0	0.0	0.0	18.9	18.7	0.0	18.0	18.6	0.0	0.0	0.0
	JDSF_3213	17.1	17.5	16.8	0.0	0.0	0.0	0.0	0.0	16.8	0.0	0.0	17.0	0.0	0.0	17.0	17.5
	FSP_5220	18.1	18.6	17.5	0.0	0.0	0.0	0.0	0.0	0.0	18.6	17.5	0.0	0.0	0.0	0.0	0.0
	FSP_5238	17.7	18.1	17.3	0.0	0.0	0.0	0.0	0.0	0.0	18.1	17.3	0.0	0.0	0.0	0.0	0.0
James Creek	JDSF_3211	15.1	15.8	14.8	0.0	0.0	0.0	0.0	0.0	15.1	15.8	0.0	14.8	14.8	0.0	0.0	0.0
	JDSF_3212	16.3	16.8	15.9	0.0	0.0	0.0	0.0	0.0	16.8	0.0	0.0	15.9	16.2	0.0	0.0	0.0

PLANNING WATERSHEDS	Site	Avg	Max	Min	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Chamberlain Creek	JDSF_3221	14.3	14.5	14.1	0.0	0.0	0.0	0.0	0.0	14.5	14.2	0.0	14.1	14.4	0.0	0.0	0.0
	JDSF_3222	15.8	16.1	15.5	0.0	0.0	0.0	0.0	0.0	16.1	0.0	0.0	15.5	15.7	0.0	0.0	0.0
	JDSF_3223	16.3	16.3	16.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.3	16.2	0.0	0.0	0.0
	JDSF_3224	17.1	17.5	16.9	0.0	0.0	0.0	0.0	0.0	17.5	17.3	0.0	17.0	16.9	0.0	16.9	17.3
	JDSF_3231	15.0	15.2	14.7	0.0	0.0	0.0	0.0	0.0	15.2	15.0	0.0	15.0	14.7	0.0	0.0	0.0
	JDSF_X14	14.1	14.6	13.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.8	13.8	14.6
	JDSF_X15	15.2	15.7	14.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.0	14.9	15.7
	JDSF_X16	14.5	14.9	14.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.9	14.7	14.0	0.0	0.0
	JDSF_X17	15.6	16.2	15.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.3	15.4	16.2
	JDSF_X18	16.9	16.9	16.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.9
	JDSF_X19	17.6	17.6	17.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.6
	JDSF_X20	15.3	15.3	15.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.3
	JDSF_X21	15.7	15.7	15.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.7	0.0	0.0	0.0	0.0	0.0
	JDSF_X22	15.7	15.9	15.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.9	15.4	0.0	0.0	0.0	0.0
	FSP_556	16.0	16.0	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.0	0.0	0.0	0.0	0.0	0.0
East Branch North Fork Big	MRC_T75-01	17.4	18.4	16.4	0.0	0.0	18.4	0.0	18.1	0.0	17.9	0.0	17.1	17.1	16.4	16.6	17.4
	MRC_T75-03	17.2	17.9	16.3	0.0	0.0	0.0	0.0	0.0	0.0	17.9	0.0	0.0	0.0	16.3	17.0	17.7
	MRC_T75-20	12.1	12.1	12.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.1	0.0	0.0
	MRC_T75-22	13.6	13.6	13.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.6	0.0	0.0
	MRC_T75-05	14.4	15.3	13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.5	15.3
	FSP_5213	17.5	18.1	16.9	0.0	0.0	0.0	0.0	0.0	0.0	18.1	16.9	0.0	0.0	0.0	0.0	0.0
	FSP_5234	15.7	15.8	15.6	0.0	0.0	0.0	0.0	0.0	0.0	15.6	15.8	0.0	0.0	0.0	0.0	0.0