DOCUMENTING PROGRESS TOWARD ACHIEVING STREAM TEMPERATURE COMPLIANCE IN OREGON TMDL PLANS

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ABSTRACT

Stream temperature is an important water quality parameter in Oregon. Over one thousand stream segments have been identified as failing to maintain a seven-day average of maximum stream temperature equal to or less than 64°F. Large amounts of volunteer labor have been invested in planting trees along riparian zones to increase stream surface shading. This paper proposes and evaluates an approach to data collection that can indicate the extent to which these activities are effectively lowering water heating. The strategy is to monitor a segment being restored and a similar control segment. By comparing the temperature change in the restored segment divided by the temperature change in the control segment both before and after trees have been allowed to grow, it is possible to determine with statistical confidence that the targeted segment is being effectively restored. Data from Pea Creek, Curry County, Oregon are used to demonstrate that one twenty-four hour set of monitoring data collected before and after restoration are sufficient to demonstrate progress.

INTRODUCTION

Stream temperature standards have been established in Oregon for stream segments in which aquatic life is one of the designated beneficial uses. That means that all stream segments in which salmon and trout migrate or spawn have a stream temperature standard. Those stream segments that do not meet the water quality criteria for their designated beneficial uses are listed on the State of Oregon 303d List. Approximately two thirds of the stream segments listed on the Oregon 303d List have failed to meet the stream temperature standard. For most of these segments, the stream temperature criterion is that the seven-day average of maximum stream temperatures shall not exceed 64°F. As a result of these listings, many Watershed Councils and other volunteer organizations have become involved in efforts to restore temperature stability to 303d listed stream segments. One of the challenges facing these organizations is documentation that these efforts are being effective. Stream temperature reductions are particularly difficult to document because of the many variables that control stream temperature. It is difficult to collect stream temperature data that demonstrate that a particular restoration project has contributed to the improvement.

Stream temperature restoration efforts have largely focused on restoring riparian areas with the goal of providing shade to protect stream surfaces from direct solar radiation. Efforts have been devoted to such activities as tree planting, riparian fencing, off-stream livestock watering and, where possible, to the re-establishment of wetlands and other structures that promote rainfall infiltration to serve as summertime groundwater inflow. Each of these efforts has been modeled as having potential benefit in restoring appropriate stream temperatures. Unfortunately, none of these efforts have an immediately measurable impact on maximum stream temperatures. Thus the volunteer organizations labor tirelessly but with only minimal feedback to assure them that their efforts are being effective or that by perseverance, their objective will be achieved.

Oregon State University has responded positively to the plight of watershed councils by providing a variety of services and educational support. Initial efforts were devoted to identification and documentation of stream temperature problems. Following the problem identification, an intensive research effort was launched which culminated in the development of a highly detailed descriptive model of stream temperatures. The model developed was a reach model which allowed the user to predict temperature changes over a reach using detailed inputs to account for stream flow, stream cross section, stream orientation, shading, position of the sun, stream bed composition and other minor variables. This model had the additional usefulness of being a convenient tool to evaluate the potential benefit of alternate restoration strategies.

This paper proposes and evaluates an approach to data collection that can indicate the extent to which riparian tree planting activities are effectively lowering water heating. The approach is particularly useful for watershed councils and groups aiming to demonstrate changes in stream temperature.

Highlights of Previous Work on Factors Affecting Stream Temperature

The stream's temperature regime is the result of the heat energy budget per stream flow volume as the water flows downstream (Brown, 1969). The heat budget is the sum of net radiation, evaporation, convection, conduction, and advection. Net radiation is generally dominated by the amount of direct solar radiation reaching the stream surface. Vapor pressure gradients and temperature gradients determine the heat gain or loss from evaporation and convection, respectively, between the stream water surface and the air immediately above the surface. Wind speed at the air-water interface is also an important variable controlling evaporation and convection. Conduction efficiencies between the streambed and water depend on the type of bed material. Advection is the heat exchange between the tributaries, groundwater, or different temperature mixes with the main streamflow. (Beschta et al. 1987)

Stream temperature is the result of complex interactions between geomorphology, soil, hydrology, vegetation, and climate within a watershed that affect the stream's heat energy budget. Channel characteristics such as surface area over which energy transfers occur influence the amount of heat gained and lost (Beschta et al. 1987). Stream warming and cooling are also dependant on the amount of flow volume. Vegetation in the form of trees, shrubs, and overhanging vegetation intercepts direct solar radiation and produces cover for the stream. Stream shade is the percent of cover that casts a shadow on the stream. Vegetation also affects stream channel processes that influence the amount of heat gain or loss of a stream. This could include streambank erosion, stream flow, microclimate, wind speed, humidity, soil temperature, water use, air temperature, and infiltration (Independent Multidisciplinary Science Team, 2000).

Numerous studies have been completed in small, forested watersheds that measure and model changes in stream temperatures with a change in stream shading (Brown, 1969; Brown and Kryger, 1970; Holtby, 1988; Feller, 1981; Harr and Fredriksen, 1988; Johnson and Jones, 2000). These studies have indicated that decreasing streamside shade causes increases in stream temperature for small streams (less than 20 liters per second). These studies have also indicated that stream temperatures increase when a majority (>25%) of the watersheds are harvested. Stream temperature could be an indicator of cumulative effects of logging activities in watersheds. Holtby (1988), Beschta and Taylor (1988), and Hatten and Conrad (1995) found strong correlations between stream temperature and the increase in forest harvesting in sub-basins within watersheds.

Influence of stream characteristics and grazing intensity on summer stream temperatures was studied in Eastern Oregon (Maloney et al. 1999). Streams with greater than 75% stream shade maintained lower stream temperatures. Percentage of stream shade, week of the year, weekly flow, stream width, year, travel time, elevation, and aspect explained 67% of the variation in stream temperatures. Stream flow ranged from approximately 0.4 L/sec to 14 L/sec.

Boyd (1996) created Heat Source, a stream model and used it to predict and verify stream temperatures for 8 stream reaches at elevations of 820, 1640, 1250 and 1280 meters (five at 1280 meters). Canopy density, stream flow and upstream temperature were the factors most likely to raise stream temperatures, channel width was medium, and the other factors were low (elevation, atmospheric conditions, etc.). The simulation showed high changes in temperature for flows less than 115 L/s. Simulations showed that canopy density and vegetation shade angle had minor affects on temperature when shade angle was less than 60^{o}F.

Streams have a natural temperature warming trend line (equilibrium) that is useful in comparing alterations to stream shade for a reach. Zwieniecki and Newton (1999) created standard warming curves for low discharge and high discharge creeks (average 66 L/s) in undisturbed forests to compare stream temperature trends associated with typical forest riparian buffers (8.6 to 30.5 meters wide). Stream temperatures increased above the warming trend line then cooled to the trend line within 150 meters downstream. High discharge creeks had higher buffering capacity to stream warming.

Riparian shading and site elevation were found to be the best factors at predicting stream temperatures in Washington streams (Sullivan et al. 1990). However, effectiveness of shade varies with elevation. Sites below 100 meters are most likely to have significant temperature impacts from vegetation removal, even with high amounts of shading. Higher elevation sites are rarely temperature sensitive under any riparian shading levels. On a basin scale, main-stem temperatures of basins with past logging were higher within 50km of the watershed divide compared to mature conifer forests. It is estimated that streams less than 40km downstream from the watershed divide have potential for effective amounts of shading because of stream width and flow volume.

Relationships between air temperature and distance from divide on stream temperatures were found in a 21-year study of Steamboat Creek (Holaday, 1992). Three streams had slight increases since the mid 1980’s along with increasing air temps. As Steamboat flows downstream from the divide, it increases in temperature until it reaches within 1^{o}F of the mean basin air temperature at 24 km from the divide. Canton Creek shows similar relationship at 25.7 km from its divide.

Meays (2000) analyzed elevation and thermal environment relationships with stream temperature for four high elevation streams in Northeastern Oregon (1830 – 1370 meters elevation). Elevation, air, and soil temperature were most associated with stream temperature increases through a two-mile reach. The shaded stream had the highest increase in temperature with elevation and was lower in temperature than the other streams.

THE TASK AT HAND

The challenge facing many watershed organizations is to collect the data necessary to demonstrate the remediation efforts (generally the planting of trees or other riparian zone restoration efforts) have resulted in the targeted segment absorbing less energy than before. There are three alternate strategies generally in use to answer questions of this type. These approaches are compared in Table 1.

Table 1. Comparison of three alternate strategies to demonstrate that a remediation effort has been effective in controlling a nonpoint source of pollution.

Strategy	Description	Strengths	Weaknesses
Before and after sampling	A particularly important point in a watershed is sampled before and after the remediation action was taken.	1. Simple in concept. 2. Represents a direct response to the purpose of the program.	1. Does not consider other causes of observed changes. 2. Least powerful statistically and may be difficult to carry to completion
Above and below or upstream and downstream sampling	Samples are collected at the upstream and downstream limits of the segment being restored. The changes within the segment are compared on a before and after basis.	1. Eliminates the impact of upstream activities. 2. Focuses on the treated segment.	1. No basis to measure change 2. Does not consider natural downstream warming
Paired watersheds	Comparison of two matched watersheds, one the control, the other the target watershed. Before restoration, it is important to document the behavior of the two watersheds.	1. Weather conditions have similar impact on both watersheds. 2. If the relationship between the target and the control change, that can be statistically demonstrated.	1. Matched watersheds are often difficult to identify. 2. Maintaining the control may be difficult. 3. It may not be appropriate to restore the entire watershed.

Adoption of the paired watershed approach for stream temperature can be modified slightly so the watersheds are replaced by two stream segments, one immediately downstream of the other. By measuring the stream temperature at the upstream and downstream ends of two contiguous segments, it becomes possible to compare heat additions and heat losses. If the stream segments were identical, you would expect that:

$$T(U) - T(M) = T(M) - T(L)$$

Where: T(U) = Temperature at the upper sampling point
T(M) = Temperature at the middle sampling point
T(L) = Temperature at the lower sampling point

This can also be expressed as:

$$\text{Delta } T_{(\text{Control})} = \text{Delta } T_{(\text{Treatment})}$$

Since, we cannot expect the two segments to be identical, (flow, aspect, depth, width and shading), a more reasonable expectation is that:

$$\text{Delta } T_{(\text{Treatment})} = m_1(\text{Delta } T_{(\text{Control})})$$

Where: m_1 = slope of curve, Delta $T_{(\text{Treatment})}$ versus Delta $T_{(\text{Control})}$ before restoration.

If the treated stream segment was effectively restored by the sufficient growth of trees or other restoration efforts, we would anticipate the slope of the curve to decrease. This establishes a criterion by which to effectively judge progress. If the slope, m_2 (after restoration) is significantly less than m_1, the treated segment is heating less than before. Using this approach, a 24-hour temperature monitoring period should be sufficient to document progress.

RESULTS FROM THE FIELD

Pea Creek is a tributary to Euchre Creek in Curry County, Oregon along the South Coast. Trees were planted in the fall of 1995. Cindy Ricks Meyers and the Curry Soil and Water Conservation District helped collect stream temperature data with data loggers in the summer of 1996 and again in the summer of 2002. To test the suggested evaluation procedure, it was arbitrarily decided to evaluate stream temperature data for August 12 of each year. In this particular case, since Pea Creek has a flow of approximately 15 liters/sec, 100 meter control and treatment segments were identified. The control segment is immediately upstream of the treatment segment. The control is young growth forest providing full shade, while the treated segment was a shadeless grazed area. Temperature data are given in Table 2 for August 12, 1996 and 2002. The Upstream sampling point was 100 m into the forested area, "Middle" was the divide between the control and the treated segments, and "Lower" was 100 m into the tree planting area. Hourly temperature measurements are presented for each of the sampling locations.

Table 2. Temperature measurements for Upper, Middle and Lower sampling points (Pea Creek August 12, 1996 and 2002). Upper is the upstream end of the 100m Control segment, Middle is the break between control and treated segments and Lower is the downstream end of the 100 m restored test segment.

Time	Upper, '96	Middle '96	Lower '96	Upper '02	Middle '02	Lower '02
Midnight	54.18	54.46	53.9	54.9	54.74	55.23
1:00	53.9	54.46	53.9	54.9	54.46	54.95
2:00	53.9	54.46	53.62	54.9	54.18	54.67
3:00	53.9	54.18	53.34	54.9	54.18	54.39
4:00	53.9	54.18	53.34	54.62	53.9	54.39
5:00	53.62	54.18	53.34	54.62	53.62	54.11
6:00	53.9	54.18	53.06	54.34	53.62	53.83
7:00	53.62	53.9	53.06	54.34	53.62	53.83
8:00	53.62	53.9	53.9	54.34	53.9	53.83
9:00	54.18	54.18	55.02	54.34	54.46	54.39
10:00	54.74	54.74	57.25	54.62	54.74	54.95
11:00	55.02	55.3	60.07	54.9	55.02	55.51
Noon	55.58	56.13	62.07	54.9	55.58	56.34
1:00 pm	55.58	56.41	63.51	54.9	55.86	56.89
2:00	55.86	56.69	63.8	55.18	55.58	57.17
3:00	55.86	57.25	63.22	55.18	55.86	57.45
4:00	55.86	56.97	61.79	55.18	55.86	57.73
5:00	55.86	56.69	59.5	55.18	56.14	57.73
6:00	55.58	56.13	57.53	55.18	56.42	57.73
7:00	55.58	55.86	56.41	55.18	56.14	57.17
8:00	55.3	55.3	55.58	55.46	55.58	56.89
9:00	55.02	55.02	55.02	55.18	55.02	56.34
10:00	54.74	55.02	54.74	55.18	54.74	55.51
11:00	54.46	54.74	54.46	54.9	54.74	55.23
Midnight	54.46	54.74	54.18	54.9	54.18	54.95

The temperatures measured at the three locations in 1996 are shown in Figure 1. These data are typical for a stream exposed to solar radiation. The impact of little or no shade is evident. Note that the temperature at the downstream measuring point reaches a maximum around 3 in the afternoon and cools until about eight o'clock the next morning. Note also, that the other two sampling points follow a similar pattern but the temperature changes at the upper two locations are less dramatic because of the shading. Figure 2 shows similar data collected at the same locations in 2002, which is seven years after the riparian zone was planted to trees as a restoration effort. This figure clearly shows the Treated Segment behaving much more like the Control Segment.

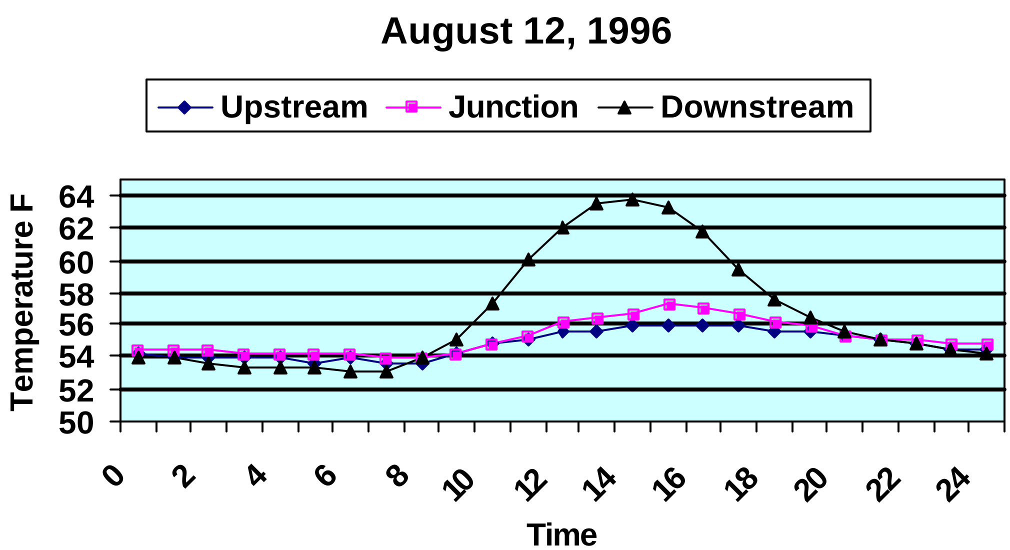

Figure 1. Temperature profile at the three sampling points on Pea Creek on August 12, 1996. The 100 m segment between the upstream and junction sampling points is in a shaded area, while the lower segment, junction to downstream, was fully exposed to the sun.

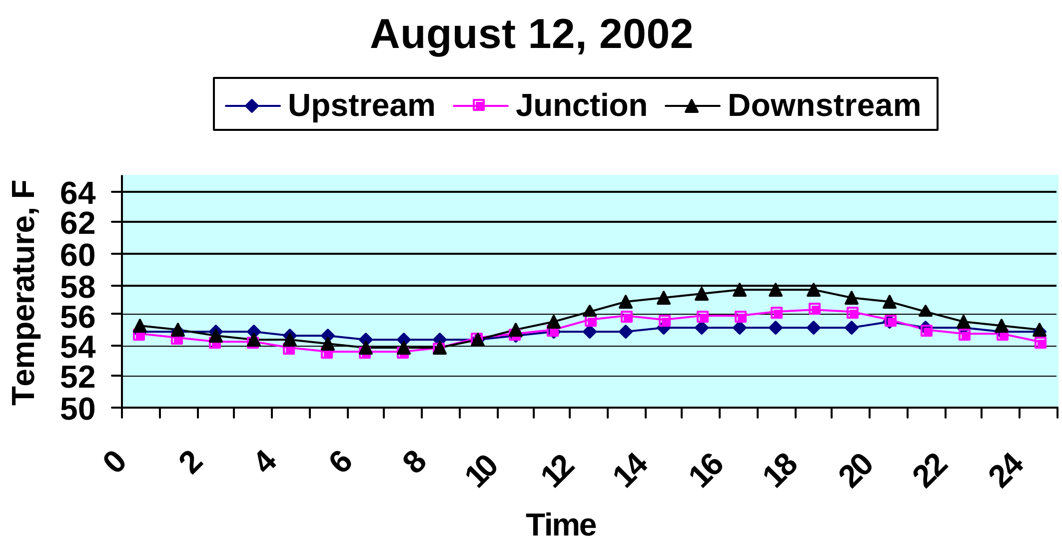

Figure 2. Temperature profile at the three sampling points on Pea Creek on August 12, 2002. The 100 m segment between the upstream and junction sampling points is in a shaded area, while the lower segment, junction to downstream, was shaded by the development of trees planted in 1995.

In order to determine the slope of the curves relating Delta T $_{(Treatment)}$ to Delta T $_{(Control)}$, a least squares fit of the 1996 data was calculated.

m_{1996} = 4.87
intercept = -0.69
Variance of the slope = 0.0052

A similar analysis was made of the August 12, 2002 data. In that case,

m_{2002} = 0.54
Intercept = 0.78
Variance of the slope = 0.016

Tables 2 and 3 present the data used in this analysis. Figure 3 illustrates the change in temperature relationships and associated fitted curves for both 1996 and 2002.

Table 3. Temperature changes across the control and target segments during sampling on August 12, 1996 and 2002.

Time	Temperature change Control '96	Temperature change Treatment '96	Temperature change Control '02	Temperature change Treatment '02
Midnight	0.28	-0.56	-0.16	0.49
1:00	0.56	-0.56	-0.44	0.49
2:00	0.56	-0.84	-0.72	0.49
3:00	0.28	-0.56	-0.72	0.21
4:00	0.28	-0.84	-0.72	0.49
5:00	0.56	-0.84	-1.0	0.49
6:00	0.28	-1.12	-0.72	0.21
7:00	0.28	-0.84	-0.72	0.21
8:00	0.56	0	-0.44	-0.07
9:00	0	0.84	0.12	-0.07
10:00	0	2.57	0.12	0.21
11:00	0.28	4.77	0.12	0.49
Noon	0.55	5.80	0.68	0.76
1:00 pm	0.83	7.10	0.96	1.03
2:00	0.83	7.11	0.40	1.59
3:00	1.39	5.97	0.68	1.59
4:00	1.11	4.82	0.68	1.87
5:00	0.83	2.81	0.96	1.59
6:00	0.55	1.40	1.24	1.31
7:00	0.28	0.55	0.96	1.03
8:00	0	0.28	0.12	1.31
9:00	0	0	-0.16	1.32
10:00	0.28	-0.28	-0.44	0.77
11:00	0.28	-0.28	-0.16	0.49
Midnight	0.28	-0.56	-0.78	0.77

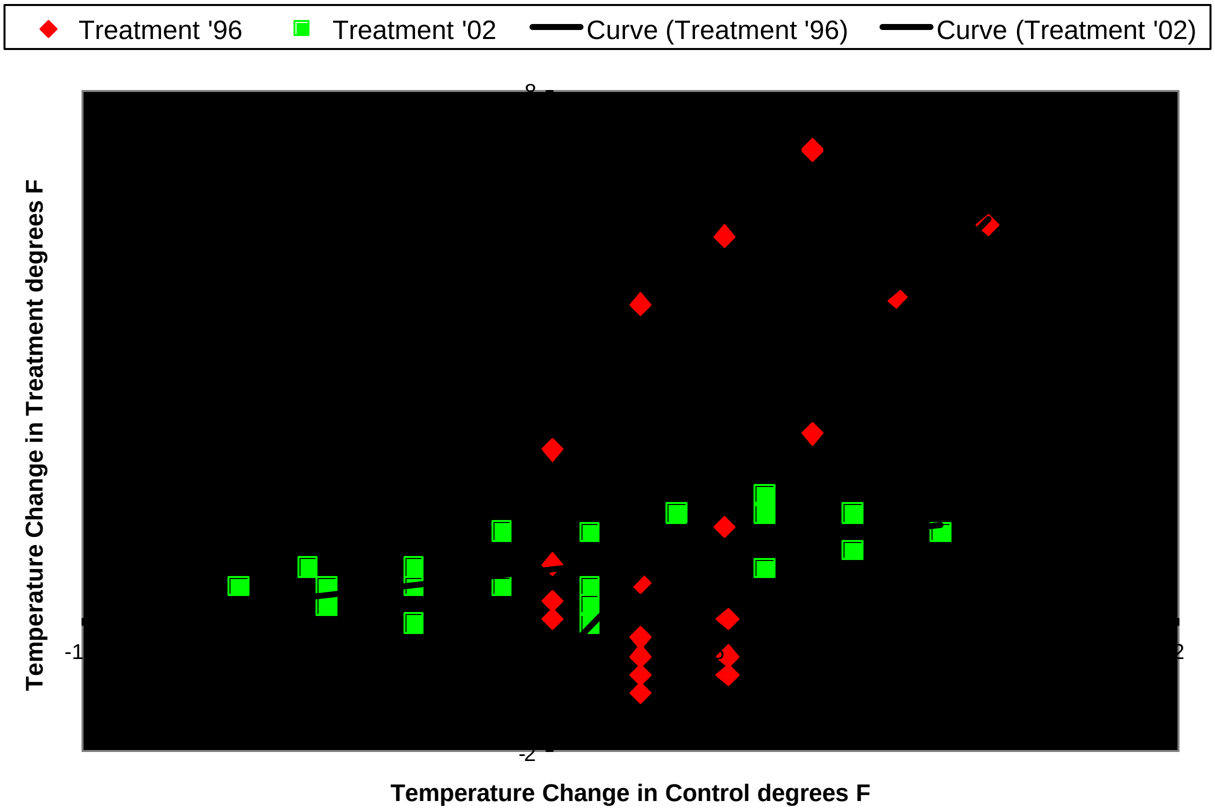

Figure 3. Temperature change over the Treatment Segment as a function of temperature change over the Control Segment. This figure includes the data for 1996 and 2002 as well as the calculated least squares fit line through the data.

Application of the Student t test clearly demonstrates the two slopes are significantly different at the nominal 0.05 test significance with P = 0.0217, thus the conclusion that restoration efforts have reduced the heating of the target segment. Remaining is the question of whether a single day's sampling is sufficient to document the relative vulnerability to radiation related to temperature change. To answer this question, two additional, arbitrarily selected days of monitoring data were evaluated. Results of that evaluation are summarized in Table 4. This table shows the slopes, Delta T $_{(Treatment)}$ versus Delta T $_{(Control)}$ for August 12, 17 and 18, 2002 are statistically indistinguishable.

Table 4. Slopes of the Least Squares fit slope of Delta T $_{(Treatment)}$ versus Delta T $_{(Control)}$ for August 12, 17 and 18, 2002. There is no statistically significant difference in the calculated slopes for these three days.

Date, 2002	Slope Delta T $_{(Treatment)}$ versus Delta T $_{(Control)}$	Variability of the slope
August 12	0.542	0.55
August 17	0.384	0.235
August 18	0.720	0.254

CONCLUSIONS

1. The Oregon Stream Temperature Standard, which specifies the maximum seven-day average temperature, reflects a complex interaction of several variables including stream flow, width, depth, aspect and shading. Without a planned monitoring strategy, it is difficult to demonstrate effectiveness of stream restoration efforts.

2. The planting of trees along Pea Creek in Curry County, Oregon in 1995 has resulted in reduced radiant energy absorption as reflected by the temperature behavior of the stream.

3. Monitoring a control and a target segment of the stream for a 24-hour period during the low flow season of the stream provides sufficient data to document the effectiveness of the restoration efforts.

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