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Stability of Water Temperature Attributes Over a 20-Yr Period

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ABSTRACT

The objective of this study was to determine if the stability of water temperature attributes suggested by an analysis conducted in 2003 (Larson and Larson 2001; 2003) was continued over a 20-yr period. The pattern of degree accumulations observed in the daily heating and cooling cycles of three streams in 1998, 2013, 2014, 2016, and 2018 were studied in Grant County, Oregon. The average air and water temperatures remained stable at each site and followed the expected natural patterns (Larson and Larson 2001) described in an earlier study. Within each sampling year, mean air and water temperature remained within 1–2°C and there were no significant differences between the rates of heating between the study years or between sites.

Introduction

On a watershed scale, the energy of the environment surrounding a stream (air temperatures) provides an index for the rates of heating and cooling that take place day to day (Larson and Larson 2001). This thermal response results when two different materials are brought into thermal contact with each other. The two materials will move toward thermal equilibrium but not experience the same changes in temperature because of their different specific heats and masses. The heat lost by the hotter object is equal to the heat gained by the colder object (Kirkpatrick and Wheeler 1995).

Sustainable management practices on the riparian areas in Oregon and Washington have been used to manage land with regard to mitigating exceedances of the Oregon 18°C temperature standard for the protection of salmonid habitat. These efforts have yielded variable results due to differences in ecological rate potential. Knowledge of these differences directly impacts management practice success. Stoneman and Jones (1996) studied thermal characteristics of streams based on warm water, cool water, and cold-water classification of sites. Larson and Larson (2001) described stream temperatures at 10 sites in four watersheds in Oregon, and through a discriminant analysis stream sites were separated by topographic elevations as high (2 134–1 372 m), mid (1 372–914 m), and low (below 914 m). Their study used air and water accumulated degrees associated with the daily temperature differences between air and water to establish the rates of heating and cooling at stream sites. In 2003 Larson and Larson summarized the relationship between the air and water temperature data. The study demonstrated that weather and elevation are prominent characteristics that can be used to describe water temperature patterns. By contrast, land use influences of grazing, no grazing, and hay production were not sufficient to cause differences in water temperature attributes during periods of heating, rates of heating, or diurnal fluctuations between sites at similar elevations.

The purpose of this study was to determine if management practices implemented during the past 20 yr on sites described in Larson and Larson (2003) changed rates of water heating between sites at similar elevation. The baseline data collection for this study was collected in the summer of 1998 on three sites in the Blue Mountains in Grant County, Oregon. Sustainable management practices intended to mitigate stream temperatures were undertaken shortly after baseline data collection. Water and air termperatures were sampled on the stream sites from 1998 through 2018.

Study area

Fig. 1 identifies the general study area located 45 mi north of John Day (941 m elevation) within the Middle Fork of the John Day river, which drains about 2 000 km^2 in northeastern Oregon. The Middle Fork is in the John Day Ecological Province (Anderson et al. 1998) and is characterized by long deep valleys and canyons surrounded by mountains, buttes, and plateaus. The headwaters are located in Lodgepole pine forests and summer flows are derived from springs and marshy seeps. Midelevation sites used in this study are open valley bottoms surrounded by mixed conifer forests

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Table 1
Mean air and water temperature at three sites with elevation, stream length, width and flow during July-August for six different years.

Sites	Site 1				Site 2				Site 3			
Site Elevation (m)	1079				1102				1092			
Rosgen (1996) Classification	B3				B3				B3			
Length km	2.1				1.4				1.2			
Stream Width (m)	2.5				5				12			
Average flow	0.3-0.6 m^{3}s^{-1}				0.3-0.6 m^{3}s^{-1}				2.0-2.8 m^{3}s^{-1}			
	Air C^0	SE	Water C^0	SE	Air C^0	SE	Water C^0	SE	Air C^0	SE	Water C^0	SE
1998	18	3.6	18	3.1	18	2.9	18	.97	17	3.1	15	1.5
2000	19	2.9	17	1.1	17	1.8	17	1.5	16	3.1	16	1.5
2013	18	2.3	18	1.1	19	3.2	18	1.3	19	3.0	19	2.9
2014	20	1.1	20	1.6	19	2.0	19	2.6	19	2.9	19	3.0
2016	17	2.3	16	3.1	18	3.2	18	1.3	18	3.2	18	3.5
2018	19	2.7	18	2.0	19	3.2	17	1.3	19	3.1	18	1.5

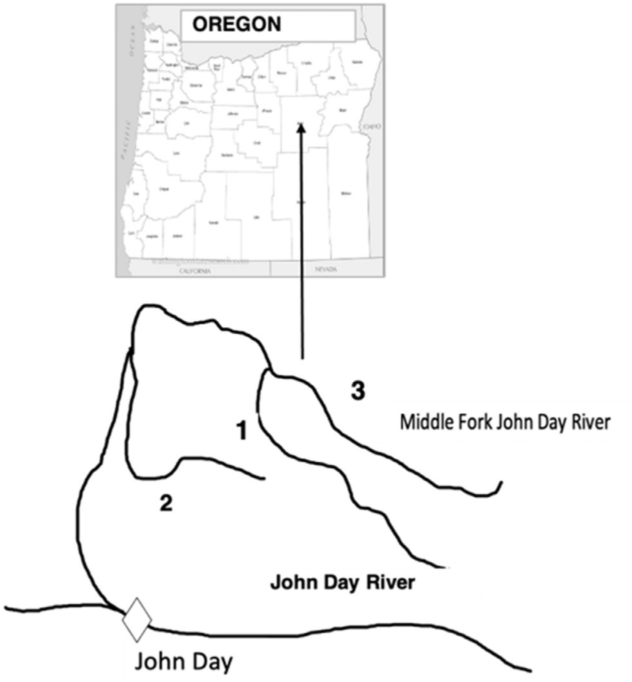

Fig. 1. General location of the study sites located north of John Day, Oregon.

composed of grand fir (*Abies grandis* [Douglas] Forbes), Douglas fir (*Pseudotsuga menziesii* [Mirbel] Franco), and Pondersoa pine (*Pinus ponderosa*, Douglas). Sites 1, 2, and 3 have varying amounts of riparian overstory vegetation composed of black cottonwood (*Populus trichocarpa* T. & G.), willow (*Salix* spp. L.), thinleaf alder (*Alnus incana* [L.] Moench), and Douglas hawthorne (*Crataegus douglasi* Lindl.). Understory vegetation adjacent to the streams was dominated by Torrent sedge (*Carex nudata* W. Boott), reed canarygrass (*Phalaris arundinacea* L.), and associated obligate and facultative species. Low-elevation lands are sagebrush steppe with agriculture croplands occurring on the floodplain and terraces adjacent to the streams. Average annual precipitation measured at 1 260-m elevation (18 yr of climate data) is 470 mm (19 in) with 62% occurring November–March and 22% April–June. Lower elevations average 250–380 mm per yr (Anderson et al. 1998). The average June, July, August, and September monthly temperatures at John Day were 18°C, 18°C, 19°C, 19°C,18°C, and 19°C in 1998, 2000, 2013, 2014, 2016, and 2018, respectively (Center for Forest Conservation Genetics 2019).

Materials and methods

Field studies were conducted at similar elevations (Table 1), on three B3 (Rosgen 1996) eastern Oregon streams, which have a 2–3% gradient, a riffle/glide structure, and substrates dominated with cobble-size material. Sites were randomly selected on three different private properties along three streams. Management practices on the riparian areas were implemented after the period of baseline data collection to manage land with regard to the Oregon 18°C maximum 7-d running average temperature standard intended to protect salmonid habitat.

The management practice implemented on Site 1 consisted of excluding livestock from riparian vegetation through the construction of a 5-strand corridor fence (10.6 m on each side of the stream) with water gaps. The adjacent terrace continued to be grazed as part of a managed rotation grazing strategy. Sustainable practices on Site 3 continued an established rotational grazing system on irrigated pasture containing riparian vegetation. In addition to traditional fencing, electric fencing was used to enhance the management of forage consumption and growth within irrigated units. Site 2 was managed for irrigated hay and pasture production. A managed rotation grazing strategy was employed by the landowner providing late season grazing access.

Riparian shrubs were observed (Larson and Larson 2019) within 50 randomly located 1-m^2 plots at the bankfull location along the stream channel of each site. Site 1 had 90% shrub occupancy (multiaged), Site 2 had 88% shrub occupancy (multiaged), and Site 3 comprised mature Douglas hawthorne (*Crataegus douglasi* Lindl) and black cottonwood (*Populus trichocarpa* T. & G.) trees occurring in $<$ 2% of the plots. Sites 1 and 2 had mature shrub heights (willow, alder, and hawthorne) of 4–7 m, whereas mature tree heights on site 3 could reach 20–25 m.

Two Stowaway temperature loggers (Onset Computer Corp., Pocasset, MA) were randomly placed at each study site to measure water and air temperature. Water loggers were placed in a well-mixed stream flow, and air loggers were placed in a shaded area near the water logger deployment area. Stowaway temperature loggers have a manufacturer specified accuracy of ± 0.2°C. Each logger was set to document the air and water temperature at 1-h intervals throughout the time they were deployed. Air temperature was used as an index of the thermal environment of the watershed and was used to calculate the thermal gradient (Kirkpatrick and Wheeler 1995) between the air and water at each hour, which influences the rate of streamwater heating and cooling. Accumulated degree hours (Richardson and Leonard 1980; Miller and Donahue 1990) were calculated for both air and water temperature data sets for each day between 5 a.m. and 5 p.m. Pacific Daylight Time (PDT) (Larson and Larson 2001; 2003).

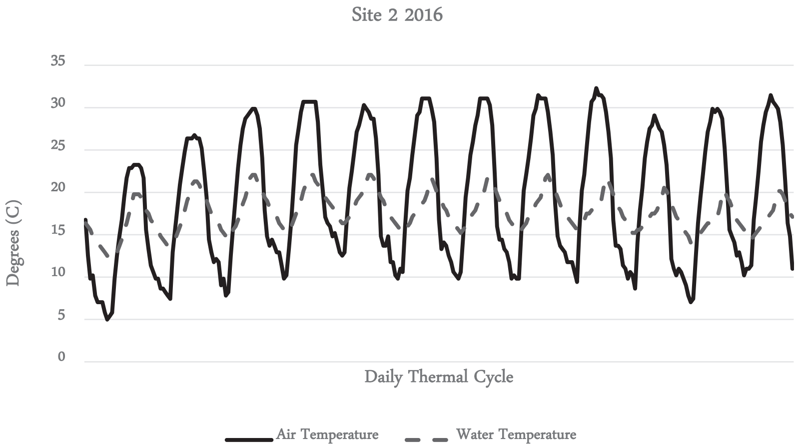

Fig. 2. Periods of energy gain and loss in air and water temperature over a 12-d period in August 2016 on Site 2.

Accumulated degree hours were calculated using the following equation:

$$ACDH = \sum_{i=1}^{P} T_i \qquad (1)$$

where $ACDH$ = the accumulated degree hours for the period of the day being studied, p = period of accumulation = the number of hours per day being studied, and Ti = the temperature of the thermal body for hour i of the study period.

Linear regression equations were calculated for each daily heating period to provide a time average of the thermal response of the air and water rates of increase recorded by the data logger. The data were then grouped by site, year, and 15-d periods and averaged for each stream site. Each property was tested for significant differences using ANalysis of VAriance (ANOVA) between sites to investigate patterns influenced by different land management practices. All statistical comparisons were conducted at $P \leq 0.05$.

Results and discussion

Heat is energy that flows between a body of water and its environment by virtue of the temperature difference that exists between them (Kirkpatrick and Wheeler 1995), which is a gradient that establishes the rate at which stream temperatures increase or decrease. A number of studies have demonstrated that stream temperatures follow and lag behind air temperatures (Edinger et al. 1968; Larson and Larson 2001; Borman and Larson 2003). The large reservoir of air over rivers and streams has a direct influence on the rate of heating and cooling. Water temperatures are impacted by that environment and are reflected in the mean water temperature, as well as the upper and lower temperature limits that water can achieve.

Table 1 displays the average daily air and water temperature during July–August at each study site for the annual periods 1998, 2000, 2013, 2014, 2016, and 2018. The summertime mean temperatures for air and water were not significantly different during each time period through the 20 yr regardless of land use activities. Within each period, mean air and water temperatures were near or within 1–2°C, indicating that equilibrium conditions were being approached through the study period. Edinger et al. (1968) and Adams and Sullivan (1989) reported that the influence of atmospheric conditions increases as stream temperatures approach equilibrium conditions. Adams and Sullivan (1989) also noted that mean daily water and air temperatures will be similar as water temperatures come into balance with the daily pattern of the thermal environment. In this study, sites were located in broad valley bottoms at midelevations within each watershed and did not receive significant cold-water inputs. This suggests that weather would be strongly associated with water temperatures and that mean air and water temperatures would be similar in these stream segments and downstream. These results also indicate that the management practices implemented at each site were ineffective in changing the thermal environment and the pattern of energy exchange in which the streams occur. Fig. 2 graphically illustrates periods of energy gain and loss in air and water over a 12-d period in August 2016 on Site 2. The figure illustrates the daily adjustment of temperature patterns in both thermal bodies as the mean values for air and water continually move toward equilibrium.

Table 2
ANalysis of VAriance (ANOVA) comparison of mean rates of temperature increase (5 am and 5 pm PDT) at the three study sites averaged by each year shown.

	Rates of Temperature Change		
Sites	1998	2013	2018
Site 1	0.79 a[1]	0.87 a	0.71 a
Site 2	0.76 a	0.85 a	0.78 a
Site 3	0.83 a	0.75 a	0.73 a

[1] Similar letters within columns are not significantly different (p≤0.05).

As stated earlier, a number of studies have observed that stream temperature patterns closely follow and lag behind air temperature patterns, which has led them to describe the local air temperature as the single most important parameter associated with daily mean stream temperature (Bartholow 1989; Sinokrot and Stefan 1994; Lewis et al. 2000). The relationship of air and stream temperatures between 5 a.m. and 5 p.m. PDT at the three study sites is illustrated for 1998, 2013, and 2018 (Table 2). The results show that stream temperature patterns followed the pattern of air mass heating and cooling, and when weather conditions changed, the fluctuations remained consistent with the natural thermal cycle. There were no significant differences between rates of heating at the study sites between the yr 1998, 2013, and 2018. The pattern of nonsignificance between rates of heating seen in Table 2 was observed across years. The range in heating rates observed across the 20-yr period indicates that heat exchange hour to hour during a daily heating period between air and water occurs as a consistent rate as the water flows past the thermistor.

The pattern of degree accumulations observed in the daily heating and cooling cycles of streams is similar to those reported by Larson and Larson (2001). In that study, land use influences of grazing, no grazing, and hay production were not sufficient to cause differences in water temperature increases during periods of heating, rates of heating, or diurnal fluctuations between sites at similar elevations. These results suggest that a management practice would need to overcome the thermal inertia established by the pattern of the air mass to effect temperature change.

Gregory et al. (1991) reported that riparian canopy and shade are critical factors in determining the heat input in a given reach of stream. Beschta et al. (2003) used energy balancing models to speculate that reductions of shade along a channel would result in increased summertime maximum temperatures. Assumptions that stream temperatures can be controlled through shading regimes and woody vegetation have daunted land owners simply because of the limited studies that have addressed the natural thermal cycling (Larson and Larson 2001). In amenable contrast to the modeling predictions, Larson et al. (2003) provided a mathematical derivation for the distance river water traverses given certain physical stream properties for a 1°C cooling event. The results determined that water cannot cool or heat over short distances and time scales, because the rate of energy transfer would have to be extraordinarily high (Larson et al. 2002). The energy balance modeling premise was negated because under such scenarios a stream in full sunlight would need to be “hot” to the human touch while in shade water would be “cold” to the touch.

Air and water temperatures were observed through the day to monitor energy changes at each site. In this study, application of the degree hour accumulations provided an objective and accurate assessment of the thermal cycle at each site. Thermal cycles are best explained through the Laws of Thermodynamics (Kirkpatrick and Wheeler 1995), which describes the energy exchange between different substances established by the thermal differences between two masses. The thermal difference between air and water temperature at the stream sites drives the rates of temperature change from the high concentration to the low concentration, such as the water-to-air interface. Reliance on a maximum 7-d moving average precludes the effectiveness of applying an objective determination of a temperature impaired water body.

Implications

During the late 1990s, researchers observed that stream temperature data needed to be consistent so that agencies could benefit from the collections and comparisons could be made between years and sites (Essig 1998). Using degree hour accumulations to assess the rates of temperature change has provided a repeatable and consistent method through many years to compare annual or weekly thermal cycles. The difference between air and water temperature (thermal gradient) influences the rate at which the water will warm or cool. The smaller the differences are between air and water temperature, the longer it will take for the water to heat or cool. Generally, water at higher elevations accumulates energy at a different rate than those at lower elevations (Larson and Larson 2001). Higher elevations have lower water temperatures at sunrise and greater average gradients during the day. Lower elevations have warmer water, but they have warmer air temperatures on a daily basis. Understanding the differences in ecological site potential has a direct impact on the ability of land managers to mitigate stream temperature. Sustainable management practices intended to mitigate water temperature need to overcome the thermal inertia established by the diurnal pattern of the air mass to effect water temperature change. The closer the system is to a thermal equilibrium, the more difficult it becomes for land management to bring about thermal corrections in a stream.

Temperature is a central concept in thermodynamics, and thermometers are based on the zeroth law of thermodynamics. Application of thermodynamic principles to stream temperature data being measured with thermistors provides a cost-effective ubiquitous method for describing stream temperature cycles regardless of where the study sites are located. Researchers need to be able to explain variations in thermal cycles using terms and conditions that are common to all streams in order to differentiate the impact of thermal environments.

Declaration of Competing Interest

The research and preparation of this article are a personal endeavor. The study design, the collection, analysis and interpretation of data, and writing of the report did not involve any other funding source.

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