Principles Involved With Prediction of Stream Temperature

Introduction

On May 5th, I met with Adam Stebbins and DEQ staffers Ryan Michie, Chris Bayham and David Waltz at the Benton County offices near Avery Park. Benton County is evaluating projects with watershed councils and examining ways of "improving" stream resources by protection measures.

Emphasis in watershed council projects addresses temperature issues. In the Marys River Watershed, concern is for discharge of warm waters into the Willlamette R. the Alsea Watershed Council is more concerned with issues dealing with a cold-water fishery, primarily salmon. During this meeting, Ryan presented a power point talk dealing primarily with interaction of streamside buffer features and influence on temperatures of relatively large rivers, with emphasis on eastside conditions. I was there to share some information gained in 20 years of detailed studies of timber effects near streams and how buffer design influenced warming/cooling of streamwater in harvest units and downstream. The following summarizes what I learned from DEQ and some of the principles emerging from our research that addresses some of the DEQ issues.

The DEQ is a regulatory agency. Among its responsibilities are the establishment of standards and guidelines for water quality in the waters of this state, including chemical hazards and stream temperatures. They have responsibility for establishing temperature standards for various fisheries, and this discussion concentrated on possible roles of elevated headwater stream temperatures as persistent heat sources, processes leading to warming and cooling, persistence of accumulated heating pulses, and other temperature-related impacts of anthropogenic origin.

The following topics were addressed:

A. Factors involved in stream warming
   1. Direct radiation
   2. Stream depth and velocity (time of exposure and volume heated)
   3. Air temperature, including rise in air temp with lapse rate, drop in elevation
   4. Buffer design, location of sources of shade; features of shading cover
   5. Time of summer, i.e discharge, sun angle and day length

B. Factors in cooling of streamwater; evidence of cooling
   1. Outgoing radiation—net loss of heat
   2. Transpiration by phreatophyte cover and removal of water at the warmest time of day—net loss of warmed waterbut not nighttime cool water

3. Springwater replacement of transpired water in maintaining discharge; turnover of volume
4. Evidence of rapid loss of daily mean heat pulses downstream from an energy source in proportional mirror-image of upstream heat rise
5. Simultaneous occurrence of peak temperatures along the full length of a stream rather than temporal occurrence depending on distance downstream from a heat source

C. Factors involved in degree of influence of small streams on rivers
   1. Ratio of release of dams to baseflow in Willamette River system
   2. Volume of Willamette R. water in late summer today vs. pre-dams
   3. Comparison of current maximum temperatures in the Willamette River compared with those before dams were installed and flow timed by planned releases
   4. Loss of most of discharge through phreatophytes before water reaches the river
   5. Decrease in discharge per km^2 of basin as streams pass from headwater to larger streams (also see item 4)

D. Biological consequences of temperature shifts
   1. Range of temperatures leading to variation in growth as a function of food supply (Brett, 1956)
   2. Placement of regulatory ceiling at a level that probably reduces productivity by depressing season-long temperature below optimum; integration reducing the value of spring and fall growth periods.

E. Not discussed
   1. Factors determining equilibrium temperature of streams/rivers
   2. Dissipation of energy generated by turbulence

A. **Factors involved in stream warming**

Radiation. By nearly all accounts, the primary factor in the warming of streamwater is direct radiation on open water. Our data make this clear, and are supported by an abundant literature.

Our data indicate that radiation-induced warming is quantitative with the cumulative exposure of water moving through unshaded reaches.

Depth and velocity. Shallow water warms faster than deep.

Slow-moving water may or may not warm faster than fast water, depending on depth; deep holes are typically slow to heat. Very deep holes develop a thermocline that discharges warm water from the upper layer. Impoundments display this behavior; beaver ponds are seldom deep enough to have a distinct thermocline unless discharge is very low.

Beaver ponds increase surface area receiving sunlight and beaver activity reduces streamside cover.

Air temperature heat transfer. There is considerable transfer of energy between air and water, proportional to differences in temperature occur at the interface. This is the primary factor involved in large-scale warming in which whole stream systems warm appreciably during long periods of hot weather. Our research reflects differences of mean daily water temperature more than a degree centigrade from year to year because of differences in week-long hot spells, whether harvesting has occurred or uncut riparian areas.

Air temperature increases with decrease in elevation except in inversions. This is especially visible in forested areas where forested watersheds give way to savanna and prairie conditions in broad valleys.

Air temperature increases near the ground in clearcuts, especially in the presence of red slash. A narrow strip of shrubs along the stream provides shade and likely has a positive influence on the broundary layer above the stream, reducing heat transfer.

Buffers and their design. Buffers have a primary function in reducing radiation load on open water. The most critical factor in buffer designs, in order, are apparently: continuity in providing shade between 9 AM to 6 PM shadows over open water. Conifers have denser canopies, hence provide some increment of protection, but gaps in cover are more of a problem than density of crown. Lean of hardwoods, e.g. alder, may allow the sun to shine beneath the crowns onto water. In this instance a south-side buffer may need to be wider than 40 feet to provide adequate cover. Buffer cover that does not interrupt sunshine directly on the water has little effect on the stream. When there are gaps in original standing trees on a sun-sided buffer, there is merit in leaving trees further from the stream to intercept radiation. Height of these trees may need to be greater than that of the sun-sided buffer, in general.

There is limited evidence that buffers wider than 50 feet may provide detectable improvement in radiation control. This may be a statistical matter based on variance in continuity of the near-stream cover; gaps allow radiation. Removal of all buffer cover but shrubs will lead to a period up to a decade to re-grow continuous shade on the water, depending on width of stream requiring shadows across the channel. In streams up to two meters wide, protection a salmonberry cover on the streambank is likely to restore shade in very few years.

Much has been said about wide buffers and their benefits. (See section on stream productivity). In general, sources of future woody debris nearly all come from trees growing within 50 feet of the stream, and nearly all of those fall in the face of south-southwestern gale winds. North banks furnish little LWD.

Most buffers below 1500 feet elevation are dominated by hardwoods, primarily red alder and bigleaf maple. Neither species provides durable wood but both produce leaf litter readily decomposed so as to produce mycelia for benthic insect consumption. Durable woods, in declining order, are western redcedar, Douglas-fir and Sitka spruce; hemlock and true firs are nearly as non-durable as hardwoods. Stormflows tend to flush out non-durable woods within 2-4 years of deposition. There is justification for regenerating streamside cover with mixtures of Douglas-fir (durable, fast growing) and western hemlock (dense crowns, fall easily away from wind). Western redcedar is at extreme risk of loss from deer, elk and beaver predation. Beavers are a major obstacle to regeneration where stream gradient is less than about 3%. In the absence of beavers, restoration of cover is best provided by clearcutting to within 10 feet of the northern bank, whichever the stream runs, and as close as possible to the south boundary of residual trees, followed by planting very large conifer seedlings and protecting with herbicide.

<u>Effect of summer sun</u>. Sun angle is lower in September than in June or July. A low sun angle is intercepted by shorter trees, but a low sun angle may direct sunshine beneath the tree canopy of a recently exposed boundary stand.

B. Factors in cooling of streamwater—evidence of cooling

<u>Outgoing radiation</u>. Outgoing radiation accounts for significant but very small loss of energy. For practical purposes, the magnitude is irrelevant during the daytime because it is over-balanced by direct radiation. Overhead canopy will reflect outgoing long-wave further reducing the escapement when canopies close overhead. This mechanism may be most important when sun-sided buffers provide enough canopy to screen out direct sun but only intercept a fraction of outgoing long-wave.

Transpiration by phreatophytes. Transpiration is driven by warm air, low humidity and primarily, the energy of direct sun on foliage. Transpiration will remove a great deal of water from free-flowing streams, and nearly all this is during the warmest part of the day. This process is selectively depleting water when it is at its warmest, and is virtually inactive during the cool part of a day.

Diurnal fluctuation in discharge has been reported on our research program for some time (Newton and Zwieniecki, 1998. ODF Final Research Report). We obsereved discharge fluctuations of about 30 percent. Removing water during the warm part of the day increases the ratio of cold water in the day's discharge, hence has a cooling effect on the streambed and sources of hyporheic flow. Perhaps more importantly, it decreases the probability that a given molecule of water will travel very far, whatever its temperature. Transpiration will occur wherever trees with certain attributes of root structure have access to available water; red alder is perfectly adapted because of straw-like structures on roots that have about 10% of the resistance to flow compared to normal roots. And they produce high leaf areas and have high velocity stem-flow leading to high rates of water demand. When the warm water is so depleted, and daily discharge maintained by springs and tributaries, the portion of cold water is further increased, leading to minimum net warming. And in the process, as water is removed and replaced the probability of any molecule reaching confluence with a major river is reduced very sharply.

There are numerous references to diurnal fluctuation in discharge owing to phreatophytes. In the 1950 and 60s,thousands of acres of salt cedars (Tamarix octandra) were killed/removed in the arid southwest at great cost to conserve river and ditch water.

Dissipation of heat pulses. Our research has demonstrated that heat pulses triggered by direct sun on open water when not buffered rapidly dissipate beneath uncut cover downstream. The degree of dissipation is less than the rate of increase in the sun, but there is nonetheless an accelerated loss of heat in the thousand feet of fully buffered channel downstream from a completely clearcut unit. The rise in temperature is offset by a rapid onset of convergence, gradually fading to merge with the pre-harvest pattern within 2000-4000 feet. When merging is not complete, one usually observes sources of radiation that prolong the persistence of elevated temperatures pending passage through more continuous cover.

Simultanaeous occurrence of diurnal peaks in temperature. There is a strong tendency for peak temperatures in harvested and unharvested reaches to reach peak temperatures within an hour of the same time, regardless of how much temperature has been elevated. Skaugset and his students (2009) have shown that as whole streaks rise and fall in temperature during a sunny day, there is not a strong pattern of a very high peak originating in a shrub-only clearcut persisting as that warm water moves downstream. The peak is detectable, but is a minor part of the heat pulse. This requires examination to distinguish the partial contribution of the daily solar load and the pulses from upstream when water is being depleted by phreatophytes concurrently with the highest rate of warming. To my knowledge, the partial coefficients of the various processes here have not been calculated.

C. Factors involved in degree of influence of small streams on rivers

Ratio of release of dams to baseflow in Willamette River System. Large sums are expended monitoring and providing for precise control of temperature of large river systems. The Willamette River is an example of this. TMDLs are prescribed for tributary streams to minimize the elevation of river temperature. While the principle makes sense where there has been a history of elevated anthropogenic water impacts, the Willamette is an odd case because it may well be substantially *cooler* today than previous to World War II. Before dams were constructed, this river fluctuated greatly in discharge, ranging from many exposed gravel bars in summer to large-scale floods in winter; temperature doubtless fluctuated in an inverse pattern. Today, winter discharge peaks are skimmed while impoundments absorb peaks, and summer low flows are maintained at higher-than-traditionally by drawing water from the impoundments to maintain flows for irrigation and domestic use. Indeed, by late August, a very high proportion of Willamette water is from released waters from the cold bottom layers of Corps of Engineering impoundments. The very small percentage of water that enters the Willamette from small tributaries, and the small fraction of those streams which, at the confluences, reflects effects of upper-reach land clearing, virtually eliminates the chance of warming the river. Where such influx might occur, it is doubtless overcome by small increases in release from dams.

Volume of river water in late summer vs. pre-dam periods. The time when warm water entering a large river from small tributaries might have been a problem with water temperature would have been when pre-dam conditions prevailed, leading to lack of summer releases that augment discharge. The enhanced summer discharges today are predictably insulated against harmful levels of increase, and are equipped to add cool water if necessary to meet a particular TMDL.

Loss of most of discharge in tributaries through phreatophytes minimizes chance of violating TMDLs in rivers. This is simply a replacement process. Removing warm water decreases average temperature and also the level of discharge into the river. It also isolates the near-river reach from upper reach by dissipating upper-stream warm water.

Decrease in discharge per km^2 with distance from the divide. Confluences of relatively large streams with rivers are also likely to have the upper reaches isolate from near-river reaches that might introduce warm water to the river. A very small part of upper-reach water survives a number of miles of travel, whether harvested or not. By the time it reaches the river, what flows into the larger river represents discharge largely from low-elevation sources. This phenomenon suggests that if forest practices are undertaken to minimize warming, these measures should be implemented near the confluence.

D. Biological consequences of temperature shifts.

Range of temperatures leading to variation in growth as a function of food supply (Brett 1956). Brett conducted experiments leading to series of curves illustrating that salmonids, including various trout and salmon spp, responded to food supplies differently at different temperatures. At 64^{o}F, young fish showed maximum vigor with good food supply, and productivity that decreased progressively at temperatures above and below that level. The implication of those data is that maximum productivity, if an adequate index of ideal temperature, would be reduced in warmer or cooler water if held steady. The diel patterns of temperature must remain below peaks of 64 F, most of the time water will be in the range of 58-62, where productivity is significantly less than at 64. Not being a fish biologist, these numbers may not reflect other limitations on fish. However when looking at a season-long pattern, most of the season would be held well below optimum for fish if the extremes were kept at or below optimum. If fish were threatened by a few degrees of exceedances, the risk would need evaluation, but it would likely bring season-long vigor to a significant increase.

F. Not discussed

Factors determining equjilibrium temperatures of streams, rivers. Streams are fed in summer by water sources that are increasingly of winter origin in seasons of highest water temperatures. The water enters the stream at 11-12^{o}C. and on encountering air at 12-30^{o} C gradually warms as long as it is exposed to the air. Our streams typically had velocities of about200m/hr in early summer and a fourth or less of that in late summer. The length of time water is exposed to summer air, the closer it comes to the rising equilibrium temperature of the air as it moves to lower elevations. Rivers are exposed to a relatively constant, level course, in which the average air temp is moderated slightly by daily sunshine and nighttime cooling. Rivers tend to flow at higher velocities reflecting their greater mass, hence lower internal friction, and these factors tend to smooth out further changes as it moves toward the sea. This "equilibrium" temperature will vary, but will be quite even for log reaches. Moreover,as tributaries converge with main stem rivers, they are exposed to the same set of energy sources and sinks, hence will tend to merge toward river conditions. Thus, at the confluences, the tributary is likely to be adapting to the river equilibrium before confluence occurs.

Dissipation of energy generated by turbulence. The inertia and viscosity of water are the only factors that resist flow of water moving down a slope. Overcoming these resistances requires energy, and releases some energy as heat that warms. In addition to this, the same principle applied to streams flowing down a mountain as that applied to penstocks that drive a generator that generates electrical energy. A pound of water falling a thousand feet generates a thousand foot-pounds of energy, which is quite a lot. It converts potential energy to kinetic energy, which results in release of heat. These small factors are inescapable, but are often ignored when determining influences on water temperature. Stream gradient and bottom roughness are used in computation of energy release.

Hyporheic flow. Water that moves into gravel or some conduit other than the open water channel of a moving stream is included in hyporheic flow. Such water may travel beneath a gravel bed or beneath an off-channel gravel bed, moving slowly because of resistence to flow in that matrix. This has often been described as having a cooling effect on streamwater. Care should be taken here. If this water originally came from the stream being monitored, it is the same kind of water as was flowing on the surface. Its temperature when it goes below surface will be approximately what it comes up with, so its effect may be slight warming or slight cooling. It probably will not be greatly different from the source that went under the stream bed.