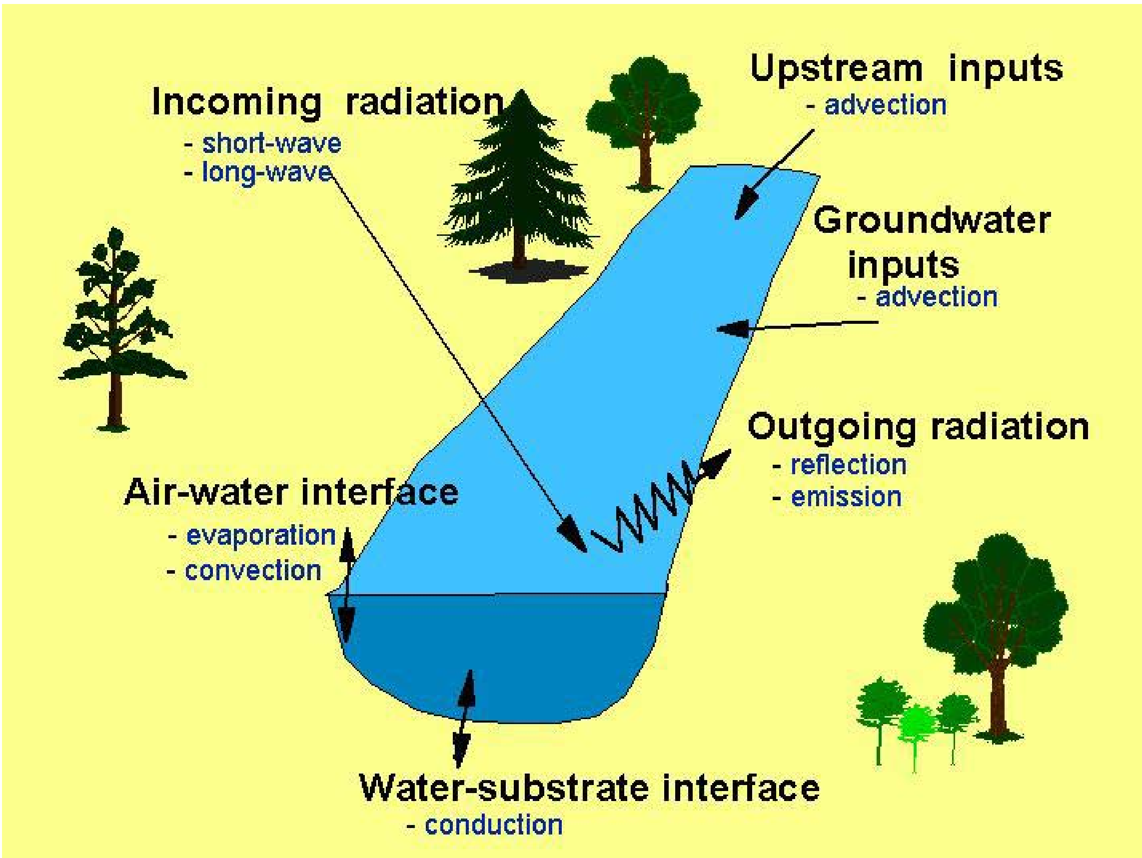
# Summary Report

## CMER/RSAG Temperature Workshop - 2001

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***prepared for***

**Washington Department of Fish and Wildlife**
**Olympia, Washington**

***prepared by:***

**EDAW, Inc.**
**Seattle, Washington**

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## Executive Summary

The purpose of this report is to summarize the proceedings and discussion from two workshops on the subject of heat transfer processes in forested stream environments. The workshops, held in Lacey, WA in February and May of 2001, were organized as part of the Cooperative, Monitoring, Evaluation, and Research (CMER) program, and sponsored by the Riparian Scientific Advisory Group (RSAG).

The goals of the Temperature Workshops were to identify where scientific consensus exists and where it is lacking on **heat transfer processes in forested watersheds**, to provide overviews of past and current research, and to identify future priorities based on stakeholder review of this information. Specific topics addressed included:

- The effects of direct **solar radiation** to surface waters and the cumulative effects of heating from upstream sources;
- Currently used **temperature models**, addressing their inputs, strengths, and weaknesses;
- Heat transfer processes via **groundwater**; and
- Heat transfer processes via **microclimate** conditions (both in the riparian zone and over the stream).

**Recognized scientific leaders in current research efforts were identified and invited as panelists in the workshops. Invited panelists included Dr. George Ice, NCASI (who addressed solar radiation inputs); Dennis Schult, Western Watershed Analysts (who discussed current temperature modeling efforts); Dr. Patricia Olson, Pacific Watershed Institute (who addressed groundwater inputs); Dr. Sam Chan, PNW Lab/USFS (who addressed microclimate conditions in riparian areas); and Dr. Sherri Johnson, OSU (who addressed microclimate effects on stream systems).**

**Areas of Consensus Among Panelists.**

**Solar Insolation.** The panelists noted that the best science to date has confirmed that solar insolation (i.e., direct solar radiation to the water's surface) is the dominant source of heat energy to surface water. Although other heat sources received considerable attention in recent years, validation of these effects is lacking.

**Microclimate.** Although older reviews on water temperature frequently refer to microclimate, successful measurement of this effect on surface water temperature has been elusive. In the past four years, a number of careful studies have taken advantage of the availability of reliable low cost submersible data loggers to isolate the microclimate effect. These data loggers should be reliable enough to detect differences in water temperature 0.5 centigrade units or less. These studies (Brosofke et al 2000, Johnson and Jones 2000, James pers. comm.) have not been able to measure a microclimate effect on water temperature where there was a buffer 15 meters (50 feet) wide or greater. Where buffers are narrower or absent, it becomes impossible to separate the microclimate effect from the more significant solar insolation effect.

The microclimate hypothesis suggests water temperatures will always move towards equilibrium with the surrounding air. Panelists noted that this was still a fundamental fact. However, elevated air temperature occurs only during the middle of the day. Air has a significantly lower heat capacity than water, thus it takes significant time for air to bring a body of water into equilibrium. Furthermore, microclimate effects from timber harvest are a combination of three effects; higher mid-day air temperatures, lower mid-day humidity, and higher wind speeds. The latter two effects combine to increase evaporation from the water's surface, which has a cooling effect on water temperature.

**Solar Tracking.** Several panelists suggested that a better measure of solar insolation would to measure the shade in the path of the summer sun, i.e., solar tracking, rather than measuring the shade from the entire 'view to sky'. The current board manual densiometer method assumes the latter.

**Groundwater.** More research is needed to determine forest practices induced groundwater effects on surface water temperature. At this time relatively little is known with certainty.

**Headwater Temperature Transfers.** Panelists agreed that surface water temperature in headwater streams did re-establish temperature equilibrium with air upon re-entering shaded stream reaches The distance and time that it takes to re-establish equilibrium is a function of many variables.

**Areas of Non-Consensus.**

There were no major areas of non-consensus among the panelists.

**Future Research Priorities.**

**Solar Insolation.** No future research is needed to validate the fundamental effects of solar insolation.

**Solar Insolation Measurement**. Research is needed on the most effective measure of solar insolation. Current rules require a densiometer, which is time consuming to use and readings are subjective. In recent years, there have been a number of additional tools available that appear to be more precise and eliminate user subjectivity. Research into the utility of these tools for research measurements and rule implementation would be desirable.

**Solar Tracking.** Research on this subject as it applies to forest channels is sparse. If solar tracking proves to be a better predictor of water temperature response, this would create flexibility to manage for other riparian functions on the north bank of stream channels. Evaluation of tools for measuring shade along summer solar pathway is needed. This is a moderate priority for research.

**Headwater Temperature Transfers.** Additional research is needed to validate the distance and/or time needed to achieve equilibrium with surrounding physical conditions. This is a moderate priority for research.

**Microclimate.** In light of recent findings and current riparian buffer requirements, additional research on the effects of microclimate on water temperature is a low priority. It may be worthwhile reviewing the scientific literature in several years. The data logger technology will likely facilitate additional scientific publications.

**Groundwater effects.** Research on groundwater is in a very early phase of development. Both the theory and field methodology need development. A workshop discussion group identified that need for a conceptual model of heat transfer to groundwater, and then from groundwater to surface water. The model will be used to identify priority areas for initial research. This is a high priority.

**Eastern Washington Nomograph.** There was a broad consensus that the eastern Washington nomograph that is currently in the Board Manual should be revised using current datasets. If possible, a model that considers more that elevation should be developed. This is a high priority

**Western Washington Nomograph**. With the current 50 foot core zone and an additional inner zone, the western Washington nomograph is not likely to see much use, and thus, it is a low priority for research.

**Hyporheic Exchange**. Initial research by Johnson and Jones 2000 suggests that hyporheic heat exchange in alluvial streambeds and valley floodplains could have a significant effect on surface water temperature. It appeared to be considerably more significant than the microclimate effect. Other studies also suggest this effect may be under-rated. If significant, the restoration of bedrock channels that were historically alluvial channels, and the restoration of incised channels may be legitimate methods for water temperature restoration. Although this in not a Schedule L-1 question, further research on this subject may be worth considering.

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### Appendices

The appendices contain about 100 pages of material distributed during the workshop. Paper copies of these appendices are available upon request from either Heather Rowton at the Washington Forest Protection Association (hrowton@wfpa.org) or Mark Hunter at the Washington Department of Fish and Wildlife (huntemah@dfw.wa.gov).

**The panelists have requested that these appendices not be cited directly or reproduced in a published document without permission.**

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# 1.0 INTRODUCTION

The purpose of this report is to summarize the proceedings and discussion from two Temperature Workshops held to address the subject of heat transfer processes in forested stream environments. The workshops, held in Lacey, WA in February and May of 2001, were organized as part of the Cooperative, Monitoring, Evaluation, and Research (CMER) program, and sponsored by the Riparian Scientific Advisory Group (RSAG). The workshops were organized as part of the larger effort associated with the Forest and Fish Report (FFR), a Washington State legislative bill passed in May 1999 with the goal of bringing Washington State forest practices into compliance with the Endangered Species Act (ESA), Clean Water Act (CWA), and Indian Treaty Rights.

This June 2001 version is a revised draft, representing review and revisions by workshop panelists and RSAG committee members. A final version will be prepared and distributed based on any additional review and comments.

## 1.1 Objectives and Goals

The goals of the Temperature Workshops are to identify where scientific consensus exists and where it is lacking on **heat transfer processes in forested watersheds**, to provide overviews of past and current research, and to identify future priorities for funding and research based on stakeholder review of this information. The Workshops served foremost an educational purpose, intending to provide stakeholders a common basis of understanding in order to implement the FFR. Discussion and dialog that occurred during the Workshops also served as the starting point for additional research associated with CMER and FFR.

The objectives of the workshops were to establish and articulate to stakeholders what is known on significant heat transfer effects that may change surface water temperature in forested basins, with a focus on the inputs of solar radiation, heat loss from surface waters, microclimate effects, and groundwater and hyporheic zone processes. The cumulative effects of forest practices on surface water temperature were also examined.

As noted above, one of the primary purposes of the Temperature Workshops was educational – that is, attempting to establish a common understanding among stakeholders. Discussion was focused on identifying the following:

- Areas of consensus and non-consensus
- Overall priorities for future research

The primary resource topics addressed in the workshop format were organized as follows:

- The effects of direct **solar radiation** to surface waters and the cumulative effects of heating from upstream sources;

- Currently used **temperature models**, addressing their inputs, strengths, and weaknesses;
- Heat transfer processes via **groundwater**; and
- Heat transfer processes resulting from changes in microclimate.

Recognized scientists were identified and invited as panelists in the workshops. Invited panelists included Dr. George Ice, NCASI (who addressed solar radiation inputs); Dennis Schult, Western Watershed Analysts (who discussed current temperature modeling efforts); Dr. Patricia Olson, Pacific Watershed Institute (who addressed groundwater inputs); Dr. Sam Chan, PNW Labs/USFS (who addressed microclimate conditions in riparian areas); and Dr. Sherri Johnson, OSU (who addressed microclimate effects on stream systems).

Prior to the workshops, RSAG presented the panelists a list of key questions that their presentations should ideally address, focusing on current theory, uncertainty/variability, and applications and alternatives. These lists of questions are included in appendix material included with this Summary Report.

## 1.2 Workshop Format & Participants

The Temperature Workshops were organized by RSAG members Mark Hunter (WDFW), Steve McConnell (NW Indian Fisheries Commission), and Domoni Glass (Watershed Professionals Network). The Workshops were open to the public, and all Forest and Fish Report stakeholders were invited. Attendance ranged from approximately 45 to 55 people for each workshop. Stakeholder attendees included representatives from federal, state, and tribal agencies; and the forest products industry. Copies of the sign-in sheets for the workshops' three days are presented in Appendix A.

The first Temperature Workshop was held on February 6 and 7, 2001, at the U.S. Fish and Wildlife Service (USFWS) Sawyer Hall in Lacey, Washington. The first Workshop was scheduled to address the effects of solar radiation, temperature modeling efforts, and groundwater inputs. The second Workshop was held May 1, in the same location, and was scheduled to discuss microclimate effects, as well as continue the dialog on synthesis and cumulative effects. The original intent was to conduct a single workshop, covering all resource topics in a 2-day meeting. However, schedule coordination among participants necessitated a second scheduled date to address microclimate and continue synthesis dialog.

For each resource topic, the overall organization and agenda consisted of the following: (1) an approximately 1.5 hour presentation by the panelist, followed by a short break; (2) a ½-hour question and answer period. Following the three presentations at the February workshop (i.e., solar radiation, temperature models, groundwater), the floor was opened up for discussion, with the goal of synthesizing the information presented. At the February Workshop, these discussions were facilitated by Mike Liquori. Small group discussions were also held to focus and synthesize the material presented. Each group drafted conclusions and these were reported back to the entire Workshop. The May workshop followed a similar format but without a moderator and without small group sessions.

### 1.3 Purpose of this Document

This document was prepared to summarize the results of the presentations and subsequent dialog. It will be useful as a reminder for people who attended the Workshops, as well as a reference document for interested stakeholders who were unable to attend. A primary purpose of the report is to identify priorities for future research efforts based on the material presented at the Workshops and the subsequent dialog that occurred. The document is **not** intended to be a comprehensive account of all discussion that occurred – that is, it is a summary document and not a transcript. Nor is the report intended to resolve all questions or areas of potential disagreement that were raised. As one panelist humorously (but astutely) noted, CMER stakeholders can agree that the earth orbits the sun, but beyond that debate can be assumed. Therefore, the focus of this document is on issues identified by Workshop participants as the most significant and worthy of future efforts.

To meet this purpose, this report is organized as follows:

- Section 2.0 summarizes the key findings of the Workshops, focusing on key issues identified, as well as priority for future funding efforts and research efforts.
- Section 3.0 presents a summary of each of the five presentations.
- Appendix material includes more detailed information related to the individual presentations, such as copies of slides presented, summary analysis prepared by the participants, and bibliographies/reading lists of related topics

The appendices contain about 100 pages of material distributed during the workshop. Paper copies are available upon request from either Heather Rowton at the Washington Forest Protection Association (hrowton@wfpa.org) or Mark Hunter at the Washington Department of Fish and Wildlife (huntemah@dfw.wa.gov).

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# 2.0 Key Findings – Identified Priorities

As the primary "product" of the Temperature Workshops, this Summary Report presents the following: (1) key issues identified by the Workshop participants and stakeholders; and (2) priorities for future research efforts, as well as associated funding. This section of the summary report presents the key findings of the Workshops, based on the discussion among the participants and stakeholders. It was determined appropriate to present these conclusions at the beginning of the Summary Report (rather than after the summary of the scientific presentations), as these identified priorities and key issues are essentially the primary outcome of the Workshops.

Of particular note, there seems to be a solid consensus among stakeholders about what is of importance from a management perspective, as well as what research efforts should be considered priority items, when considering heat transfer processes in forested watersheds. Consensus was frequently not reached on some of the finer points of the technical and scientific discussions, where individual stakeholders often had their own differing observations or perspectives to discuss. However, these disagreements did not extend into what was considered significant from a management point of view; rather, disagreements belonged more to the realm of theory and research.

As described above, scientific presentations were followed by discussion periods, and "break-out" groups to discuss and identify priority items. Prior to the break-out sessions, Mike Liquori prepared summary lists, by topic, of issues that were most discussed or contentious during question & answer/discussion periods. Break-out groups were encouraged to use these summary lists as a starting point and identify the important issues, or to identify other important issues. Groups then reported back to the full participant body, with further discussion occurring to clarify and reach consensus. Priority issues and research agendas are summarized below, based on the Workshop discussions and organized by topic (i.e., Stream Physics, Modeling, Groundwater, and Microclimate).

## 2.1 Priority Issues Identified

### 1. Stream Physics Subgroup

The Stream Physics Subgroup identified the following four priority issues:

- **East Side vs. West Side Streams Conditions** – There was a general consensus that the current models and understanding of stream systems west of the Cascades are adequate for use in management decisions, with primary physical processes fairly well understood; such consensus, however, is lacking on east side stream systems, where conditions and results may differ significantly. Therefore, stakeholders identified an important need to develop a better understanding and design a better model for the east side, incorporating site-specific inputs for such input as shade and stream temperature. In short, a need was identified to build a better eastside model.

Discussion from the larger group on this item noted that a subtask of such an effort would be to better define what data currently being used are a poor fit for the east side, as both elevation and shade levels are model inputs and that these inputs are frequently what differentiate east side and west side systems.

- **Shade Measurement Standardization** – Based on extensive discussion during the Workshops, stakeholders identified a need to standardize shade measurement protocols, especially when using densiometers. Of particular issue is the relationship between solar angle and its correlation with water temperature. As noted and discussed in several of the presentations, there are numerous ways currently being used to measure shade, and these various techniques have their respective strengths and weaknesses. We need to develop a more standardized way to use the densiometer, as well as determine if it is an accurate measurement of effective shade. In short, the stakeholders would like better standardized shade measurements.

  A question from the larger group involved why we are continuing to use densiometer measurements if they don't appear to be an effective tool for measuring shade. Subsequent discussion noted that there is no such agreement that densiometers are NOT an effective tool; rather, the goal would be do additional research on the accuracy of densiometer readings, perhaps comparing measurements with other currently available methods. We need to determine if we need a better tool. In summary, it is important to determine if measurements taken from densiomenters are reproducible, and if such data are an adequate measure of effective shade. Note that the issue of measuring effective shade came up during several dialogs held over the course of the three days of the Workshops – it is a cross-disciplinary issue of primary concern.

- **North Side Buffers** – Stakeholders would like to pursue the idea of removing or reducing shade target levels on north side buffers, allowing these riparian areas to be managed for other objectives (e.g., LWD, etc.) depending on site-specific conditions. Such a change in policy would provide greater management flexibility not tied to a potentially irrelevant shade target; as evident from current scientific research, empirical evidence shows that north side buffers do not affect stream temperatures in the Pacific Northwest. In short, the stakeholders would like to explore alternative north side buffer options.

- **Headwater Stream Temperatures** – Stakeholders identified the need to develop a clear protocol for measuring temperatures in headwater channels. Dr. Ice's presentation noted differences among currently used techniques which may lead to differing results. A single measurement might not accurately reflect average conditions. Stakeholders are therefore concerned with developing a protocol to obtain more accurate and useful measurements. In short, the stakeholders would like to develop a protocol for measuring headwater temperatures.

**2. Temperature Modeling Subgroup**

The Temperature Modeling Subgroup identified the following two priority issues:

- **Evaluate How Existing Models Relate Specifically to FFR Applications** – The stakeholders would like to see a project to evaluate the application of the existing models (see section 3.2 for a list of the specific models considered) to a suite of forest and fish management applications (e.g., modeling effective shade; modeling as a diagnostic tool for sensitive applications such as bull trout; alternative plans for riparian harvest; modeling application to evaluate type N watershed buffer scenarios). The existing models are available and it wouldn't be too difficult a task to conduct such an evaluation. There was general consensus that it would be valuable to examine the various models and evaluate/compare them.

- **Evaluate the Existing Nomograph** – The stakeholders recommended conducting a project to examine the existing model (i.e., the nomograph). It was noted that some further diagnostic work would be valuable to determine why the model doesn't seem to work or fit certain site-specific conditions, such as on some eastside stream systems. Note that this item overlaps with the first priority identified above under Stream Physics, and it also relates to the ongoing discussion on what constitutes effective shade. In short, the stakeholders would like to identify situations where the nomograph isn't working and figure out how to address such situations.

  In the larger group discussion, it was noted that we have a huge data set to work with at present, and it doesn't make sense to throw out this valuable resource and start from scratch. Rather, we need to examine the relative strengths and weaknesses of the current model and adjust as necessary.

An additional issue raised during the larger group discussion focused on developing an adaptive management strategy based on incorporating equilibrium temperature and microclimate conditions, and the potential need to subsequently refine the modeling physics based on such factors. It was generally agreed that this issue wasn't discussed in greater detail as it represented more of a monitoring and/or research opportunity and less of a modeling issue.

**3. Groundwater Subgroup**

As described in more detail in Section 3.0, the current research efforts addressing the role of groundwater effects on stream temperature conditions in Pacific Northwest systems are in an early stage of academic and scientific development (that is, relative to stream physics and modeling efforts). The Groundwater Subgroup therefore approached the identification of key issues more as a prioritization of steps necessary to better understand the role of groundwater influences in forested watersheds, with the eventual goal of incorporating such results as appropriate into the management process. Thus, the

Groundwater Subgroup identified the following four-step process as management priorities:

- **Develop a Clear Conceptual Model (Step 1) –** Stakeholders generally agreed that we don't seem to have a current understanding of the specific variables and cause-and-effect relationships linking groundwater inputs and stream temperatures in forested environments in the Pacific Northwest. The current research identifies the important inputs and variables but doesn't provide a model or description that we can adequately understand and hence apply. Ideally, the model would focus on linking groundwater temperature and flow to stream temperature, incorporating other inputs as well (such as solar radiation).

- **Fit the Conceptual Model into a Washington Context (Step 2)** – After developing the initial conceptual model, it will be essential to apply it to the site-specific conditions that occur in Washington State (e.g., shallow soils in upland, deeper in lowlands, account for variations in latitude, etc.) to see if it provides a predictive water temperature response.

- **Identify Areas Where We Need More Data (Step 3)** – During this process, we'll need to identify data gaps and pursue missing information as necessary (e.g., from literature and/or additional field work) so we can better understand how forest management could influence these processes.

  During the larger group discussion, it was noted that there are currently very little site-specific data to work with (particularly for Washington State), and this step will require significant resources.

- **Find and Investigate Sensitive Sites (Step 4)** – We need to gather site-specific data and determine specific areas and sites that we want to further investigate, most likely with a focus on sensitive sites (e.g., bull trout habitat).

## 4. Microclimate Effects and Identified Priorities

Unlike the previous topics, which were discussed at the February Workshop, there were no break-out group discussions at the May Workshop addressing microclimate effects. Instead, after the initial scientific presentations and question and answer period, an informal discussion amongst participants ensued. In short, the informal discussion posed the following main question: recognizing that current scientific understanding demonstrates that microclimate effects on stream temperatures do occur, what priorities should CMER/RSAG consider in terms of future research and funding?

In answer to this question, participants acknowledged that the current riparian buffer requirements on fish-bearing streams appear to provide adequate stream temperature protection relative to microclimate variables such as humidity, wind, and air temperature. Existing research shows that large temperature changes (i.e., more than 1 degree) to stream systems likely do not occur from microclimate effects along streams with riparian buffers. Therefore, it would not necessarily be a high priority for CMER to pursue or fund additional research efforts. Obviously, stakeholders should keep abreast with ongoing microclimate research, and evaluate the need for possible future microclimate related studies.

Dr. Chan also noted that research regarding microclimate effects in riparian areas is generally concerned with much more than stream temperature effects – such as the role of LWD, litter, etc.; in addition, Dr. Chan continually stressed in his presentation and subsequent discussions that the relevance of microclimate research must be considered in the context of physical and ecological functions and processes (such as considering the requirements of various suites of biological organisms – for example, amphibians). While important, these considerations are outside the scope of this Temperature Workshop, which is tasked specifically with examining effects on stream temperatures.

## 2.2 Ranking and Scheduling the Priority Issues

As documented above, Workshop participants identified 10 key issues for CMER/RSAG consideration in prioritization – four key issues for stream physics, two for temperature modeling, four priority steps for groundwater, and no additional key management issues for microclimate. Recognizing the constraints of funding opportunities and scheduling considerations for CMER, it was then necessary to ask three additional questions:

1. Which of these issues are urgent?
2. Which of these issues are important to address at sometime in the future?
3. Which of these issues are linked?

In this management context, "urgent" means those projects that we need to implement on the ground at this time. In addition, it would be ideal to focus on items that can be accomplished in short amount of time and within existing budgetary constraints. Mark Hunter (WDFW) also stressed that in ranking priorities, it was important to consider the effectiveness of current practices – that is, if a technique appears to be effective as currently used, it doesn't make sense to invest scarce resources to attempt to refine it.

Workshop participants generally agreed that all of the priorities identified above are important to address at some time in the future (that's why they were identified as priorities). Based on participant and stakeholder dialog, the following three priority issues were identified as **urgent**:

- **Standardize Shade Measurements**
- **Build a Better Eastside Model**
- **Develop a Clear Conceptual Model of the Role of Groundwater**

Developing an effective shade/densiometer protocol was identified as an immediate action item, as results from this effort will have an influence on other related issues (such as nomograph refinement and developing an eastside model). If densiometer readings are shown to be precise but not necessarily accurate, it might be possible to develop a correction factor. Building a better eastside model was also identified as an extremely urgent item; it would have immediate utility, and stakeholders have been frustrated in the past over what they perceive as a lack of applicability to actual conditions east of the Cascades. Finally, participants agreed that developing a conceptual groundwater model is an urgent item, as we currently lack a basic understanding of groundwater functions and processes, especially in the Pacific Northwest. Groundwater inputs function as the key factor in depressing stream temperatures below air temperature, and we need to develop a better understanding of the physical processes involved.

### 2.3 Issues Discussed but Dismissed from List of Priorities

The priority issues listed and summarized above were culled from a larger list of issues developed to capture significant dialog occurring over the course of the Temperature Workshop. While these other issues raise important considerations, stakeholders eventually dismissed them from this evaluation and prioritization process, often due to lack of significance or relevance to management practices. These other issues are listed below, by topic, in an effort to more completely report and organize the dialog that occurred over the three days of Workshop discussions. Most of the issues are phrased as questions, which the stakeholders then discussed.

<u>Non-Urgent Issues – Stream Physics</u>

- Do we need to identify the role of air temperature? This issue was deferred until the May Workshop on microclimate.
- Can (should) we better define when shade no longer significantly affects stream temperatures?
- What is the role of substrate (sediment size, sorting, etc.) on hyporheic exchange? This issue was deferred to the Groundwater Subgroup. In addition, it was noted that this is primarily a research question, as management practices have limited influence on streambed texture.
- Do we need to better understand how feedback loops (e.g., convection, evaporation, etc.) act to limit thermal accumulation? Again, this issue was deferred to later discussion on microclimate issues.
- Do we need to better understand winter temperatures?

<u>Non-Urgent Issues – Modeling</u>

- Should we develop a monitoring design to calibrate models?
- Should we seek to develop a better groundwater smoothing/mixing model?
- Can we use process-based models to focus on microclimate effects?
- Should we further examine the relationships between solar vs. air temperatures in driving stream temperatures response in process models?
- Should we seek to explain the discrepancy between the use of regional air temperatures vs. local air temperatures in both empirical and process-based models?
- Should we examine the use of process-based models as diagnostic tools?

- How can we use models to address questions related to microclimate?
- Are there specific model assumptions that need to be addressed to build applicability for any specific model?

Non-Urgent Issues– Groundwater

Note: a list of approximately eight research-related questions was developed related to groundwater; these questions focused on the mechanisms and processes by which groundwater temperatures translate to differences in stream temperatures. The questions specifically addressed such elements as depth of groundwater, relevance to forested mountain environments, soil structure, topography, field methods, and recharge. The Groundwater Subgroup recommended that we develop a clear conceptual model addressing groundwater processes as they relate to stream temperatures in the Pacific Northwest, and presented this recommendation as a stepwise process. The questions identified during discussion of groundwater issues would be incorporated as appropriate during this stepwise process.

# 3.0 PRESENTATION SUMMARIES

Section 3.0 presents brief summaries of the individual scientific presentations, organized as follows:

- Section 3.1 summarizes the effects of direct **solar radiation** to surface waters and the cumulative effects of heating from upstream sources, as presented by Dr. George Ice;
- Section 3.2 summarizes currently used **temperature models**, addressing their inputs, strengths, and weaknesses, as presented by Dennis Schult;
- Section 3.3 summarizes heat transfer processes via **groundwater,** as presented by Dr. Patricia Olson; and
- Sections 3.3 and 3.4 summarize heat transfer processes via **microclimate** conditions, as presented by Dr. Sam Chan (addressing riparian conditions) and Dr. Sherri Johnson (addressing effects on stream temperatures).

Each of these panelists provided copies of their presentation materials, which are included in this report as Appendices B through F. This report is intended to be a summary – the reader is referred to the appendices for detailed information. Information presented in Sections 3.1 through 3.4 is provided primarily for context in support of the priorities and key issues identified in Section 2.0.

The summary of information presented here is organized by individual panelists' presentations. In addition, summary & conclusion information, when available, is presented first, with the goal of providing the reader the "take home message" first.

### 3.1 The Effects of Direct Solar Radiation to Surface Waters
**(*Presented by: Dr. George Ice, NCASI)***

## Summary & Conclusions (Key Points):

- Solar heat flux is the major input that raises the stream temperature above the local air temperature.
- Groundwater inflow is the major input that lowers the stream temperature below the local air temperature.
- All other heat flux terms involve both the air and water temperature, so the water temperature is always near the local air temperature.
- Energy transfer between the stream and its local environment always tends to bring the stream into equilibrium, with a zero net heat flux for the day.
- The rate at which stream temperature approaches equilibrium is strongly influenced by the average stream depth (small streams relax toward equilibrium more rapidly than large streams).
- The slow response of larger streams to changes in the environment make these streams slow to respond to diurnal variations, thus reducing diurnal temperature variations.
- The shade factor, represented by the view-of-the-stream-for-the-sky, Fwsky, is important in determining peak stream temperatures.
- Other shade and cover measures can be used to estimate the role of vegetation in reducing direct solar radiation inputs to a stream.
- Shade from riparian vegetation offers a practical management option to control changes in stream temperature.

In addition to these conclusions compiled by Dr. Ice, he also presented a list of conclusions recently (2000) prepared by the Independent Multidisciplinary Science Team (IMST, an advisory group to the Oregon State legislature). Some of the most relevant conclusions from the expert panel were as follows:

- Solar radiation is the principal energy source that causes stream heating.
- Direct absorption of solar radiation by the stream and the streambed warms water; interception of solar radiation by vegetation reduces potential warming.
- Shading (vegetative and/or topographic cover) reduces direct solar radiation loading and stream heating.
- The factors that human activities can affect to influence stream temperature are vegetation, stream flow (hydrology), channel morphology, and subsurface/surface interactions.
- The influence of vegetation decreases with increasing channel width.
- The type of vegetation and its influence on temperature vary over time.
- Streams tend to heat in the downstream direction.
- Stream temperature tends to move toward equilibrium temperatures based on the energy balance, which is a function of several variables. As these variables

change in time and space, the energy balance and equilibrium temperatures also change.

- It is more efficient ecologically to use shade to protect cool water from warming than to attempt to cool water that has already warmed.
- Vegetation is an important influence on microclimate, which may affect stream temperature if it sufficiently changes the stream environment.
- Riparian vegetation influences other aspects of the thermal environment of streams other than simply intercepting solar radiation.
- The change in temperature is a function of energy input, water surface area, and discharge.
- An increase in the surface area/volume ratio (or width/depth ratio) increases the rate of temperature change when there is a constant input of energy.

## Presentation Summary

Note to the reader – In addition to copies of his slide presentation, Dr. Ice prepared an excellent 30+ page summary of issues addressed in his presentation. The reader is encouraged to review this paper, included in Appendix B. Dr. Ice also prepared specific answers to the "Key Questions" prepared by RSAG, also included in Appendix B.

The focus of the presentation was on solar radiation, the effects of shade, and the causes of temperature relaxation, all related to the overall energy balance. To address these issues, the presentation included the following:

- An introduction to heat balance theories
- More detailed information on forest stream heating
- The role of riparian vegetation and shade
- Relaxation of increases in temperature

## Thermodynamics and Earth/Sun Geometry

Thermodynamics examines energy changes accompanying physical and chemical processes. The first law of thermodynamics relates to the conservation of energy: the temperature change in a stream is proportional to the thermal energy added or removed from the stream. The second law of thermodynamics is that all systems tend to approach equilibrium. Definitions of specific heat, calories, BTUs, heat of fusion, and heat of vaporization were presented.

Understanding earth/sun geometry is critical when considering solar radiation inputs in the Pacific Northwest. The farther north we are from the equator, the lower the maximum angle of the sun hitting the stream. For example, Sacramento is located at $38.5^{o}$N, Salem at $45^{o}$N, and Olympia at $47^{o}$N. Because of its location, the maximum solar angle for Olympia is $66.5^{o}$ (at summer solstice). The maximum solar angle for Sacramento, in contrast, is $75^{o}$, significantly closer to directly overhead. This geometry has important implications for measuring incoming solar radiation and determining the effectiveness of buffers. For example, the higher angle of the sun near summer solstice translates directly into more potential solar radiation inputs to the stream system compared to the wintertime.

In addition, the short-wave reflectivity coefficient (i.e., albedo) changes with solar angle; at an angle of 60 degrees, for example, 5% is reflected, whereas at 30 degrees, 10% is reflected. The lower the angle, the more solar radiation is reflected.

## Forest Stream Heating

Energy inputs and outputs to consider in a stream system include primarily the following: incoming solar radiation (both short-wave and long wave); outgoing radiation (via reflection and emission); stream sensible heat inputs and outputs (via advection); groundwater inputs and losses (via advection); the air-water interface (evaporation and convection); and the water-substrate interface (via conduction). Note – see the figure on the cover of this report. A simplified energy balance is captured in Brown's equation, which considers maximum potential solar radiation input (based on maximum radiation rate, exposed surface of the stream, and time of travel through the exposed reach) and volume being heated. Using Brown's equation allows us to estimate the average net absorbed solar radiation based on time of day and season.

Brown's equation was tested at the Lewiston Idaho Experimental Streams (Brown, 1970), where artificial streams were constructed, including both pools and riffles. In this experiment, 100-m stream reaches were fully exposed, had plastic bottoms, and were designed with a 30-minute travel time. Brown's equation was used to estimate the change in temperature from upstream to downstream. Predictions were accurate to within $1^{o}$F. Obviously, natural systems are more complex and difficult to quantify, but the basic considerations of Brown's equation are still very useful.

Another factor to consider is solar radiation transfer to the stream; water is relatively transparent to shortwave radiation – that is, little radiation is absorbed directly by the stream. However, the streambed can absorb the shortwave energy and transfer it back to the water column via conduction. The effective absorption therefore can be very high (e.g., up to 95%).

Other heat transfer processes to consider include long-wave radiation exchange, heat flux due to convection, and heat flux due to evaporation.

## Vegetation, Canopy Cover, and Shade

Riparian vegetation can block direct solar radiation. The shade factor is represented by the view-of-the-stream-for-the-sky, Fwsky, with a value of 1.0 Fwsky representing fully exposed and 0.1 Fwsky indicating heavily shaded. The fraction of maximum solar flux increases proportional to Fwsky; for example, a Fwsky of 0.2 corresponds to a 30% fraction of maximum solar flux, whereas a Fwsky of 0.6 corresponds to approximately 80%. In addition, the shading influence is greater when the solar angle is lower.

Of particular note, east to west flowing streams are exposed differently than north to south flowing streams. For example, in an east to west flowing stream, riparian vegetation on the north streambank blocks virtually no direct solar radiation.

Dr. Ice presented information on relevant case studies that examined the relationship between stream temperature changes and direct solar radiation. Experiments covered included the Alsea Watershed Study (Moring 1975), and the HJ Andrews Experimental Watershed. In the Alsea Study, Needle Branch was clearcut down to the stream in the winter and spring of 1966. In 1967, the harvest units were broadcast burned and the stream was cleared of woody debris. This resulted in an extremely exposed system. In 1967, the high summer temperature was 26.1°C at the gauging station, and exceeded 30°C in the upper watershed. Temperature changes over time were examined as regrowth occurred in the riparian zone. By 1973, shading from the young riparian alders had returned high summer temperatures almost to to pre-harvest levels. It should be noted that at this time, upslope forest regeneration in Needle Branch was proceeding poorly, thus microclimate effects from the upslope forest did not appear to be contributing to this temperature recovery.

A similar response was observed in the H.J. Andrews Experimental Forest, where three different treatments were examined (clearcut and burned, no treatment, and 25% clearcut and burned). In these cases, high solar radiation exposure contributed to significantly elevated stream temperatures, with recovery exhibited over time (Johnson and Jones 2000). In general, the response of stream temperatures to increased direct solar radiation indicates that direct solar radiation is the driving factor in increasing stream temperatures.

A recurring point of discussion in the Workshops is the difference between canopy cover and shade. Canopy cover refers to the percent of the sky occupied by vegetation and shade, whereas shade refers to the amount of energy that is obscured or reflected by vegetation or topography. Dr. Ice provided an overview of current measurement tools and techniques, including spherical densiometers, ocular estimates (e.g., computer cards), “moose horn” densiometers, Angular Canopy Density (ACD), solar pathfinder, hemispherical shade photography, and others. The various methods have their respective strengths/weaknesses, biases, correlations, and costs. For information comparing and evaluating these methods (including correlation data), please see Appendix B. In summary, Dr. Ice recommended examing how we quantify canopy cover/shade and determine the effects on stream temperature. Research is needed to determine whether improvements in measurement techniques warrant extra cost and difficulty. This was a recurring theme throughout the Workshops: Can we improve on the spherical densiometer?

Numerous studies have been conducted to examine the role of shade on solar radiation inputs; these case studies have ranged from simplistic and very highly controlled environments to examining more complex, natural systems. In a recent (1999) study, Moore et al. conducted a simplified shade experiment in different water tanks – shallow vs. deep tanks, and shaded vs. unshaded tanks. Diurnal temperature fluctuations measured. The unsurprising results were that deep, shaded tanks heated the least, and shallow unshaded tanks heated the most. In another recent (1998) study, temperature changes in an irrigation ditch were examined, with varying shading levels (e.g., 20, 40, 60, and 80 percent shading). Similar results were documented, with increased shading contributing to less temperature increases.

In another study that more closely approximated a natural stream condition (compared to a water tank or irrigation ditch), another HJ Andrews Experimental Forest study examined the effect of experimentally shading a bedrock stream channel. Over the 200-m reach, maximum stream temperatures decreased with shade, even while air temperatures remained high. Due to rapid travel times within the reach, there was no response for daily mean or minimum temperatures.

In yet another shading experiment, Jackson (2000) examined water temperature effects of blocking solar radiation input with slash (as opposed to live riparian vegetation), and results indicated that slash moderated temperatures, functioning much like live riparian vegetation in preventing temperature increases. A recent study in Maine (Hagen 2000) found that \stream temperature responded to various forms of shading, and showed that topographic shading, vegetation shading, and a stream being subterranean all reduced the effects of solar radiation input into the system.

### Temperature Relaxation in Streams

Dr. Ice noted that much of the information presented so far, including results from the various case studies, examined temperatures in rather conservative, static way; however, temperature is non-conservative in that it is constantly changing and moving toward equilibrium. Larger streams and smaller streams tend to react differently in terms of relaxation, with smaller streams tending to recover more rapidly than larger streams from large temperature increases. Studies have also addressed the temperature-related effects of a clearcut portion of a reach (and hence higher Fwsky), demonstrating that after higher maximum temperatures along those portions of the stream, the temperatures relax toward equilibrium both as a function of time and distance. In short, the temperature moves toward equilibrium after being exposed to higher inputs of solar radiation.

## Questions & Answers, Additional Dialog

- Question/Issue – In Washington's Hoh River, a glacially fed stream system on the Olympic Peninsula, we see a situation where the tributary temperatures average much warmer than the mainstem, in contrast to the "normal" pattern of stream temperatures increasing as they flow downstream. The mainstem average can be 7 degrees, while the tributaries can average up to 17 degrees. What could be the contributing factors? Answer – Site-specific factors would obviously have to be examined.

- Question/Issue – The conclusions presented state that solar radiation is the principal energy source; what about air temperature and the degree to which riparian forest conditions affect air temperature, when shade is held constant? Answer – There is undoubtedly an air temperature influence (which will be addressed in more detail at the Microclimate portion of the Workshop). The ambient air temperature sets the baseline level. However, the data show that the major change above air temperature is driven by solar radiation. For example, the Alsea Study shows that the role of shade is a more significant factor compared to air temperature. The water tank study showed the same results. Tanks respond more to solar radiation, less to air temperature. Air temperature is an energy source, but a muted source of change relative to solar radiation. Related Question– Isn't air temperature the primary factor in that water temperature is striving to reach equilibrium with air temperature? Response - Air temperature is a factor, but not the primary factor. Energy input has a more significant effect than the surrounding air temperature, and air temperatures are also fluctuating in reaction to those same energy inputs.

- Question/Issue – Regarding relaxation, is time or distance a more predictable/relevant measurement?. Which is a better predictor of recovery factors - time or distance? Response – This could be approached better from a modeling or research perspective; we could examine both time and distance and develop guidelines as appropriate.

- Question/Issue – What role do channel structure and alluvium have in relaxation? Should we look at in-channel structure restoration for temperature benefits? Response (from an attending stakeholder) – BCC studied this, attempting to create a narrower, deeper channel. Empirical evidence showed that channel structure change can have a significant, measurable effect. However, our ability to influence or modify alluvial texture through management practices is obviously reduced relative to our ability to manage for shade.

- Question/Issue – Also regarding relaxation, what are the physics that would affect temperature changes going from cold to warm, rather than warm to cold? (e.g., a tributary feeding colder water to a warmer mainstem). Response – The same physics are working, but evidence shows that the cooling is slower than warming. The IMST concluded that cooling takes longer unless other processes (e.g., groundwater input) are present. The radiation outputs from the sun exceed those from earth surfaces.

- Question/Issue – In our experience and studies examining eastside vs. westside streams, different streams with similar shading characteristics (and other factors as well) show different temperature responses. What factors could be contributing to these observations? Response – As an example, we can look at recent studies on the fog belt; radiation isn't always at maximum (but we often assume this or analyze for maximum solar radiation input); fog, clouds, etc. can attenuate the effect. There are other factors to consider – "age" of water and its equilibrium state, groundwater inflow, etc. All of these can affect the results.

- Question/Issue – From a temperature perspective, is there any scientific reason to maintain north side buffers (referring only to east to west flowing streams)?. Response – For attenuating temperature effects, only vegetation on the south side prevents significant temperature increases. Convection effects would be worth additional study, but empirical evidence to date shows that evaporation and convection are both relatively minor components. Note, however, that there are other considerations beside stream temperatures when considering north-side buffers (e.g., wood recruitment for channel structure).

- Question/Issue – Regarding the canopy vs. shade issue, the presentation focused on canopy cover adjacent to the stream. What happens to a ray of sunlight as it passes through a vegetation buffer? That is, how important is the degree of solar radiation filtered through the canopy? Answer – Most research has been done on vertical process (direct solar radiation), showing that a full canopy obscures about 80 to 90 percent of solar radiation. Vegetative density, as well as its architecture, are important as well (e.g., consider a mature alder stand with a higher crown and little understory). At a lower angle of the sun, some sunlight does filter through the buffer. Note, however, that this same increased light would tend to contribute to a rapid vegetation response in the understory, which would change the filtering process and amount of solar radiation over time. Also, remember that at lower angles, more energy is reflected from the stream's surface. This issue will be addressed directly in the microclimate portion of the Workshop.

- Question/Issue – Are there any other architectural factors that influence solar radiation inputs, specifically in hardwood vs. conifer stands. Answer – See Dr. Ice's prepared response to Key Question #4; in short, there is scant empirical evidence at present. The west side vs. east side discrepancies need to be further studied, and other factors such as aspect and stocking levels seem to be relevant.

- Question/Issue- I'm concerned with the statement/assumption that downstream temperatures are independent of upstream temperatures. Cumulative effects from upstream sources are a component of the equilibrium process – downstream temperatures must be dependent to some degree on upstream cumulative sources. Response – This assumption is predicated on that fact that all of these processes are time and spatially dependent. At some point, downstream temperature becomes independent of temperatures at a remote upstream source. The energy balance acts on local conditions, constantly working toward equilibrium.

## 3.2 Stream Temperature Modeling

***(Presented by Dennis Schult, Western Watershed Analysts)***

### Presentation Summary

Prior to delving into actual models used to predict and describe stream temperature fluctuations, some basic characteristics of equilibrium conditions were reviewed. Acknowledging that models examine heat transfer downstream (as opposed to temperature transfer downstream), Schult noted that:

- Heat transfers downstream, but heat transfer processes cause the water temperature to change only until net heat transfer is balanced.
- Energy in equals energy out.
- The temperature where the balance occurs is the equilibrium temperature.
- Downstream temperature is then independent of upstream temperature.

Also reviewed were some basic conclusions regarding the influence of air temperature and stream depth:

- At equilibrium, mean daily air and water temperatures are nearly the same.
- Diurnal water temperature cycle is due to the cycle of solar radiation and air temperature.
- Water temperature variations are smaller for deeper streams, and time to equilibrium is longer.

Schult's presentation addressed four different stream temperature models currently being used at the reach-scale:

- Heat Source* (ODEQ 1999), a process-based model which predicts hourly temperatures for one day; it can report both average temperatures as well as maximum temperatures. It is a Visual Basic model with an Excel interface.
- SSTEMP (USFWS)*, a process-based model which predicts daily average temperatures. SSTEMP is an executable file and provides a single input/output screen.
- TEMPEST (developed by Adams and Sullivan1990).
- TEMP-86 (developed by Beschta).

Temperature models are also used to predict temperature changes at the basin-scale, which in general is a much more challenging process:

- SNTEMP (USFWS), a process-based model. (note that "SN" stands for stream network).
- QUAL2E (EPA), a process-based model which is also used to model nutrients.
- Washington Screen (T/F/W), an empirical model.
- Idaho CWE* (IDL 2000), an empirical model.

*Indicates models that Schult typically uses and hence are addressed in more detail in this presentation.

Schult's presentation focused on the differences among commonly used process-based models and empirical-based models, as described below. For all models, the assumption is that stream temperature changes are the result of changing physical inputs. The various heat transfer processes – such as solar radiation, cloud cover, atmospheric reflection, evaporation, and convection – constitute the primary inputs.

**Process-based Models**

Process-based stream temperature models (such as SSTEMP and Heat Source) use several different heat transfer process inputs to account for net energy flux; primary inputs accounted for in the models include solar radiation, stream vegetation and shade, evaporation from the stream, convection between the stream and the air, conduction between the stream and streambed, and groundwater exchange. Specific input parameters fed into the process-based models include stream characteristics (such as aspect, depth, width, and flow); riparian characteristics (such as buffer height, width, overhang); atmospheric conditions (such as air temperature, humidity, and wind); and upstream water temperatures (typically reported hourly throughout the day). Depending on the model used, 25 to 30 input parameters are required for each reach; this can require a substantial amount of time and effort.

Of these input parameters, the process model results tend to be most sensitive to air temperature, humidity, wind speed, stream depth, and – to a lesser extent - shade. Schult provided specific examples showing sensitivity to inputs such as air temperature, humidity, wind speed, stream depth, buffer height, and reach length; see Appendix C for these graphs.

Based on a limited sampling run prepared specifically for this presentation, Schult also provided examples of model output sensitivity to variations in model inputs for the SSTEMP and Heat Source process models. In most cases, the two models compared closely, but output temperature variations differed between the two models for certain input parameters. For example, the change in daily average water temperature (i.e., ranges in output in degrees C) resulting from a change in daily average air temperature inputs were identical (2.6$^{o}$C) for both SSTEMP and Heat Source; however, output temperatures ranged 1.2$^{o}$C for SSTEMP for changes in average stream depth inputs, whereas Heat Source output ranged 0.6$^{o}$C for the same changes in average stream depth inputs. In short, the different process based models are more sensitive to certain input parameters, and results therefore vary a bit.

Heat Source has two advantages relative to SSTEMP. First, Heat Source allows you to predict both average and maximum temperatures, not just the average. Secondly, as Heat Source is a Visual Basic tool, it allows you to examine specific source files to explain potential anomalies. As SSTEMP is an executable file, you can't examine the actual code to explain individual results. In addition, SSTEMP appears to be a bit weak in examining buffer considerations

To help compensate for such variability, as well as to account for site-specific and local variations, process models require calibration. Input parameters such as air temperature, humidity, wind speed, and groundwater temperature can be adjusted to more accurately reflect site-specific conditions. In particular, air temperature is a key parameter to adjust, as we frequently don't have good site-specific data over individual stream reaches (such data typically come from monitoring stations that can be some distance from the study sites).

In summary, the advantages of process-based models include the following:

- They predict temperatures for any condition
- They are very useful to investigate "what-if" scenarios.

On the other hand, process models have certain drawbacks:

- They require numerous inputs.
- They require calibration, which can be very time consuming.
- SSTEMP in particular is a poor predictor of maximum temperatures.
- Linked processes (such as buffer width and ambient air temperature) are not accounted for in the models – input parameters have to be fed in manually.

## Empirical Models

Empirical models (such as Washington T/F/W Screen and Idaho CWE) use actually measured stream temperatures throughout a region to fit a regression model using selected input parameters such as elevation, shade, stream size, average air temperature, and drought index. Schult showed several examples of model output changes based on changing input parameters, such as canopy density; he also showed examples comparing results from different empirical models (Washington T/F/W Screen and IDL 2000). See Appendix C for graph results for these comparisons, best represented in table and graph form.

Mr. Schult noted that for the Washington Screen model, the key input parameters tend to be canopy density and elevation; these inputs provide the best predictors for stream temperatures. Results can be reported as maximum weekly temperatures, as well as rolling averages. For the Idaho CWE model, canopy density and elevation are also key variables; in addition, the drought index improves the output.

In summary, the advantages of empirical models include the following:

- They require few input parameters and no calibration
- They can be executed rapidly.
- Current models are already developed for many Pacific Northwest regions.

On the other hand, process models have certain drawbacks:

- They require substantial data input up front, and such data are not always available.
- The regressions fit to only specific temperature parameters (such as maximum summer temperatures).

For comparison purposes, Schult showed output for two process models (SSTEMP and Heat Source) as well as one empirical model (IDL 2000); the case study involved was Cold Springs Creek (ID). Based on one run, predicted temperature ranges among the three models varied by up to 7$^{o}$C for site-specific locations along certain reaches of the stream, but at other points along the stream were nearly identical. In addition, actual temperature measurements taken along two stream locations indicated that all models tended to overpredict temperature in this specific run (in this case, by up to 4$^{o}$C). On average, SSTEMP tended to overpredict temperature by about 1 to 2 degrees C. Heat Source overpredicted by 1$^{o}$C. Idaho CWE overpredicted by 0.5 to 1$^{o}$C. Schult noted that this was just one model run using specific conditions on a specific day, and that parameters could be adjusted/calibrated as appropriate in the process models to obtain more accurate predictions. SNTEMP would also have been an appropriate tool to use, but he did not prepare such output for this Workshop because the algorithms used are identical to SSTEMP. He noted that the level of effort required to obtain model output varies widely among models, which raises the essential consideration regarding the law of diminishing returns – is it worthwhile to triple your level of effort for a 0.5$^{o}$C change in result?

For the presentation, Schult also presented numerous sample output graphs demonstrating various "what-if" scenarios for such inputs as buffer width and effective shade. For example, Heat Source was used on the Upper Grande Ronde to help determine TMDLs – eight separate reaches were considered, and five different buffer configurations were examined. The reader is referred to Appendix C to see these sample outputs.

In conclusion, Schult identified some potential future research directions that might be appropriate for evaluating temperature modeling:

- The potential use of microclimate effects as input parameters.
- The potential use of groundwater measures as input parameters
- Evaluate the balance between simplicity vs. accuracy. (i.e., do large data input requirements improve accuracy?).
- Examine the role of stratification and mixing.
- Examine sensitivity differences between models.

## Questions & Answers, Additional Dialog

Dialog that occurred subsequent to the Modeling presentation is summarized below.

- Question – In modeling, what is the definition of effective shade? Response – One minus the ratio of radiation that hits the stream/radiation that hits the canopy.

- Question/Issue – Do you have any recommendations for the design/protocol for monitoring canopy density to be used as model inputs? What does the model call for? Response –For SSTEMP, spherical densiometer measurements were used. Related Question-Would hemispheric photography be better to use and, if so, where should you take measurements? Response – I'm not sure which method would be more appropriate. Where to measure is situation-dependent. For example, for a mile long reach, you should use the stream's edge.

- Question/Issue – How do you deal with groundwater input, as it varies over the range of the reach? Response – This applies especially to Heat Source, which assumes complete mixing. Due to the model configuration, that's the best we can do, which is why stratification is listed above as an appropriate research direction.

- Question/Issue – How do the models incorporate microclimate conditions? Do microclimate effects have any bearing on empirical models? Response – You don't have to worry about microclimate effects/inputs when working with empirical models. But microclimate effects are indeed input parameters for process models and can be adjusted as the user sees fit.

- Question/Issue – Is there a possible contradiction between the Solar Radiation presentation and the Temperature Modeling presentations? Specifically, Dr. Ice concluded that shade is a significant contributor to buffering stream temperature changes. But the model output does not show shade as such a key input; rather, air temperature is shown as the driving factor. Is this a disagreement? Response – No, this isn't a contradiction or disagreement; we are reporting different, but related, results. Solar radiation is the key driver that influences maximum temperatures; air temperature tends to drive average temperatures. Dr. Ice also clarified that solar radiation is the key input in driving stream temperatures above air temperatures; groundwater is the driving factor in cooling water below air temperature. Shade and direct solar radiation both influence these changes, and air temperature is the base/foundation for which the changes take place. Schult reiterated that these models do not take into account the interactions among the various inputs, which exist in nature (e.g., air temperature/humidity); these need to be input manually into the models.

- Question/Issue – Can process models be used for diagnostic purposes, such as evaluating the results of empirical models? Response – Schult noted that he hasn't specifically used process models for this purpose.

- Question/Issue – Is canopy density/closure a reasonable proxy for effective shade measurements? Response – Not necessarily. Canopy density does not account for enough geometric variables (such as aspect, latitude). Effective shade does account for these factors. For example, you can get relatively high shading levels without a high canopy density.

- Question/Issue –Regarding microclimate, are there ways to predict local air temperatures under the canopy for different riparian conditions/configurations. Response – According to Dr. Ice, there is a thesis in preparation at Berkeley examining this situation along the Sacramento River. In addition, Dr. Sam Chan is working on this issue, specifically examining buffer widths. This a missing link for this (i.e., February) Workshop, and the issues will be examined at the May Workshop addressing microclimate. Schult also noted that air temperatures derived from local weather stations – which are often fed into empirical models – do not necessarily reflect air temperatures over the water column. Stakeholders agreed that the discrepancies in regional vs. local (i.e., over the stream) temperatures, and how these relate to both empirical and process models, are topics worthy of additional examination.

- Question/Issue – In the example comparing output from various models, the results indicated that output tended to be more conservative for all models examined, when compared to actual stream measurements. Is this typical? That is, does model output tend to be more conservative than actual temperatures? Response – Because of the ability to calibrate process-based models, these results can vary. This sample output was worked up specifically for the Workshop and just represents one modeling scenario.

### 3.3 Groundwater and Heat Transport in Forested Ecosystems: Where Are We?

***(Presented by Patricia Olson, Pacific Watershed Institute)***

## Key Conclusions

- Very little research has been conducted on this specific topic, especially in the Pacific Northwest; historically, groundwater research has focused on resource extraction and contaminant transport. There is a body of research addressing heat transfer by subsurface flow, but these studies have not addressed the effects of vegetation removal.

- Groundwater systems and heat transport mechanisms are highly variable and extremely complex.

- The primary elements of subsurface flow that influence heat transport include flux, storage, and recharge-discharge. These processes are influenced by hydraulic conductivity and porosity.

- In the unsaturated zone, heat transport depends on water content, hydraulic and thermal conductivity, heat and storage capacity, porosity, runoff processes, and travel time.

- In the saturated zone, heat transport depends on hydraulic and thermal conductivity, porosity, heat and storage capacity, travel time, and recharge-discharge dynamics.

- As porosity increases, hydraulic and thermal conductivity, and dampening depth generally decrease.

- Water storage capacity and retention and heat capacity generally increase as porosity increases.

- Theoretical equations for dampening depth and time lag with depth apparently do not predict thermal regimes in forested areas.

## Presentation Summary

Note: Like Dr. Ice, Dr. Olson prepared a separate written paper summarizing her presentation's key points; this paper is included in Appendix D.

It's important to note that we don't have very much research on this specific topic yet. Historically, groundwater was viewed and studied primarily as being an extractable resource. Later, groundwater research focused on contaminant transport processes. Neither of these research designs are particularly relevant to the management of forested areas. Current research is being conducted on hyporheic processes, but these data tend to focus specifically on the interaction zone, not the entire groundwater system. Also, very few of the existing studies were performed in the Pacific Northwest, so their results might not be particularly relevant to our local conditions.

When modeling groundwater systems, we often have to make numerous assumptions regarding such factors as temperature, flow, and volume throughout the entire system. But groundwater systems are highly variable and dynamic, much like stream systems. This variability isn't always captured in current modeling efforts. Obviously, they are difficult systems to model and study.

Given these difficulties and the current state of research, today's presentation does not address volume or modeling specifically; rather, the presentation focuses on basic concepts of the groundwater systems, addressing the following:

- Subsurface flow systems
- Groundwater flow in forested areas
- Heat transport in the subsurface domain
- Factors influencing heat transport
- Examples in forest systems
- Hypotheses

## Subsurface Flow Systems and Groundwater Flow in Forested Systems

The groundwater domain is defined as the subsurface zone of permeable material through which water moves. This includes both the unsaturated zone (or vadose zone), as well as the saturated zone. Important processes that occur in this domain include redistribution of soil water, percolation, capillary rise, plant uptake, exfiltration, matrix flow, and thermal energy exchange. When examining the groundwater domain, it is also important to consider the hyporheic zone (the transitional zone between the stream aquatic ecosystem and other groundwater systems). Some of the most important physical and chemical fluctuations occur here. The interactions between streams and groundwater systems are complex processes. In some cases, groundwater functions to recharge streams; under other conditions, the streams recharge the groundwater system; both effluent and influent processes occur.

The key elements of subsurface flow that influence heat transport include **flux, storage,** and **recharge-discharge**. These processes are influenced by hydraulic conductivity, permeability, and porosity.

Flux – the movement of subsurface flow – is governed by Darcy's Law (equations are provided in Appendix D). Important characteristics of subsurface flow include the following:

- Water moves where there is a gradient.
- For a given hydraulic gradient, discharge will be greater as permeability increases.

- Groundwater velocity increases as hydraulic head, grain size, and pore size increase.
- Hydraulic conductivity decreases as porosity increases in unconsolidated sediments.
- Hydraulic conductivity increases with temperature.
- In the unsaturated zone, hydraulic conductivity decreases as moisture content decreases.

Storage characteristics in groundwater systems play a significant role in affecting heat transfer. In general, the greater the storage capacity, the more opportunity for attenuating heat.

Groundwater recharge areas occur where percolating water moves from the unsaturated zone (or surface water) to the saturated zone; discharge areas occur where saturated flow moves to the surface via springs, seeps, or surface water bodies. Factors that influence recharge/discharge areas include climate, lithology, and physiography. In recharge areas, small differences in local conditions can cause large differences in recharge capacity.

Groundwater flow systems can be examined at a variety of spatial scales, including local flow systems, intermediate flow systems, and regional flow systems. Within these scales, flow rates are extremely variable, with numerous interactions occurring. In general, flow systems tend to discharge at low elevation points in a basin, or at faults/fissures that are present.

## Heat Transport in the Subsurface Domain

The primary processes governing heat transfer within a porous medium include conduction (especially by gradient), radiation (emitted because of a body's temperature), and convection. Other factors to consider include soil composition, evaporation, infiltration, recharge characteristics, hillslope topography, and seasonality.

Soil factors, such as mineralogical composition, significantly influence heat transport in groundwater systems. There is a dampening effect of heat transport for soil radiation, and dampening depths can be theoretically calculated for different soil types. However, there are very few data on actual measured temperatures, and these are mostly for agricultural soils.

Another factor to consider is the process of evaporation and its effects on heat transfer. For evaporation to occur, there must be a continual supply of water through the soil matrix. Higher evaporation rates will occur in warmer, wetter soils. In a recent study in Minnesota (Bridgham et al. 1999), a summer decline in subsurface temperatures measured at 15 cm was caused by higher evapotranspiration rates. In general, heat losses by evapotranspiration are more than offset by heat gains from increased solar radiation.

Infiltration is an additional factor influencing heat transfer. In general, high water content tends to increase thermal conductivity, while low water content decreases conductivity.

Limited studies have been conducted examining recharge and its relationship to heat transport. Taniguchi and Sharma (1993) used soil temperature differences to predict recharge. Their findings indicated that the higher the annual recharge, the greater change in soil temperature from initial surface temperatures. In addition, the seasonal change in soil temperature was greater in a sparser pine area than a dense pine area.

Hillslope and topography influence heat transport processes, as well as recharge-discharge processes. In steep topography, a large part of the available water moves downslope to areas where it can percolate deeper. These processes are complex and site-specific, with flow often regulated by topographic factors. On hillslopes, macropore flow is a potentially significant water and heat transport mechanism.

Seasonal variations are also important to consider in heat transport. In the wet season, recharge filtering through the cool soil matrix moved through saturated zone, mixing and warming as it transported, resulting in warmer discharges than the initial recharge temperature. In the dry season, the opposite occurred, with discharge being cooler than the infiltrate.

## Examples of Forested Systems and Influence on Stream Temperature

Only a few studies have examined groundwater systems in forested areas. Temperature profiles have been developed in forested systems (e.g., Olson 1995, Taniguchi et al. 1997), as well as in comparison with harvested sites. In Taniguchi's study, removal of forest vegetation and the establishment of agricultural lands resulted in temperature increases to a depth of 40 m.

Another local (Carnation Creek) study examined the role of summer storms and groundwater and streams' response to these storms. Fannin et al. (2000) found that rainfall in May through September caused a groundwater temperature response on hillslopes. Heat that accumulated at the surface is transported into the deep soil by convection.

Site-specific studies have also examined the role of groundwater influencing stream temperatures. In a study of 3$^{rd}$ and 4$^{th}$ order streams in Minnesota, Sinokrot et al. (1995) found that groundwater discharge exhibited an influence on stream temperatures downstream 48 km. In another study, Webb and Zhang (1997) concluded that groundwater has a significant impact on the heat budget, although results were variable by season, and patchy over short distances.

## Potential Questions to Examine

When examining groundwater influences in a specific watershed, it is important to consider the following questions:

- Where in a watershed does groundwater contribute to surface water, and what role does it play?
- What is the source of subsurface flow to surface water (i.e., local, intermediate, or regional flow system)?
- Where is the groundwater system recharged and discharged?

Very few studies have specifically addressed groundwater systems and related temperature effects in Pacific Northwest forested areas. Future research should focus on the following key questions:

- Do clearcut conditions significantly alter groundwater discharge temperatures when groundwater levels are deeper than 1 meter?
- Do buffer widths influence groundwater discharge temperatures when groundwater levels are deeper than 1 meter?
- How are stream temperatures related to soil temperatures?

## Questions & Answers, Additional Dialog

- Question/Issue – Based on the presentation, it's obvious that there is a substantial amount of research needed to answer our more specific questions. Specifically related to western Washington conditions, how can groundwater transport affect summer stream temperatures? This is the primary issue we'll need to focus our efforts on. Also, the CMER process is concerned specifically with how forest management practices provide adequate protection. We have to start looking at potential problems, which might initially best be examined at local recharge areas closer to streams. Given the complexity of the issue, how do we narrow down what needs to be looked at? Response – Recharge areas close to streams would be a logical initial step in examining the processes.

- Question/Issue – Eventually, we'll need to define mechanisms by which harvest practices translate to groundwater changes that could influence stream temperatures. For example, we should consider the effects of vegetation conditions on soil temperatures.

- Question/Issue – Some of the material presented showed thermal penetration to depths up to 40 m. What types of sites are these, and are similar they to our mountainous areas? Response – Those 40 m sites were in hilly areas, not flatland. Some were in stream valley bottoms.

- Question/Issue- How much does organic matter (vs. mineral content) affect temperature changes? Response – Organic matter can significantly influence temperature changes in soil and groundwater systems.

- Question/Issue – Have there been any studies examining the relationship between vegetative cover and groundwater recharge dynamics? Response – There are some recent studies in Australia examining this issue.

- Question/Issue – As you move downstream, does groundwater temperature contribution and influence decrease? Response – Yes, but it's a matter of scale. The amount primarily depends on the contribution of groundwater-fed streams

- Question/Issue – Is there a field method for evaluating groundwater temperatures on a site scale in a forested habitat? Response – There are different methods; in areas with a shallow water table, steel probes are appropriate. For deeper groundwater systems, sinking a well is required.

## 3.4 Upland/Riparian Microclimate Processes

***(Presented by Dr. Sam Chan, Pacific NW Laboratories, USFS, Corvallis; note – this presentation was a portion of a previous presentation developed with Robert Danehy of Boise Cascade)***

### Key Conclusions/Considerations

- Our knowledge of the interactions between the drivers of microclimate (macroclimate, vegetation, geomorphology, topography) with microclimate is still limited.
- Our understanding of interactions that arise from different patterns of microclimate, such as evaporation and convection, is limited.
- Concepts of "interior forest conditions" must be defined on spatial and temporal scales in the context of functions and process.
- When considering riparian microclimates, the complexity of gradients, patterns, and distribution of edges is of great importance.
- The relevance of microclimates must be considered in the context of physical and ecological functions and processes. For example, what are the effects to target organisms such as amphibians?
- Microclimates are often described and often "managed" at a stand or small stream reach scale.
- The mosaic of microclimates associated with patterns in the landscape (drainage, watershed) should first be considered.
- Empirical evidence from recent scientific studies indicates that processes and factors such as relative humidity, soil temperature and characteristics, evaporation, convection, wind speed, air temperature, topography, and solar radiation, can have significant influences on riparian forest conditions at the microclimate scale; however, of particular relevance to this Stream Temperature Workshop, microclimate effects within managed buffer zones DO NOT appear to significantly affect stream temperatures. Microclimate effects should be considered important and warrant additional study when examining potential effects (e.g., to lichens, bryophytes, terrestrial mollusks, amphibians, and vascular plants).
- Management practices, such as use of herbicides, mounding, and blading – can and do change microclimate conditions (e.g., affecting vegetation conditions and accumulated growing degree days). However, these changes do not necessarily translate to changes in macroclimate. It is therefore important to examine effects on a watershed scale.

### Presentation Summary

Dr. Chan began his presentation by referencing *Forest Influences* (Kittredge 1948), noting that microclimate patterns and influences have been the subject of physical scientific study for over 50 years, and that much of the information presented from that era, as documented in the text, is still relevant. For example, this text addresses climate, soils, physiography; forest factors; solar radiation; air temp; wind; precipitation; stream flow; evaporation/condensation; soil temperate; floods/erosion; and watershed management – all topics of current and relevant concern. Also noted was the fact that microclimate studies tend to exhibit a high degree of variability due to the difficulty in controlling experimental design factors. This variability was a continuing theme in Dr. Chan's presentation, and he frequently stressed that it is essential to examine research design in microclimate studies and associated results before extrapolating broader conclusions. Often, results can be less conclusive than other research dealing with less complex systems and processes.

Dr. Chan also stressed that due to site microclimate variability and diversity, it is often difficult to develop specific recommendations (such as defined buffer widths); an additional complicating factor is that conditions favorable for one variable (e.g., high shade levels to moderate stream temperature) might be unfavorable for another (e.g., sunlight needed to promote understory growth).

According to Daubenmire (1947), microclimate can be defined as "strictly local combinations of atmospheric factors which, owing to uneven topography, plant cover, etc., differ from the macroclimate as measured in locations where these modifying factors have negligible influence. Within each area embraced by one macroclimate, there exists an intricate matrix of microclimates, at least some of which differ sufficiently to be ecologically important." In particular, in riparian zones microclimates can change substantially in just a few feet, as measured by canopy cover, soil conditions, and other factors. Riparian areas are physically diverse, with components and inputs that include but are not limited to light, soil, soil moisture, geomorphology, edge, and disturbance. For example, a conifer-dominated riparian zone on one side of a stream differs substantially from an alder stand on the other side of the stream, especially when considered from a seasonal perspective. Dr. Chan's presentation therefore focused on the key forest microclimate factors – soil radiation, relative humidity, air temperature, and soil temperature; to a lesser extent, he also addressed precipitation, wind, and soil moisture.

## Overview of Microclimate Factors

It needs to be stressed that Dr. Chan's research and presentation focused primarily on microclimate drivers and effects within riparian stands, generally with the goal of promoting complex riparian structure. The data and research results he summarized were not specifically designed to observe stream temperature effects. For this Temperature Workshop, his discussion and results need to be evaluated in this context. In these studies, the experimental design generally involves placing multiple sensors along a transect with prescribed distances upslope from the stream (e.g., 5 m, 10 m, 25 m, etc.), and measuring microclimate conditions at sites subject to differing harvest and buffer treatments.

The presentation began with an overview and examples of various microclimate processes and relationships, with the intent of demonstrating their complexity and diversity. For example, riparian areas often exhibit very complex soils; samples along transects taken every 30 feet show large variability, from sandy loam to silty clay, all of which have different water retention patterns.

As another introductory example, Chan's recent study of Callahan Creek was referenced. At Transect 3B, total radiation, soil temperature, air temperature, and relative humidity were examined, contrasting forested and clearcut conditions. Results indicated that large changes were noted in radiation, medium changes were evident for humidity and temperature, and very little change in soil temperature was observed. Data results change significantly, depending on time of day, and Dr. Chan stressed that results and conclusions were therefore relative to the specific factors examined, with generalizations difficult to make.

**Solar Radiation and Shade**

As noted previously in Dr. Ice's presentation, the effects of solar radiation are well studied and fairly well understood, particularly in relation to other physical processes. Dr. Chan showed multiple hemispherical images to demonstrate variation in canopy closure. He pointed out its effectiveness in measuring shade levels relative to the human eye, which picks up a much more limited portion of the total light input. Light levels were compared and contrasted for areas above the stream, in the riparian buffer, and in thinned stands. Using the Callahan Creek study as an example, light levels were measured at 8 points from the stream center up to 97 m upslope; light levels ranged from 3 and 4% up to 10%, with levels being very similar up to 61 m.

Especially with solar radiation inputs, the greatest changes in microclimate are often due to weather patterns. Also, because of diurnal cycles, it is essential to examine the extremes (high and low values); average values often are not very meaningful. This holds true for other microclimate variables as well.

Another major theme of the presentation was the importance of maintaining a diverse, complex riparian structure. In contrast to managing for higher shade levels to protect stream temperatures, Dr. Chan emphasized the need to thin buffer stands to allow light to reach the understory, thereby promoting regrowth and structural diversity (which also contribute to greater canopy coverage over time). For example, a 35-year old Douglas-fir stand managed primarily for wood production – the classic "tree farm" environment with even age and high density characteristics–lacks structural diversity; despite a 100% canopy cover, the understory is open, and both light and wind pass through the clean boles. Silvicultural practices can be used to increase complexity under the canopy, and there are obvious tradeoffs that need to be examined when making such choices.

Dr. Chan also addressed various ways to examine and quantify total canopy cover. For example, when measured near the ground (at a height of 1 m), it is possible to obtain cumulative canopy coverage up to 400%, as the forb, shrub, and overstory layers are all considered and cumulative totals reported. As a gross generalization, a coverage of

150% (measured in this fashion) reduces the “available sunlight” reaching the forest floor to about 20%.

When considering canopy coverage, it is also important to consider results over time. Much of Dr. Chan’s research focuses on examining differences in riparian structure over time when subject to different thinning rates, with the overarching goal of promoting structural diversity. Numerous examples of light-related effects on various thinning rates (e.g., ranging from 40 TPA to 100 TPA) over time were presented, with copies of the hemispherical photos presented in Appendix E. Microclimate effects can vary substantially over different treatments and at different sites. He also noted that about 3 years after thinning, similar canopy closure rates are exhibited between conifer and hardwood stands. Overall, however, it is difficult to make generalizations about percent sky effects from thinning levels – benefits from thinning are not necessarily proportional to the number of stems removed.

## Relative Humidity/Temperature

Unlike the more straightforward, consistent results of canopy coverage and shade, the interpretation of results from relative humidity and temperature studies are more variable and controversial. Dr. Chan noted that very recent changes in technology have greatly improved measurements of microclimate; only within the last four years or so have there been affordable, portable instruments/sensors for relative humidity. When examining the current literature regarding temperature and relative humidity, Dr. Chan stressed the importance of considering the experimental design.

Most current studies indicate that in areas with adequate riparian buffer zones, microclimate conditions do not adversely affect stream temperatures. In one recent study, it was demonstrated that a buffer width of between 0.5 and 1 tree height would be effective in maintaining most microclimate variables, including soil moisture, radiation, soil temperature, and air temperature at levels similar to no-cut situations. An exception in this study was relative humidity. Buffer widths of greater than two site potential tree heights were required to maintain relative humidity at levels comparable to no-cut situations. While not a primary driver in influencing stream temperatures, relative humidity is nonetheless crucial for maintaining healthy macrophyte conditions along a streamside. In general, microclimate plays a critical role in plant regeneration, growth, and distribution. Another recent study - Brosofske et al. (1997) –analyzed the relationship between microclimate variables and stream temperatures, concluding that wind speed, relative humidity, and solar radiation had little or no relationship to stream water temperatures. In addition, buffer width did not appear to affect stream water temperature at the sites examined, except in the case of an almost complete absence of streamside trees. When considering factors other than stream temperatures, however, that study concluded that riparian microclimatic gradients existed for air temperature, soil temperature, and relative humidity, noting that even conservative buffer width recommendations might not be adequate for preserving an unaltered microclimate near some streams.

Other recent studies have yielded less definitive results. For example, Dong (1998) found that 100-m buffers did not seem to provide protection for soil and water temperature conditions; however, it is difficult to interpret these results due to experimental design.

Other recent studies cited included Chen et al. (1999) and Cajun James' Millseat Creek study. Although Dr. Chan noted difficulties in extrapolating conclusions from these, he noted that James' study examining soil and water temperatures at the stream indicated that there were no detectable changes within her instruments' limits; this study design involved clearcutting in stages closer to the stream, with varying buffer widths decreasing over time. This study examined both north and south side sites. In short, no increase in stream temperature was caused by prescribed forest harvest, nor were increases in turbidity or sediment noted.

Similar results have been noted for relative humidity effects. Danehy and Kirpes (2000) examined both eastside and westside streams. They found that the greatest changes in relative humidity occurred close to the stream (within 5 m), after which the differences become very small. In these studies, macroclimate (local weather) often accounted for the majority of the observed variation in microclimate.

Dr. Chan also referred to several studies examining thinning treatments and their effects on air temperature, soil temperature, and relative humidity. Results for these studies (which included the Green Peak Adaptive Management Project and the Keel Mountain Soil Temperature Study) were highly variable and exhibited substantial uncertainties, although both soil and temperature variations appeared to be surprisingly narrow.

## Questions & Answers, Additional Dialog

Note: Due to the interconnections between riparian microclimate and conditions over the stream, questions and additional dialog for riparian microclimate are included below in Section 3.5.

### 3.5 Microclimate Effects on Stream Temperatures
***(Presented by Dr. Sherri Johnson, OSU)***

#### Key Conclusions:

- Solar radiation is a dominant factor influencing stream temperature dynamics. Numerous other factors also contribute to stream temperatures (see the illustration on the cover of this report).
- Mechanistic studies are necessary to understand the relative proportions of various factors influencing stream temperatures. Because of microclimatic variability, stream heat budgets calculated using climatic information from distant or upslope sites may not be accurate.
- Forest harvest practices such as clearcutting have been shown to dramatically increase maximum and minimum stream temperatures. Recovery occurs over time as riparian areas are revegetated. The effects on stream temperature of current selective harvest practices with riparian buffers have been examined in only a few studies.
- The correlation between diurnal or seasonal temperatures of air, water, and soil do not imply causation. Correlation is a comparison of similarity of patterns and all temperatures are responding to incoming solar radiation.
- Stream temperatures within stream networks are just beginning to be studied in a systematic manner. Landscape factors, such as elevation, gradient, width, depth, discharge, and watershed area, are all changing from headwaters to downstream, and stream temperatures generally increase with distance downstream. But that does not imply that these factors are mechanistic drivers of stream temperature.

#### Presentation Summary

Numerous temperature dynamics occur in a stream system, including the following factors: incoming radiation, upstream inputs (advection), groundwater inputs, the air-water interface (evaporation and convection), outgoing radiation (via reflection and emission), and the water-substrate interface. The processes influencing stream temperature dynamics are very complex and interrelated, making it very difficult to identify the primary controls on stream temperature. Factors other than microclimate influence temperature and subsequent stream ecology, such as climate, landforms, and biosphere.

Existing theories of temperature influences on stream systems examine both effects evident at the reach scale (generally applying an energy budget approach), as well as at the network scale (incorporating such factors as landscape patterns and theories about longitudinal patterns). In addition, variability of stream temperatures can be examined at the temporal scale (e.g., annual, seasonal, diurnal), as well as at the spatial scale (e.g., upstream vs. downstream). When assessing microclimate, the primary factors examined include incoming and outgoing radiation, advection, groundwater, the water-substrate interface, and the air-water interface. The length of time that water is exposed to various factors influences stream temperatures. Dr. Johnson noted that microclimate effects have also been studied in lakes as well, which tend to be easier to understand due to the longer water retention time, as well as more stable inputs and outputs. Streams are by nature more dynamic systems, with changing influences along their length.

**Air Water Interface (Evaporation and Convection)**

Dr. Johnson described of her recent research using heat balance/budget models. In Watershed 3 of the Andrews Experimental Forest, she examined the magnitude of influences of solar radiation versus air water interactions. In this example, a $4^{o}C$ increase in temperature was observed in a 200-m reach scoured to bedrock. Initial calculations of heat budget for this reach showed inputs of solar energy (at 600 $W/m^2$) and convection (100 $W/m^2$), and outputs of evaporation (200 $W/m^2$) and conduction (50 $W/m^2$). The resulting $4^{o}C$ temperature increase equated to +450 $W/m^2$, showing solar radiation inputs to be the driving factor behind water temperature increase in this reach, and the air-water interchange much less of a significant factor. Studies from other regions (Sinokrot and Stefan 1993; Webb and Zhang 1997) also show that convection, or flux of heat to the stream from warmer air, is generally less of a factor in heat budgets than evaporation, where heat is lost to the atmosphere.

A portion of the bedrock reach in Watershed 3 was shaded to examine the effects of reducing solar radiation, with temperatures recorded both above and downstream. Results showed that maximum stream temperatures decreased (by $1^{o}C$) despite the presence of high air temperatures still in this reach, indicating that stream temperatures were less influenced by air temperature than by solar inputs.

**Effects of Forest Harvest on Stream Temperatures**

Dr. Johnson presented numerous examples of studies examining microclimate effects on stream temperatures related to differing management practices (referenced studies included the Alsea Basin, the HJ Andrews Experimental Station, the Beschta and Taylor [1988] study). Forest harvest practices, such as clearcutting and leaving no riparian buffer, led to increased maximum and minimum stream temperatures during summers (Johnson and Jones 2000; Brown and Krygier 1970). The timing of summer maximums also shifted to earlier in the summer, which coincided with seasonal solar maxima. Removal of forest cover results in increased surface soil temperatures and may increase stream substrata temperatures. Studies have documented recovery of stream temperatures following clearcutting and found recovery times to be influenced by rates of riparian revegetation which occurs over ~15 years in the Cascade and Coast ranges.

Present harvest practices have been less studied. Riparian buffers can shade small streams and prevent increased amounts of solar radiation from reaching the stream. Questions exist over: (1) the density of riparian buffer needed to prevent harvest effects on stream temperatures, and (2) the recovery of stream temperatures downstream of harvested areas where increased temperatures occur.

Conduction with the substrates can be an important microclimatic variable, depending on the type of stream substrates. Streams that have much hyporheic exchange can have reduced diurnal fluctuations compared to streams that have been channelized or those over bedrock.

## Questions & Answers, Additional Dialog

- Question/Issue – Regarding the energy balance equations that were cited, these seem to relate to smaller streams; would larger streams react differently? Answer – Small streams are more quickly responsive to surrounding conditions than larger streams. Input factors change rapidly in the smaller headwater streams relative to the downstream areas; farther downstream, shade by riparian vegetation is less of a factor but wind and evaporation may have more importance. Related Question – Is the air temperature driving this? Answer – It's a factor, but not the main driver.

- Question – One of the initial heat budget equations showed solar radiation levels to be approximately six times the energy of other factors. Does that indicate that solar input is six times more important in terms of influencing temperature than air temperature? Answer —Energy balances are a function of all of the physical processes occurring at that particular stream segment. Tying this into management implications, it seems we can focus on solar inputs – it's the driver and we can also influence it by managing shade levels. On the other hand, air temperature is less of a factor, but we can't necessarily manage for air temperatures effectively. Related Question – What role might narrow riparian buffers have in terms of contributing to elevated air temperatures and related impacts on elevated stream temperatures? Answer – It depends on the amount of solar inputs reaching the stream as well as additional microclimatic factors. One factor that we have very little data on is wind in managed riparian buffers, and evaporation can be a significant factor. The interrelationships indeed are very complicated; you can't necessarily isolate or manage for a single factor as they are interrelated.

- Question – Given these varying results, where should we focus our research priorities? Is microclimate something we need to put our limited resources into, relative to other issues, especially given current buffer zone requirements? Answer – There's a lot we don't know and a good deal of uncertainty; these issues will obviously require additional research. But focusing on what CMER is specifically tasked with, we're not sure what the return would be from a management perspective on microclimatic research. Riparian buffers are important for much more than just stream temperatures and provide benefits such as wood inputs, litter, bank stability, etc. When examining amphibians and plants, riparian microclimate effects are crucial and additional research is needed to address unanswered questions. But from strictly a stream temperature perspective, CMER resources would likely be better focused elsewhere. We'd recommend that CMER do a more thorough review of the existing literature before considering any additional field research efforts examining microclimate effects on stream temperatures.

- Question – East side buffer requirements are different than west side requirements, with east side requirements as little as 65 feet in some cases. Should we consider funding additional microclimate research specifically for east side scenarios? Answer – Danehy's research shows that a 10-m buffer will provide effective protection in terms of stream temperatures related to microclimate factors.

- Question - For microclimate, would stream temperatures be better protected by a wider but thinned buffer stand, or a narrower but packed (unthinned) stand? Also, what thinning levels are appropriate? Answer – Regarding stream temperature, those studies have not been conducted yet. And the responses would change over time since harvest. Within buffers, it's important to consider changes to plant structure over time related to thinning (e.g., thinning lets in more sunlight that promotes plant growth in the understory, and the canopy coverage and structure thus change over time); it's often critical to thin a buffer to maintain complexity and promote a multiple layored canopy. For bank stability reasons, we tend not to thin directly adjacent to the stream, and these streamside trees provide effective shade directly over the channel. Regarding appropriate thinning levels, historical conditions in Western Washington and Western Oregon exhibited relatively low density, ranging from 20 to 50 trees per acre (TPA). Thinning to 80 TPA translates to approximately 65 percent effective shade, but again this will change over time. Although you may want higher levels of shade for stream temperature reasons, you do want some solar energy to promote understory growth. A related issue is the appropriate target for down wood; this is currently a controversial issue and requires additional research. But it appears that the region is lacking adequate down wood in decay classes 1 and 2, and we should be promoting recruitment. Again, though, this is for healthy riparian conditions and isn't directly related to stream temperatures.

- Question/Issue – In the Watershed 3 example (i.e., scoured to bedrock reach), how were values for evaporation and convection specifically derived? Answer – Formulas were used from atmospheric sciences books for evaporation and convection, because they are very difficult to measure directly. However, these were an initial first approximation, using microclimatic values from a climate station approximately 500 m away. This summer, Dr. Johnson will be measuring those microclimatic factors on site in order to be able to construct as accurate a heat budget as possible. Wind velocity is certainly an important factor to consider, but overall it's a very difficult pattern to predict.

- Question/Issue – As a recurring theme, why are similar streams warmer on the east side and how might this relate to microclimate? When other factors tend to be the same – elevation, canopy cover, etc. – we see warmer streams on the east side. Could warmer air temperatures be a factor? Answer – It could be that initial temperatures of groundwater are warmer on the east side, that there is increased solar inputs due to riparian vegetation densities and high grazing densities, and that the length of time of exposure to surface environmental factors is longer in the east side streams.

- Question – In one of the studies cited, shading at 1 m above the ground was identified as providing coverage greater than 100 percent; what field method was used? Answer – In our studies, we stratify our canopy coverage measurements, accounting for the herbaceous/forb layer, the understory, and the canopy. Cumulative coverage totals can therefore be larger than 100 percent. Also, in the canopy, overlapping limbs increase the coverage. For example, to achieve (i.e., reduce to) a 40 percent shade level in an alder stand, you'd have to remove 90 percent of the stems.

- Recommendation – Echoing concerns raised in the February Workshops, CMER should consider evaluating the correlation between effective shade and densiometer measurements. Densiometers measure cover, not effective shade, and the correlation might not be very good, especially at the high and low ends of the readings. A microclimate-related study should be considered to further address this uncertainty.

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