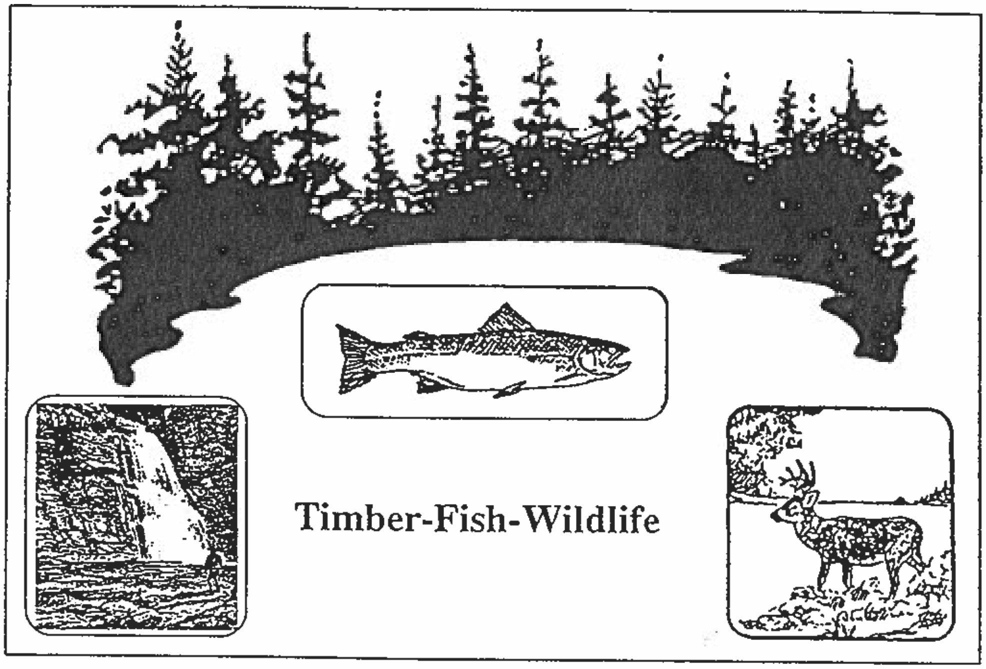
2 TFW-WQ3-90-006

TIMBER-FISH-WILDLIFE PROJECT

EVALUATION OF PREDICTION MODELS AND CHARACTERIZATION OF STREAM TEMPERATURE REGIMES IN WASHINGTON



December 1990

EVALUATION OF PREDICTION MODELS AND CHARACTERIZATION OF STREAM TEMPERATURE REGIMES IN WASHINGTON

By

TIMBER/FISH/WILDLIFE

TEMPERATURE WORK GROUP

Prepared for the
TFW/CMER Water Quality Steering Committee
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Forest Regulation and Assistance
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TIMBER/FISH/WILDLIFE
COOPERATIVE MONITORING, EVALUATION AND RESEARCH COMMITTEE

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DISCLAIMER

The opinions, findings, conclusions, or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of any participant in, or committee of, the Timber/Fish/Wildlife Agreement, the Washington Forest Practices Board, or the Washington Department of Natural Resources, nor does mention of trade names or commercial products constitute endorsement or recommendation of use.

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EXECUTIVE SUMMARY

The potential effects of forest practices on stream temperature were identified as a major concern during negotiations of the Timber/Fish/Wildlife Agreement of 1988. The direct effects of timber removal on the temperature of larger, fish-bearing streams (types 1-3) were addressed by riparian zone management rules that specified leave tree requirements along streams that were designed, in part, to preserve shading and maintain suitable water temperature. Alternative management plans generally specifying greater amounts of shading may be required where streams are found to be temperature sensitive according to a threshold temperature of approximately 60°F. Vegetation buffers are not required for very small streams (type 4 and 5) and concerns remained that inadequate temperature protection measures in upstream waters could raise temperature in downstream reaches to adverse levels.

TFW identified key management issues to focus for further research efforts, including: (1) criteria for identifying temperature sensitive streams, (2) a method for describing their geographic extent, and (3) a reliable method of predicting water temperature at sites where alternative prescriptions may be desired. The management process may be envisioned as follows. A general screening tool would be used to identify temperature sensitive basins or locations. Where sensitivity was not identified, riparian zone management rules would serve to protect stream temperature. Where sensitivity was identified, alternative management prescriptions would be designed with the aid of a temperature prediction model that had suitable capabilities to evaluate various management alternatives. Modeling needs could include analyzing temperature effects for both individual forest practice applications and basin planning, if necessary. Analytical models based on physics of stream heating or empirical models based on common patterns of temperature in relation to site characteristics would be considered.

A temperature study was undertaken in 1988 by the Temperature Work Group (TWG) of the Cooperative, Monitoring, and Evaluation (CMER) Committee to develop a method to address temperature sensitivity on a site and basin scale. The temperature study was designed to generate information for two primary purposes: data was collected from forest streams extensively (92 sites) throughout the state to develop a temperature sensitivity screening method and intensively at a smaller number of sites (33) to evaluate the predictive capabilities of existing reach and basin temperature models. Study sites represented type 1-3 streams located in all regions of the state having a variety of riparian shading conditions ranging from mature conifer forest to sites completely open and devoid of shade.

The study was supported by TFW cooperators throughout Washington. Over 50 individuals representing 35 organizations including tribes, industrial forest managers, small tree farm owners, environmental groups and state, county and federal governments participated. Individuals contributed their time to maintain field monitoring equipment, data from ongoing studies, and funding.

This report documents the results of the Temperature Study and recommends a method to TFW. In addition, a preliminary evaluation of the effectiveness of riparian management regulations is provided based primarily on temperature modeling.

Many of the 92 study sites were found to exceed water quality temperature criteria including most reaches with less than 50% shade but including some reaches with mature forest canopies along larger rivers. Where timber harvest had occurred, activities at all sites except one had been conducted *prior* to the TFW Agreement and did not reflect riparian conditions left according to the regulations adopted in 1987. Of all sites, 62% were found to be temperature sensitive according to the Forest Practice temperature standard and 72% exceeded the DOE water quality temperature standard. This large number of sites exceeding biologically-determined criteria confirm that past riparian management practices had significantly affected temperature in forest streams.

All basins showed general warming of water temperature in the downstream direction, which is consistent with theoretical relationships. Some local influence of tributary heating (primarily nearer the headwaters) and cooling (primarily in lower reaches) were observed. However, there were no clear trends in the relationship of basin temperature to harvest patterns in tributaries as opposed to effects of timber removal along the mainstem of the rivers themselves, a practice common in earlier decades.

Stream and basin characteristics of sensitive sites were evaluated to identify what features could be used to recognize existing or potentially sensitive streams. Typically, a combination of local environmental factors including air temperature, stream width, stream depth had an important influence on water temperature, but no one factor alone was a good predictor of stream temperature. Shading from riparian vegetation was found to have an important influence on stream temperature but the extent of the cooling effect varied with site elevation. Temperature prediction models that account for local environmental conditions were found to be useful if very accurate estimates of site-specific temperature are required for decision-making.

Although many characteristics were shown to correlate with stream temperature, two factors were of such overwhelming importance that they could be used to reliably predict temperature sensitivity--shading and elevation (which probably indicates air temperature regime). A simple graphic model (the temperature "screen") based on these characteristics correctly identified the temperature category according to water quality criteria of 89% of the sites.

An appreciation of the effectiveness of riparian rules for temperature protection was an essential element in developing a method to recognize those sites <u>not</u> protected during normal administration of the regulations. Current riparian zone management rules specify maintenance of 50 or 75% of the *existing* shade along stream types 1, 2 and 3, depending on the temperature sensitivity of the reach. The effects of riparian rules on stream temperature were not directly measured in this study, although the adequacy of the riparian rules was evaluated by analysis of stream data collected throughout the state and by using the temperature prediction model.

Shading specified by the regulations was found to be generally inadequate for protecting temperature of type 1-3 waters. Based on study results, *total* stream shading of 50-75% after cutting is needed to maintain water temperature in most streams within water quality standards (rather than the 50-75% of the *existing* shade as specified in current rules). However, because the importance of shade varies with elevation, a shading guideline based on elevation of the site is recommended.

Surveys of riparian buffer zones left under the TFW rules indicate that forest managers are tending to leave more shade in riparian zones than required in the current regulations and that shading generally meets the recommendations of this study. As expected, riparian zones along large streams (type 1) tend to have less shading, especially on the eastside of the state, although sample sizes were small.

The temperature sensitivity screen based on site elevation and shading forms the basis for the recommended TFW temperature method. The screen can be used to estimate temperature conditions of a reach before and after timber harvest based on an easy to measure shading parameter with good reliability. Where greater precision may be needed, a temperature prediction model requiring more carefully conducted field measurement may be used.

The effectiveness of temperature prediction models was analyzed to identify models that could be used where needed. Four reach temperature prediction models (Brown's Model, TEMP-86, U.S. Fish &Wildlife Service SSTEMP, and TEMPEST) were rigorously evaluated for prediction accuracy and practicality of use. A sensitivity analysis was performed to determine each model's sensitivity to key input parameters of importance to stream temperature (for example, shading, air temperature, solar radiation, and stream depth). Several of the models were found to predict water temperature with reasonable reliability, even when input data is estimated, although models varied in predictive capability and practicality. One reach model was selected that satisfied both prediction accuracy and practicality criteria developed with TFW field managers in mind. The computer model is simple to use by anyone.

Three basin, or multi-site, models were tested (EPA QUAL2E, USF&WS SNTEMP, and MODEL-Y). on sites grouped in three river basins,(Coweeman River, the Deschutes River and the Little Natches River). The basin models were very cumbersome to use than reach models. Data requirements were intense to the extent that general forest managers could not be expected to routinely commit the time or resources required to run a basin model on a widespread basis.The models were also not very reliable temperature predictors when used in a manner that could be expected in routine TFW use. None of the basin models performed well enough, were sufficiently practical and reliable, or had appropriate gaming capabilities to recommend their use.

Prior to the study, it was perceived that dispersing harvest units throughout a watershed guided by a basin temperature prediction model might be a feasible approach to addressing downstream temperature concerns related to type 4 waters. However, study results suggest that a basin approach introduces unnecessary complexity and difficulty into the management process without improving temperature protection. Primarily, study results also showed that a large number of streams should be adequately protected under forest practice regulations administered on a site-by-site basis.

Instead of trying to use basin temperature model in harvest planning, the Temperature Work Group recommends that temperature sensitivity of water types 1-3 be addressed by the TFW temperature method and that the need for alternative methods for determining temperature protection needs for type 4 waters be established after a carefully designed field study. A suggested approach is provided.

The recommended method includes an easy to apply temperature screen based on elevation and shade of a site. From this, the amount of shade needed to maintain temperature within water quality standards can be determined. This temperature screen can adequately predict temperature of most sites. In some cases, more careful design of riparian leave trees with shade in mind may be warranted. The computer model may be used at sites where unusual situations suggest that screening results may be inaccurate or to verify predictions made with the screen. Widespread need for the computer model is not foreseen. (It is likely that a temperature sensitive type 4 streams can be identified in a manner similar to that of the temperature screen for type 1-3 waters.)

This report provides a detailed documentation of data and analysis used to draw study conclusions. Chapters are written to stand alone for the most part. Readers may refer directly to the following chapters for discussion of elements of the study of interest to them:

- TFW framework, literature review and project overview (Chapter 1)
- Study design, sites and methods (Chapter 2)
- Background information on stream and basin characteristics (Chapter 3)
- Reach model-testing (Chapter 4)
- Basin model-testing (Chapter 5)
- Temperature characteristics of forest streams in Washington (Chapter 6)
- Temperature sensitivity and forest practice regulations (including description of the recommended TFW temperature method) (Chapter 7)
- Summary of study conclusions and recommendations for future monitoring and research needs (Chapter 8)

A separate TFW "user's" manual will be provided that describes how to use the temperature method agreed on through the TFW process. Field measurement techniques, decision steps and model applications are described.

ILLUSTRATIONS

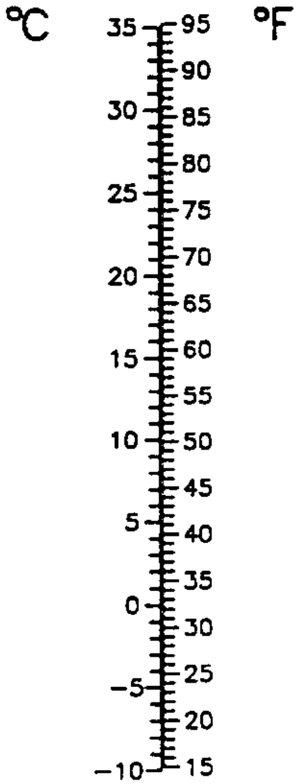
TABLES

CONVERSION TABLES

Multiply Metric Units	BY	To Obtain English Units
Meters (m)	3.28	Feet (ft)
Kilometers (km)	0.621	Miles (mi)
Sq. Kilometers (km^2)	0.386	Sq. Miles (mi^2)
CMS (m^3/s) (cubic meters per second)	35.314	CFS (ft^3/sec) (cubic feet per second)

Degrees Celsius to Degrees Fahrenheit: $^{o}C = (^{o}F - 32)(0.55)$

Degrees Fahrenheit to Degrees Celsius: $^{o}F = (1.8)(^{o}C) + 32$



CHAPTER 1
PROJECT SCOPE AND RATIONALE

TIMBER/FISH/WILDLIFE TEMPERATURE ISSUE

Stream temperature is important to aquatic life, affecting fish directly and indirectly through all parts of the ecosystem (Hynes 1970). Local and downstream changes in temperature with timber harvest is an important land use consideration. Many studies throughout the United States have documented the effects of riparianvegetation and its removal on summer stream temperatures with consistent results (reviewed by Beschta and others 1987.) Removal of riparian vegetation can significantly increase daily mean and maximum temperatures during the summer months (Brown and Krygier 1970) although the effects during the winter months, if any, have not generally been studied. The summertime effects are most pronounced in smaller streams. Because timber harvest patterns create a mosaic of vegetation conditions within watersheds, and because heat can move downstream with flow, there are also concerns that inadequate temperature protection measures in upstream waters may have adverse downstream impacts.

Prior to the Timber/Fish/Wildlife (TFW) Agreement, in 1988, temperature has been an often volatile and sometimes misunderstood issue. The potential effects of forest practices on stream temperature were identified as a major concern during negotiations of the TFW agreement. The direct effects of timber removal on the temperature of larger, fish-bearing streams (Washington stream types 1-3, WAC 222-16-020) was addressed by riparian zone management rules that specified leave tree requirements along streams that were designed, in part, to preserve shading and protect temperature.

Through TFW negotiations it became clear that additional information was needed to develop scientifically-based procedures for identifying situations where riparian zone rules may not provide sufficient shade protection. Furthermore, past forest practice regulations for temperature sensitive streams were vague as to what special precautionary actions were necessary. TFW identified specific key issues relative to management considerations that would serve as a focus for further efforts, including: 1) criteria for identifying temperature sensitive streams, 2) a method for describing their geographic extent, and 3) a reliable method of predicting water temperatures at sites where alternative prescriptions may be desired. The Agreement states that the Washington Department of Ecology, industry representatives, other agencies, tribes and interested parties will "...take a lead role in establishing a process to identify temperature-sensitive basins. A model or methods shall be established to predict temperature increases associated with any future management activities."

The envisioned management process could be as follows: a general screening tool would be used to identify temperature sensitive basins or locations. Where sensitivity was *not* identified, riparian zone management rules would serve to protect stream temperature. Where sensitivity *was* identified, alternative management prescriptions would be designed with the aid of a temperature prediction model that had suitable capabilities to evaluate various management alternatives. Modeling needs include analyzing temperature effects for both individual forest practice applications and basin planning.TFW managers likely to use the recommended sensitivity criteria and prediction models include State, private and tribal foresters, fisheries biologists and water quality regulators.

Prediction Models. Several computer models that predict water temperature at a single site, or at sites in a stream system are available. The models vary in the complexity of detail with which site characteristics including meteorology, hydrology, stream geometry, and riparian vegetation must be described and the mechanics of how temperature is calculated. The simpler models require fewer variables while the complex models can require many variables to be measured or estimated. Some models have been used on a project basis in developing forest management prescriptions. Some of the models have had limited testing, although none have been verified in widespread and well-documented studies. Field-testing of all potential model candidates was considered essential by the Temperature Work Group before a model could be adopted for routine TFW use.

Deciding which predictive model to use on a routine basis requires consideration of a number of factors. How well does the model predict temperature at a site, or downstream? (The effectiveness of models in estimating existing conditions, not just the warmest possible temperature, must be carefully considered in their performance.) What types of variables will need to be measured, or estimated, to satisfactorily run the model? (Variables that are difficult to measure are not practical in widespread application of a model.) How precisely can important variables be measured in the field? (The measurement precision will influence how accurately models can be expected to perform.) Will it be feasible for field managers to use the model, given the required knowledge, costs and staff time? (Most TFW field managers are charged with a wide range of responsibilities and do not generally have time for extensive field data collection.) Is a model easy enough to use to be an effective tool? (Familiarity with computer models varies among potential users. Highly specialized or complicated models may not be desirable since only a few people have access to the technical information driving decisions.)

Sensitivity Criteria and Screens. Sensitivity and screening criteria that use temperature models have not been well developed, although standards based on biologic thresholds exist. Washington's forest practice regulations simply specify that the average maximum stream temperature may not exceed 15.6°C (60°F) for more than 7 consecutive days. How effective these criteria are for discriminating temperature sensitivity from a biological perspective is not known. In addition, it was recognized that methods to correctly identify potentially temperature sensitive streams during the forest practice application phase would have to be developed.

SCIENTIFIC RATIONALE

Physics of Stream Temperature

Stream temperature has been widely studied and the physics of heat transfer is one of the better understood processes in natural watershed systems. Water temperature is extremely important to aquatic life, and changes in temperature in both large and small streams may have significant effects on aquatic communities (summarized in Hynes 1970, Beschta and others 1987). Changes in water temperature regimes in streams and river basins can arise from human activities such as forest cover removal, irrigation or construction of impoundments, industrial plants, and thermal electric power plants.

Most researchers have used an energy balance approach based on the physical processes of heat transfer to describe and predict changes in stream temperature. Efforts have primarily focused on developing models for predicting: (1) thermal changes of larger rivers from thermal pollution (Messinger 1963, Edinger and Geyer 1968, DeWalle 1976); (2) reservoir cooling effects on larger rivers (Raphael 1962, Delay and Seaders 1966, Morse 1970, Ryan and others 1974) and, (3) removal of riparian vegetation along forest streams with logging (Brown 1969, Beschta 1984, Theurer and others 1984, Adams and Sullivan 1990).

The six primary processes that transfer energy in stream environments are: 1) solar (short-wave) radiation, 2) radiation (long-wave) exchange with the sky and vegetation, 3) convection with the air, 4) evaporation, 5) conduction to the soil and, 6) advection from incoming water sources (Figure 1.1). Some of these processes primarily determine heat input and others determine heat loss. During summer, direct solar radiation is the primary source of energy for heating streams while reradiation of energy to the sky and vegetation and evaporation are the major sources of heat loss. A detached discussion of these processes can be found in Brown (1969), Theurer and others (1984), or Adams and Sullivan (1990).

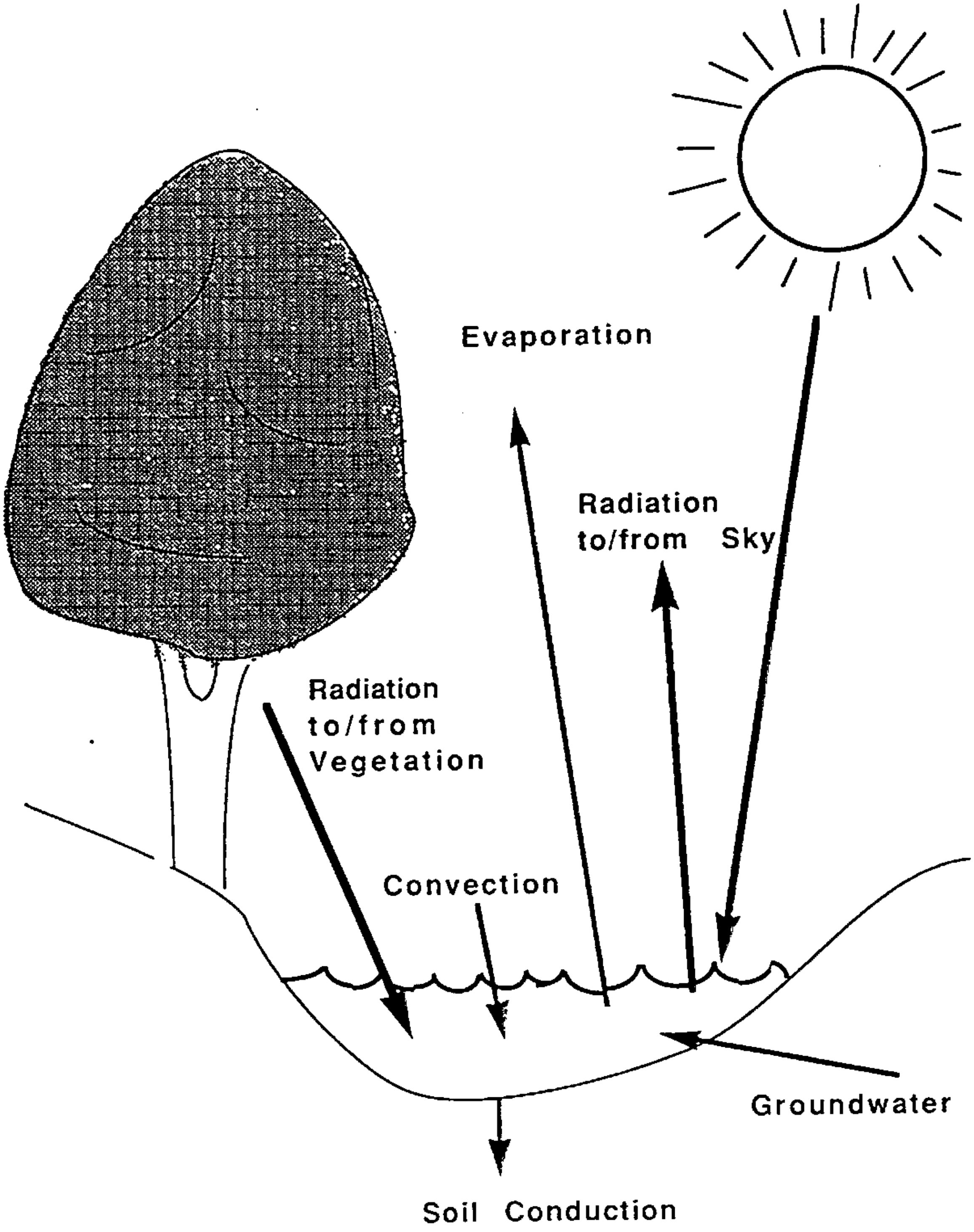


Figure 1.1 Modes of heat transfer contributing to the stream energy budget assuming summertime daylight conditions. Although heat transfer can often occur both into and out of the water, arrows indicate dominant direction and relative importance in forest streams.

The net energy balance, which is influenced by local environmental factors, determines the water temperature at a particular location. Figure 1.2 provides a simplified example of a daily energy budget in mid-summer for an intermediate-size, open stream predicted by a stream temperature model (from Adams and Sullivan, 1990). However, predicting temperature is complicated because the net energy balance is highly variable in 1) time with daily and annual variation in solar radiation and, 2) throughout the stream system as stream characteristics and environmental factors change (Beschta and others 1987).

Environmental Factors That Influence Temperature

Heat transfer processes operate in all streams but the significance of each process on the net energy and stream temperatures vary. Previous research has identified several variables that are important in determining the temperature profiles of streams including meteorologic, stream, vegetative and flow characteristics. A list of the types of variables that are included in evaluation of heat transfer in stream environments is shown in Table 1.1.

While there are many specific climatic and stream variables accounted for in the energy balance equations, a sensitivity analysis of stream heating processes performed by Adams and Sullivan (1990) showed that four environmental variables primarily regulate heat input and output from the stream environment, and thereby determine stream temperature under any given solar loading. These are: **riparian canopy, stream depth, local air temperature, and groundwater inflow.**

The importance of riparian vegetation in determining stream temperature has been extensively studied in smaller streams (Brown and Krygier 1970, and many others reviewed in Beschta and others 1987). Other investigators have also discussed the importance of environmental factors in influencing stream temperature including local air temperature (Smith and Lavis 1975, Holtby and Newcombe 1982, Hewlett and Fortson 1982, Kothandaraman and Evans 1972), stream depth (Brown 1970, Theurer and others 1985) and groundwater inflow rate (Smith and Lavis 1975, Hewlett and Fortson 1982, Beschta and others 1987).

Figure 1.2 Example of daily average heat flux in a partially shaded forest stream due to the various energy transfer modes.

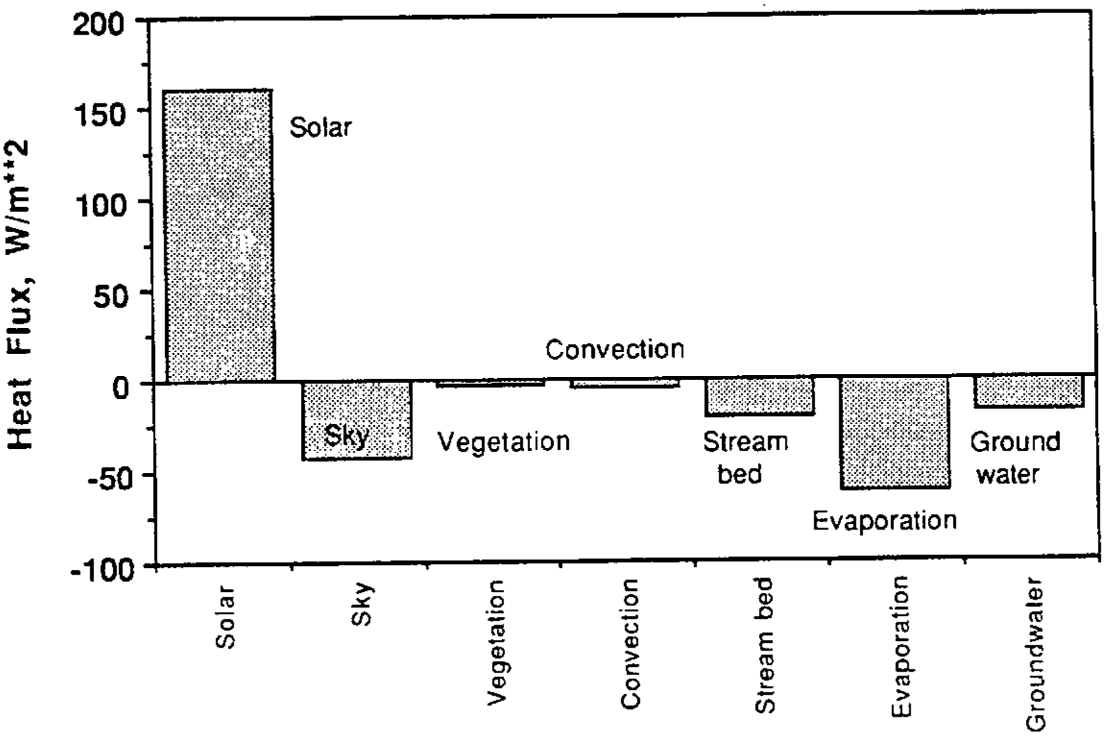


Table 1.1. Types of variables considered in stream heating processes.

GENERAL VARIABLE	EXAMPLE
GEOGRAPHIC	latitude, longitude, elevation
CLIMATIC	air temperature, relative humidity, wind velocity
STREAM CHANNEL CHARACTERISTICS	stream depth, width, velocity, substrate composition
RIPARIAN OR TOPOGRAPHIC SHADING	sky view factor (% shade), canopy density, vegetation height, crown radius, topographic angle

Effects of Forest Management on Stream Temperature

Considerable research has been conducted in forested watersheds on temperature changes as a result of removing shade along channels during timber harvest. Brown and Krygier (1970) demonstrated that reduced stream shading results in generally higher stream temperatures and increases in diurnal water temperature fluctuation in Oregon forest streams. Daily maximum temperatures in very small streams tend to have the largest response to forest canopy removal. Studies conducted in various locations in the United States have also shown potentially large increases in daily maximum temperatures with removal of forest vegetation. Beschta and others (1987) provide a complete review of harvest effects in forest stream environments from previously published studies, summarized in Table 1.2 taken from that report.

The magnitude of potential temperature change with removal of streamside vegetation varies with stream size (Brown 1969, Adams and Sullivan 1990). One of the largest increases in daily maximum temperature (16°C, maximum 1-day temperature) was documented by Brown (1969) in a very small stream in coastal Oregon. More typically, increases of 3-7°C in daily maximum temperature can be expected with removal of significant amounts of shade from the streamside zone. Brown (1969) noted that net energy exchange differs between small and large streams because of the rapid response times of shallow streams to changes in solar radiation. Energy transfer process studies in the forest environment have been conducted primarily in relatively small streams.

The beneficial effect of streamside shading for temperature protection is a function of the proportion of the sky view that is blocked from the sun (shaded) both before and after harvest. Brown and others (1971) concluded that leaving sufficiently wide vegetation buffers (25-100 ft) along streams can be as effective as undisturbed forests for protection of water temperature. Swift and Messer (1971) reported from the southern Appalachians that water heated in upstream clearcuts tends to return to normal temperature as it flows through downstream buffered reaches (700-1000 ft). It should be noted that not all stream temperature studies have agreed on the effectiveness of riparian buffers. Hewlett and Fortson (1982) concluded that buffers along streams in the Georgia piedmont terrain did not protect stream temperature due to suspected increases in shallow groundwater stored in cutover floodplains. The extent of changes in groundwater temperature have not been well-documented.

Several heat transfer temperature prediction models have been developed for use as management tools to assist managers to calculate probable temperatures with different levels of shading (e.g. Brown 1970; Beschta and Weatherred 1984). Forest practice regulations also specify shading requirements as part of riparian zone management practices.

Where shade is reduced during harvesting, recovery to full mature forest shade levels may take approximately 5 to 10 years to reach 50 and 75% shade respectively according to a riparian survey conducted by Summers (1982). Old growth forest sites averaged approximately 84% shade and recovery to this level of shading was estimated to take approximately 14 years.

Table 1.2 Summary of summer temperature changes associated with forest management activities on forest watersheds, Pacific Northwest (from Beschta and others 1987).

Location	Treatment	Stream Temperature Variables	Temperature Change (°C)	Reference
Alaska (southeast)	Clearcut and natural openings	Δ Temperature per 100 m of channel	0.1 to 1.1°C/100 m Average = 0.7°C/100m	Meehan (1970)
British Columbia (Vancouver Island)	Logged (Tributary H)	Average June-August diurnal temperature range	0.5 to 1.8°C increase over pre-treatment levels	Holtby and Newcombe (1982)
	Logged and burned (Tributary J)	Average June-August diurnal temperature range	0.7 to 3.2°C increase over pre-treatment levels	Holtby and Newcombe (1982)
Oregon (Cascades)	Clearcut	Average June-August maximum	4.4 to 6.7°C	Levno and Rothacher (1967)
	Clearcut and burning	Average June-August maximum	6.7 to 7.8°C	Levno and Rothacher (1969)
Oregon (Coast Range)	Clearcut	Average June-August maximum	2.8 to 7.8°C	Brown and Krygier (1967)
	Clearcut and burning	Average June-August maximum	9 to 10°C	Brown and Krygier (1970)
Oregon (Cascades)	Mixed clearcut and forested reaches	Δ Temperature per 100 m of channel	0 to 0.7°C/100 m	Brown et al. (1971)
	Tractor striped area	Δ Temperature per 100 m of channel	15.8°C/100 m	Brown et al. (1971)

Basin Temperature Relationships and Heat Transport

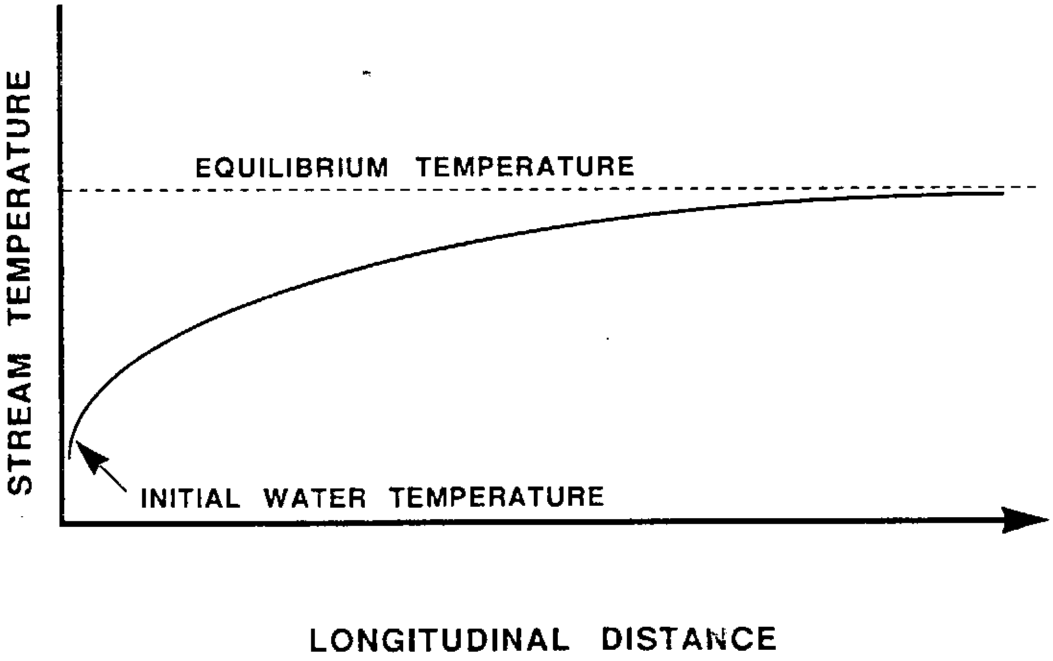
Of increasing concern in Washington and elsewhere are the downstream or cumulative effects that removal of vegetation along headwater streams may have on larger streams and rivers. Temperature can move downstream with a mass of water, and therefore the effects of forest management practices on temperature in one location can have impacts downstream. Brown and others (1971) showed that local water temperature can change measurably at locations where cooler or warmer water joins a stream. Temperature changes occur in proportion to the discharge and temperature of the individual sources. Although the local effects of stream temperature mixing have been identified, little is known about the extent that changes in upstream areas influence conditions downstream.

There have been relatively few studies documenting the occurrence of increased temperature at a watershed scale with history of timber removal in the basin. Beschta and Taylor (1988) observed an increase in maximum temperatures in a larger river over time. This increase reflected general harvest patterns in the basin and the occurrence of large natural storm events that may have significantly modified channels during the measurement period.

Heat can be transported downstream with flowing water, although water temperature adjusts to local environmental conditions as it moves. The influence of mixing processes on the downstream transport of heat has been studied by Brown and others (1971) and is treated in existing basin temperature models. As water moves downstream, its temperature seeks an equilibrium with air temperature dictated by the local environmental factors. The rate of adjustment and background ambient conditions vary with stream size (Edinger and others 1968.) The equilibration of water to air temperature has not been extensively studied, and needs to be better understood in forest streams, since this will determine the downstream extent of the influence of canopy removal at locations within a watershed.

Stream temperature tends to increase in the downstream direction from headwaters to lowlands, even under mature forest conditions, and creates characteristic basin temperature profiles (Hynes 1970, Theurer and others 1984, Sullivan and Adams 1990). Most of the important environmental variables that control stream temperature also vary systematically within watersheds. The general increase in

Figure 1.3 A conceptual temperature profile of a stream system based on the physics of headt transfer and geographic relationships. (After Theurer and others, 1984).



temperature from headwaters to lowlands occurs for several reasons: air temperature increases with decreasing elevation, groundwater inflow decreases in importance compared to the volume of flow already in the channel in larger rivers, and rivers widen resulting in decreased shading by riparian vegetation (Beschta and others 1987). A conceptual diagram of basin temperature with longitudinal distance from divide is shown in Figure 1.3 (Theurer and others 1984).

Temperature Prediction Models and Methods

A number of analytical models have been developed to predict onsite and downstream temperature response to human activities. Several have been developed specifically for application in forest stream environments. Stream temperature and forest management effects can be predicted at stream sites by measuring or estimating the variables used by the models to evaluate the energy balance including stream flow, shading, meteorology, valley orientation, and watershed topography. These stream heating models have yielded specific conclusions about stream temperature that have proven helpful in forest management considerations.

Temperature prediction models appropriate for forest management decision-making fall into two categories. Reach models predict temperatures in relatively short reaches of stream (hundreds to thousands of meters) by characterizing conditions within the reach. Basin models attempt to predict temperature for entire watersheds. They generally do so by predicting temperature at specific locations using a reach model, then routing water downstream to the next prediction location while attempting to adjust temperature for the environmental conditions the stream passes through. Reach models have been more extensively applied, and are relatively easy to use since the measurement requirements are defined for a relatively finite area. Using basin models is far more problematic. Stream and riparian conditions are difficult to characterize for large areas, and model mechanics are far more complex. Models tested are listed in Table 1.3.

Reach Models

Brown's Model

Before the advent of computers, Brown's equation (1970) was developed for general use by foresters for developing silvicultural prescriptions. To allow easy application of a model based on heat transfer processes, Brown simplified some of the energy transfer relationships and restricted the aspects of temperature regime to be modelled. Specifically, Brown's equation uses a few variables to predict the maximum daily change in temperature at a site with different levels of riparian shading.

More detailed characterizations of an energy balance approach have been developed in recent years, and encompass factors left out of Brown's (1970) original work. Recent versions more closely resemble the SSTEMP and TEMP-84 models, and may be more accurate in a wider variety of conditions, but have also become more complex. We remain interested in the simple equation since computers are not universally available to landowners.

Table 1.3 Temperature prediction models evaluated in the Timber/Fish/Wildlife Temperature Study.

Reach Models	USF&WS SSTEMP, Ver.3.3 TEMPEST TEMP-86 Brown's Equation
Basin Models	USF&WS SNTEMP, Ver. 3.5 EPA QUAL2E MODEL Y (Basin TEMPEST)

TEMP-86

Recently, two heat transfer models have been developed for use on computers that treat heat transfer relationships more completely (Theurer and others 1984; Beschta 1984). Both models require extensive consideration of riparian shading factors and can be used to predict temperature response to changes in riparian vegetation. Because they are more complete, these models require more measured and estimated variables and are thus more difficult and costly to apply than Brown's model. TEMP-86 (Beschta 1984) is a reach-specific energy budget model and is oriented specifically to evaluating the effects of shade or riparian characteristics on predicted water temperatures. While this model calculates heat-loading similarly to the SSTEMP model the shade, analysis is more detailed. The model predicts hourly temperatures for any selected day.

USF&WS--SSTEMP

The SSTEMP model (Theurer and others 1984) also predicts temperature of relatively short stream reaches. The calculations on the reach level are similar to Beschta's model, and this model can use discrete, user-selected time steps. Both the SSTEMP and TEMP-86 models rely on measurement of a number of site and basin-specific variables. The SSTEMP model is perhaps the most widely used in project applications, while Brown has been used more extensively in forestry.

TEMPEST

Adams and Sullivan (1990) developed a heat transfer model (TEMPEST) that considers each of the heat transfer processes in detail but simplifies the variables needed to describe them. This model was designed to perform sensitivity analysis of stream heating processes although the full model can be used with relatively few parameters to predict water temperature at a site. It is intermediate in ease of use between Brown's equation and other computer models because data demands are minimal (5 variable input parameters). The model predicts hourly temperatures over any specified interval of time such as days or months.

Basin Models

Several of the temperature models are able to predict stream temperature for river basins (USF&WS SNTEMP Flow Network Model, EPA QUAL2E, and MODEL-Y). These models first estimate stream temperature for specific reaches as described above. They then route heat downstream and account for additional heat inputs and losses from groundwater inflow and tributary mixing.

QUAL-2E

QUAL2E is a general water quality model supported by the U.S. Environmental Protection Agency (EPA) Center for Water Quality Modeling. QUAL2E is a comprehensive water quality model used primarily to simulate wastewater treatment plant discharges. It can simultaneously simulate up to 15 water quality parameters including temperature. This model has evolved over the last twenty years with revisions and enhancements provided by a variety of interests. The last major review and revision was done by the National Council of the Paper Industry for Air and Stream Improvement (Brown and Barnwell 1987).

This model contains a detailed heat budget and transport module but it does not contain a provision for riparian or topographic shading. It operates in both steady state or dynamic modes; the latter was chosen for this test. While it would be possible to emulate shading by altering the solar radiation values, this was done done because other aspects of the energy balance that shading effects could not be correctly simulated. In addition to the shading limitation, major constraint of the model is that all computational elements must be equal in length and only six tributary streams are allowed. This requires many extra nodes be included in the network, and tributaries must often be altered in location where they enter the mainstem.

SNTEMP

SNTEMP is a steady state model developed by the U.S.Fish & Wildlife Service (Theurer and others 1984). (The SSTEMP reach model was developed from the SNTEMP model.) Input parameters are entered as the constant averages for the time-step used. The minimum time step (the shortest period of time for which an individual temperature prediction is made) is 24 hours. The model predicts maximum, minimum and mean temperatures at user-specified points in the stream network. Regression smoothing and calibration modules are also included. The model can be run on microcomputers with a math co-processor. The user can specify the network geometry with relatively few constraints. There is essentially no minimum reach length, and no upper limit to the size of basin that can be modeled. Efforts are being made to improve the friendliness of this model, although currently it is advisable to receive some special training in its use.

MODEL-Y

MODEL-Y is a simple basin model utilizing the TEMPEST model's energy balance equations combined with travel time, stream depth, and regional air-temperature profiles developed as part of this study (see Chapters 3 and 6). After experiencing some frustration with the other basin models, MODEL-Y was developed by the TWG as a simple basin model designed for the needs of the TFW community. It offers ease of use, minor data needs, and logical Geographical Information System interfacing, and an easy method of testing different scenarios,. MODEL-Y's strength is it's data requirements: only the sky view factor, (described in Chapter 2), ecoregion, and the stream network are required. MODEL-Y's current data set provides for dynamic simulation with a one-hour timestep. The simulation period is July 15 to August 15 typically the hottest 30 days of the year. As more hourly air temperature data become available the simulation period can be expanded. MODEL-Y is still under development and documentation is limited to the current version (version 1.0).

Model Evaluation

The models described above differ in regard to ease of use, predictive capabilities, cost of application, and appropriate stream conditions. Brown's equation has been widely used. Some documentation of its predictive capabilities for Washington forest streams is available in Wooldridge and Stern (1979) and for an Oregon stream system in Brown and others (1971). Numerous other evaluations can undoubtedly be found in the files of organizations who have applied these models in developing site-specific silvicultural prescriptions. Brown's simple model appears to predict temperature reasonably well (within approximately ±1°C) in small to intermediate size streams over relatively short reaches, particularly where incoming groundwater or tributary inflow is not a factor. However, the model does not appear to work as well for larger streams and rivers based on data presented in Brown and others (1971).

The other computer models have been increasingly used in recent years, although documentation of their predictive capabilities is less extensive. Carefully described tests of the models were not found in the literature for either the USF&WS SSTEMP Model (Theurer and others 1984) or TEMP-84 (Beschta 1984) and the later version, TEMP-86. The TEMPEST model (Adams and Sullivan, 1990) has not been verified at specific sites. Instead, general temperature relationships predicted by the model based on important environmental factors were established with temperature data collected in 24 streams and rivers in Washington and Oregon.

Case studies of the USF&WS SNTEMP network model have been described for the Tucannon River in southeast Washington (Theurer and others 1985) and for the upper Colorado River (Theurer and others 1982). In both cases the authors' primary intent was to suggest the general model capability, and its application in evaluating temperature effects on fish habitat. Methods and results were not described sufficiently to evaluate the model's accuracy and precision in predicting temperature within stream segments (between nodes) based on watershed factors and forest management. Better verification of basin models is necessary given the difficulty in predicting offsite temperature effects. Basin temperature prediction is more difficult than local site prediction because of the way the models treat downstream transport of heat and because of the difficulty of characterizing important environmental parameters, such as riparian vegetation, for entire drainage basins.

Characteristic Temperature Regimes

Despite the considerable temperature data that has been collected by various groups and agencies throughout the state, no synthesis of these data has yet been attempted and no clear understanding of temperature regimes and their association with forest management exist. It is unlikely that all Washington streams are temperature sensitive in relation to forest practices (i.e., exceed the current sensitivity standards). To properly identify sensitive streams, characterization of typical stream temperature regimes in the various ecoregions of the state was considered essential. Emphasis would be placed on using existing temperature monitoring sites to determine the extent of temperature sensitivity in Washington forest streams.

Sensitivity criteria and model predictions must be evaluated as to their ability to correctly identify when the standard will be exceeded with a proposed forest practice. Stream heating models have yielded conclusions about stream temperature that have proven helpful in management considerations. In addition to site-specific and basin modelling, generalized temperature characteristics can be helpful for predicting effects of forest management.

The physical models identify a number of climatic, geographic, stream, and vegetation characteristics that influence stream temperature. However, past emphasis on temperature prediction, especially in land use considerations, has led to perceptions that stream temperature is uniquely determined at each stream location based on a complex array of site characteristics. As a result, predictive models are increasingly viewed as a necessary basis for land management decisions. The specificity of models in capturing heat transfer variables, as opposed to more generalized techniques, bears directly on cost of application.

In contrast to the extent of analytical research and modeling, there has been little attempt to identify general trends and patterns in stream temperature in relation to basin characteristics. Furthermore, many previous field studies have emphasized the importance of streamside vegetation in providing shade while excluding consideration of other important environmental factors. With the current interest in designing forest practices to reduce temperature effects on a site-by-site and basin scale, a better identification of the underlying relationships affecting basin scale temperatures is needed.

Sullivan and Adams (1990) offer a more generalized understanding of stream temperature based on heat transfer and geomorphic processes. Their stream heating and temperature regime analysis provides a conceptual framework for evaluating temperature relationships in forest streams and they demonstrate that parameters can be identified that allow meaningful comparison of temperature from stream to stream. When important environmental factors were accounted for, data from disparate streams could be compared despite differences in the myriad of other factors that influence stream temperature. For example, significant patterns and similarities between streams and rivers located in western Washington and Oregon were found.

Characterizing important environmental variables and demonstrating their relationship to stream temperature allows determination of probable temperature regimes for managed and unmanaged stream sites and provides better values for use in the predictive models. Importantly, it may help us to examine whether current riparian management strategies provide adequate protection from adverse temperature increases in Washington streams.

The existence of general temperature patterns could prove highly useful for TFW. If a general understanding of characteristic temperature responses can be improved, temperature sensitive locations where modeling and monitoring efforts should be focused can be identified. Furthermore, characterizing probable temperature changes with a reasonable degree of certainty based on general relationships may provide a suitable alternative to costly temperature modelling in many situations.

Temperature Sensitive Streams

Criteria for temperature concerns may include a stream's natural or management history suggesting where particularly high temperatures may be expected; the presence of sensitive fish species that are intolerant of high stream temperatures; or sensitive time periods when fish are more vulnerable to a particular range of temperatures. Washington's forest practice standards simply specify that the average maximum stream temperature shall not exceed 15.6°C for more than seven consecutive days.

What stream temperatures are most critical to model from a biological viewpoint are not agreed upon, but some treatment of both average as well as extreme temperatures is probably useful. Maximum and minimum temperatures may be more important for consideration of detrimental or lethal temperature conditions. Because most aquatic organisms are poikilothermic (cold-blooded), mean temperatures may be more informative of the metabolic capacity of aquatic stream communities, and therefore important in understanding stream productivity.

Biological considerations dictate the degree of resolution required in temperature prediction. Matching sensitivity screening and model performance to biologically-derived standards such as the exceedance threshold over a time period adds a new dimension to temperature prediction. Prediction models have not in the past often been used to model realistic temperatures over longer time periods, although most of those available can be used to do so with some modification. Continuing biologic studies are working to improve understanding of what temperatures are of importance to fish, and to describe their occurrence. Application of the study results may be aided by the development of models capable of predicting the occurrence and distribution of those temperatures.

PROJECT OBJECTIVES

A number of objectives relating to model performance and practicality, and temperature sensitivity screening criteria were carefully developed in the 1988 temperature study to provide a useful and verified temperature method to meet TFW needs. The scope of the study included a thorough evaluation of model performance, and an analysis of temperature data collected throughout the state.

The objectives of the 1988 TFW temperature study were to:

- Evaluate the ability of models to predict temperature at a site and downstream and select a method for temperature prediction by TFW decision-makers.
- Quantify the distribution of important environmental variables that control water temperature by stream type and ecoregion in relation to watershed and riparian conditions.
- Develop methodologies to assess stream conditions for input to temperature prediction models.
- Establish general temperature regimes for various stream types in ecoregions of the state and the effects of forest management.
- Evaluate temperature sensitivity screening criteria.
- Characterize streams likely to exceed temperature criteria

Effectiveness of the current riparian rules was also considered, but was not directly tested.

GENERAL PROJECT STRATEGY

The Temperature Work Group (TWG) conducted a multi-faceted study of stream temperature and temperature prediction models using data collected from over 75 streams throughout the state during the summer of 1988. A brief overview of the project and a discussion of how the various study elements fit together is provided here. Specific data collection methods and site characteristics are described in Chapter 2.

Air and water temperature and a number of hydrologic, riparian, channel and meteorologic data were collected at monitoring sites distributed within thirteen Washington ecoregions (CMER-AMSC Work Plan, 1989). Data collected at these sites were used for: characterization of stream and riparian characteristics (Chapter 3) , site model evaluation (Chapter 4), basin model evaluation (Chapter 5) and description of general water temperature regimes in forest streams of Washington (Chapter 6). Data were also used to evaluate the probable effectiveness of forest practice regulations pertaining to riparian zone vegetation management in meeting temperature water quality standards and to devise a TFW temperature method (Chapter 7). Study conclusions and recommendations are summarized in Chapter 8.

Site-specific or reach model-testing formed the basis of the 1988 field study. Stream temperature was monitored during the summer months and required model input variables were measured or estimated for stream lengths of homogeneous riparian and channel conditions in a variety of streams throughout the state. Model temperature predictions were compared with measured water temperature at each site.

In order to evaluate the basin models, a number of the reach sites were clustered within several basins located in different ecoregions of the state. Thus, sites in these basins served to test both site and basin models. In addition to temperature and reach data, surveys were conducted within these basins to describe the range of conditions with respect to groundwater inflow rates and flow regime.

The TWG conducted several "methods" studies in some locations in order to improve methods for better measuring or estimating variables input to the model. Variables were measured in several ways to determine the best means of evaluating them. Results from the "methods studies" allowed the TWG to develop recommendations for measurement or estimation of parameters describing channels, stream flow and regional climate characteristics (described in Chapter 3). Several model input variables were considered, but stream dimensions, riparian canopy, air temperature, relative humidity and groundwater inflow rate were emphasized because of their overriding importance in governing water temperature.

The Temperature Work Group developed and coordinated the project. For the site-specific and basin-wide modeling elements of the study, the TWG coordinated the field studies, centralized the data management and analysis, conducted the model testing with computer analysis, and interpreted the results presented in this final report. The TWG also provided a two-person field team to perform site evaluation of environmental variables for input into the models.

Table 1.4. *Timber/Fish/Wildlife 1988 Temperature Study cooperators.*

Co-operator	Contact	Nature of Assistance
Boise Cascade	Candace Parr	Field Assistance
Colville Confederated Tribes	Jerry Marco	Operate Thermograph
Cowlitz County Conservation District	Sheldon Somers	Purchase & operate Thermograph
Longview Fiber Co.	Monte Martinson	Purchase & Operate Thermograph
Makah Tribe	Rick Klinge	Operate Thermograph
Muckleshoot Tribe	Larry Ratte	Operate Thermograph
Nooksack Tribe	Kent Doughty	Temperature Work Group, Provide & OperateThermograph
Northwest Indian Fisheries Commission	Dennis McDonald	Funding
Plum Creek Timber Company	Bruce Beckett	Funding
Puyallup Tribe	Mark Heckert	Operate Thermograph
Quileute Tribe	Mark Mobbs	Field Assistance
Quinault Tribe	Greg Watson	Operate Thermographs
Squaxin Island Tribe	Dave Shuett-Hames Michelle Stevie	Field Assistance
Landowner	Fran Moelman	Operate Thermograph
Tulalip Tribe	Kurt Nelson	Provide & Operate Thermograph, Field Assistance
Upper Columbia United Tribes	Eileen MacLanahan	Operate Thermographs
US Environmental Protection Agency		Funding
US Bureau of Indian Affairs	Dennis Olson	Data
USFS Colville National Forest	Bert Wasson	Data
USFS Gifford Pinchot National Forest	Deigh Bates	Data
USFS PNW Range & Experiment Station	Fred Everest	Provide Thermographs
USFS Umatilla National Forest	Ed Calame	Data
USFWS Fisheries Assistance Office	Phil Wampler	Provide Thermographs
USFWS Makah National Hatchery	Dan Sorenson	Data
USFWS Fisheries Research Res Center	Jack McIntyre	Data
USFWS Leavenworth National Hatchery	Jim Mullen	Data
	Reg Reisenbichler	
Washington Dept of Ecology	John Tooley	Work Group, Project Coordinator
	David Roberts	Purchase Thermographs
	Jim Carrol	Field crew, Data reduction
	Anita Stohr	Computer Programming
	Elizabeth Lanzer	Equipment
	Brad Caldwell	Equipment
	Bob Johnson	Equipment
Washington Dept of Fisheries	Pamela Knudsen	Work group,
	Maggie Bell McKinnon	Field crew, Data reduction
	Bob Buggart	Operate Thermograph
Washington Dept of Natural Resources	Jim Ryan	Data
	Bob Bannon	Provide & Operate Thermographs
	Evan Pryor	Provide & Operate Thermographs
Washington Dept. of Wildlife	Thom Johnson	Provide & Operate Thermographs
	Steve Leider	Provide & Operate Thermograph
Washington Environmental Council	Cinnamon Zakar	Field Crew
	Roger Garrett	Operate Thermograph
Weyerhaeuser Company	Kate Sullivan	Work Group, Data management
	John Heffner	Technical & Field Assistance, Operate Thermographs
	Steve Anderson	Operate Thermograph
	Jim Booher	Operate Thermograph
Yakima Indian Nation	Joel Hubbel	Provide & operate Thermographs
	Dale Bambrick	Thermographs

Most important were the numerous cooperators throughout the state who collected temperature data and assisted the project in a variety of ways.

Cooperators collected temperature data using monitoring field equipment provided by the TWG or themselves as well as contributed data from existing studies.

STUDY COOPERATORS AND SPONSORS

This TFW temperature study was funded primarily by the Washington Department of Ecology, Weyerhaeuser Company, Washington Department of Fisheries, and the Nooksack Tribe. Additional staff and funding was supplied by Washington Environmental Council, Northwest Indian Fisheries Commission, and Plum Creek Timber Company.

This comprehensive statewide study was made possible by the TFW cooperators (Table 1.4), who provided temperature data and other invaluable assistance for the 1988 field work and model testing. These cooperators contributed resources and/or personnel to operate temperature measuring equipment, or provided water temperature data from their existing sites.

The cooperating organizations and agencies included:

Boise-Cascade Corporation, Longview Fiber Company, Weyerhaeuser Company, Cowlitz County Conservation District, Washington Environmental Council, Colville Tribe, Makah Tribe, Muckleshoot Tribe, Tulalip Tribe, Puyallup Tribe, Quinault Tribe, Quileute Tribe, Squaxin Island Tribe, Upper Columbia United Tribes, Washington Department of Ecology, Washington Department of Fisheries, Washington Department of Natural Resources, Washington Department of Wildlife, Washington Forest Protection Associaton, U.S. Bureau of Indian Affairs, U.S. Forest Service Colville, Gifford Pinchot and Umatilla National Forests, the U.S.Forest Service Pacific Northwest Range Experimental Station, and the U.S. Fish & Wildlife Service Fisheries Research Center, Fisheries Assistance Office, Leavenworth & Makah National Fish Hatcheries.

CHAPTER 2
STUDY DESIGN, SITES AND METHODS

SITE SELECTION

Study sites were established in all forested ecoregions of the state. Data from several sites in predominantly non-forested areas of southeastern Washington were also contributed by the U.S.D.A. Forest Service.

An array of sites was needed to reflect the size range and riparian conditions of typical streams for an ecoregion (clearcut, buffer strips, second growth, and mature conifer forests). Site selection for the study was not random, but instead reflects cooperator interest in a watershed (involvement in ongoing studies or because of suspected stream temperature sensitivity) because the study was entirely dependent on cooperators.

Data from existing studies, supplied by co-operators, was accepted if it met one or more of the following criteria: 1) Temperature was measured daily or hourly with continuous recorders (as opposed to maximum/minimum thermometers read infrequently); 2) Air and water temperature was measured simultaneously; 3) Water temperature and stream/riparian characteristics were measured for a reach; 4) Systematic basin water and air temperature profiles existed (where a number of streams are monitored in the same basin); or, 5) Microclimate data (air temperature, relative humidity, evaporation, barometric pressure, sky cover or cloudiness, or solar radiation) was available from stream environments.

The 1988 Temperature Study included 82 ongoing temperature monitoring sites operated by TFW co-operators, and 10 new sites located specifically for this study for a total of 92 sites (Table 2.1). The general location of all sites within Washington is shown in Figure 2.1. These sites were stratified according to three classes of river size, and three classes of riparian zone density to help cooperators identify a range of suitable sites (Table 2.2).

Study sites were classified as primary or secondary sites depending on the available data. Primary sites are those where both air and water temperature were measured. The Temperature Study field crew visited each of the primary sites and measured stream and riparian characteristics. Most of the model performance evaluations was conducted using data from the 33 primary study sites (Table 2.1). Because of the importance of air temperature in several of the models, direct measurement of this variable was considered essential to an adequate test of the models. Primary sites represented a wide array of shading and stream width characteristics (Figure 2.2).

Sites where only water temperature was measured are classified as secondary sites. Data from 59 secondary sites was used along with primary sites in the general analysis of regional temperature regimes. Stream characteristics were estimated at the secondary sites.

STUDY DESIGN

The study design was to determine how well each model was able to predict ambient stream temperatures in stream reaches with different riparian vegetation conditions and stream characteristics. (The ability of the model to serve as a predictive tool for silvicultural prescriptions was inferred by the model's ability to correctly predict temperature in both shaded and partially or non-shaded streams.) In a sense, a variety of "treatments" represented by the array of existing site conditions had already been applied. This sampling design tested each model's ability to predict ambient temperature in varying geographic and managed stream conditions. Water and air temperature was measured only at the downstream end of each of the temperature reaches. (Temperature was not measured at the upstream end of the reach because of limited temperature measurement equipment.)

Although there is no conceptual limitation to evaluating model performance by predicting ambient conditions, this data collection method represented a departure from the recommended method for using the SSTEMP and TEMP-86 models, which generally assume that calibration data is available for both the up and downstream end of a study reach. Several of the computer models require input of the upstream water temperature to predict the downstream water temperature. We estimate these upstream temperatures. Since upstream or pre-treatment calibration temperature data will rarely be available in TFW use of the models,

Table 2.1 Timber/Fish/Wildlife Temperature Study site list. Sites are grouped by ecoregion. Temperature measurement start and end dates (1988), site code and testing type are listed. (Models were tested at primary sites.)

				TEMPERATURE MEASUREMENT	
ECOREGION	**SITE**	**CODE**	**TYPE**	**START**	**STOP**
Northwest Coast	Red Creek Tributary	GA	Primary	29JUN	01NOV
	Red Creek	GB	Secondary	29JUN	06OCT
	Red Creek (Site2)	GC	Secondary	29JUN	30SEP
East slope Olympics	Snow Creek	JA	Secondary	01JAN	31OCT
South Coast	Naselle River	BC	Primary	20JUN	04OCT
	Smith Creek	BD	Primary	20JUN	05OCT
	Bear River	BE	Primary	07JUL	07JUL
	Abernathy Creek (Lower)	BA	Secondary	09JUN	30SEP
	Abernathy Creek (Upper)	BF	Secondary	09JUN	30SEP
	Germany Creek (Upper)	BB	Secondary	09JUN	30SEP
North Cascades	Squire Creek	HC	Primary	05AUG	05OCT
	N. Fork Stillaguamish (RM 38.8)	HG	Primary	10AUG	05OCT
	Higgins Creek	HD	Secondary	13JUL	05OCT
	Little Deer Creek	HA	Secondary	13JUL	22AUG
	S. Fork Nooksack River	HE	Secondary	24AUG	25SEP
	Edfro Creek	HF	Secondary	02AUG	15SEP
	Deer Creek (at mouth)	HI	Secondary	13JUL	21AUG
	Deer Creek (above Deforest)	HH	Secondary	13JUL	14OCT
	S. Fork Nooksack (Upper river)	HJ	Secondary	28JUL	05OCT
	Segelson Creek	HK	Secondary	07JUL	05OCT
	N. Fork Stillaguamish (do. Deer Cr)	HL	Secondary	20JUL	15OCT
	N. Fork Stillaguamish (up. Deer Cr)	HB	Secondary	12JUL	15OCT
Central Cascades	Ten Creek	IA	Primary	29JUN	07OCT
	S. Prairie Creek (upper)	IC	Primary	21JUL	04OCT
	Greenwater River	ID	Primary	22JUL	06OCT
Puget Lowlands	Porter Creek	AP	Primary	24JUN	05OCT
	Pilchuck River (RK15.4)	DA	Primary	04AUG	25OCT
	Pilchuck Creek	DB	Primary	05AUG	25OCT

Table 2.1 Timber/Fish/Wildlife Temperature Study site list (continued).

ECOREGION	SITE	CODE	TYPE	TEMPERATURE MEASUREMENT START	TEMPERATURE MEASUREMENT STOP
Southwest Cascades	Ware Creek	AA	Primary	17MAY	01NOV
	Hard Creek	AR	Secondary	17MAY	31OCT
	Huckleberry Creek	AC	Primary	21APR	01NOV
	Thurston Creek	AD	Primary	17MAY	01NOV
	Little Deschutes Creek	AE	Primary	01JUN	04OCT
	Deschutes River (RK75.5)	AG	Primary	01JUN	03OCT
	Deschutes River (RK60.2)	AF	Primary	17MAY	01NOV
	Deschutes River (RK41.7)	AS	Primary	09AUG	01NOV
	Deschutes River (near Offut Lake)	AW	Secondary	10AUG	31AUG
	Schultz Creek	AB	Primary	25MAY	06OCT
	Herrington Creek	AO	Primary	25MAY	30SEP
	Hoffstadt Creek	AQ	Primary	25MAY	06OCT
	Coweeman River (above Mulholland)	AK	Primary	06JUN	03OCT
	Coweeman River (above Goble)	AL	Primary	06JUN	03OCT
	Coweeman River (above Baird)	AN	Primary	06JUN	03OCT
	Coweeman River (above Andrews)	AM	Primary	06JUN	03OCT
	Mulholland Creek	AH	Primary	06JUN	03OCT
	Goble Creek	AI	Primary	06JUN	03OCT
	Baird Creek	AJ	Primary	06JUN	03OCT
	Gobar Creek	AT	Secondary	22APR	31OCT
	Muddy River (Baseline)	PA	Secondary	01JUN	23AUG
	Clearwater Cr. (Baseline)	PB	Secondary	02JUN	31AUG
	Clearwater Creek (at rd.9300)	PC	Secondary	16MAY	28SEP
	Clearwater Creek (upper)	PD	Secondary	18MAY	30SEP
	Clearwater Creek (Below. M. Bridge)	PE	Secondary	02JUN	31OCT
	Clearwater Creek (at Paradise Falls)	PF	Secondary	18MAY	27SEP
	Hungry Creek (Upper)	PG	Secondary	28JUN	30SEP
	Hungry Creek (Lower)	PH	Secondary	28JUN	30SEP
	Catt Creek (above Big Cr)	PI	Secondary	08JUN	30AUG
	Johnson Creek (Baseline)	PJ	Secondary	02JUN	31AUG
	S. Fork Willame Cr. (Baseline)	PL	Secondary	06JUN	23AUG
	Clear Fork Cowlitz Cr (Baseline)	PM	Secondary	01JUN	23AUG

Table 2.1 Timber/Fish/Wildlife Temperature Study site list (continued).

				TEMPERATURE MEASUREMENT	
ECOREGION	**SITE**	**CODE**	**TYPE**	**START**	**STOP**
SWt Cascades	N. Fork Willame Cr. (below unit 06)	PN	Secondary	01JUN	29AUG
	N. Fork Willame Cr. (at 4700 rd)	PO	Secondary	01JUN	27AUG
	Quartz Creek (Baseline)	PP	Secondary	23MAY	30SEP
	Lewis River (Baseline)	PQ	Secondary	16MAY	30SEP
	Canyon Creek (Baseline)	PR	Secondary	17MAY	31OCT
	Siouxon Creek (Baseline)	PS	Secondary	17MAY	31OCT
	East Fork Lewis River (Baseline)	PT	Secondary	17MAY	30OCT
Northeast Cascades	Wenatchee River --Site1	KA	Secondary	19MAY	14SEP
	Wenatchee River --Site 2	KB	Secondary	19MAY	14SEP
	Wenatchee River --Site 3	KC	Secondary	19MAY	14SEP
	Wenatchee River --Site 4	KD	Secondary	19MAY	14SEP
	Icicle Creek Bypass	KE	Secondary	02JUN	31OCT
SE Cascades	Bear Creek	CA	Primary	21JUL	10OCT
	S.Fork Little Natches River	CB	Primary	21JUL	10OCT
	Little Natches River (at Kaner Flat)	CC	Secondary	21JUL	01SEP
	Crow Creek	CD	Primary	21JUL	31AUG
	Bear Creek Watershed (Baseline)	CE	Secondary	11MAY	30SEP
	Wind River (Baseline)	CF	Secondary	11MAY	22OCT
	Trout Creek (Baseline)	CG	Secondary	11MAY	28JUL
	Trapper Creek (Baseline)	CH	Secondary	23MAY	21SEP
Pend Oreille	Cee Cee Ah Creek	EA	Primary	28JUL	18OCT
	Chamokane Creek	EB	Primary	27JUL	06SEP
	Norwegian Creek	FB	Secondary	03JUN	11OCT
Blue Mountains	Tucannon R (bel. M.Russels Springs.)	LA	Secondary	01AUG	09SEP
	Tucannon River (at Bridge 14)	LB	Secondary	01AUG	20OCT
	M. Russels Spring--(Tucannon R)	LC	Secondary	01AUG	20OCT
	Hartstock Cr--(Tucannon R.)	LD	Secondary	01AUG	08OCT
	Tucannon River (Below Panjab Cr)	LE	Secondary	11MAY	23SEP
	Tucannon River (Below Big 4 Lake)	LF	Secondary	11MAY	06OCT
	Tucannon River (Below Deer Lake)	LG	Secondary	11MAY	31OCT
	Tucannon River (Below Cummings Cr)	LH	Secondary	11MAY	26OCT
	Tucannon River (Below Beaver Lake)	LI	Secondary	11MAY	30OCT

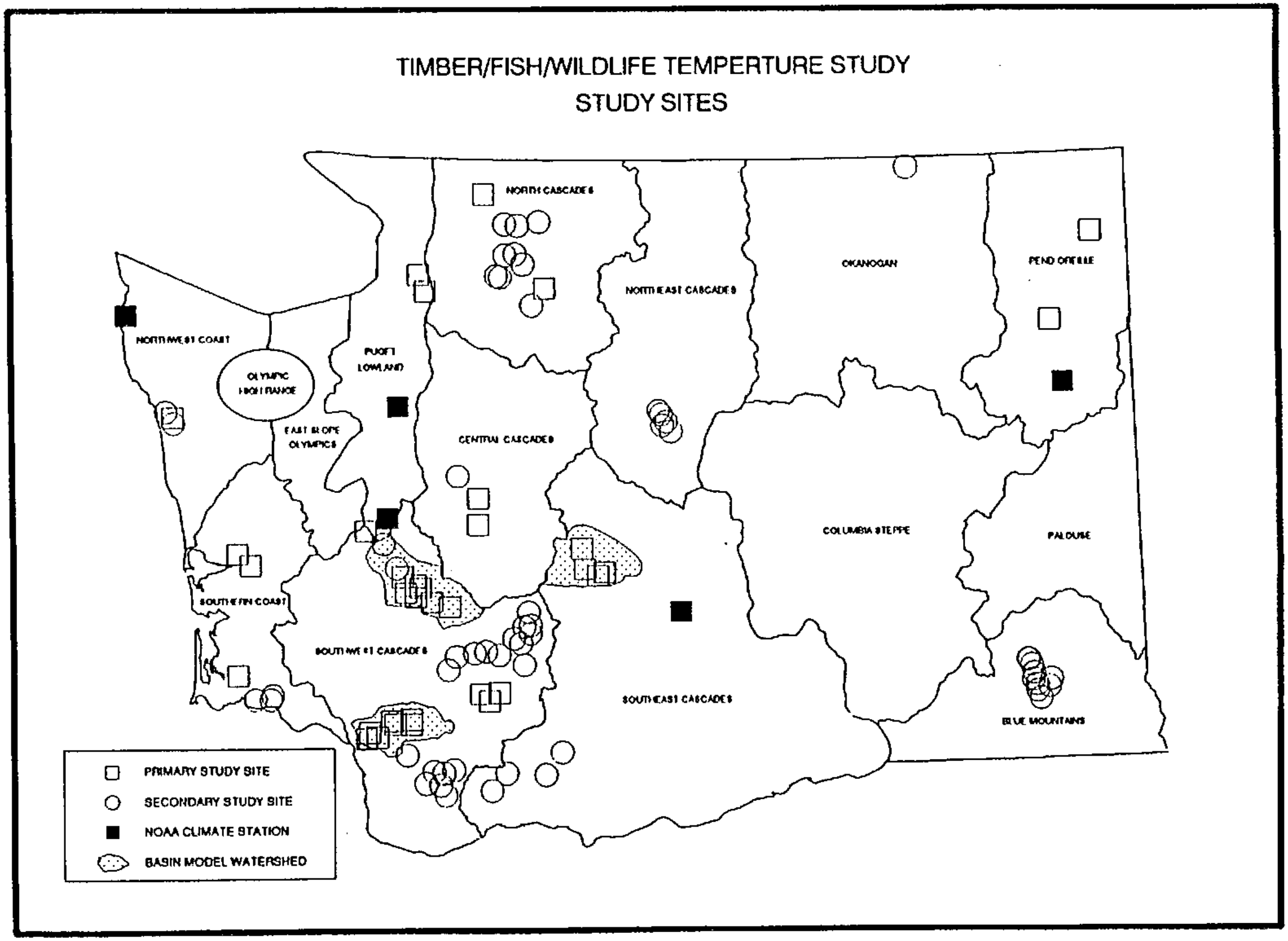
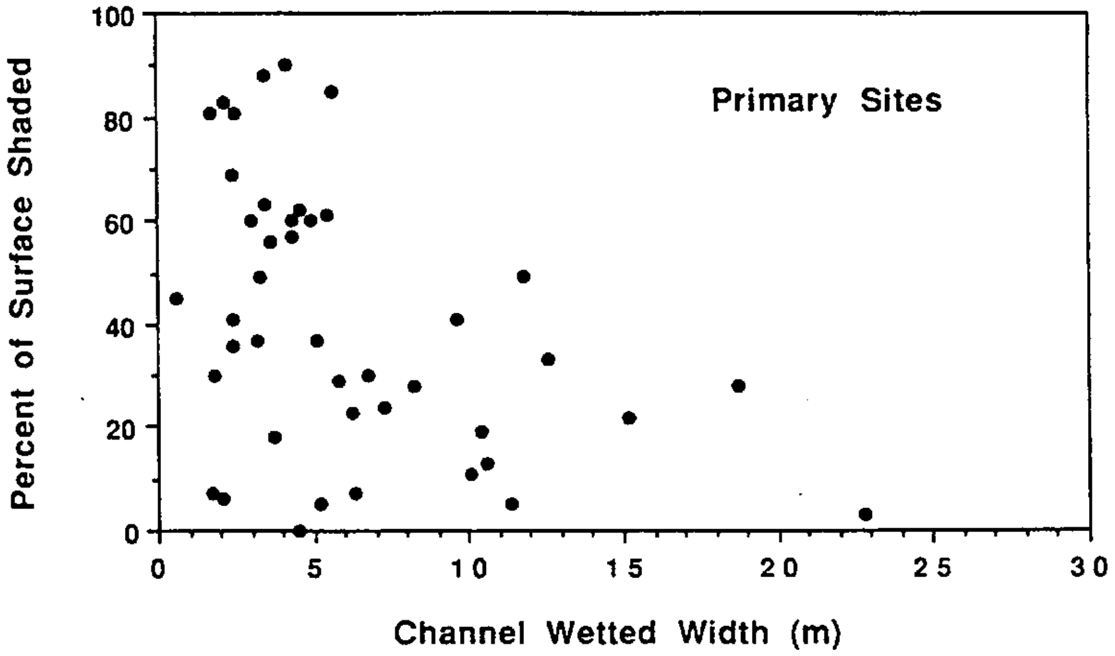


Figure 2.1 Temperature Study Sites

Figure 2.2 Channel width and shade characteristics of primary study sites.



the TWG felt that it was important to determine how well the models describe temperature regimes in general. If the models could be shown to accurately predict water temperature in a variety of stream conditions, then the model input parameters could be manipulated to determine what influence vegetation management has had, or will have, at a given site.

Input data required both by the models and for regional temperature regime evaluation required measurements or estimates of a variety of parameters to describe geographic location, meteorology, hydrology, stream geometry, and riparian vegetation. Likewise, basin temperature models required variables which describe the overall stream system. A summary of the array of non-temperature input values is shown in Table 2.3. The array of site and map-generated data from which these input values were calculated was stored on spreadsheets. A description of each parameter can be found in the TFW Temperature Study Data Dictionary (Appendix B).

The TWG field team visited each primary site to measure site specific variables required for model-testing or stream characterization. Standardized measurement techniques were obtained by having the TWG field team sample all sites.

The thermal reach refers to the entire length of stream at each site. Temperature measured at the downstream end of the temperature reach reflected the riparian and stream conditions found upstream. The thermal reach had relatively homogeneous riparian and flow conditions within it. The upstream boundary of the thermal reach occurs where there is a distinct change in riparian conditions or at the junction of a major tributary (increase in flow greater than 10%). The minimum length of the thermal reach was 600 meters (approximately 2000 ft). A general schematic of a thermal reach and its subsampling units is shown in Figure 2.3. The downstream end of the temperature reach was where the temperature recording device was located. The upstream end was located where there was a distinct change in riparian vegetation conditions or at the junction of a major tributary.

Table 2.2 Stream size and general riparian vegetation canopy condition matrix for study site selection.

	SMALLER STREAMS Depth: <0.41 m)			MODERATE SIZE STREAMS Depth: 0.41 m to <0.60 m)		
	RIPARIAN (% Shaded)			RIPARIAN (% Shaded)		
REGION	Open (<25%)	Partial (26-74%)	Closed (>75%)	Open (<25%)	Partial (26-74%)	Closed (>75%)
Coastal	1	4	2	1	0	1
Southwest WA Cascades and Puget Sound	11	22	9	6	5	1
Eastern	6	8	1	1	0	0

The thermal reach was subsampled for stream and riparian characteristics. The field team established three channel reaches for measurement of channel characteristics. The length of each channel reach was 25 times the average bankfull channel width. Information gathered in the channel reach included channel unit (microhabitat) distribution, stream depth, particle size, and average flow velocity. While three channel reaches are identified, one to three were sampled depending on stream size. Larger streams had fewer channel reaches sampled.

Riparian characteristics were evaluated in 50-ft long riparian transects selected within each channel reach. At least three riparian transects were measured in each channel reach, for a total of 9-15 transects. The field crew measured one transect at the downstream end of each of the channel reaches, and evenly spaced the remaining two within the reach. If vegetation characteristics were not homogeneous in the reach, the crew selected representative sites to establish transects. A transect perpendicular to the stream was selected, and riparian vegetation conditions were measured for an area 25-ft up and downstream of the transect were measured.

Input values for the measured riparian, stream, and meteorologic variables were determined for each study site by averaging the measurements from all of the channel or riparian reaches within the temperature reach.

FIELD MEASUREMENT METHODS

Temperature

Water temperature was measured with continuously recording electronic or analog instruments. Several different types of instruments were available including Omnidata electronic Datapods, Ryan and Unidata temperature recorders, and Partlow thermographs. A list of temperature instruments used in the study and their estimated accuracy is provided in Table 2.4. Air temperature was also recorded where instruments were available. Electronic recorders were programmed to measure temperature each hour. Output from analog recorders was digitized and data was interpolated to hourly values.

Table 2.3 Temperature model input parameter summary.

Model:	Brown	TEMP EST	SS-TEMP	TEMP-86	SN-TEMP	EPA QUAL 2E	MODEL-Y	REMARKS
Type:	Reach	Reach	Reach	Reach	Basin	Basin	Basin	
Parameters								
Local Air Temperature		F	F	F			R	Air temperature at site
NOAA Air Temperature					C	C		NOAA air temp.CD/LCD
NOAA Wet Bulb Temp.						C		NOAA wet bulb temp. LCD
NOAA Barometric Pressure						C		NOAA barometric pressure LCD
NOAA Relative Humidity		C	C	C	C			NOAA relative Humidity LCD
NOAA Wind Speed		C	C	C	C			NOAA wind speed LCD
NOAA % Possible Sun			C		C			NOAA possible sun LCD
Solar Radiation	M	M	sssolar		sssolar	R		computed from various sources
Cloudiness		C				C	R	cloud cover
Daylight Hours			sssolar					hours of daylight
Upstream Water Temp.		F	F	F	sntemp	QUAL 2E		water temperature entering reach
Water Emissivity		M						back radiation
Ground Temperature			M		M			annual ground heat flux
Soil Heat Transfer		M						soil heat flux
Thermal Gradient					M			thermal input from streambed
Groundwater Inflow Rate		F/R	F/R	F/R	F/R	F/R		
Groundwater Temperature		M/R	M/R	M/R	M/R	M/R		
Date				F	F	F		date of simulation
Latitude				M	M	M		
Longitude				M	M			
Longitude of Time Zone				M	M			
Elevation of Site				M				
Channel Azimuth			M	M	M			orientation of stream reach
Topographic Altitude					F			Average incline to horizon
Stream Width	F		F	F	F			
Stream Depth	F	F		F			R	
Percent Pools				F				
Average Pool Depth				F				
Reach Length	F		F	M	F			
Upstream Elevation			M		M			
Downstream Elevation			M	M	M			
Upstream Streamflow	F		F	F	F/R	F/R		
Downstream Streamflow				F				
Travel Time			F	F	F	F	R	average stream velocity
Channel Gradient				M				slope of energy grade line
Flow Regression Constants			F		F	F		depth and velocity constants
Stream Network					M	M	M	network of stream reaches and junctions

Table 2.3 Continued

Model:	Brown	TEMPEST	SS-TEMP	TEMP-86	SN-TEMP	EPA QUAL2E	MODEL-Y	REMARKS
Water-Sky View Factor		F			srshd	F		openness factor topographic and forest
Avg. Angle Topo. Shade S				F				topographic shade in various directions
Avg. Angle Topo. Shade SE				F				
Avg. Angle Topo. Shade SW				F				
Avg. Angle Topo. Shade L			F	F	F			
Avg. Angle Topo. Shade R			F	F	F			
Avg. Angle Forest Shade S				F				Forest shading in various directions
Avg. Angle Forest Shade SE				F				
Avg. Angle Forest Shade SW				F				
Avg. Angle Forest Shade L			F	F	F			
Avg. Angle Forest Shade R			F	F	F			
Percent Canopy Cover L			F	F	F			Percent forest cover on each side
Percent Canopy Cover R			F	F	F			
Buffer Strip Width L				F				
Buffer Strip Width R				F				
Vegetation Height Left			F	F	F			
Vegetation Height Right			F	F	F			
Crown Diameter East			F		F			diameter of shade-tree crowns
Crown Diameter West			F		F			
Vegetation Offset East			F		F			distance to shading vegetation
Vegetation Offset West			F		F			
Vegetation Density East			F		F			vegetation screening factor
Vegetation Density West			F		F			
% Stream Shaded Overhanging Vegetation				F				

C = NOAA Climate Station; F= Field Measurement; R = Regional Relationship
srsolar = USF&WS Solar Model; **srshd** = USF&WS Reach Shade Model;
sntemp = USF&WS Network Temperature Model

All instruments supplied by the TWG were calibrated by a hydrology technician before being placed in the field. It was assumed that cooperators supplying data underwent similar calibration procedures. Water temperature probes were placed in the stream near the bank and out of direct exposure to sunlight. Air temperature probes were placed several feet above the ground , in the vicinity of the channel under what shade was available. Accuracy of temperature data may differ because of the different instruments used.

Field visits were made to the sites to calibrate instruments at least once every two weeks by study cooperators. Air and water temperature were measured with hand-held thermometers and recorded on field sheets. Instruments were checked for accuracy (compared to hand-held thermometers) and recording time.

Stream and Riparian Measurements

Stream and Channel Characteristics

Discharge (m^3/s). Discharge was the instantaneous rate of streamflow. Flow was measured both in the vicinity of the thermograph and at the upstream end of the thermal reach using standard stream gaging techniques described by Corbett and others (1962) in USGS Water Supply Paper #888. Velocity was measured with an electronic (Swoffer™ or Marsh-McBirney™) or mechanical (Price-AA™ pygmy) current meter with at least 15-20 measurements across the channel. Stream depth was measured, and a velocity-area calculation was made for total streamflow at the cross-section. Flow gaging cross-sections were established where the stream bed in width and substrate characteristics was relatively uniform (typically at riffles).

Average Stream Velocity (m/s). Average flow velocity was estimated with dye tracer studies performed in one or two of the channel reaches at each site. A small amount of tracer dye (rodamine WT) was added at the upstream end of the reach and sampled at the downstream end. The major occurrence of dye was determined by visually estimating maximum coloration of the water. Travel time divided by reach length calculated average velocity. An ISCO™ automated pumping sampler or manual method of sampling was used.

Stream Gradient (%). Stream gradient of channel reaches was measured in several ways to determine a reasonably accurate technique for TFW purposes.

Autolevel Method: Gradient of the lower-most channel reach was measured with an autolevel and story pole. Using standard surveying technique and notation, a difference in water elevation was determined by a backsight and then a foresight to a calibrated storypole resting at water surface. The height of the stationary autolevel was used as the reference point. If necessary, a turning point was made by moving the autolevel to a new stationary point and using the previous foresight location as the next backsight.

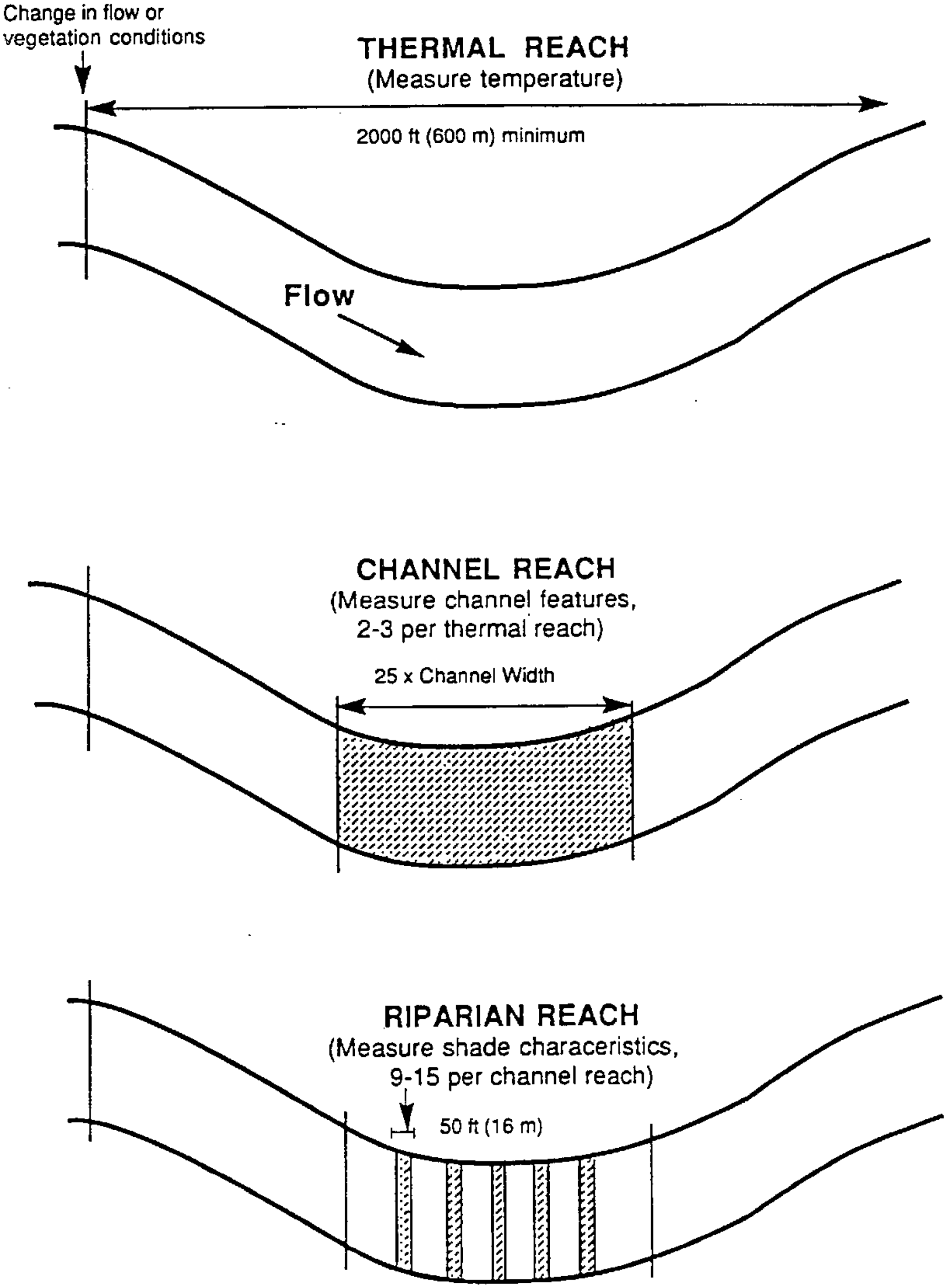
Length of backsights and foresights was measured along the course of the stream with a rangefinder. Gradient (or slope) was calculated by dividing the total change in elevation by the total length of the stream course surveyed.

Abney Level Method: Gradient of the uppermost channel reach was measured with an abney level, support pole and sighting pole. For stability the abney level rested on the support pole with the base of pole at water surface level. The abney level was sighted at another pole of matching length with the base at a different water surface level. For ease in sighting, a fluorescent ribbon was tied to the top of the sighting pole. The slope (gradient) was read from the abney level in degrees and minutes. The length of abney level sighting was measured along the course of the stream with a rangefinder. Typically, several consecutive linear sightings were made along the course of the channel reach. Gradient was calculated by conversion to a decimal proportion, taken as the tangent of the degrees/minutes multiplied by the weighted length of the sighting. Summing the decimal proportions of the sightings resulted in the length-weighted decimal equivalent slope of the reach.

Digitized Map Method: Gradient of the thermal reach was computed by digitizing the elevations of the lower and upper end of the thermal reach from USGS 1:24,000 (or 1:62,500) topographic maps. The difference in elevations was divided by the length of the thermal reach digitized (typically 600 meters). This method relies on the accuracy and resolution of the topographic contour lines, the accuracy of the stream channel representation on the map, proper placement of sites on maps, as well as the accuracy of digitizing.

Channel Unit Survey. Channel units were surveyed in each channel reach. Channel units were identified according to the methods of Bisson and others (1982). Channel units include pools (plunge, scour, eddy, backwater or dammed), riffles (low-gradient riffles, cascades, cascade/step pools, rapids) and glides. The channel unit survey of each channel reach was done by a single individual outfitted with a calibrated pole,

Figure 2.3 Schematic of sampling scheme of primary sites.



rangefinder, and recording notebook. A consecutive inventory was kept of the units as they were identified and measured for length, width and depth. Measurements were kept within the stream's wetted perimeter. Measurements were made with a five foot pole calibrated in tenths of feet as well as a 6-150 foot rangefinder when applicable.

Unit Length (m). The length of each channel unit was measured parallel to unit-specific streamflow. Judgement was required as to the division between units as this can be an ambiguous distinction at times. Divisions generally run roughly perpendicular to streamflow. Gradient breaks of water surface slope were used as an indicator of unit longitudinal boundaries. The up and downstream boundaries of some channel units often occur diagonally across the channel (e.g. slip-face cascades) reflecting gravel bar deposition patterns. To estimate length of these units, the diagonal boundary was divided in half and measured at that point.

Unit Width (m). Width was measured perpendicular to the streamflow within the unit. If both edges of the width perimeters were roughly parallel and straight, then a simple measurement was taken with the calibrated pole or rangefinder. In the case of a unit with nonparallel width perimeters such as a pool, the point of average width was estimated by eye, with the measurement transect perpendicular to the unit streamflow. A volume weighted average width for the reach was calculated by dividing the sum unit volume by the sum by the unit length times depth.

Unit Depth (m). Depth was measured in three places within each unit using the calibrated pole. Locations of measurements were made quickly and randomly, although they were generally located within the thalweg or mainflow portion of the channel. In the case of riffle and glide unit types, the measurements generally ran perpendicular across the thalweg. In the case of pool unit types, the measurements ran parallel down the thalweg. The average unit-specific depth was computed as the simple average of the three measurements for riffle and glide unit types and as the sum of the three measurements divided by four for the pool unit types. A volume weighted average depth for the reach was calculated by dividing the sum unit volume by the sum unit surface area. A volume weighted average depth for the reach was calculated using average depths for each channel unit proportioned by channel unit distribution

Substrate (%). Substrate size was visually estimated as percent of surface material in broad substrate classes. The classes and rough size associations used to estimate them were:

clay/silt	<0.063 mm
sand	0.064 - 2.0 mm
gravel	2.0 - 64 mm
cobble	64 - 256 mm
boulders	>256 mm
bedrock	

Substrate evaluations were done once in each channel

Table 2.4 Temperature recording instruments used in this study, and their estimated measurement accuracy.

Instrument	**Model**	**Estimated Accuracy**	**Citation**
OMNIDATA	Datapod DP212	±0.2% of reading	1
UNIDATA	6507A	±0.2°C	2
RYAN	RTM	±0.3°C	3
PARTLOW	analog	±2.0 °F.	4

1. Omnidata Intl, 1982. Operating instructions for model DP212 Two Channel TEMP/VOLT recorder, Version 1.0, March 1982.
2. Unidata America 1987, Starlog Portable Data Logger Product Catalogue
3. Ryan Instruments, 1986, Ryan Tempmentor Specifications Sheet.
4. John Heffner, Weyerhaeuser Technology Center, Tacoma, WA. Oral communication.

reach in a riffle unit. The estimate was made by establishing a transect perpendicular to the streamflow across the streambed and included the gravel bar outside of the water's edge if one was associated with the unit. Depending on length, the transect was divided into sections. Visual estimations of the percentage of each substrate size classification were made in each section. These estimations were summed across sections.

Where the stream depth was less than 0.2 meters in the vicinity of the substrate transects, a visual estimate was made of the percentage of wetted streambed comprised of boulder size or larger.

<u>Bankfull Channel Width</u> (m). A field measurement of bankfull width was assessed from a section of the channel where the channel geometry was easily recognizable. This was usually done in a riffle section where bankfull discharge produced a recognizable active channel with an adjacent flat area (active flood plain) or where the ordinary high water mark could be estimated by deposited debris or lack of perennial plants. The active channel was measured for bankfull width.

Riparian Vegetation

All but one of the temperature models tested requires an estimate of the portion of the sky that can be viewed from the stream's water surface. (A stream without a riparian canopy views 100% of the sky while one with a dense canopy may view 0% of the sky.) The openness of the stream has a major influence on both the rate of energy input to the stream (solar radiation) as well as the rate of energy lost from the stream back to the sky (re-radiation). Models vary in the level of the detail in which this sky-view factor was evaluated. TEMP-86 and SSTEMP require sectioning the sky view into zones or quadrants and analysis of vegetation characteristics in each one. Within each zone the models may individually characterize shading contributed by overstory, understory and topography. The model then internally computes the total sky-view factor from the individual zone measurements. TEMPEST requires a more simple estimate of the total sky view factor by considering the entire field of view at once. A schematic of sky-view and terminology used in this study to identify specific measurement locations is provided in Figure 2.4.

A number of parameters describing riparian vegetation and topographic shading characteristics were measured in the riparian reaches. Some riparian variables were required by several models but may differ between between models in estimation method. Therefore, some variables appearing in Table 2.3 may appear redundant. Definitions for each parameter and calculation methods adhere as closely as possible to those provided by the user's manuals or other model documentation. The following vegetation characteristics were measured at each site.

<u>Vegetative Communities.</u> The species and age class of the dominant overstory vegetation type and the dominant understory vegetation type were recorded for each of the riparian reaches.

<u>View-to-the-Sky (densiometer)</u> (%). The view-to-the-sky was the fraction of the total hemispherical view from the main stream surface sky can be seen. A spherical densiometer was used to provide an estimate of the view-to-the-sky factor. Readings were taken from mid-channel facing in four directions (upstream, downstream, right bank and left bank) and an average of the four readings was used.

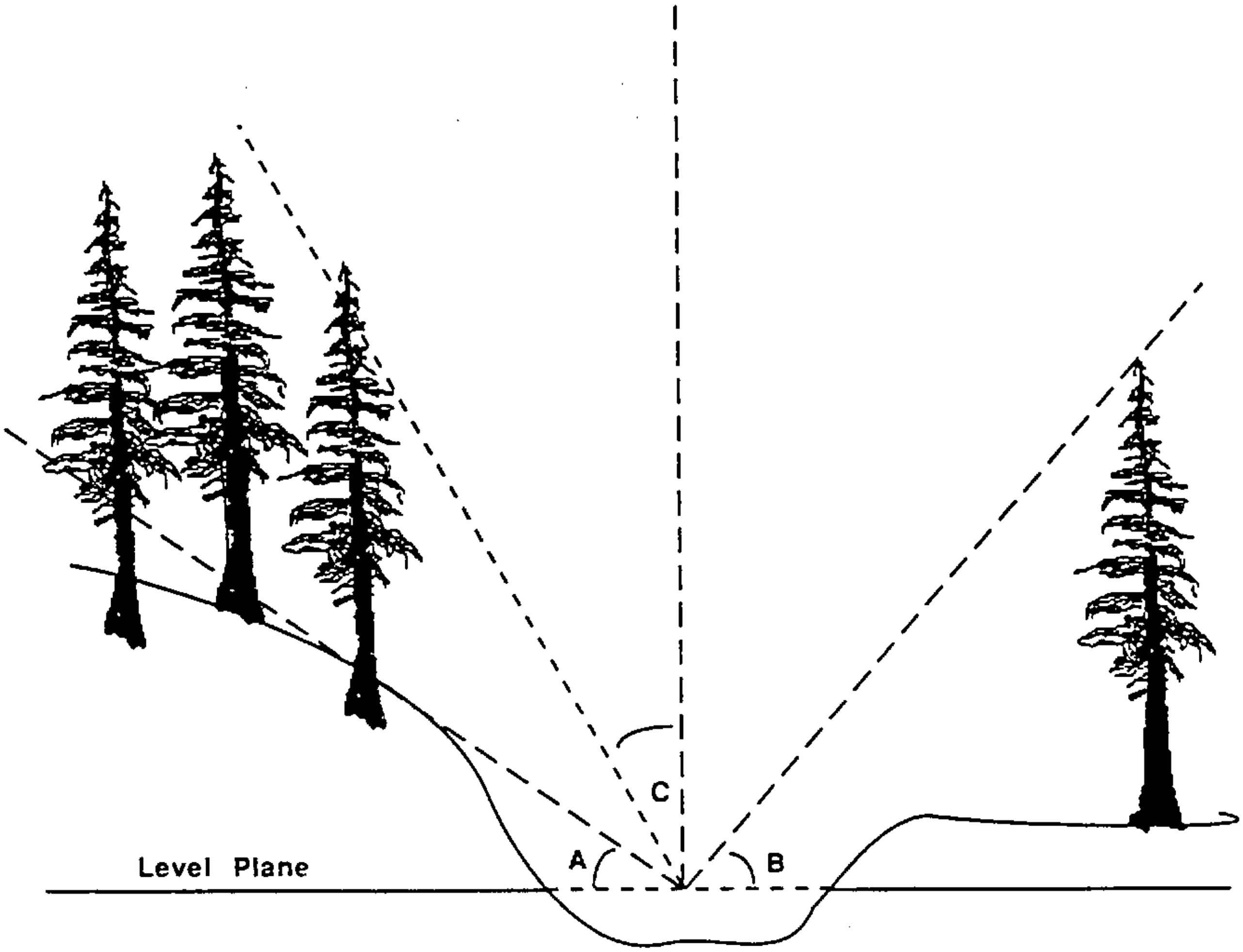
<u>View-to-the-Sky (subjective)</u> (%). A subjective value of the view-to-the-sky factor was estimated in mid-channel by visualizing a conical sphere running at a 60 degree angle upwards from the viewer's eye. This delimits a circular area containing the top third of the canopy, and a visual estimate of the percentage of sky was made.

<u>Vegetative Density</u> (%). Density is a measure of the screening of the sunlight that would otherwise pass through the shaded area in the upper one-third of the streambank canopy. This describes both the continuity of riparian vegetation along the stream bank and the filtering effect of leaves and stands of trees along the stream. A clinometer was used from mid-stream to measure the angle from 60 to 90 degrees. Density was subjectively evaluated as the percent of the vegetative shading in that zone. For example, if only 50% of that zone had riparian vegetation and if this vegetation actually filtered only 50% of the sunlight, then the density was 25%.

<u>Topographic Angle (degrees).</u> The topographic angle is the angle formed from a line connecting a point at the center of the stream to a point on the topographic feature producing shade, with the horizontal plane of the stream defined as zero degrees. It was used to determine local sunrise and sunset times. Angles were taken with a clinometer in five directions: southeast, south, southwest, left side (measured perpendicular to the channel), and right side.

<u>Forest Angle (degrees).</u> The forest angle is formed from a line connecting a point at the center of the stream to a point at the top of the streamside vegetation, with the horizontal plane of the stream at

Figure 2.4 Schematic of the topographic angle (A), forest angle (B) and vegetation density zone between 60 and 90 degrees (C). The sky view factor is the percent of the entire horizon from level plain open to the sky.



zero degrees. Angles were taken with a clinometer in five directions: southeast, south, southwest, left side (measured perpendicular to the channel), and right side. If the top of the riparian vegetation formed an uneven horizon, the average top of the vegetation was chosen.

Vegetation Height (m). Vegetation height was measured with a rangefinder from the base of a tree or shrub to the top of the foliage. The vegetation selected for measurement was representative of the streambank foliage for 25 feet on either side of the riparian transect. Measurements were taken on both the right and left banks at each riparian transect.

Vegetation Offset (m). This is an estimate of the distance from the water's edge to the main trunk of the dominant shade producing vegetation on the left and right banks of the riparian transects. The vegetation selected for measurement was representative of the stream bank vegetation for 25 feet on either side of the riparian transect. Measurements were taken on both the right and left banks at each riparian transect.

Crown Radius (m). The crown radius is the average distance that the foliage radiates from the trunk or stem of the streamside vegetation on the left and right banks of the riparian transects. The vegetation selected for measurement was representative of the stream bank vegetation for 25 feet on either side of the riparian transect. In general, the same vegetation was selected for measurement of the vegetation height, vegetation offset, and crown radius. Measurements were taken on both the right and left banks at each riparian transect.

Riparian Zone Buffer Width (m). The riparian zone is the area along the stream banks which contains shade producing vegetation. The width was measured going outward from the bank. If there was no vegetation then the buffer width was recorded as zero. If there was continuous vegetation going outward from the stream then the buffer width was recorded as infinite. If there was a break in the vegetation going outward, such as a recently harvested area with a buffer strip, then the buffer width was measured with a rangefinder. Breaks in the vegetation more than 150 feet from the bank were usually nondetectable and such buffer widths were considered infinite. Measurements were taken on both the right and left banks at each riparian transect.

Overhanging Vegetation (%). The percentage of overhanging brush or vegetation was measured at each riparian transect. A segment was visualized within the wetted perimeter of the stream running perpendicular to the streamflow. This segment was then split into quarters and a qualitative visual estimate was made of the percentage of overhanging vegetation directly above each quarter section. Overhanging vegetation was subjectively evaluated as the percent of the vegetative shading. For example, if only 50% of the zone directly above the quarter section has overhanging vegetation and if this vegetation actually filtered only 50% of the sunlight, then the percent of overhanging vegetation was defined as 25%. Visual clumping of the closed-to-sky area vs. opened-to sky area was done to make the estimate.

Stream Azimuth or Aspect (degrees). The stream reach azimuth orients the general stream direction. (If the stream meanders greatly the aspect can be separated into multiple steps and the results combined for a weighted reach average. The aspect of the stream was measured, and expressed in two ways because of model input requirements. For the USF&WS models, azimuth was expressed as a value ± 90 , with 0 at due North. For TEMP-86, azimuth was expressed as a value between 0 and 360 , with 0 at due North.

Measured Climatic Values

Climate data was used from two sources. Field measurements were taken on the day of the site visit and in a few cases using continuous recording meteorological instruments. Data collected by NOAA and available in published records was also used (see regional data).

Air Temperature in Riparian Zone (°C). Air temperature during the field crew site visit was measured three to four feet above the stream surface using the dry bulb of a sling psychrometer. Air temperature transects in the riparian zone were conducted by a perpendicular traverse away from the stream banks through the riparian zone, taking a measurement at the stream bank and at successive intervals along the transect. If a buffer strip existed, the transect was run into the adjacent cutover stand. Transects were measured on the right and left banks in each channel reach.

Relative Humidity (%). Relative humidity was measured with a sling psychrometer in mid-channel, three to four feet above stream surface, at each channel reach.

Cloud Cover (%). The percent of cloud cover was visually estimated in categories of 0, 25, 50, 75 or 100% for the day of site visit.

OFFICE DATA METHODS

Map Data

Maps were used to generate some needed information for model input values. The study sites were located on USGS 1:24,000 topographic maps (except when only 1:62,500 topographic maps were available). Placement of the thermograph sites on the maps was corroborated by each site cooperator.

Measurements of basin area, total perennial stream length, and distance from the end of the perennial stream to the watershed divide were made. Also specified was the site's latitude and longitude, and average stream azimuth, average stream gradient, and upstream and downstream elevations of the study reach. Digitizing software programs were developed to expedite this large data collection (ALTEK3T1.BAS AND REACHALT.BAS, listed in Appendix C).

Digitizing was performed on an ALTEK™ AC40 digitizer operated by the Washington State Department of Ecology.

Total basin area was determined and drawn in on the maps for each study site. The mainstem of the river was identified and outlined in each basin area, and was defined as the larger contributor of flow at a stream juncture. Each site and accompanying basin area were labelled with a site code. A list of site codes is supplied in Table 2.1. Basin areas and stream lengths for each respective site were unique and exclusive of adjacent upstream study sites, although the total basin area, or stream length of the downstream study site, could have included the measurements of the upstream site.

Table 2.5 National Oceanographic and Atmostpheric Agency (NOAA) weather stations used in the Timber/Fish/Wildlife temperature study to obtain regional climate data.

Station	NOAA Number	Mean Air Temp	Max Air Temp	Min Air Temp	Departure from Normal	Rel Humidity	Wind Speed	Percent Possible Sun	Sky Cover
Olympia Airport	6114	yes	yes	yes	yes	yes	yes	no	yes
Quillayute Airport	6858	yes	yes	yes	yes	yes	yes	yes	yes
Seattle/Tacoma Airport	7473	yes	yes	yes	yes	yes	yes	yes	yes
Spokane Airport	7938	yes	yes	yes	yes	yes	yes	yes	yes
Stampede Pass	8009	yes	yes	yes	yes	yes	no	no	yes
Yakima Airport	9465	yes	yes	yes	yes	yes	yes	no	yes

Note: yes indicates parameter available; no indicates parameter not available

The following map-based variables were developed:

(1) Upstream and Downstream Elevations (meters).
(2) Latitude/Longitude (decimal/degrees,minutes,seconds).
(3) Average Stream Azimuth Measured from North (degrees).
(4) Average Stream Gradient (%).
(5) Mainstem Length to Divide (meters).
(6) Total Stream Length (meters).
(7) Basin Area (hectares).

In addition to the digitized variables, a variety of other study site characteristics were recorded. These included cooperating agency, TFW ecoregion, county, nearest town, river basin(tributary to), Water Resource Inventory Area (WRIA) number (Williams and others 1975), legal description, Washington stream type, stream order (determined from 1:24,000 U.S.G.S. maps), magnetic declination, time zone center longitude(degrees), and dominant geologic type of the watershed (based on Washington state geologic maps).

Estimated Climatic and Regional Values

A number of climatic characteristics that were required model inputs were not measured at field sites. Instead, regional values were used. At each site, climatic data from the nearest of 5 NOAA weather stations distributed throughout Washington were used (NOAA 1988) (Table 2.5).

Relative Humidity (%). The relative humidity input value for each day was assumed to be the value for midday (1300 hours). Relative humidity data were obtained from NOAA climate stations and corrected to local air temperature by the following formula as described in U.S.F.&.W.S. SSSOLAR user documentation (Bartholow 1987).

RH = Ro * (1.064^(ToTa))*((Ta+273.16)/(To+273.16))

where RH=relative humidity at study reach (decimal),

Table 2.6 Physical constants used in various models included in model testing

Parameter	Physical Constants
C_b	evaporation coefficient, $1 \leq C_b \leq 5$; use C_b =1.68
C_T	adiabatic temperature correction coefficient; use C_T = -0.007 $^oC/m$
c_p	specific heat of water = 418 6J/kg/^oC
K_g	thermal conductiviity coefficient; use K_g = 1.65 J/m/sec^oC/ for water saturated sands and gravel mixtures
k	type of cloud cover factor, $0.04 \leq k \leq 0.24$; use k = 0.17
q_s	solar constant = 138 J/m^2/sec
r_l	longwave radiation reflection; use r_l = 0.05
T_{ab}	absolute zero correction (^oK) = add 273 to ^oC
ρ	density of water = 1000 kg/m^3
σ	Stefan-Boltzman constant = 5.68x 10^{-8} J/m^2/sec/K^4
ε_w	water emissivity; use ε_w =0.95
ε_v	vegetation emmissivity; use ε_v = 0.95
L_v	latent heat of vaporization of water, use L_v = 2440x10^3 J/kg

Ro=relative humidity at NOAA index station (decimal),
Ta=mean daily air temperature at study reach (C),
To=mean daily air temp at NOAA index station (C)

Regional Air Temperature (degrees Centigrade: ^{0}C). Air temperature was recorded at 3-hour intervals. This data was used to correct relative humidity values, and to show 1988 temperatures in relation to long-term averages.

Wind Speed (meters/second). Windspeed was assumed constant and should have represented the average windspeed at the stream surface. Average daily wind speed was used.

Cloud Cover (%). Daily percent of the sky covered by clouds recorded at NOAA weather stations was used.

Time Zone Center Longitude (degrees). This is the longitude of the center of the Pacific Time zone. The value was specified as 120 degrees W meridian for all sites in Washington.

Physical Constants

Some of the parameters input to the models were of constant value, insensitive to site conditions. Table 2.6 lists the constants and their values used in each model.

CHAPTER 3
STREAM AND BASIN CHARACTERIZATION

An expression of basic relationships between stream, watershed, climate and temperature characteristics were needed a number of times during model-testing (Chapters 4 and 5) and to characterize stream temperature regimes (Chapter 6). The derivation of these relationships is described in this chapter. For a number of important variables, a discussion of their importance to stream heating is provided, as well as descriptions of how the relationships were developed, including statistical tests where applicable. This section also explores whether there were consistent regional variations in relationships that would suggest a need for regional modifications of TFW temperature modeling methods.

Data collected at the 33 primary sites was used to generate most of the regionalized relationships. Although this is a small amount of data considering typical variability of geomorphic variables, the relationships were considered adequate for our modeling purposes given the relatively low sensitivity of temperature model predictions to most of these variables. Other data sources included NOAA weather station records for climatic variables, United States Geologic Survey (USGS) stream gage and well records for streamflow and temperature data. Data analysis used linear regression extensively; analyses were performed with the SAS statistical package.

We do not use the regionalized relationships presented here until later analyses. For those readers not interested in their development, the TWG recommends skipping to Chapters 4 and 5 for a discussion of model-testing or to Chapter 6 for a discussion of temperature regimes in Washington. The reader may prefer to refer back to this chapter after seeing how the relationships are used, when their development may seem more meaningful.

STREAMFLOW

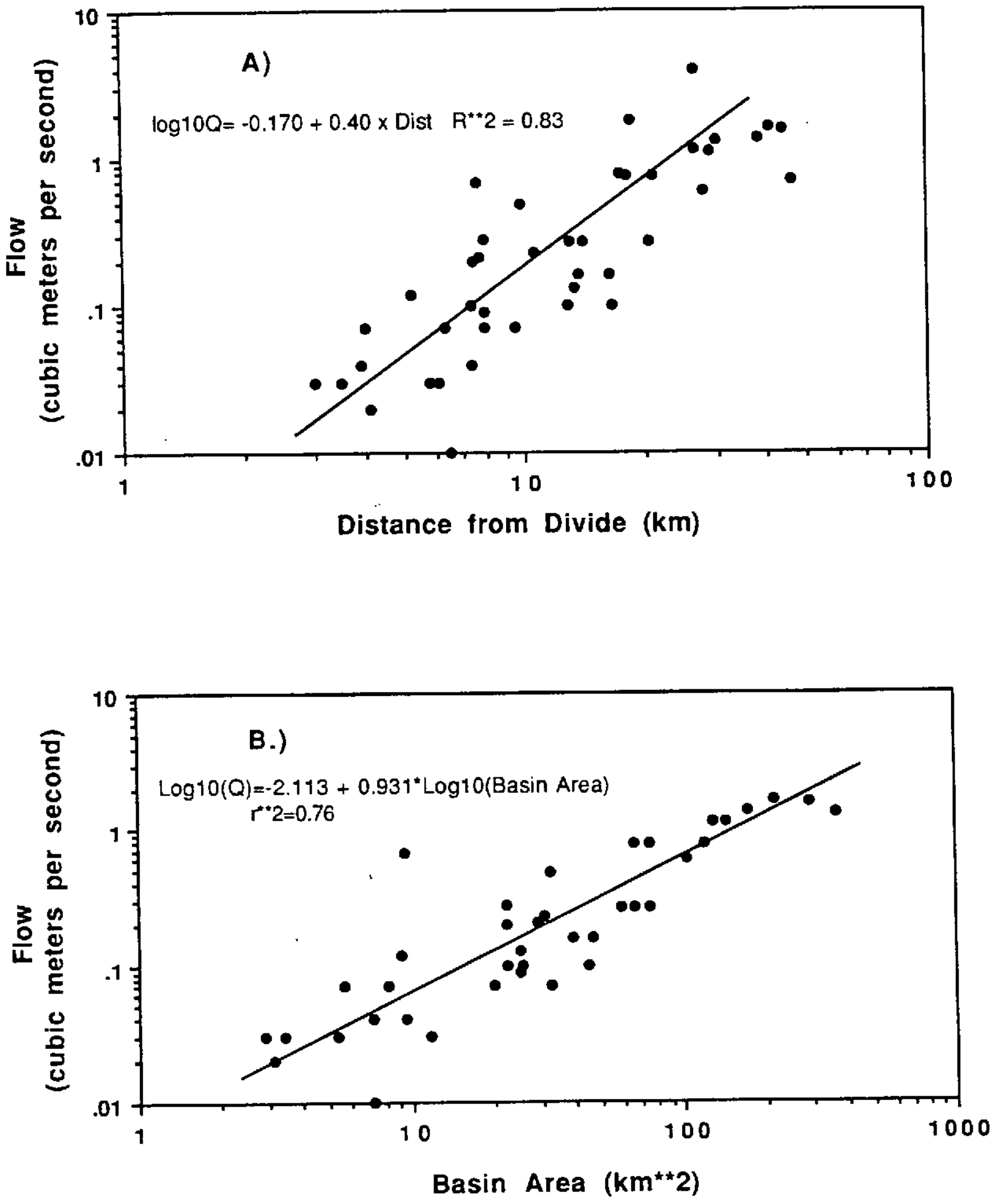
Stream Flow Volume

Stream flow or discharge (Q) is a required input variable to temperature prediction models. Streamflow is fairly easily measured, but requires specialized instruments (see Chapter 2). Generating estimates of streamflow for temperature prediction would be preferable to requiring field measurements if relationships were reasonably reliable over large geographic areas. Predictions of streamflow can be made based on a relationship of flow to some index of stream or basin size for gaged streams. Relationships determined from gaged streams can then be extended to ungaged streams.

Streamflow was measured by the TWG field crew at all primary study sites during the late summer site visits when flow was approaching the annual minimum. The relationship between flow ($\log_{10}$; m^3/s) and the distance from watershed divide ($\log_{10}$: km) is shown in Figure 3.1a and the relationship between flow and basin area ($\log_{10}$; km^2) is shown in Figure 3.1b. Relationships are good using either index of stream size (R^2=0.83 and 0.76 respectively). (The distance water travels downstream from the watershed divide is a useful way of looking at stream systems from a temperature viewpoint, since it not only indexes stream size but indicates the time that water has been in the stream approaching equilibrium temperature).

Another estimate of the streamflow and basin area relationship was made using long-term August mean daily streamflow records from USGS gaging stations located in Washington (Table 3.1). The records were selected from the hundreds published by the USGS because gages were sited in watersheds that the TWG knew were relatively small, at least partially forested, and did not contain large lakes or reservoir structures

*Figure 3.1 Streamflow in relation to distance downstream from watershed divide (A), and basin area (km**2) (B).*



upstream of gage sites. Gages with multiple years of record were also preferred. Ninety USGS gaging sites fit these criteria with basin sizes ranging from approximately 3 km^2 to nearly 600 km^2. (It should be noted that there was only one suitable USGS gaging station available in eastern Washington.)

The relationship between the long-term August flow and the point estimate of streamflow measured at the TFW study sites in 1988 are shown in Figure 3.2. Regression lines drawn through each data set show that the TFW sites have a relationship of flow to basin size similar to the USGS sites although estimates are somewhat lower. However, variability is relatively large and the slopes and intercepts of the two regressions are not statistically different (Table 3.2).

Either relationship can be used, but the USGS relationship will yield an estimate of streamflow that averages approximately 50% greater than that estimated by the relationship based solely on the TFW sites. The lower TFW flow estimates probably result from the fact that the TFW data are only one measurement in time while the USGS sites represent a multi-year average of August daily flows. Flows in 1988 could have been lower on average than the long-term mean. For this reason, the TWG decided that the USGS relationship is probably better for estimating flows on ungaged streams for model testing (Chapter 4). It has the added advantage that it can be compared to historical site records for determining the long-term mean or for examining the effect of probable extreme high or low flows.

Both of the data sets were analyzed to determine whether there was significant regional variability in estimated streamflow relative to basin area. Most of the data in both sources came from the western Cascades and Puget Sound lowlands (26 TFW sites; 80 USGS sites), with relatively few locations in coastal Washington (6 TFW sites; 10 USGS sites) and eastern Washington (4 TFW sites). There were regional differences in estimated streamflow, especially for smaller watershed areas (Table 3.2.). As might be expected, streamflow estimates as a function of basin area tended to be lowest in eastern Washington and greatest for coastal streams.

Although prediction equations differ regionally, the differences are not statistically significant. The wide scatter in the data and the relatively few data points in the coastal and eastern regions preclude drawing

Figure 3.2. Estimated flow at USGS gaging sites for the long-term August mean and for the TFW primary sites, measured in 1988. (USGS: Log10(Q)=-1.928 + 0.9381 (Log10Area), TFW:-2.113+0.931 x (Log10Area).

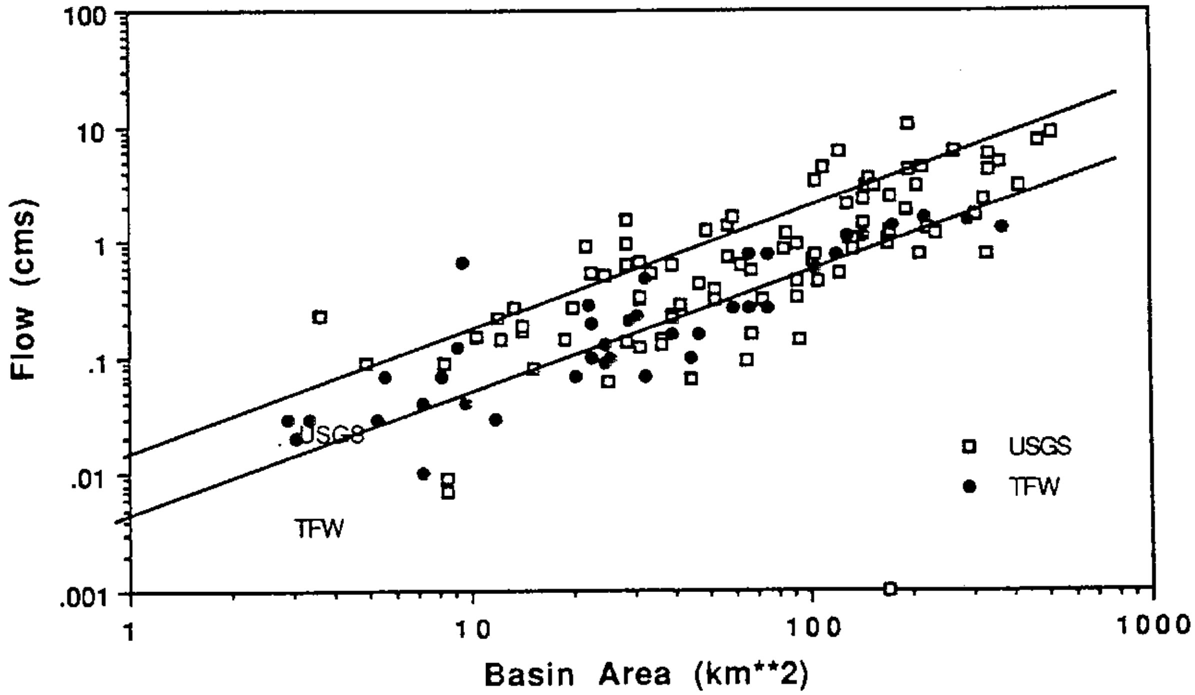


Table 3.1 Streamflow and basin area information used to develop estimates of groundwater inflow rate and August mean daily flow.

Region	Data Source	Site Name	Site Code	Basin Area (BA) (km^2)	Flow (Q) (m^3/s)	Groundwater Inflow Rate (Q/BA) ($m^3/s/km^2$)
Coast	TFW	Naselle River	BC	3.10	0.020	0.0060
		Smith Creek	BD	22.60	0.100	0.0040
		Bear River	BE	3.40	0.030	0.0090
		Red Creek tributary	GA	5.60	0.070	0.0130
		Red Creek	GB	9.50	0.680	0.0720
		Abernathy Creek	BA	22.60	0.200	0.0090
		Germany Creek	BB	24.90	0.090	0.0040
	USGS	Charlie Creek	12018500	15.28	0.082	0.0050
		E.F. Hoquiam	12038660	67.34	0.566	0.0080
		Moclips River	12039220	90.65	0.934	0.0100
		Raft River	12039520	196.83	4.106	0.0210
		E.F. Dickey River	12043080	103.60	0.765	0.0070
		Dickey River nr LaPush	12043100	222.73	1.303	0.0060
		Sooes River	12043163	82.88	0.850	0.0100
		Sail River	12043190	13.99	0.167	0.0120
		Hoko River	12043300	132.08	1.048	0.0080
		E. Twin nr Pysht	12043430	36.26	0.144	0.0040
		W.F. Grays River	14250500	38.85	0.623	0.0160
Eastern	TFW	Bear Creek	CA	32.30	0.070	0.0020
		S.F. Little Natches River	CB	39.10	0.160	0.0040
		L. Natches River at Kaner	CC	368.00	1.320	0.0040
		Crow Creek	CD	104.00	0.600	0.0060
		CeeCeeAh Creek	EA	11.70	0.030	0.0030
		Chamokane Creek	EB	--	0.720	--
		Norwegian Creek	FB	2.30	0.000	0.0000
Western	TFW	Ware Creek	AA	2.90	0.030	0.0100
		Schultz Creek	AB	9.60	0.040	0.0040
		Huckleberry Creek	AC	5.30	0.030	0.0060
		Thurston Creek	AD	9.10	0.120	0.0130
		Little Deschutes River	AE	20.10	0.070	0.0030
		Deschutes River (RK 60.2)	AF	145.00	1.140	0.0080
		Deschutes River (RK 75.5)	AG	32.60	0.480	0.0150
		Coweeman R.(a. Mulholland)	AK	129.00	1.120	0.0090
		Coweeman R. (a. Goble)	AL	217.00	1.630	0.0080
		Coweeman R. (a. Baird)	AN	74.90	0.780	0.0100
		Mulholland Creek	AH	46.50	0.160	0.0030
		Goble Creek	AI	65.50	0.270	0.0040
		Baird Creek	AJ	22.40	0.280	0.0130
		Herrington Creek	AO	8.20	0.070	0.0090
		Porter Creek	AP	24.90	0.130	0.0050
		Hoffstadt Creek	AQ	25.60	0.100	0.0040

Table 3.1 continued

Region	Data Source	Site Name	Site Code	Basin Area (BA) (km^2)	Flow (Q) (m^3/s)	Groundwater Inflow Rate (Q/BA) ($m^3/s/km^2$)
	TFW	Pilchuck River (RM 9.5)	DA	--	1.780	--
		Pilchuck Creek	DB	44.40	0.100	0.0020
		S. Prairie Creek	IC	29.30	0.210	0.0070
		Greenwater River	ID	120.00	0.770	0.0060
		Squire Creek	HC	66.10	0.770	0.0120
		N.Fork Stillaguamish River	HG	75.20	0.270	0.0040
		Coweeman R. (a. Andrews)	AM	293.00	1.570	0.0050
		Higgins Creek	HD	7.20	0.040	0.0060
		Little Deer Creek	HA	30.70	0.230	0.0070
		S. Fork Nooksack River	HE	--	3.940	--
		Edfro Creek	HF	7.20	0.010	0.0010
		Deer Creek (at mouth)	HI	175.00	1.370	0.0080
		Deer Creek (above DeForest)	HH	59.30	0.270	0.0050
	USGS	Bear Branch nr Naselle	12009500	31.08	0.340	0.0110
		Naselle River	12010000	142.44	1.473	0.0100
		Salmon Creek nr Naselle	12010500	41.44	0.278	0.0070
		Fork Creek nr LeBam	12012000	51.80	0.396	0.0080
		Clearwater Creek	12015100	10.36	0.153	0.0150
		Smith Creek	12015200	150.21	3.511	0.0230
		Deschutes River @ Rainier	12019000	233.09	1.161	0.0050
		Elk Creek nr Doty	12020500	121.73	0.538	0.0040
		Porter Creek	12020900	90.65	0.453	0.0050
		Rock Creek	12030000	64.75	0.093	0.0010
		Cloquallum Creek	12032500	168.34	0.963	0.0060
		Big Creek nr Grisdale	12035450	24.86	0.510	0.0210
		Clearwater Creek	12040000	362.59	4.899	0.0140
		Jefferson Creek	12054600	56.98	0.736	0.0130
		Dewatto River	12068500	46.62	0.425	0.0090
		Big Beef Creek	12069550	36.26	0.127	0.0040
		Cranberry Creek	12075500	38.85	0.235	0.0060
		Goldsborough Creek	12076500	101.01	0.708	0.0070
		Deschutes River @ Olympia	12080000	414.38	3.030	0.0070
		East Creek nr Elbe	12083500	31.08	0.122	0.0040
		Little Nisqually Creek	12084500	72.52	0.311	0.0040
		Mashel River	12087000	209.78	0.793	0.0040
		Ohop Creek	12088000	90.65	0.340	0.0040
		Kapowsin Creek	12093000	67.34	0.159	0.0020
		Carbon River	12093900	196.83	10.364	0.0530
		South Prairie Creek	12094400	56.98	1.388	0.0240
		Greenwater River	12097500	191.65	1.897	0.0100
		Snow Creek	12103500	31.08	0.311	0.0100
		Friday Creek nr Lester	12104000	12.17	0.147	0.0120
		Green Canyon Creek	12104700	8.29	0.091	0.0110
		Charley Creek	12105500	28.49	0.623	0.0220
		Rex River	12115500	33.67	0.538	0.0160
		M.F. Taylor Creek	12116700	13.47	0.269	0.0200

Table 3.1 continued

Region	Data Source	Site Name	Site Code	Basin Area (BA) (km^2)	Flow (Q) (m^3/s)	Groundwater Inflow Rate (Q/BA) ($m^3/s/km^2$)
	USGS	Tye River	12129000	207.19	3.030	0.0150
		Troublesome Creek	12133500	28.49	1.557	0.0550
		Wallace River	12135000	49.21	1.274	0.0260
		Elk Creek nr Sultan	12137200	28.49	0.963	0.0340
		Calligan Creek	12142200	18.91	0.144	0.0080
		Hancock Creek	12142300	19.94	0.266	0.0130
		N.F. Tolt River	12147500	103.60	3.398	0.0330
		Pilchuck River	12152500	142.44	2.322	0.0160
		Little Pilchuck Creek	12153000	44.03	0.065	0.0010
		Tulalip Creek	12158040	38.85	0.218	0.0060
		Canyon Creek	12161500	155.39	3.002	0.0190
		N.F. Stillaguamish River	12165500	212.37	4.418	0.0210
		Deer Creek @ Oso	12166500	170.93	2.435	0.0140
		Pilchuck Creek	12168500	134.67	0.850	0.0060
		Lightning Creek	12171000	334.10	4.134	0.0120
		Clark Creek	12183000	3.63	0.235	0.0650
		Jordan Creek	12183500	31.08	0.680	0.0220
		Illabot Creek	12184500	108.78	4.531	0.0420
		Jackman Creek	12190000	62.16	0.623	0.0100
		Sulphur Creek	12191800	21.76	0.906	0.0420
		Finney Creek	12194500	134.67	1.076	0.0080
		Hansen Creek	12198000	4.92	0.091	0.0180
		Coal Creek nr Sedro Wooley	12198500	25.12	0.062	0.0020
		Canyon Creek @ Kulshan	12208500	22.53	0.538	0.0240
		S.F. Nooksack River	12209000	266.76	5.975	0.0220
		Skookum Creek	12209500	59.57	1.586	0.0270
		Deer Creek nr Valley	12407520	93.24	0.147	0.0020
		Coal Creek	12464800	168.34	0.001	0.0000
		Lewis River	14213200	328.92	0.793	0.0020
		Clearwater Creek	14216300	85.47	1.161	0.0140
		Clear Creek	14216450	121.73	6.003	0.0490
		Muddy River	14216500	339.28	5.918	0.0170
		Canyon Creek nr Amboy	14219000	168.34	1.076	0.0060
		Cedar River nr Ariel	14221500	106.19	0.453	0.0040
		E.F. Lewis River	14222500	323.74	2.379	0.0070
		Dry Creek	14222950	8.55	0.007	0.0010
		Kalama River	14223000	463.59	7.447	0.0160
		Kalama River	14223500	512.80	8.807	0.0170
		Clear Fork Cowlitz River	14224500	147.62	3.002	0.0200
		Coal Creek nr Lewis	14225000	28.49	0.136	0.0050
		Johnson Creek	14230000	129.50	2.067	0.0160
		Klickitat Creek	14234000	8.55	0.009	0.0010
		Cinnabar Creek	14236400	11.91	0.215	0.0180
		Coldspring Creek	14241200	14.24	0.184	0.0130
		Coweeman River	14245000	308.20	1.671	0.0050
		Abernathy Creek	14246000	51.80	0.311	0.0060
		Elochoman River	14247500	170.93	1.218	0.0070

statistically-based conclusions. As more sites are measured systematically, this relationship could be improved. In this report, we do not differentiate relationships by region.

Where temperature data is compared to basin characteristics in Chapter 5, the TWG will use the relationship between distance from divide or basin area and streamflow based on TFW data alone (Table 3.2). This will maintain consistency between measured temperature and site data. No attempt will be made to account for regional variability.

When a streamflow estimate was made in TFW simulation setting, (Chapter 4), the following procedures were used to estimate streamflow:

If USGS gage records existed in a basin containing the site to be modeled: The average August mean discharge was divided by the basin area or stream length above the gage to obtain the unit inflow rate (termed groundwater inflow rate) (expressed in cms/m or cms/km). Multiplying the inflow rate by the basin area or stream distance above the site of interest to TFW yielded the estimate of flow. The inflow rate for most of the suitable USGS sites available in Washington are provided in Table 3.1.

If the site was in an ungaged watershed, the following relationship was used to estimate flow:

Log10(Q)= -1.928 + 0.9381 x Log10(Basin Area)

Flow is estimated for August daily mean flow, in cubic meters per second.

Stream Velocity

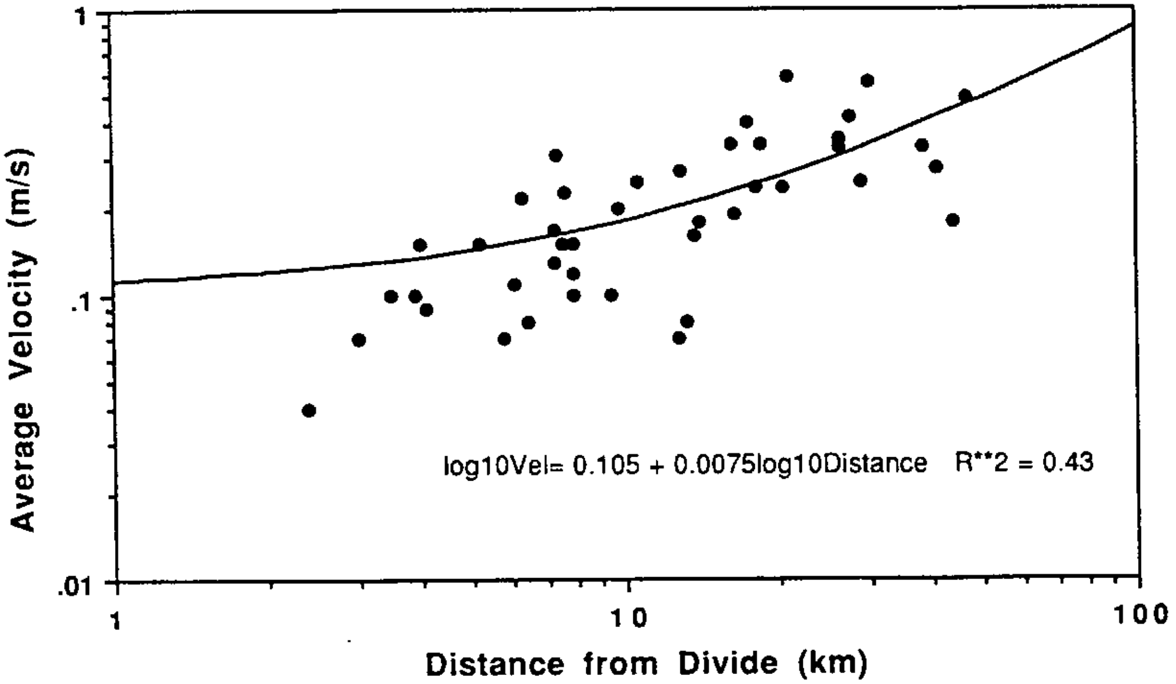
Stream velocity is important in determining the rate at which heated or cooled water travels downstream. Basin temperature models use average stream velocity to estimate the travel time of water between system prediction locations (nodes) in the stream system. Average stream velocity was measured at each of the primary study sites by dye studies conducted by the field crew during site visits (Chapter 2). The time for the majority of the the dye to travel a measured distance was used to determine the average stream velocity.

The primary use of average stream velocity is in basin-wide temperature modeling. Therefore, a useful way to characterize average velocity is as a function of distance from watershed divide (Figure 3.3).

Table 3.2 Linear regression statistics for summer streamflow (log_{10};m^3/s) in relation to basin area (log_{10}; km^2). Regressions are provided for USGS August mean daily flow records and the TFW study sites (single estimates). Data sets were sorted by general region within state to produce regional estimates.

			INTERCEPT		SLOPE		
Region	**Data Source**	**n**	**Estimate**	**SE**	**Estimate**	**SE**	R^2
Washington	TFW	38	-2.113	0.135	0.931	0.086	0.75
	USGS	90	-1.928	0.211	0.938	0.111	0.44
W.Cascades	TFW	26	-2.271	0.147	1.034	0.091	0.84
	USGS	80	-1.902	0.232	0.926	0.123	0.42
Coastal	TFW	7	-1.769	0.490	0.743	0.468	0.34
	USGS	10	-2.218	0.315	1.091	0.170	0.82
Eastern	TFW	4	-2.736	0.266	1.154	0.146	0.95
	USGS	-	-	-	-	-	-

Figure 3.3. Average stream velocity in relation to distance from divide.



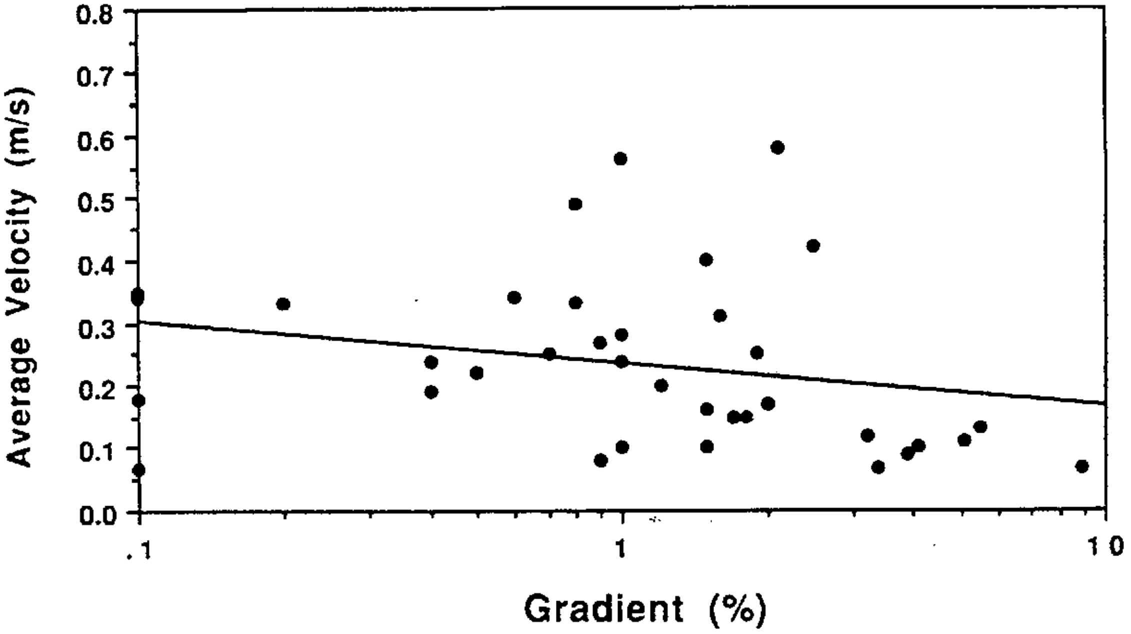
Average velocity tended to increase with distance downstream, as streams got larger. The relationship between velocity and distance from watershed divide is statistically significant, though highly variable (Probability that the slope is greater than 0=<0.001; R^2=0.50). Although not shown, the relationship between velocity and basin area is similar to Figure 3.3 (R^2=0.53).

Increasing velocity with increasing distance from divide may seem counter-intuitive, from a perception that velocity in small streams is higher compared to larger rivers. Based on streamflow equations such as Manning's or Chezy's equations, velocity and stream power are strongly influenced by channel gradient, which generally decreases as streams get larger. If gradient alone were responsible for velocity, lower gradient streams (generally larger rivers) should have lower average velocities than steeper streams (generally smaller streams). However, roughness contributed by large boulders, channel obstructions, and bedforms is significant in steeper streams. These roughness elements impede the flow, and offset the influence of channel gradient by slowing velocity on average compared to smoother rivers.

Average reach velocity was not related to channel gradient (Figure3.4; R^2=0.06), suggesting that roughness factors have a more significant effect. Estimates of roughness due to riffles, pools and large obstructions were not made for this study. Insufficient data were available from study sites to provide appropriate indices of each roughness on a reach scale to relate with velocity.

Where stream velocity or travel time was used in basin temperature modeling, the relationship between average velocity and distance from watershed divide was used. When distance of a prediction location from the watershed divide was less than 3 km, an average velocity of 0.05 m/s was assumed.

*Figure 3.4. Average stream velocity in relation to channel gradient. (Vel=0.236 - 0.068 x Log10(Gradient), R**2=0.06).*



GROUNDWATER

Groundwater influx along the stream channel can have an important cooling effect on stream temperature since the usual summertime mean daily stream temperatures are often above the temperature of groundwater (approximately 10°C in most streams). The groundwater cooling effect depends on the rate of groundwater influx relative to the volume of flow in the stream and the temperature of the groundwater relative to the temperature of the stream.

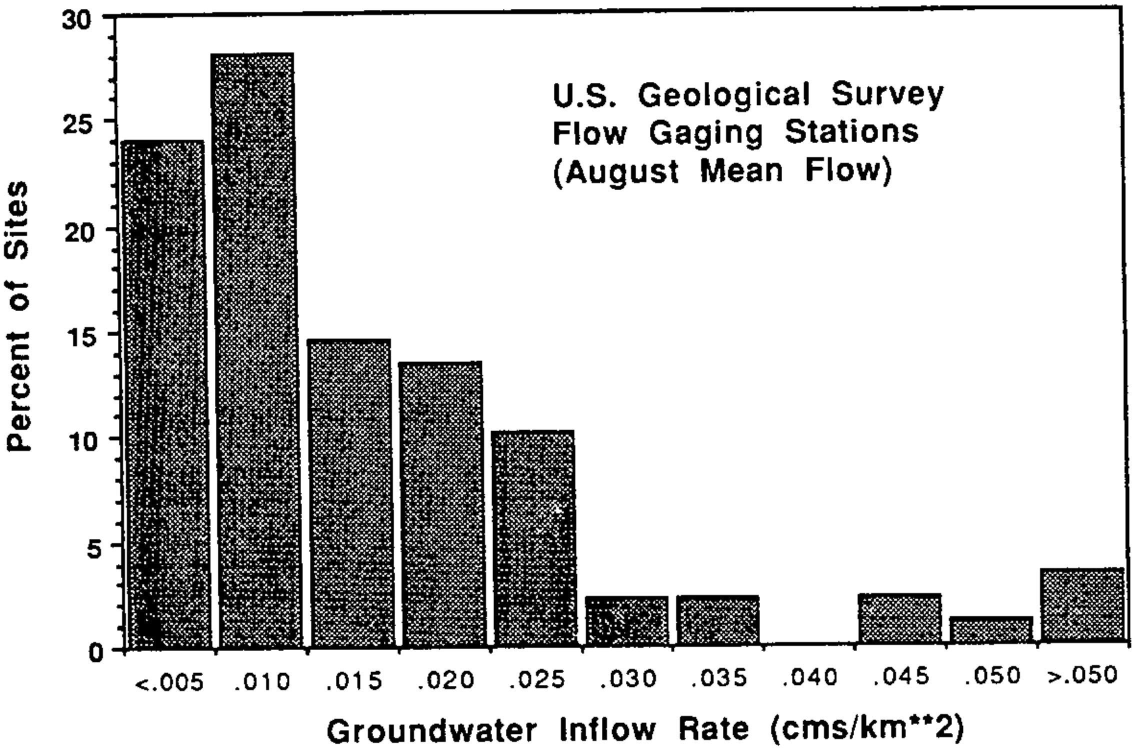
Inflow Rate

Relatively little has been characterized about groundwater inflow, including its pathways into the stream (for instance, does groundwater usually enter continually along the stream system or at discrete seep locations?) or its rate (which is probably influenced by climate, lithology, and the presence of deep and shallow aquifers). Here groundwater inflow rates are compared both regionally and within watersheds to evaluate if there were systematic patterns in spatial variability.

The groundwater inflow rate (Q_{gw}) during the summer months was assumed to be the average streamflow (Q) divided by the total length of stream (including tributaries) above a location (L), since flow is generally contributed by subsurface seepage to stream channels and not derived from direct precipitation or stormflow. Therefore, the groundwater inflow rate is the same as unit streamflow for the summer months. The units of groundwater inflow rate are $m^3/s/km$. We used distance from watershed divide as the measure of stream length. (Values calculates using the entire stream length above the location were also analyzed, but results were not found to differ from values calculates using the distance-from-divide, which is simpler to measure. We therefore include only the latter for review).

There is significant variability in groundwater inflow rates in Washington. Streamflow data for the 90 USGS gaging stations used in streamflow analysis are provided in Table 3.1, and the frequency distribution of groundwater inflow rate estimated from USGS data are shown in Figure 3.5. August groundwater inflow rate tends to range from approximately 0.004 to 0.025 $m^3/s/km$. Rates were

Figure 3.5. Frequency of observations of groundwater inflow rate for the U.S.G.S. flow gaging stations in Washington based on the long-term August mean flow and basin area.



as low as 0.0008 and high as 0.065 at some USGS locations. There was not sufficient geologic and climatic information available for the USGS sites to identify regional trends based on these factors.

To determine if there was systematic variability in groundwater inflow within basins, groundwater inflow rate was examined in relation to basin area. The hypothesis was that if groundwater inflow rate varies with stream size, the slope of the linear regression between basin area and inflow rate should be significantly different than zero. To obtain suitable sets of data, two approaches were used. In one, streamflows were measured by cooperators in some of the major basins in the TFW temperature study. Flow in a number of streams ranging in size from small to large in each basin (including but not limited to the temperature sites), were all measured on the same day when there was no storm events affecting streamflow. In the second approach, estimates from the USGS and TFW sites throughout Washington were compared to basin area.

As with the regional analysis, there was wide variability in groundwater inflow rate within basins (Table 3.3). Q_{gw} varied by an order of magnitude in every basin measured. The basin average Q_{gw}, however, was more consistent, ranging between 0.002 and 0.012 $m^3/s/km$. These basin estimates are similar to the statewide observations shown in Figure 3.5. These results suggest that there tends to be as much variability in groundwater inflow rate within basins as between them.

There was no systematic relationship between basin area and groundwater inflow rate in any of the watersheds surveyed (Table 3.3). In no case was the slope of the regression line significantly different than zero, and correlation coefficients were very low. Similar results were obtained by examining the USGS and TFW data sets. There also were no statistically significant relationships between basin area and groundwater inflow rate (Table 3.4). Therefore, groundwater inflow rate (and unit discharge) were assumed to be uniform within a basin for modeling purposes, although in reality it is highly variable. No patterns in groundwater inflow rate related to geology and climate were identified.

Table 3.3 Measured groundwater inflow rate (Q/Basin Area; $m^3/s/km^2$) for TFW basin surveys. Measurements for sites in each watershed were made on same day. The regression statistics are for the linear regression of Q_{gw} = Log_{10}Basin Area. The probability of >T tests the hypothesis that the slope of the regression line is not statistically significant than zero (no relationship). A low value of the probability (pr<0.05 or 0.10) indicates that the slope differs from zero.

		Groundwater Inflow Rate		Regression Statistics		
Watershed	**Number of Sites**	**Average**	**Range**	**Slope**	**Prob. of >T statistic**	**R-Square**
Abernathy Creek	5	0.0055	0.0036-0.0085	0.00	0.59	0.08
Chehalis River	16	0.0044	0.0026-0.0072	0.00	0.75	0.01
Deschutes River	9	0.0122	0.0014-0.0250	0.00	0.42	0.08
Cedar Creek	8	0.0034	0.0005-0.0043	0.00	0.73	0.02
Coweeman River	3	0.0062	0.0023-0.0130	0.00	0.88	0.01
Little Natches R.	8	0.0007	0.0011-0.0137	0.00	0.91	0.00
S. Prairie Cr.	6	0.0088	0.0004-0.0298	0.00	0.89	0.00
Smith Creek	4	0.0024	0.0008-0.0060	0.00	0.63	0.09
Deer Creek	8	0.0075	0.0012-0.0137	0.00	0.70	0.02

Table 3.4 Regression statistics for the relationship between groundwater inflow rate ($m^3/s/km$)and basin area (km^2)$Qgw=f(log_{10}$Basin Area)) for the USGS and TFW gaging sites. The probability statistic is the T-statistic probability that the slope of the regression is not significantly different than zero.

		Regression Statistics			
Source	**N**	**Slope**	**Intercept**	**Prob. of >T-statistic**	**R-Square**
USGS	90	0.00	0.015	0.57	0.00
TFW	38	0.00	0.007	0.98	0.00

Groundwater Temperature

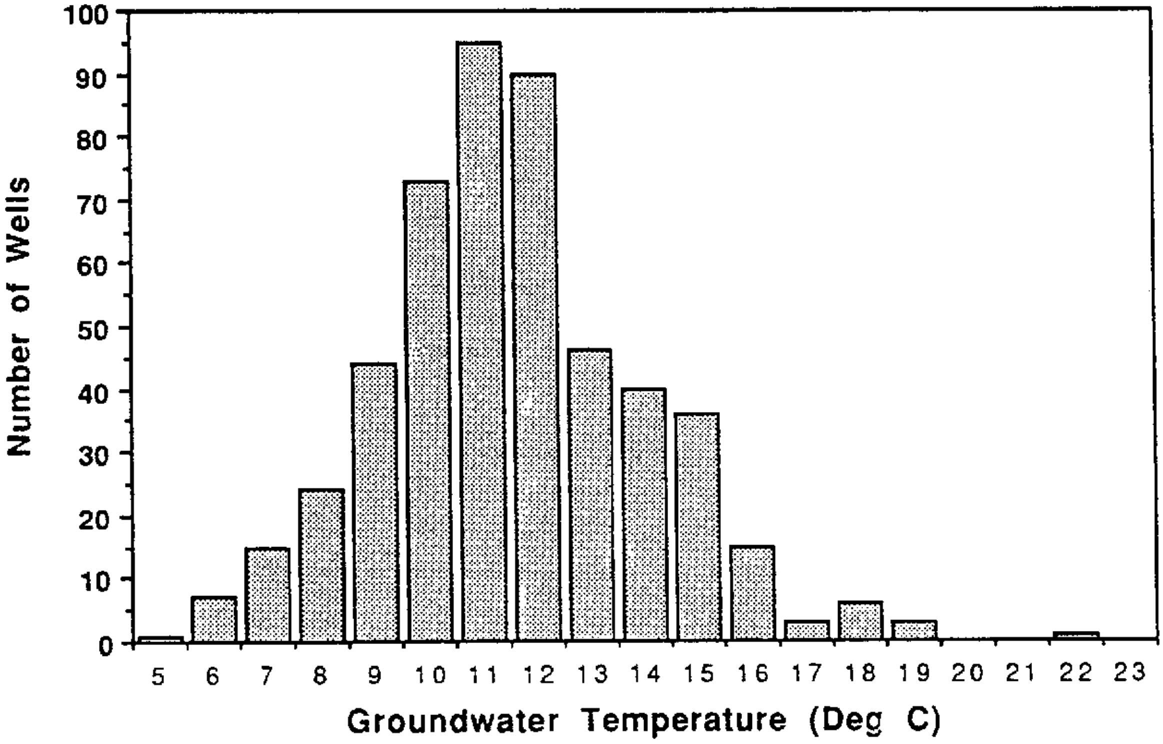
Groundwater temperature is generally cooler than observed stream temperatures and thus can have a cooling effect on stream temperature during the warmer summer months. Where there are thermal aquifers near the surface (hot springs, and so forth), groundwater temperature can also be significantly greater than stream temperature. Temperature prediction models require an estimate of groundwater temperature, but there are few available measurements of the temperature of groundwater feeding forest streams. Several approaches were taken to identify an appropriate estimate of groundwater temperature.

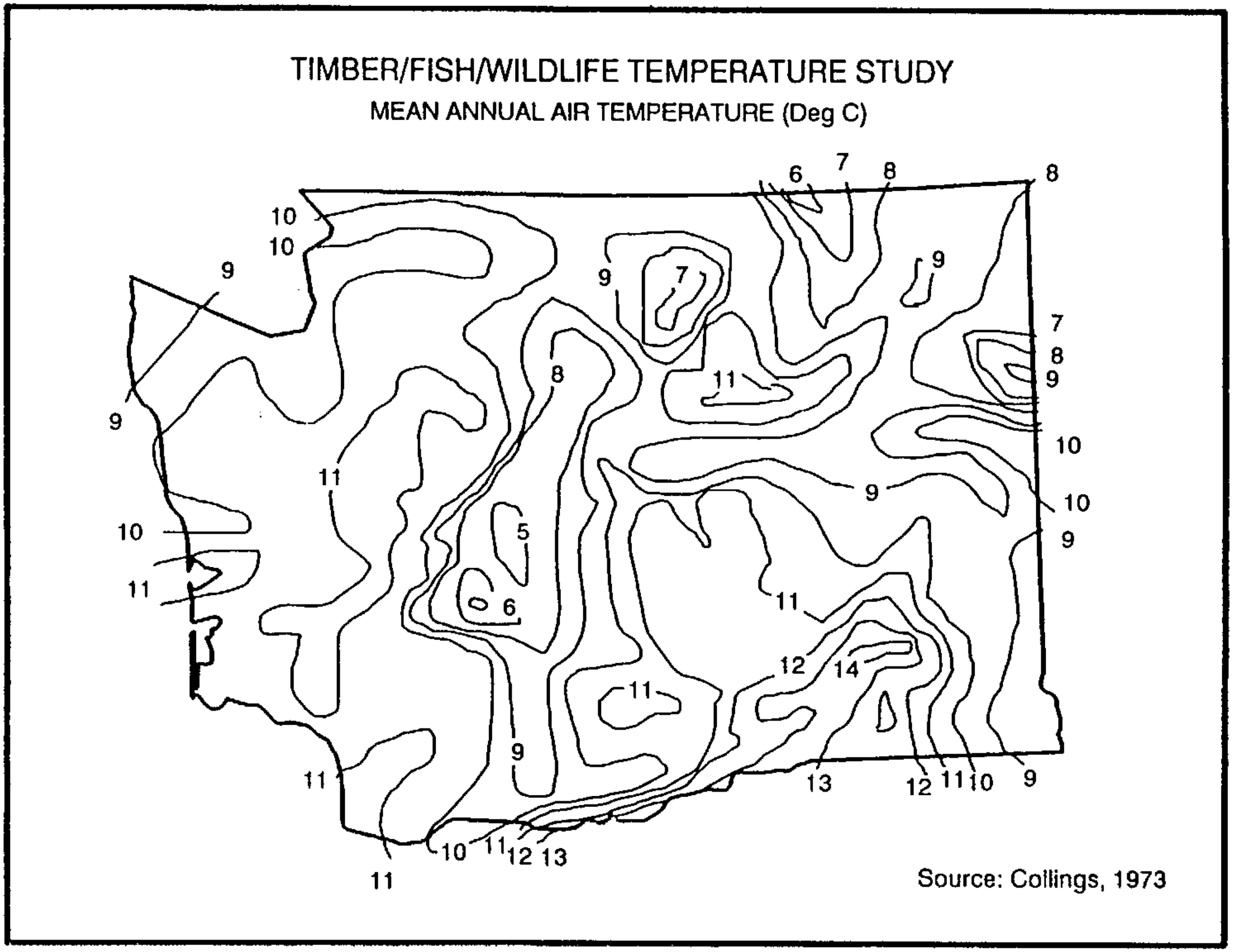
Groundwater temperature varies slowly over the course of a year. In most situations, the subsurface water temperature ranges approximately 3°C around the mean annual air temperature (Adams and Sullivan 1990). Based on an average annual air temperature of 10°C at Olympia, this would suggest groundwater temperature should vary between 8.5 and 11.5°C. Factors that would influence air temperature would also influence groundwater temperature.

Another estimate of groundwater temperature may be the minimum nighttime temperature of small streams. For several small streams in the Deschutes basin near Olympia, minimum temperature tends to be approximately 10-11°C (K. Sullivan, pers. comm.), agreeing fairly well with the estimate.

USGS well temperature records were also examined for 499 sites distributed throughout Washington. The most frequently observed groundwater temperatures in July are 10-12°C (Figure 3.6). Also observed were temperatures as low as 5 and as high as 22°C. These data are biased toward low elevation sites. An alternative method of estimating groundwater based on air temperature was examined. Since groundwater varies in a relatively constant manner with air temperature (Adams and Sullivan, 1990), the groundwater temperature was estimated based on the mean annual air temperature. Using the mean annual air temperature isotherm map for Washington from Collings (1973), groundwater temperature was estimated for each site based on the estimated air temperature. A simplified version of this map is shown in Figure 3.7.

Figure 3.6. Groundwater temperature of USGS wells in Washington State.




TIMBER/FISH/WILDLIFE TEMPERATURE STUDY

MEAN ANNUAL AIR TEMPERATURE (Deg C)

Source: Collings, 1973

Figure 3.7 Isotherms of mean annual air temperature.

CHANNEL CHARACTERISTICS

While a number of channel characteristics potentially influence stream temperature, the characteristics of greatest importance are stream depth and width. Generalized basin relationships for these characteristics are developed in this section. These relationships are used to estimate channel characteristics for sites not visited by the TWG field crew.

Stream Depth

Stream depth is one of the most important geometric characteristics that defines channel geometry for energy transfer purposes. Depth affects the response time of the stream to changes in energy, and thus the magnitude of the daily stream temperature fluctuation. Shallow streams respond rapidly to direct solar radiation reaching the stream surface (Brown 1969), and this rapid response creates potentially large daily fluctuations in water temperature in streams without shade. Deeper streams have greater thermal inertia, and respond more slowly and at lower magnitude to changes in solar insolation. Streams that have fundamentally different depth characteristics are likely to have fundamentally different temperature regimes and different responses to vegetation removal.

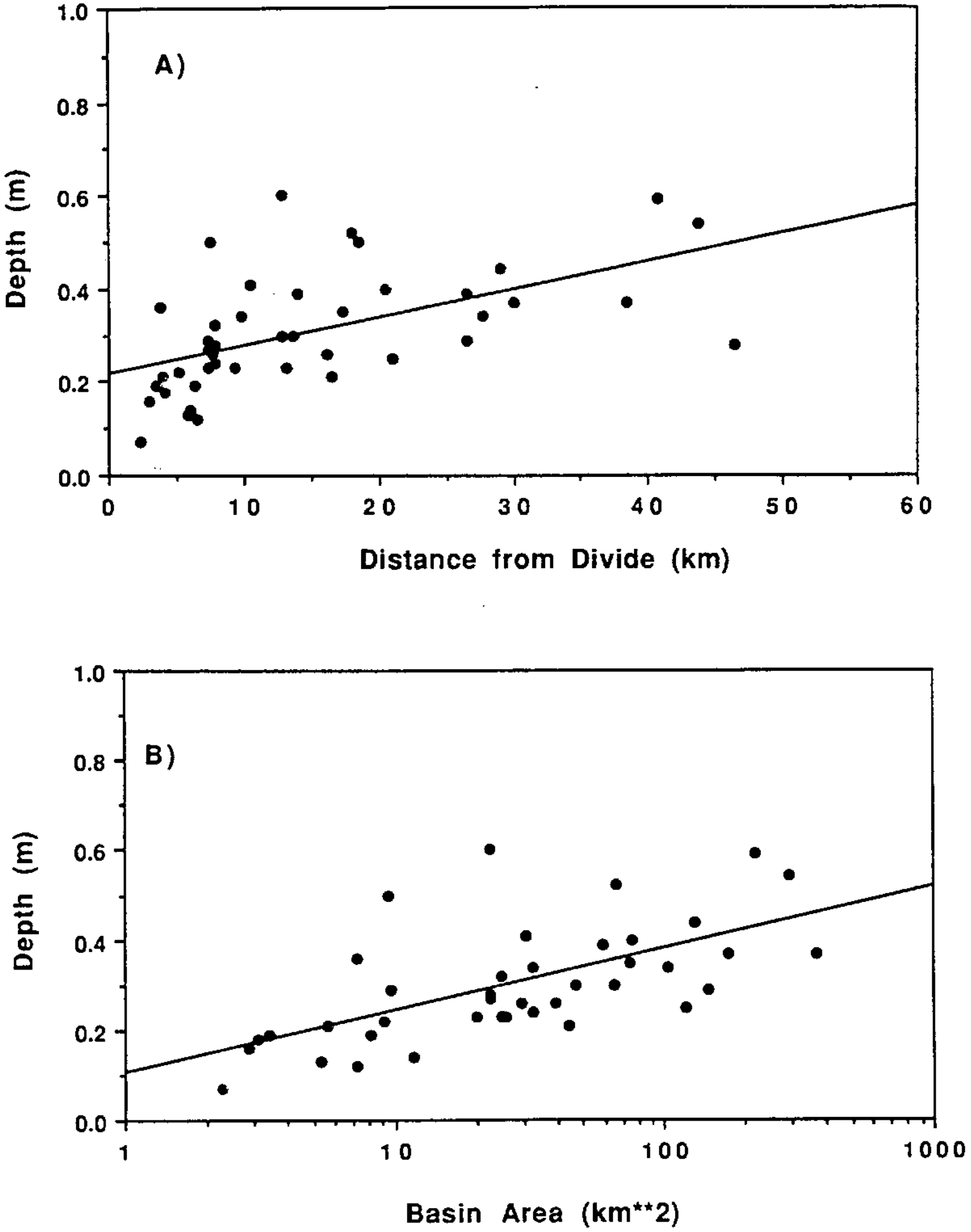
How to characterize stream depth is an important consideration since depth varies significantly over short stream lengths between riffles and pools. In this study, depth was estimated as the weighted average depth of the channel units in the sample reach measured during the summer months (Chapter 2). This measurement method was considered the most accurate estimate of average depth, although it is labor-intensive.

Streams tend to increase in depth as they get larger (Figure 3.8a,b). Linear regression shows similar results whether depth is determined as a function of distance from watershed divide or of basin area. As

Table 3.5 Regression statistics for the relationship between stream depth (m) and distance from watershed divide (km) and basin area (km^2).

			REGRESSION STATISTICS				
			SLOPE (β)		**INTERCEPT (a)**		**R^2**
	Region	**n**	**Estimator**	**S.E.**	**Estimator**	**S.E.**	
Depth = f(Distance)	All	35	0.0073	0.0014	0.193	0.0250	0.44
	Coast	6	0.453	0.0096	0.018	0.0714	0.78
	Western Cascades	26	0.0075	0.0015	0.195	0.0283	0.49
	Eastern	5	0.0093	0.0017	0.097	0.0314	0.85
Depth = f(Basin Area: (log$_{10}$)	All	39	0.1375	0.0280	0.105	0.0434	0.39
	Coast	6	0.2512	0.1468	0.078	0.1535	0.24
	Western Cascades	26	0.1625	0.0313	0.061	0.0509	0.50
	Eastern	5	0.1484	0.0145	0.011	0.0243	0.95

Figure 3.8 Stream depth (summer low flow) in relation to distance from watershed divide (A) and basin area (B).



expected, there is wide variation in depth as a function of distance or basin area (R^2=0.44 and 0.37 respectively). No attempt was made to stratify study sites by valley types, which would probably have helped to account for some differences in depth.

A tendency was noted for streams in coastal Washington to be deeper than similar-sized streams elsewhere in the state (Table 3.5), which probably reflects the geology (deeply weathered marine sediments) of many of the streams measured in this region. There were no major differences between other locations in western and eastern Washington.

Stream Width

Stream width (i.e., wetted width) is important to the extent that it affects the potential shading from streamside vegetation. Narrow streams can be easily shaded, even by relatively short vegetation, while wide streams will remain more open, even under mature forest vegetation. By influencing the baseline vegetation density, stream width tends to determine both solar radiation amounts and the air temperatures in the stream environment, which is very influential in determining water temperature. Baseline patterns of canopy density are related to those of stream width. Where canopies are more open, the air temperature in the vicinity of the stream tends to be similar to that above the forest canopy.

Wetted Width. For modeling of summer temperatures, wetted stream width was the characteristic of greatest interest. In this study, average wetted width was estimated as the weighted average width of the channel units in the sample reach measured during the summer months (Chapter 2).

Summer wetted width increased as a function of distance from watershed divide (Figure 3.9a; R^2=0.79) and basin area (Figure 3.9b; R^2=0.66). Although the predictive relationships are good, there is wide scatter in the data, particularly in larger streams. The linear regression lines are as follows:

$$\text{Wetted Width}=0.97 + 0.326 \times \text{Distance} \quad (R^2=0.79)$$

$$\text{Wetted Width}=-2.51 + 5.65 \times \text{Log}_{10}(\text{Basin Area}) \quad (R^2=0.66)$$

Bankfull Width. Bankfull width increases as a function of distance from watershed divide and basin area in a manner similar to those shown for wetted width (bankfull width not illustrated).

$$\text{Bankfull Width}=5.1 + 0.519 \times \text{Distance} \quad (R^2=0.60)$$

$$\text{Bankfull Width}=-1.60 +9.64 \times \text{Log}_{10}(\text{Basin Area}) \quad (R^2=0.57)$$

Bankfull width and wetted width are related to one another according to the following relationship:

$$\text{Wetted Width}=-0.15 + 0.141 \times \text{Bankfull Width} \quad (R^2=0.69)$$

Channel Gradient

Although not a critical input variable for stream temperature models, channel gradient is probably an important characteristic that differentiates stream types (TFW Ambient Monitoring Steering Committee Workplan 1988). Channel gradient was measured by the TWG field crew in several ways. Accurate measurement of channel gradient is difficult, especially without expensive surveying equipment. The TWG field crew developed a method using a hand level that was calibrated until measurements were reasonably similar to that obtained using an autolevel (methods described in Chapter 2). The field measurement was then compared to an estimate made using a USGS topographic map.

The measured gradient value appeared to be fairly similar to the map-derived value for the higher gradient reaches, although the scatter is significant (Figure 3.10). Considerable error could result from using a map-derived value instead of field measured data.

The average channel gradient of the study sites grouped by Washington water type are as follows: type 1=1.25%, type 2=1.75% and type 3=2.8%.

Figure 3.9. Stream wetted width (summer lowflow) in relation to distance downstream from watershed divide (A) and basin area (B).

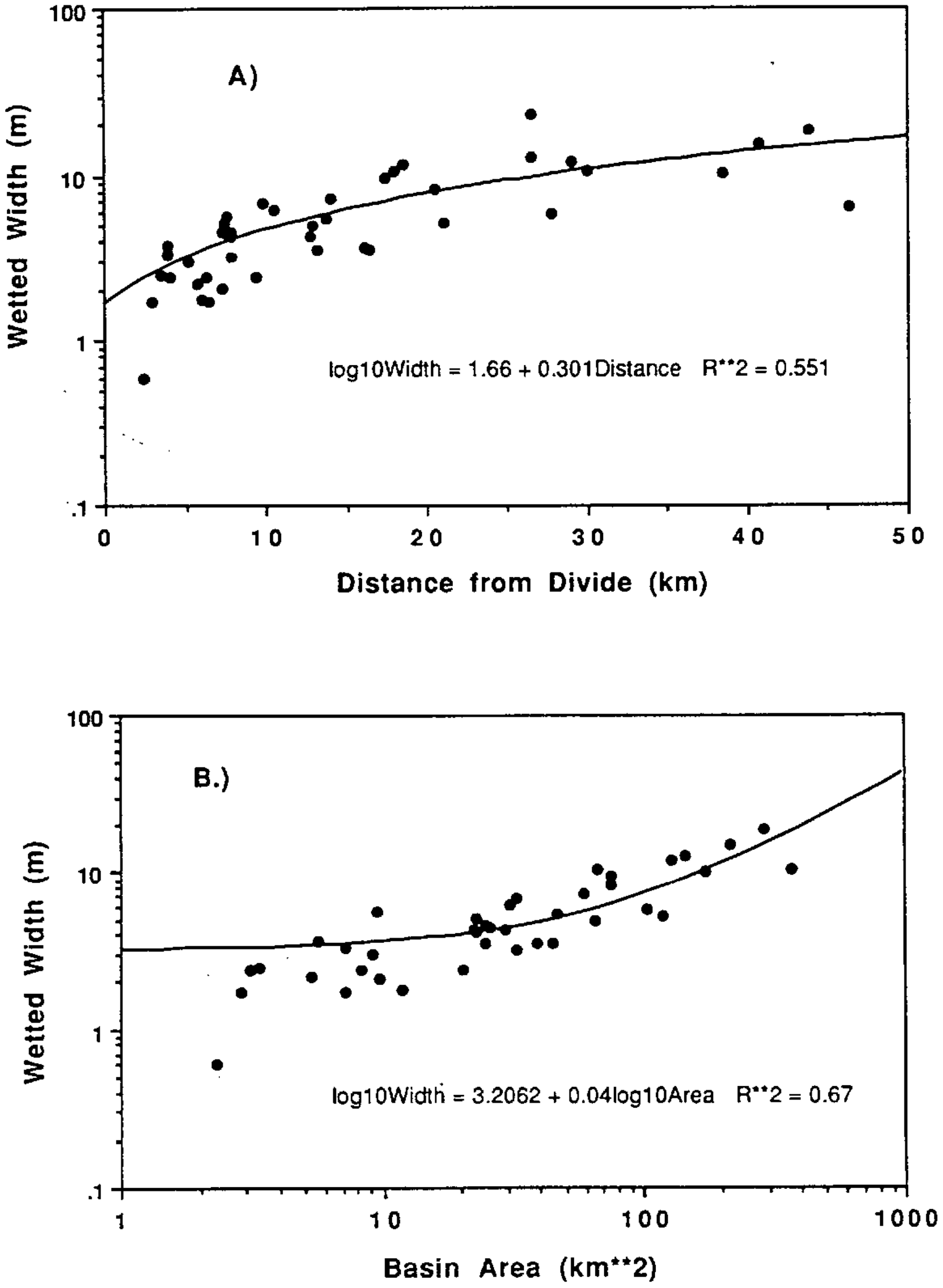
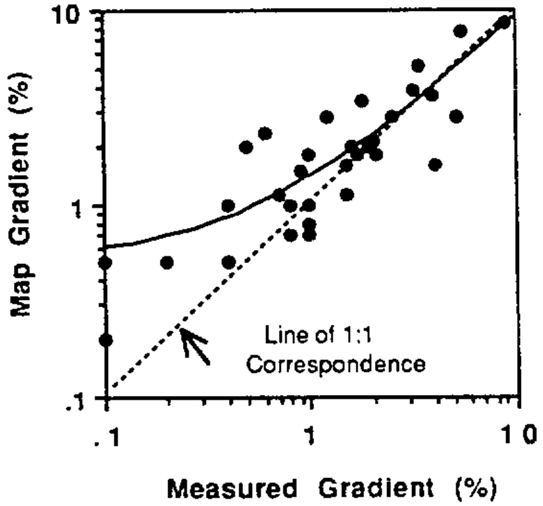


Figure 3.10.
The relationship between stream gradient measured in the field with a level and gradient estimated from USGS topographic maps.
(Log10(Map)=0.176+0.689Log10(Measured), R**2=0.66).



RIPARIAN CANOPY COVER

Riparian canopy determines the solar energy available to streams and the air surrounding them as well as the energy lost from streams from radiation and evaporation. Radiative energy transfer into and out of the stream environment is determined by how open the stream is to the sky. For stream temperature, the important shading characterisitc is the amount of the hemispherical view above the channel that is open to the sky (view factor, %) and the amount that is blocked by riparian vegetation or hillslopes (blocking or shade factor=1-view factor). The view factor, or its inverse the blocking factor, can be measured in the field with a densiometer or simply estimated visually (see Chapter 2).

Riparian vegetation is important in regulating stream temperature, especially in smaller streams where it has its greatest shading effect (Brown 1969). Riparian vegetation primarily influences the diurnal temperature fluctuation and therefore maximum stream temperature (Beschta and others 1987). Larger streams are generally wider and riparian vegetation is less effective in shading the channel. At some location along a river, channels are sufficiently wide that the influence of riparian shading on water temperature is negligible.

Baseline estimates of stream shading under mature forest canopies in relation to stream width must be established. Riparian characteristics of the primary study sites were analyzed to estimate average values of the view factor in mature forest streams over a range of stream widths. Mature riparian vegetation density was related to stream width for study sites described as mature forest or fully shaded. Where streams were described as fully shaded, the shading could come from conifers or mature second-growth hardwoods. Only eleven of the primary sites were considered reasonably suitable for estimating mature vegetation shading characteristics. A far greater number of carefully selected sites in mature forests along all stream sizes should be measured to increase confidence in the important relationship shown in Figure 3.11. This relationship is the basis for estimating the natural sky view factor under baseline forest conditions, and at sites where changes in vegetative stands has occurred in the past.

The view factor increases with distance from watershed divide (Figure 3.11). Based on the TFW sites, a site on a river approximately 30 km downstream from its source may be only 50% shaded by the forest vegetation along its banks. This would have significant effect on the baseline temperature of the river. The view factor is also related to the wetted channel width (Figure 3.12) since stream width also increases significantly as rivers and basins increase in size. The relationships are:

View Factor=13.1 + 1.95 x Distance from Divide (R^2=0.66)

View Factor=13.6 + 4.84 x Wetted Width (R^2=0.62)

*Figure 3.11. Sky view factor (100% is completely open) for mature forest vegetation in relation to distance downstream from watershed divide, (View=13.1+1.95*distance, r**2=.66).*

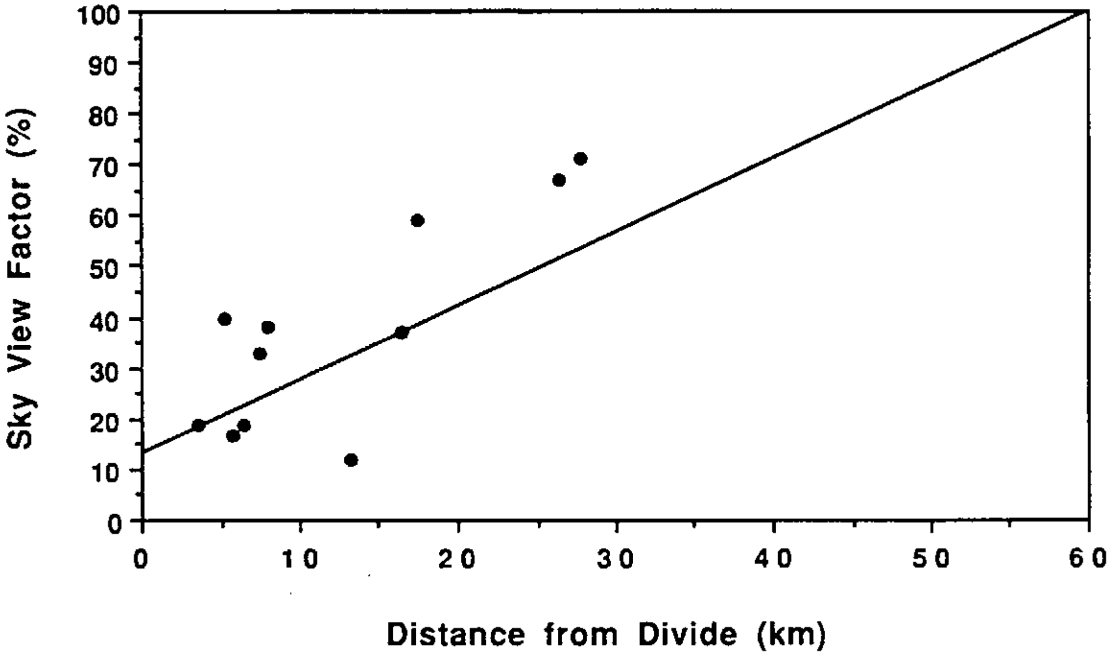
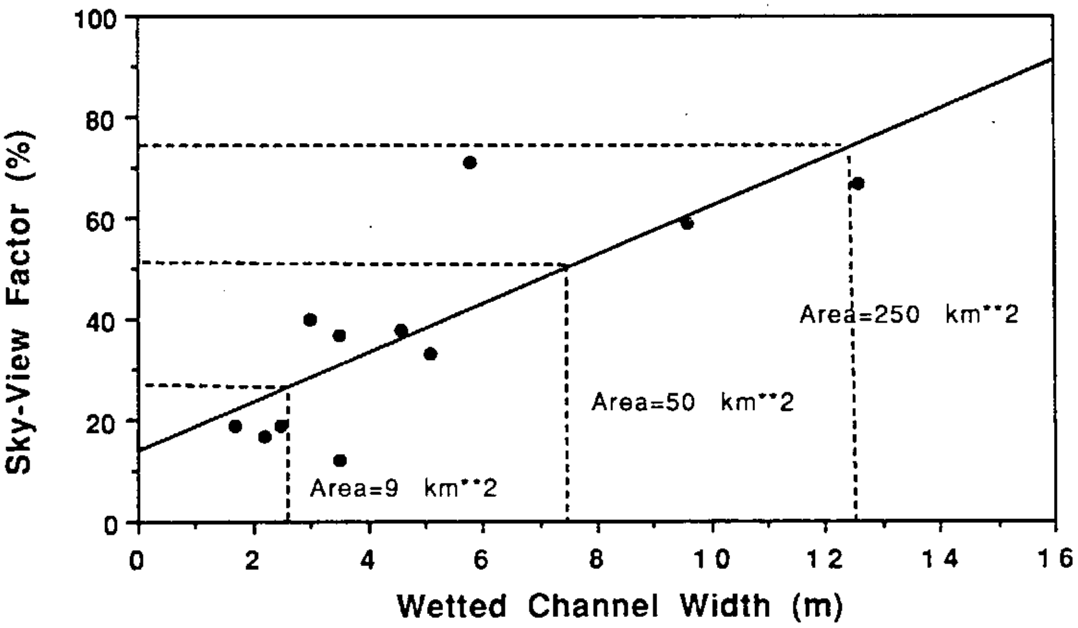


Figure 3.12. Relationship between the view factor (completely open is 100%) and wetted channel width with estimated basin area size categories equating to riparian canopy closure categories. Data is from sites with mature forests.

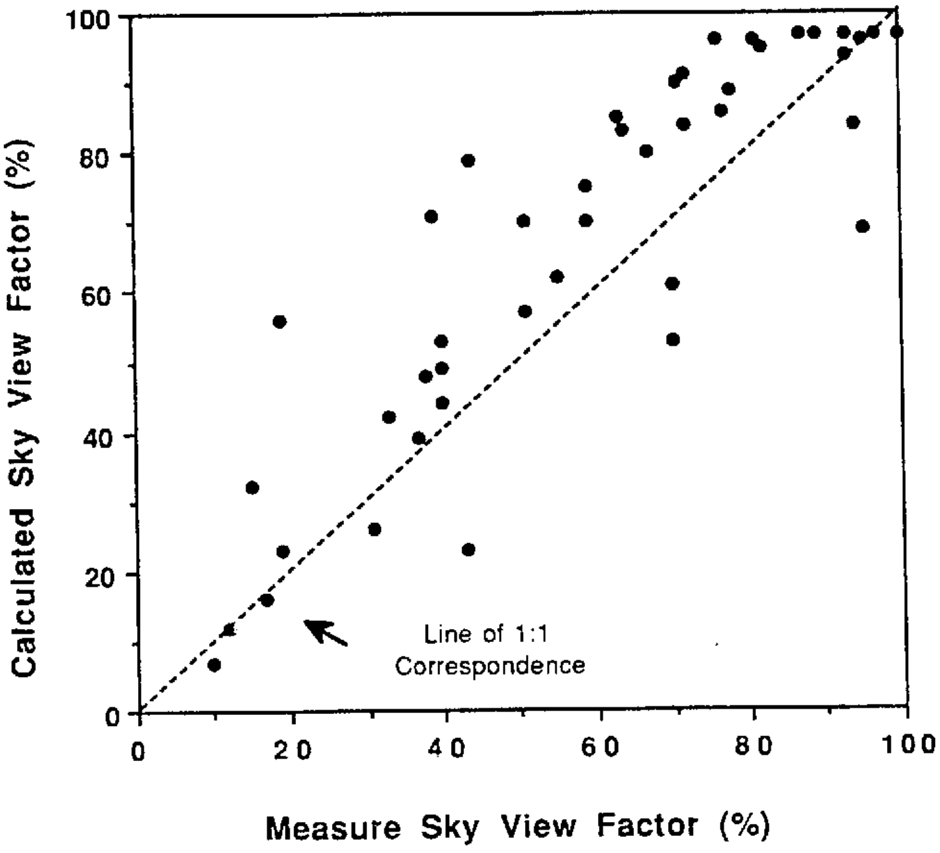


Also shown in Figure 3.12 are the approximate basin sizes, (determined from the wetted width/basin area relationship), where general shading categories occur. For example, the sky view factor is predicted to be almost 25% open when basin area is 9 km^2, 50% open at basin area of 50 km^2 and 75% open at basin area of 250 km^2.

Methods of measuring the view factor. Several of the temperature models request detailed measurements of many riparian characteristics to derive an estimate of the total percent of the sky that is open or blocked, depending on how the model expresses shading or lack of it. These detailed measurements may divide the entire sky view into zones and evaluate each separately, or may estimate the individual contribution of different components such as overstory and understory vegetation to the total shading. These refinements can add considerable complexity to estimating total shading.

If models are to be used widely to assess forest practice applications, it would be desirable to calibrate quicker methods for estimating the view or blocking factor relative to the these models' more elaborate methods, which require more training and significantly greater field time. Testing of temperature model predictions using different estimates of the view factor will be performed in Chapter 4. Here we compare the sky view factor measured with a densiometer to the calculated sky view factor of the USF&WS SRSHADE model that computes the total shading from a number of individual vegetative characteristics as described above and in Chapter 2 (Figure 3.13). The calculated sky view is generally close to the measured value (B=1.11 ; R^2=0.75), although the calculated sky view tends to overestimate the view factor when streams are more open (sky view factor greater than 50%).

Figure 3.13 Comparison of measured sky view factor (densiometer readings) and calculated sky veiw form USF&WS SRSHADE Model.



CLIMATE VARIABLES

Air Temperature

Local air temperature in the vicinity of the stream regulates many of the processes of heat loss from the stream. The difference between air and water temperature determines the rate of energy exchange for several heat transfer processes included in the energy balance. The daily mean stream temperature under equilibrium conditions is generally near the daily mean air temperature (Adams and Sullivan 1990). Furthermore, the diurnal fluctuation of water temperature will be strongly influenced by the fluctuation of solar insolation and air temperature. Therefore, air temperature influences both mean and maximum water temperature regardless of riparian cover and stream size, and is an important input variable in several of the prediction models.

Spatial variability in air temperature is an important but poorly quantified, characteristic of stream environments. Air temperature appears in 6 of the 7 heat transfer equations included in energy balance, but where the relevant air temperature is measured differs for each process. For example, the back radiation equation assumes a sky temperature well above the stream, the convection equation considers air at the stream surface and the evaporation rate is often measured 2 meters above the water surface. Lacking knowledge of the spatial variability in air temperature, it is not clear what air temperature should be used as model input. Furthermore, relatively little has been documented about changes in air temperature in the vicinity of streams with vegetation removal.

Air temperature at a stream site is rarely available for stream temperature prediction. Until recently, air temperature has not often been measured along with water temperature in forest streams. Although the SSTEMP temperature model is also sensitive to air temperature, this model allows the use of air temperature values measured at distant locations such as NOAA weather stations. Use of remote estimates of air temperature may result in inaccurate estimates of water temperature.

How does local air temperature measured at the stream relate to basin air temperature above the canopy and to regional air temperature at distant sites? Air temperature in the stream environment was characterized and its relation to regional weather stations was evaluated.

In The Riparian Zone

Air Temperature Within the Riparian Zone. Local air temperature in the riparian zone was measured while walking a traverse through the riparian zone. The traverse began at the channel bank (making the same measurement as local air temperature recorded by instruments) and proceeded perpendicularly away from the stream for a distance of up to 100 meters. Where a clear buffer strip existed, the traverse was extended through the buffer into the adjacent cutover stands and temperature was measured under both the canopied and open areas.

Air temperature tended to increase slightly with distance away from the stream banks in all riparian zones, regardless of vegetation conditions. Since time

Table 3.6. Relative change in air temperature within riparian zones of varying overstory vegetation conditions. Distances from the streambank ranged between 15-25 meters unless a buffer was present.

Vegetation Cover	Percent Change in Air Temperature Relative to Streamside Area Air Temperature (°C)
Mature Forest	+1%
Buffer	
Within Buffer	+5%
Harvest Area Beyond Buffer	+15%
No Buffer	+2%

Table 3.7 Regional air temperature analysis. Comparison of air temperature at forest sites with best matching NOAA regional site. (Each site was compared with all six NOAA stations, only the best is shown.)

		DAILY MEAN			DAILY MAXIMUM				
STREAM	ELEV (m)	R^2	Slope	Intercept	R^2	Slope	Intercept	Best Match	Average Difference (C)
Ware Creek (AA)	436	.70	.43	2.9	0	0	0	OLY	-4.5
Thurston Creek (AD)	292	.88	.77	0.8	.83	.69	2.0	OLY	-2.7
Huckleberry Creek (AC)	197	.87	.71	1.3	.84	.61	2.7	OLY	-3.0
Little Deschutes River (AE)	269	.79	.88	-0.3	.83	.82	-0.2	OLY	-2.1
Hard Creek (AR)	450	.84	.77	-0.1	.84	.85	-2.0	OLY	-3.6
Deschutes R. (RK75.5) (AG)	342	.75	.85	0.4	.76	.88	-0.9	OLY	-2.0
Deschutes R. (RK 60.2) (AF)	168	.88	.74	1.8	.88	.70	1.8	OLY	-2.1
Deschutes R. (RK41.2)(AS)	110	.83	.75	2.4	.94	.81	0.9	OLY	-1.5
Porter Creek (AP)	109	.78	.71	2.1	.91	.84	-0.5	OLY	-2.5
Goble Creek (AI)	48	.82	.72	3.3	.88	.97	0.5	OLY	-1.1
Baird Creek (AJ)	216	.59	.66	2.9	.69	.77	1.2	OLY	-1.1
Mulholland Creek (AH)	111	.79	.68	2.7	.86	.77	1.0	OLY	-2.4
Coweeman R. (at Goble) (AL)	43	.82	.72	3.3	.88	.97	0.5	OLY	-1.1
Coweeman R. (at Mull.) (AK)	115	.79	.68	2.7	.86	.77	1.0	OLY	-2.4
Coweeman R. (at Baird) (AN)	209	.59	.66	2.9	.69	.77	1.2	OLY	-2.4
Herrington Creek (AO)	375	.24	.86	-2.3	.36	1.14	-8.0	OLY	-4.5
Hoffstadt Creek (AQ)	587	.86	.92	-1.6	.86	1.02	-4.1	OLY	-2.8
Schultz Creek (AB)	540	.83	.99	-1.8	.83	1.04	-4.0	OLY	-1.9
Red Creek (GA)	41	.60	.51	5.4	.76	.63	6.5	QUIL	-1.8
Naselle River (BC)	288	.80	.75	0.8	.88	.92	-3.0	OLY	-3.1
Bear River (BE)	92	.64	.51	5.3	.80	.58	4.7	QUIL	-2.0
Smith Creek (BD)	67	.80	.65	3.0	.79	.90	-0.8	OLY	-2.5
Pilchuck River (RK 15.4)(DA)	38	.84	.75	2.4	.86	.95	-0.6	OLY	-1.4
Pilchuck River (RK2.7) (DB)	49	.76	.60	3.3	.84	.71	1.7	OLY	-2.8
Squire Creek (HC)	130	.84	.83	0.6	.85	.88	-1.5	OLY	-2.0
Greenwater River (ID)	122	.82	.91	-2.4	.77	1.04	-5.2	OLY	-3.9
S. Prairie Creek (IC)	527	.79	.68	0.6	.71	.73	1.0	OLY	-4.2
Ten Creek (IA)		.87	.84	0.7	.92	.95	-2.2	OLY	-1.9
Bear Creek (CA)	956	.91	.82	-4.2	.84	1.03	-10.7	YAK	-7.5
S. Fork Natches (CB)	949	.91	.82	-3.8	.87	.9	-9.4	YAK	-7.1
Crow Creek (CD)	827	.73	.64	0.9	.73	.89	-5.8	YAK	-6.6
CeeCeeAh Creek (EA)	1048	.97	.81	-3.2	.96	.95	-4.7	SPOK	-6.6
Chamokane Creek (EB)	446	.77	.62	3.5	.97	.85	2.4	SPOK	-4.1

of field visits varied, the change in air temperature with distance from streambank is expressed as a percentage change from the temperature measured at the bank. The increase was only about 1% of the air temperature at the bank in riparian zones vegetated with mature trees and 2% where no buffer was present at all (Table 3.6). Distances traversed ranged from 15 to 25 meters away from the stream bank.

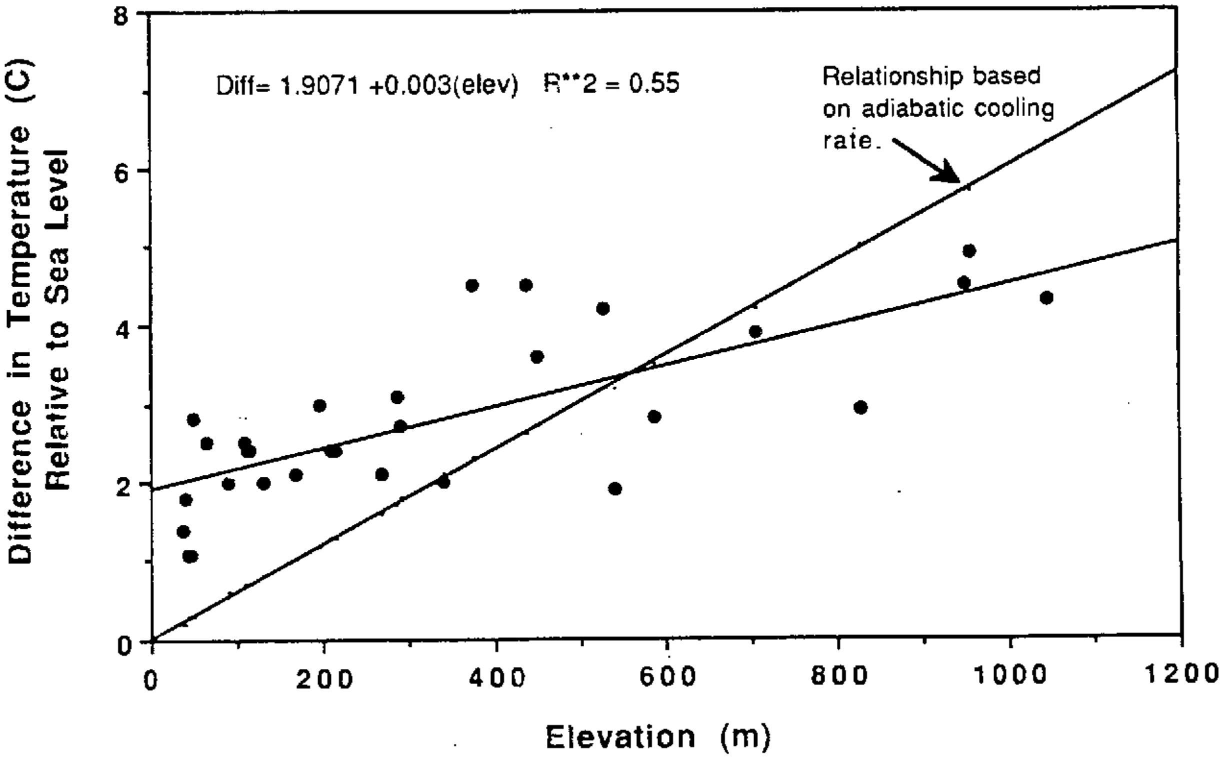
Comparisons between air temperature within and outside buffer strips revealed that buffer strips do minimize air temperature changes in the riparian zone. In paired measurements, air temperature increased about 5% with distance within the vegetated buffer, and jumped to 15% greater beyond the boundary between the cutover area and the buffer (Table 3.6). Presumably, the air temperature was already elevated near the stream bank where no buffer was present, and the small change with distance noted above was from a temperature probably on the order of 10% greater than had overstory trees been present.

Regional Relationships

Relation to Regional Weather Data. Air temperature measured near streams was compared to weather data from regional NOAA weather stations to develop an understanding of the applicability of regional weather data to basin or reach temperature modeling. This was accomplished with existing data sets where available and with data recorded at the TFW study sites in 1988. Regional weather stations used for air temperature analysis in this study were located in Olympia, Yakima, Seattle-Tacoma Airport near Seattle, Stampede Pass, Spokane, Yakima and Quillayute (NOAA 1988).

Generally, measured air temperature at stream sites was fairly well related to that at regional sites, although there was considerable variability in the relationships. Daily maximum and mean air temperature at the study sites were regressed against

Figure 3.14 Relative difference in mean daily air temperature between forest stream sites and regional weather stations at sea level. Actual temperature decreases with elevation. Eastern Washington sites are included.

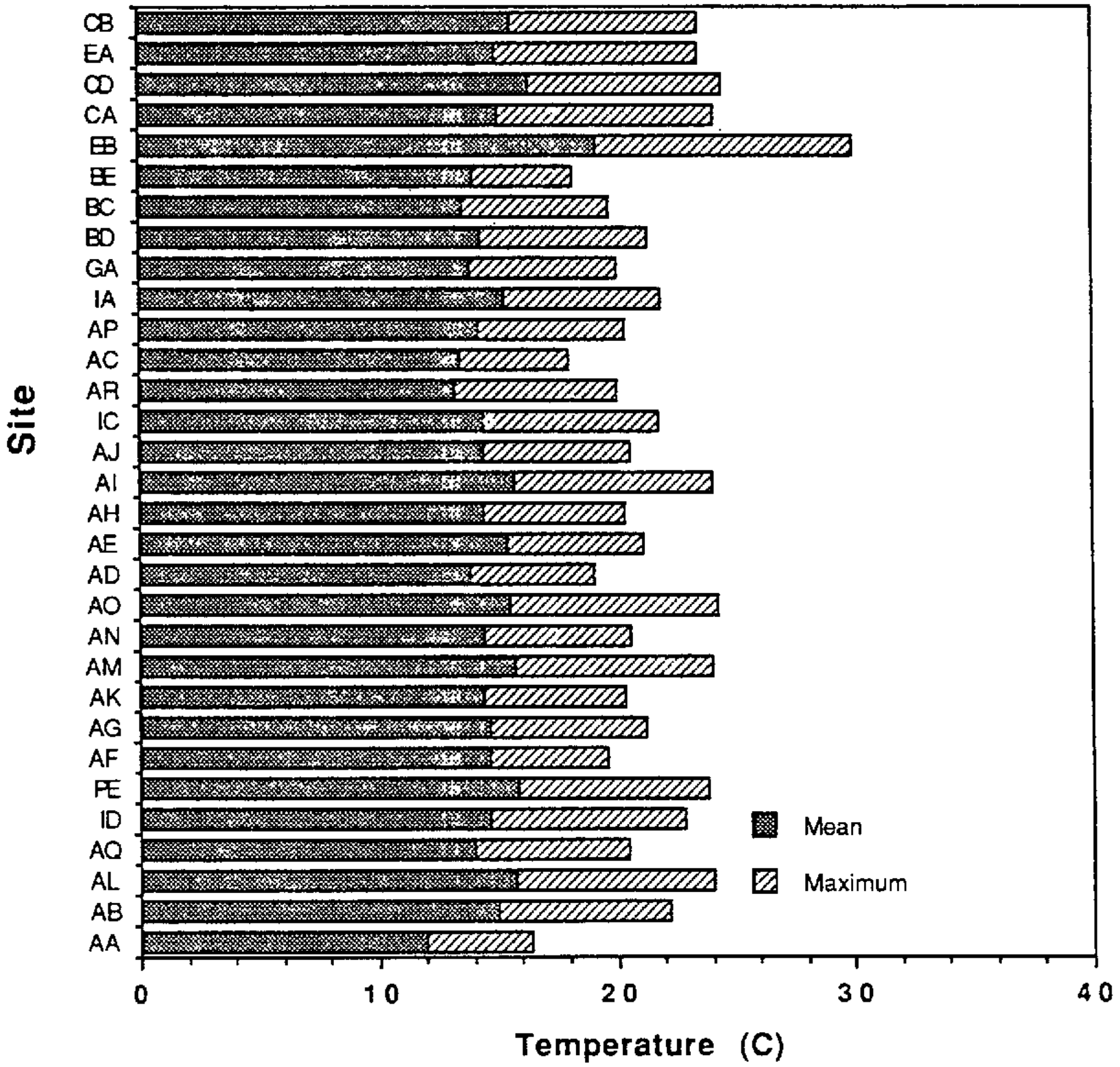


matching data from the regional sites to identify the regional site each study site was best related to, and how variable the relationship was. (All study sites were related to all regional sites.) The best regional site and the predictive relationship (R^2, slope, and intercept) for each site are provided in Table 3.7.

Somewhat surprisingly, the Olympia station was the best related to most of the forest sites on the West side of the Cascades. Coefficients of determination (r^2) ranged from 0.24 to 0.87. Although actual air temperature values at Stampede Pass tended to be closer to those at the forest stream sites, the relationships tended to be more highly variable on a day-to-day basis. Olympia predictions tended to be more accurate over the period. Air temperature tended to be lower at the forest stream study sites than at regional weather stations.

The average temprature difference is also shown in Table 3.7. This result is expected since most regional weather stations are located at lower elevations. (Air temperature should decrease approximately 2°C per

Figure 3.15 Average July air temperature characteristics of study sites.



300 meters elevation from adiabatic cooling.)

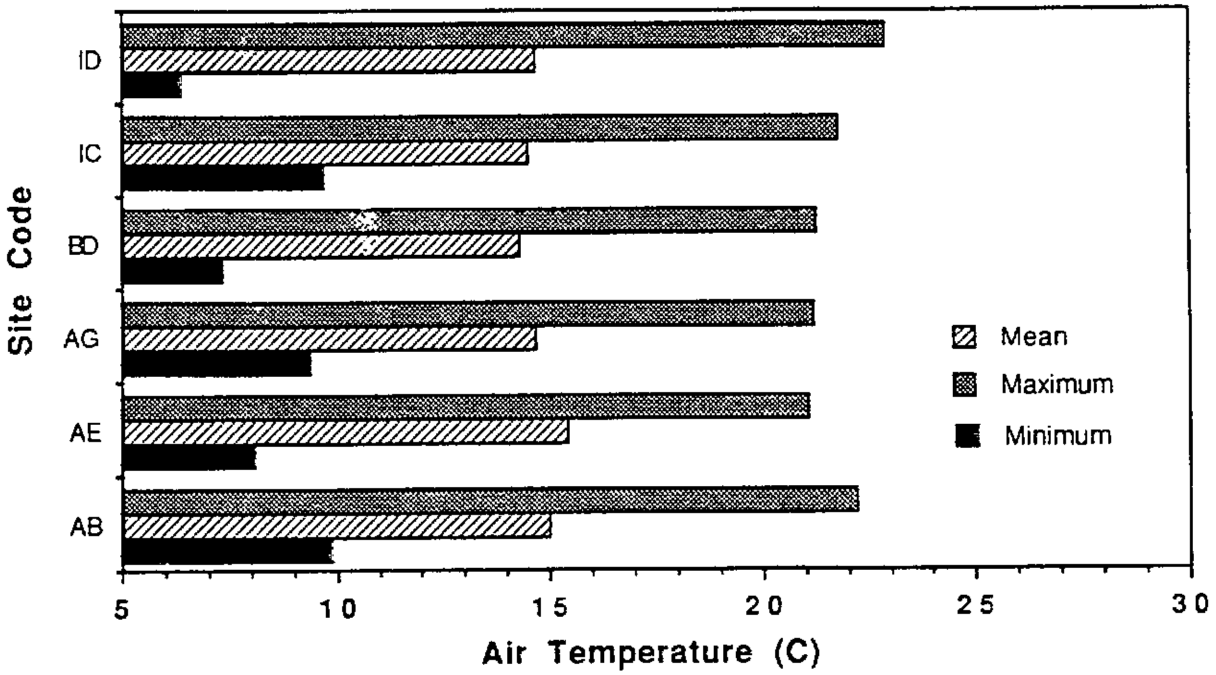
Regional weather station data was corrected for elevation differences at forest stream sites using relationships summarized from data in Table 3.7. The average difference between sea level air temperature (using Olympia as the sea level index station) and that at the forest stream study sites is plotted as a function of elevation in Figure 3.14. Adiabatic cooling relationships do not entirely explain the differences between sites, but elevation does account for approximately 55% of the variance in the relationship. (Regressions of the temperature difference and riparian vegetation cover were not statistically significant.) Lower elevation forest streams tended to be have cooler air than expected, while higher elevation sites (most of these are on the east side of the Cascades) tend to be somewhat warmer.

Characteristic Air Temperature Profiles. SSTEMP and TEMPEST require input of hourly or daily air temperature to calculate water temperature. Corrected data from regional sites (described above) can be used as this input. As an alternative method of estimating air temperature, characteristic hourly air temperature profiles were determined from the air temperature measured at the study sites. Average July air temperature characteristics for the 33 primary sites are shown in Figure 3.15 to indicate the general characteristics at each site.

The air temperature values for all sites in a category were averaged by hour for the period from July 15 to August 15. These averaged air temperature profiles can be used as input to the temperature models where measured air temperature is not available. The appropriate air category can be found by using the regression equation provided to estimate maximum air temperature based on site characteristics.

Stepwise regression was performed to determine the site and basin characteristics that best explained maximum and mean air temperatures at the study sites. The average of daily maximum and mean temperature for the period from July 15 to August 15 was used for this analysis. A number of site characteristics were identified as independent variables that could explain air temperature characteristics: elevation, distance from watershed divide, stream width, and riparian shading. The stepwise regression identified three variables that were significantly related to maximum and mean air temperature of the study sites: elevation, distance from watershed divide and stream width. Riparian vegetation conditions did not significantly influence air temperature, on average. The best regression equations for maximum

Figure 3.16 Sites in air group 3 with average maximum july air temperature = 21.0-22.9 C.



and minimum air temperature are as follows:

$$\text{Maximum} = 20.2 + ((0.215*\text{distance}) + (0.003*\text{elev}) - (0.225*\text{bankfull width})) \quad R^2=0.59$$

$$\text{Mean} = 14.3 + ((0.113*\text{distance}) + (0.001*\text{elev}) - (0.125*\text{bankfull width})) \quad R^2=0.63$$

Characteristic hourly air temperature profiles were developed by grouping sites into temperature categories based on the observed average maximum air temperature for July. Categories represented two degree increments; seven categories were needed for the range of temperatures observed at the sites. Placement of sites in air temperature categories is shown in Table 3.8. An example of the average air temperature characteristics of sites grouped in one of the air categories (category 3) is shown in Figure 3.16. Maximum and mean air temperature tends to be very similar for sites grouped within the categories, even though sites in a given category are found in a different areas of the state. Minimum temperature tends to vary more within the categories than other temperature characterisitics. Note that both of the higher air temperature categories had only one site within them.

In Relation to Long Term Average

Since the study was conducted during the summer of 1988, and many of the regionalized relationships are developed with data from this year only, it is important to understand how climatic conditions in 1988 compare with the longer term. Air temperature was used as an indicator of weather conditions. Average daily mean air temperature records (July 15-August 15) for 1988 are shown relative to the long-term average for three of the regional weather stations in Figure 3.17. Generally, air temperature tended to be slightly above normal in 1988, and was consistent at all of the weather stations. About 50% of the days tended to be warmer than average, while about 50% were equal to or less than normal.

The TWG had no efficient way of determining how 1988 data compared to the extreme values recorded historically because of the way in which data is reported by NOAA. Nevertheless, the conclusions reached in this study are indicative of climate conditions that are warmer than the long-term averages recorded throughout the state.

Table 3.8 Air temperature categories based on observed temperature (average of daily maximum air temperature during July). (Only sites with more than 25 measurement days were used.)

Categories	Sites Included
1 17.0-18.9°C	BE, AC
2 19.0-20.9	AQ, AR, BC, AN, AP,AD,AF,AK
3 21.0-22.9	AB, IC, BD, ID,AG, AE
4 23.0-24.9	CB, AL, CA, AO, EA
5 25.0-26.9	---
6 27.0-28.9	CD
7 >29.0	EB

Relative Humidity

Relative humidity, air temperature, solar radiation, wind speed, and water temperature was monitored at five sites in the Deschutes Basin with a portable climate station for about twelve days at each site during July and August 1988. Plots of these data (Fig 3.18) illustrate the linkage between relative humidity and air temperature. At a given vapor pressure, the relative humidity varies with air temperature. Due to the short period of record and lack of geographical coverage, no attempt was made to use these data for model testing. These data do, however, present intriguing questions of time variability of relative humidity and wind movement.

Solar Radiation

Regionalized model-parameter relationships were needed for simplified stream temperature simulations using the prediction models. One of the key parameters was the heat flux due to solar radiation. Fundamental to the computation is the average daily solar insolation reaching the earth's surface. Solar insolation profiles for the period from July 15 to August 15 were developed using a mix of historical weather records and estimates generated by the SS-SOLAR model. Median values of air temperature, percent possible sun, relative humidity, and cloud cover were compiled from the NOAA Local Climatological Data for Quillayute, Seattle-Tacoma airport, and Spokane stations. Site measurements and the weather data were input to the SSSOLAR model. The computed daily values were then compared to the long-term measured values for these localities (Critchfield 1978, Cinquemani and others 1978). Calibration coefficients were applied to bring the computed profile into agreement with the published values. Figure 3.19 shows the resulting profiles.

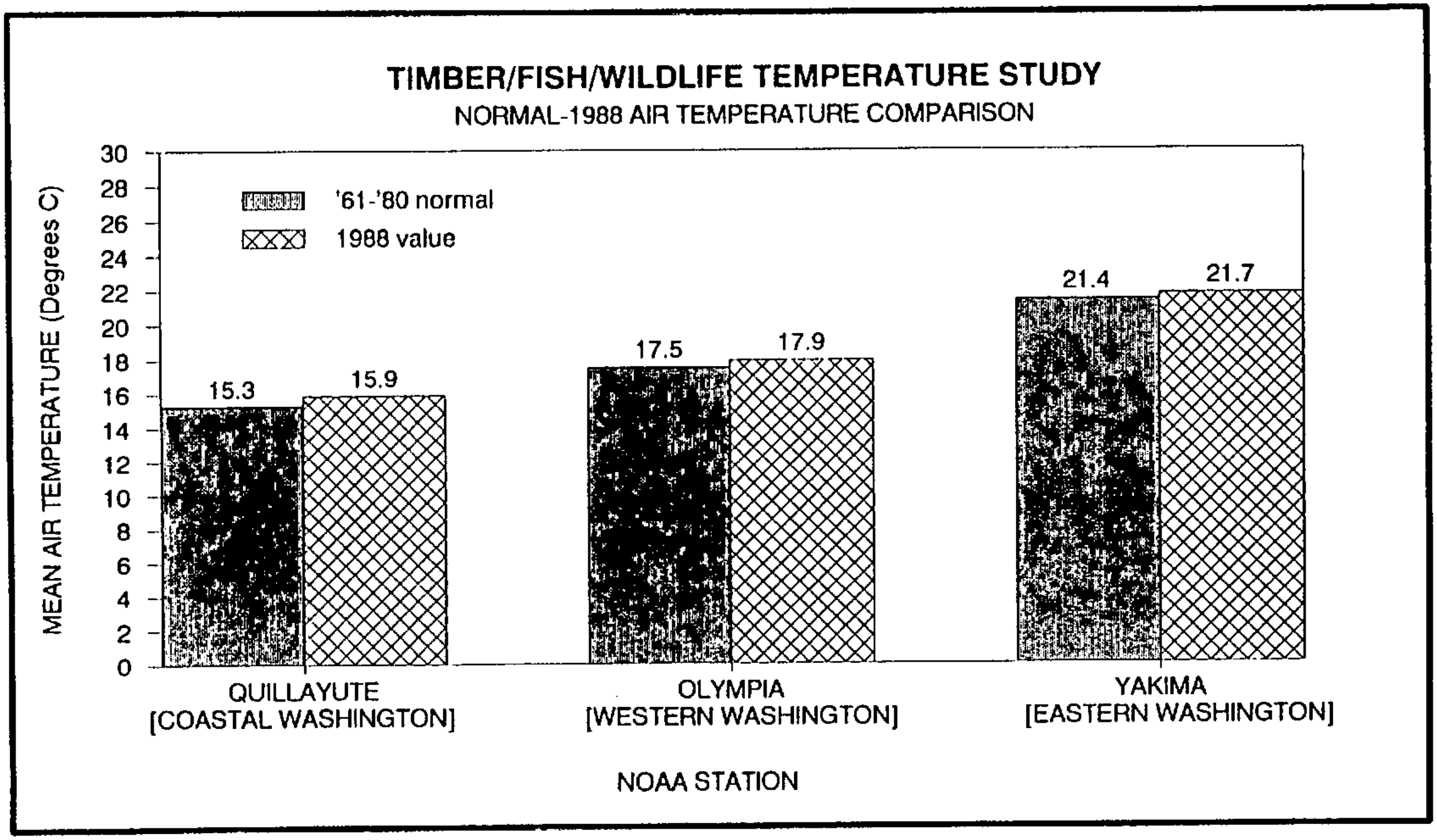
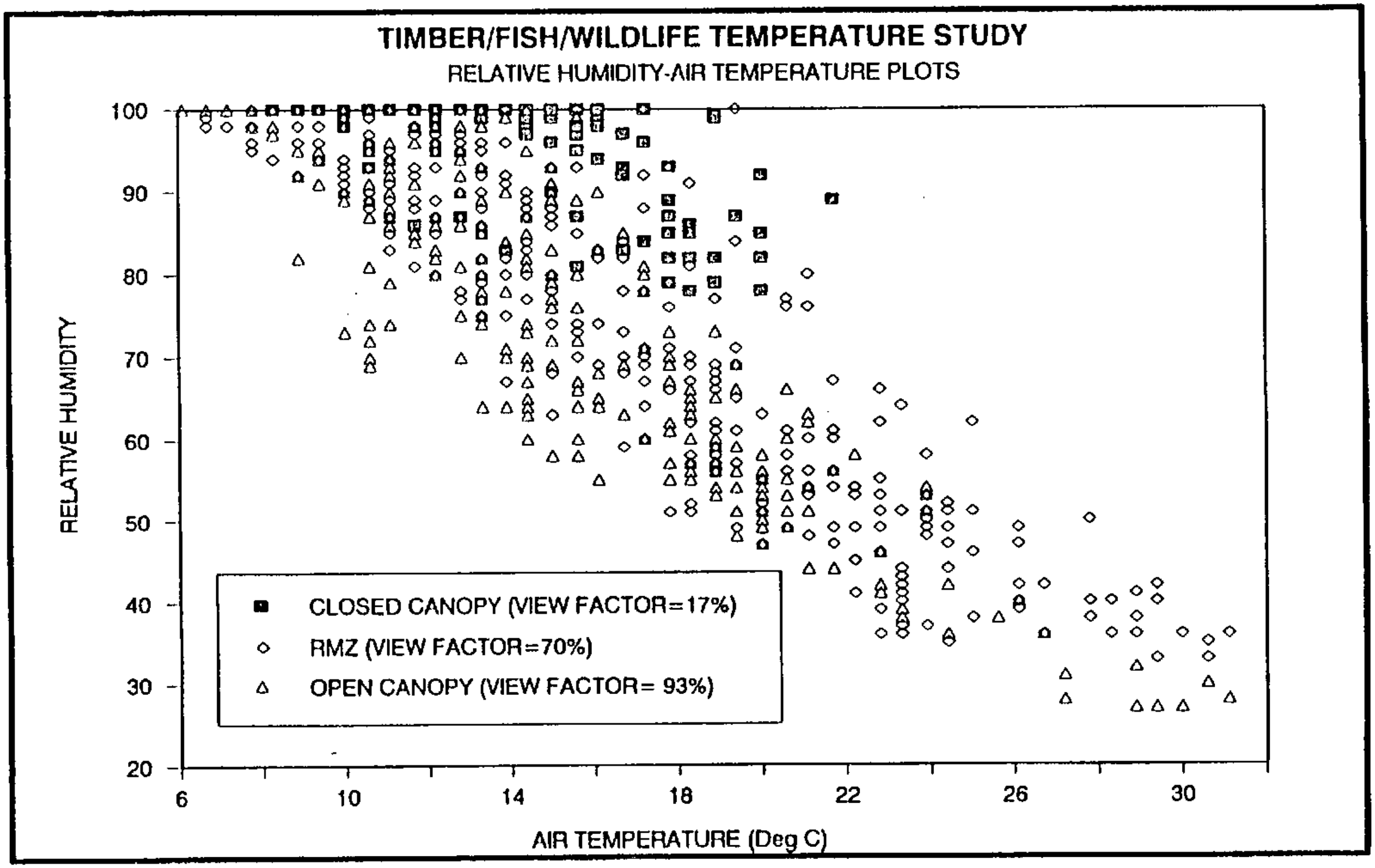


Figure 3.17 Air temperature at regional NOAA Climate Stations

Figure 3.18 Hourly air temperature /relative humidity relationship



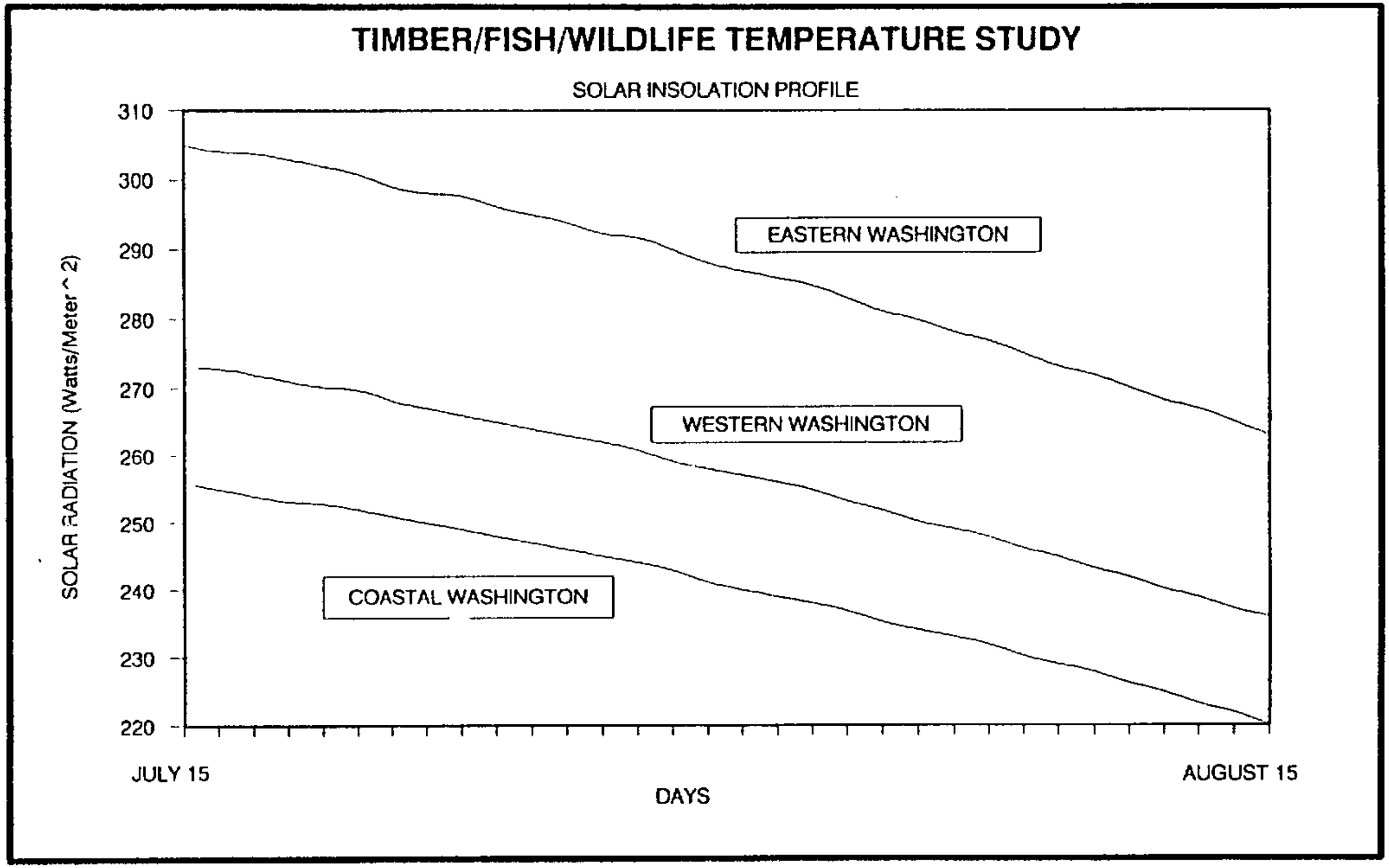


Figure 3.19 Solar insolation profiles

CHAPTER 4
SITE MODEL EVALUATION

INTRODUCTION TO MODELS AND THEIR USE

Models are useful tools in resource management. They allow managers to analyze the effects of management decisions based on objective criteria applied to the physical and biological systems influenced by management practices. However, models are often applied without a critical assessment of whether model use is appropriate in a given situation, or whether model results are reliable and can be used with confidence. Appropriate use of a model requires an understanding of: 1) the model's construction and approach to representing the physical world, 2) an appreciation of explicit and implicit assumptions and limits, 3) a review of the applications the model was designed for, and 4) an evaluation of the model's performance in the specific application under consideration. These factors were carefully considered in evaluating models for TFW application and form the basis for selection of a temperature prediction procedure.

All of the models tested in the TFW temperature study use an energy balance approach to evaluate stream heating and all were developed for field application. Each of the models is based on similar physical principles, although the actual mechanics of each model and the input variables used to describe the heat transfer processes vary. Each model requires a slightly different array of input parameters, and displays sensitivity to different variables. Because of this, predicted temperatures may vary between models. There has been surprisingly little well-documented analysis of the performance of any of the models in forest management. Nevertheless, all of the site models were expected to perform well when extensive field data was used as input. An important element of this model-testing effort included an evaluation of model performance when less detailed or accurate data is available, as will be the case in TFW application of a model.

Some of the most important questions regarding temperature models include: 1) How well does the model predict temperature?; 2) What input variables is the model sensitive to?; and 3) How well can those variables be measured or estimated in routine TFW field application of the models? Two classes of models were evaluated: those that predict temperature on a site-by-site basis (site or reach models), and those that predict temperature for an entire stream system (basin models).

Use and testing of models requires some understanding of their predictive capabilities and the variables that temperature is sensitive to. Inevitably, temperature predicted by each of the models is more dependent on some variables than others, although presumably there would be some similarity in parameter sensitivity between them if models are based on physical processes. Understanding the relative importance of the input variables in each of the models (sensitivity analysis) is important because it will determine how accurately an individual parameter must be measured to ensure reasonable model performance. The natural variability of each parameter, and the investigator's ability to accurately measure or estimate it, will influence the expected precision of temperature predictions.

A further consideration in model evaluation requires an appreciation of general procedures of using models. Modelling is rarely a completely rote process where a technician enters a series of numbers and turns the model on to await the output. More commonly, input values are entered and output results are compared against calibration data collected for the site. Input values have uncertainty associated with them due to errors that arise from a variety of sources including instrument precision, natural variability in the parameter, and so forth. When predictions fail to match observations, knowledgeable model users may adjust input parameters within reasonable limits to improve performance justified by recognition that parameter estimates may be imprecise. It should be noted that virtually any measured temperature data can be matched by a model by adjusting values for the required input variables.

Adjusting model input values is generally acceptable when done by those with the technical expertise to define appropriate ranges of input values and to understand data limitations. However, because of the complexity of model mathematics, there is often no way to know the effect of adjusting some input variables on the other variables. While data adjustment is an acceptable and often necessary practice in modelling, it poses some questions regarding routine use of temperature models in TFW applications.

It is expected that use of water temperature prediction models in TFW will be constrained somewhat by the fact that 1) calibration data will rarely be available, 2) field personnel collecting field data and using models may not always be technically trained, and 3) models may be applied at a number of sites over a wide range of climate and riparian vegetation conditions. An important element of model evaluation is whether the complexity of a model is compatible with the targeted user group considering the data and resources that will be available.

Thus, model prediction performance can be only part of the entire model evaluation criteria. A given model may predict very well, but if input data requirements are too complex, or if the interface between the model and the user is exasperatingly difficult, the value of the model's good predictive ability decreases. For application use, a model that predicts less well, but is easy to use, or requires input variables that are readily available, may be preferable to one that predicts extremely well but requires input data that is impossible to get.

This chapter reports the results of a series of model evaluations performed on the reach and basin models. Sensitivity analysis increased understanding of the mechanics of the models and identified the input parameters that had significant effect on the temperature prediction of each one. The sensitivity analysis was a key factor in establishing confidence in each model's reliability and in considering the transition from the carefully controlled TWG field experiments to possible widespread operational use in Timber/Fish/Wildlife management. Model performance was rigorously tested and then weighed against practical considerations to form the basis for selection of the best model for TFW application.

MODEL SENSITIVITY AND RELIABILITY ANALYSIS

Some variables will be inherently more influential in determining stream temperature than others. Knowing the sensitivity of model predictions to input variables that may vary in nature is important in the use of any model. Sensitivity analysis tells the user how errors in estimating values for input variables affect results, indicates the range of conditions over which model results may be applicable, and helps identify how much effort should be expended in accurately estimating any one input parameter. If only small changes in predicted temperature occur over the observed range of an input variable, than only minimal precision is required in estimating that variable. Conversely, if model results are highly sensitive to variables that are difficult or impossible to measure, the model may have low reliability in routine TFW application.

Sensitivity of Temperature to Key Parameters

The objective of sensitivity analysis was to determine the relative sensitivity of predicted temperature response to changes in the input parameters for each of the five models. Sensitivity analysis was restricted to a range of values for each variable that might be expected to occur in Washington streams. Sensitivity testing was only done for variables where measurement or estimation error was possible. It was assumed that date, longitude, latitude and other map-based information could be accurately specified. Parameters included in the sensitivity analysis are listed in Table 4.1. Sensitivity analysis was initiated prior to field data collection, although the analysis was not concluded until well after the field surveys were completed.

Table 4.1 Sensitivity analysis input values.

PARAMETER	STANDARD VALUE	INPUT VALUES USED IN ANALYSIS							INPUT VALUE EXPRESSES AS % OF STANDARD						
Air Temperature (oC)	18.72	9.36	18.72	28.08	37.44	.	.	.	50	100	150	200	.	.	.
Percent Boulders	32	0	32	83	100	.	.	.	0	100	259	313	.	.	.
Groundwater Inflow Rate															
TEMPEST (kg/m^2/s)	.001	.000	.0001	.001	.002	.005	.	.	0	10	100	200	500	.	.
SSTEMP (m^3/s)	.030	.000	.0030	.015	.003	0.006	.015	.30	0	10	50	10	20	50	1000
TEMP-86 (0.001 m^3/s)	0.33	0.03	0.16	0.33	0.65	1.64	.	.	10	50	100	200	500	.	.
Humidity															
24-Hour Mean	80	0	10	30	50	80	100	.	0	13	38	63	100	125	.
Daylight Mean	15	0	15	40	50	80	100	.	0	100	267	333	533	667	.
at noon	50	0	25	50	80	100	.	.	0	50	100	160	200	.	.
Percent Pools	57	0	29	57	86	96	.	.	0	51	100	151	168	.	.
Ave Pool Depth (m)	0.43	0.17	0.43	1.00	.	.	.	.	39	100	230	.	.	.	.
Solar Angle	65.0	44.0	65.0	90.0	.	.	.	.	68	100	138	.	.	.	.
Shade Proportion of Water Surface	0.25	0.00	0.25	0.50	0.75	1.00	.	.	0	100	200	300	400	.	.
Sky View Proportion of Water Surface	0.75	0.00	0.25	0.50	0.75	1.00	.	.	0	33	67	100	133	.	.
Solar Radiation (W/m^2)	310	210	250	310	400	.	.	.	68	81	100	129	.	.	.
Starting Water Temperature (oC)															
Maximum	22.88	13.12	16.40	24.60	28.70	.	.	.	57	72	108	125	.	.	.
Minimum	10.50	9.00	10.50	13.13	15.75	.	.	.	86	100	125	150	.	.	.
Mean	16.44	10.00	14.10	16.44	24.66	.	.	.	61	86	100	150	.	.	.
at midnight	14.00	7.10	10.00	14.20	15.62	21.30	.	.	51	71	101	112	152	.	.
Travel Time (sec/km)	4167	0	417	2084	4167	8334	20835	.	0	10	50	100	200	500	.
Stream Velocity (m/s)	0.24	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Wind Velocity (m/s)	3.58	0.00	0.36	1.79	3.58	7.15	17.88	.	0	10	50	100	200	500	.
Stream Depth (m)	0.31	small stream = 0.25			moderate = 0.40			large = 1.00							
CONSTANTS															
Water Emissitivy	0.95														
Ground Transfer Coefficient	1.65														
Clearness Factor	0.00														
Groundwater Temperature (oC)	10.5														
Percent Brush	0.00														

Analysis Steps

Standard input values for each model variable were developed from NOAA weather station data and stream survey data collected at the thirty-three primary study sites. The "standard" values approximated the average of site values. A range of values for each variable expected in Washington forest streams was also estimated from the site data (Table 4.1). A series of model runs were performed where all variables were held constant at the standard values except one that was varied over the expected range. For example, the standard air temperature input value was 18.7 °C. Holding all other variables constant, each model was run for values of air temperature of 9.4, 18.7, 28.1, and 37.4 °C. (Table 4.1).

A simple linear regression was then calculated using the input value (expressed as a percentage of the standard) as the independent variable and the change in predicted temperature as the dependent variable. The change in predicted temperature was calculated as the difference between the temperature predicted using the standard value and that predicted for each alternate input value. Maximum, mean and minimum temperatures were each investigated in this manner. Regressions were calculated for each variable for small, medium and large streams. The slope of the regression line was used as an indicator of model sensitivity to each variable. A slope of zero meant that the model was totally insensitive to the variable over the range evaluated. A steep slope indicated that the predicted temperature was highly sensitive to the input variable.

Testing models for sensitivity to shading was complicated by the fact that models vary in the specific input values used to characterize vegetation. For instance, TEMPEST specifies a single-value shade or view factor (percent of sky viewed from the stream surface) while SSTEMP calculates a similar shade value (inverse of view factor) from several vegetation input parameters in a model subroutine (SRSHADE). TEMP-86 requires several riparian input variables to calculate shade estimates used in internal model calculations of temperature, but does not produce an overall shading or view factor. For testing TEMP-86, the riparian tree height and canopy overhang values were exaggerated to insure effective shading, given the solar angle. Shade was then tested over the range by varying the canopy density value. No attempt was made to evaluate a shade variable in QUAL2E since this model does not require it as input.

Analyzing model sensitivity to stream depth was more difficult. Stream depth primarily determines the rate of response of water temperature to changes in solar radiation. Deeper streams have a slower response rate and thus tend to have a smaller fluctuation over the course of a day. Shallow streams respond rapidly, and can have a large fluctuation in response to hourly changes in air temperature and solar radiation. The diurnal flux was used as the indicator of a models sensitivity to depth, since depth directly influences this characteristic.

Stream depth was accounted for when testing other input variables, by running the tests individually for three stream depth groups: 0.16m (small), 0.4m (medium) and 1.0 m (large). Discharge was also adjusted with changing stream depth so that realistic streams would be modeled. For models that required width but not depth as input, the width value corresponding with the appropriate depth value was calculated by

Width = Discharge/ (Velocity x Depth).

Results

In general, small streams were more sensitive to changes in climatic variables than larger ones. Air temperature and humidity input values strongly affected predictions of most of the models, especially in smaller streams. Starting water temperature affected predictions more strongly for larger streams. All the models were fairly insensitive to groundwater values for the range expected in most Washington summer low-flow conditions. Smaller streams were more sensitive to groundwater than larger ones. Figures 4.1, 4.2 and 4.3 depict sensitivity ratings for the input variables. Model sensitivity to depth is shown as effect on diurnal fluctuation in Figure 4.4. The correlation coefficients for sensitivity regression analyses were 0.90 or better in most cases. Brown's equation was the only model with correlation coefficients that were consistently low. This raises a question as to the validity of sensitivity results for Brown's equation using this method of analysis.

Figure 4.1 Sensitivity analysis of the effects of variables on mean temperature for a moderate depth stream.

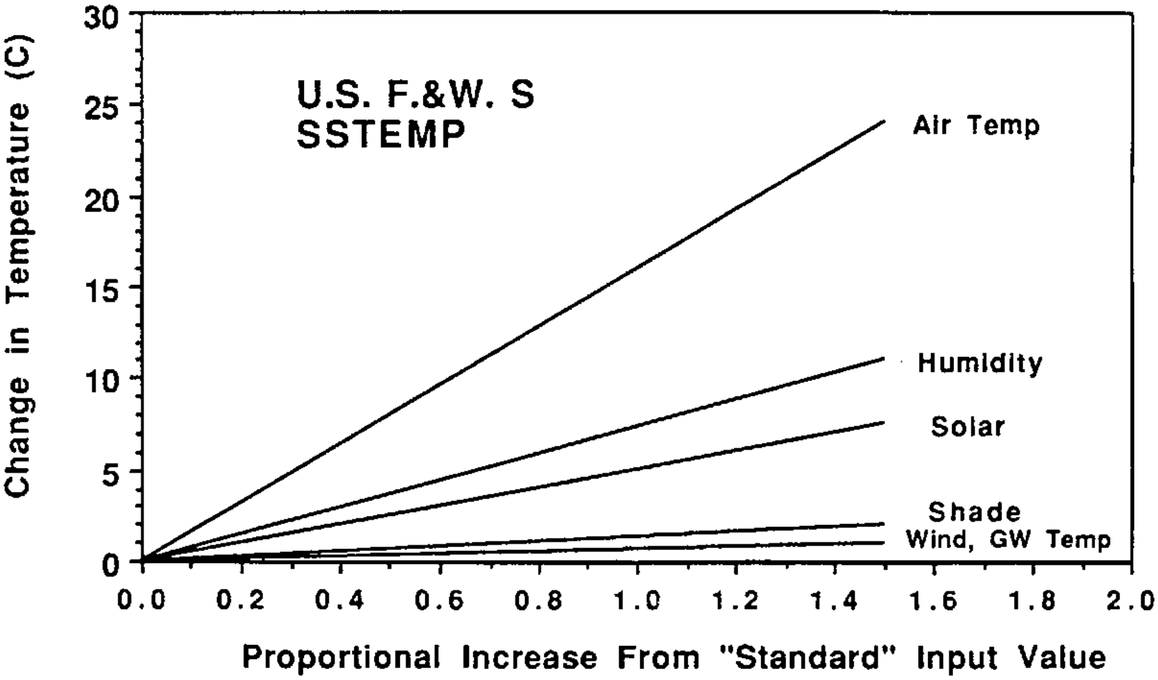


Figure 4.2 Sensitivity analysis of change in predicted mean water temperature in moderate depth streams with change in variable for the TEMP-86 model.

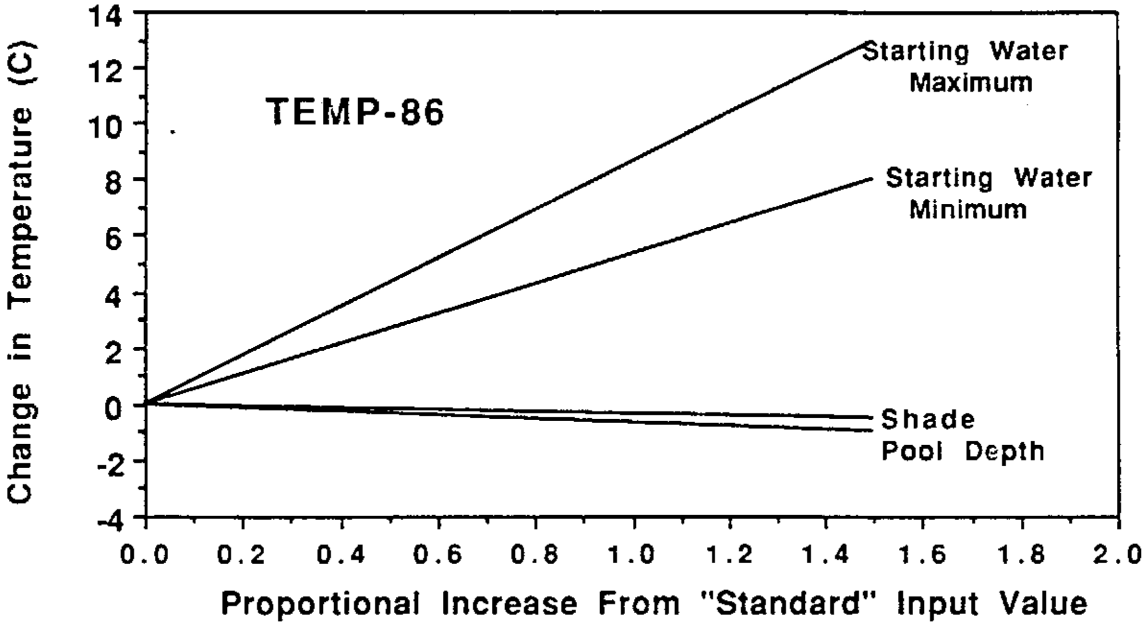


Figure 4.3 Sensitivity analysis of change in predicted mean water temperature with change in variable with the TEMPEST model

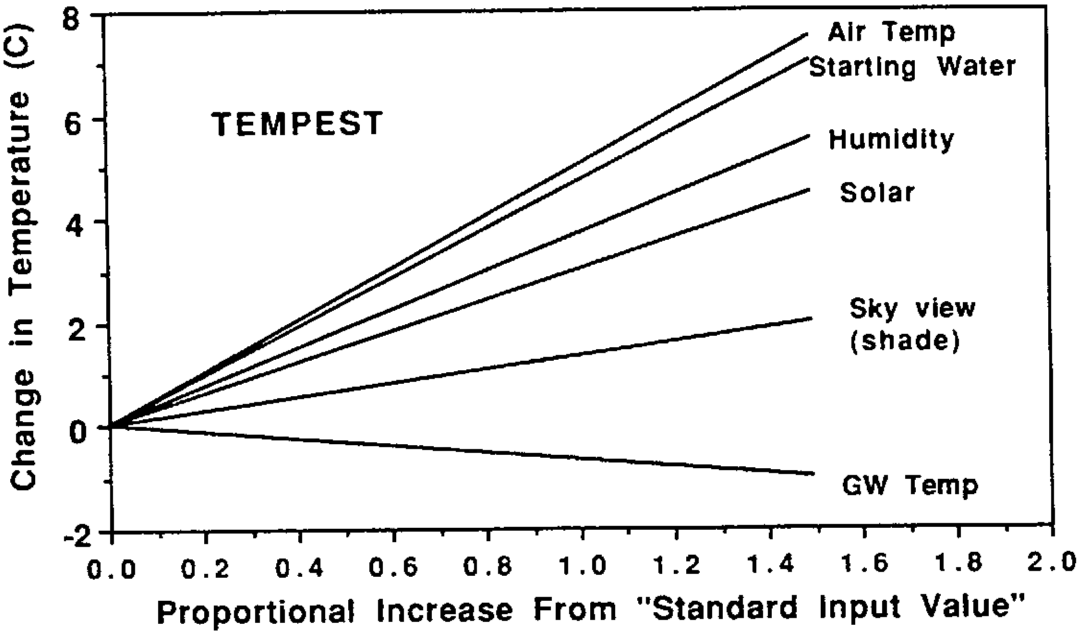


Figure 4.4 Sensitivity analysis of the effect of stream depth on the predicted diurnal temperature range for two models. (SSTEMP uses stream width but not depth as the input variable. Depth was calculated as a function of stream width.)

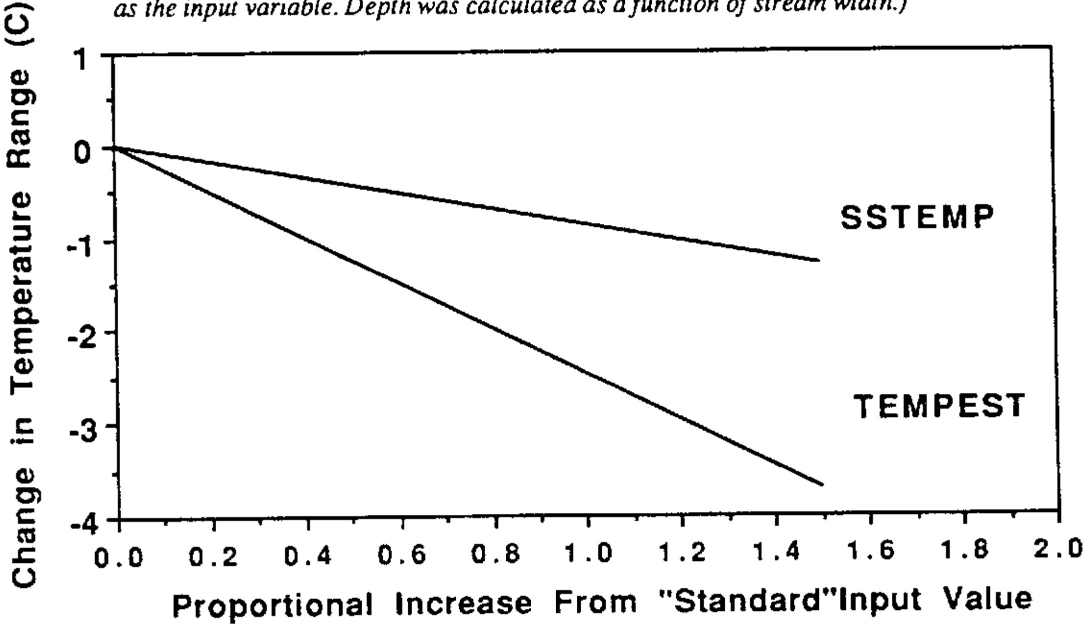


Table 4.2 Model sensitivity values of the USF&WS SSTEMP model. Values indicate the relative sensitivity value of each parameter, not an actual change in temperature.

PARAMETER	Stream Size	SENSITIVITY VALUE Maximum Temperature	Mean Temperature
AIR TEMPERATURE	Small	15.0	15.18
	Medium	15.18	15.90
	Large	11.38	11.14
GROUNDWATER RATE	Small	-0.15	-0.24
	Medium	-0.26	-0.32
	Large	-0.11	-0.11
HUMIDITY	Small	7.75	8.37
	Medium	7.58	7.64
	Large	4.52	4.50
SHADE	Small	-1.83	-1.02
	Medium	-1.66	-1.03
	Large	-0.83	-0.58
SOLAR	Small	5.49	2.50
	Medium	5.24	3.20
	Large	3.39	2.18
INCOMING WATER TEMPERATURE	Small	0.02	0.02
	Medium	0.02	0.02
	Large	6.87	7.02
WIND SPEED	Small	-0.71	-0.31
	Medium	-0.67	-0.56
	Large	-0.15	-0.16
TRAVEL TIME	Small	-0.70	0
	Medium	-0.64	0
	Large	-1.57	0
STREAM DEPTH[†]		Sensitivity of diurnal range = 0.72	

[†] This model uses stream width as an input variable. Depth was calculated as function of stream width from relationships provided in Chapter 3.

SSTEMP was most sensitive to air temperature values for both maximum and mean temperature predictions (Table 4.2). (Sensitivity analysis was not done for SSTEMP minimum temperatures since the model computes the minimum by subtracting the difference of the maximum and the mean from the mean.) The model was also strongly affected by the input value describing the length of reach, and in many cases the model produced unreasonable results for the maximum temperature when short reaches were specified. Therefore, all model sensitivity testing of SSTEMP used a reach length equal to the 24-hour travel time computed from water velocity. Travel time more strongly affected maximum temperatures than means. Small and medium streams were equally sensitive to shade and depth values. Medium streams were slightly more sensitive to groundwater inflow values than small streams, but large streams were virtually insensitive to groundwater inflow.

TEMPEST was most sensitive to air temperature and humidity input values (Table 4.3). Solar insolation values showed high model sensitivity in predicting maximum temperatures in small and medium streams but the minimum temperature predictions were insensitive to solar input. The starting water temperature value was very important for larger streams. The minimum predicted temperature showed more sensitivity to starting water temperature than did the maximum. Changes in groundwater inflow rate produced low model sensitivity and had the most effect in reducing maximum predicted temperatures in small streams. Shade affected the maximum and minimum temperature much more than the mean. Generally, minimum predicted temperatures were less sensitive than maximum temperatures for most input variables except starting water temperature. Depth was a less sensitive parameter than air temperature, solar insolation and humidity but more sensitive than the shade parameter.

TEMP-86 requires both a daily maximum and minimum water temperature as input variables in addition to the time of their respective occurrence. This model proved extremely sensitive to starting water temperature values. Timing of input water temperatures was not tested for sensitivity. The time of maximum and minimum daily temperature used as input was 1300 hours and 600 hours respectively. (It now appears that 1600 hours may be a more appropriate time to specify maximum water temperatures.) The extreme sensitivity of the model to these two starting water temperature values effectively hid sensitivity to all the other input parameters (Figure 4.2. and Table 4.4). TEMP-86 was slightly sensitive to pool depth in small streams and stream velocity in bigger streams. (During the course of model runs it was discovered that the values entered on the input screens were not all stored as shown. Therefore, the input files actually used for analysis had to be created without relying on the input screens.)

BROWN'S EQUATION was moderately sensitive to solar angle input values (Figure 4.5 and Table 4.4). Small streams were also sensitive to percent boulder and shade input values. Stream angle did not cause sensitivity for any stream sizes.

The results of sensitivity analysis for QUAL2E are reported in the basin modeling section of this report.

Discussion

Analyzing model equations is particularly helpful in understanding how a model operates and why certain parameters are more sensitive. Support documentation on TEMP-86 includes an excellent sensitivity analysis (Beschta and Weatherred 1984).

That analysis is based on the equations that the computer model uses to predict water temperature. TEMPEST was developed to study the sensitivity of stream temperature to environmental factors and results are reported in Adams and Sullivan (1990). This analysis did not determine temperature sensitivity based on model equations as these two prior tests, but rather tested the sensitivity of the model predictions themselves. These two approaches may not produce consistent results because model mechanics and the complexity of calculations. For example, TEMP-86 is sensitive to many of the other input variables within a single hour of the model's operation as indicated in the reported sensitivity analysis. However, the hourly starting water temperatures provided as input essentially calibrate the model every hour and overwhelm the model's sensitivity to other variables.

It appears that air temperature is the single most sensitive variable for both the SSTEMP and TEMPEST model predictions of water temperature. This result is not surprising. Not only is air temperature in most of the equations governing the net energy balance for streams but it is raised exponentially. Therefore, it is likely that air temperature will be an important parameter for water temperature predictions. Previous sensitivity analyses of stream temperature response have cited solar

Table 4.3 Model sensitivity values of the TEMPEST model. Values indicate the relative sensitivity of each parameter, not an actual change in temperature.

PARAMETER	Stream Size	SENSITIVITY VALUE Maximum Temp	 Mean Temp	 Minimum Temp
AIR TEMPERATURE	Small	8.59	5.87	3.60
	Medium	8.00	5.01	3.36
	Large	4.79	2.82	2.86
GROUNDWATER RATE	Small	-0.70	-0.43	-0.15
	Medium	-0.40	-0.28	-0.15
	Large	-0.21	-0.15	-0.09
HUMIDITY	Small	5.35	4.92	4.95
	Medium	4.75	3.73	2.91
	Large	2.90	2.04	1.31
SKY VIEW FACTOR (Shade)	Small	5.51	0.88	-3.09
	Medium	3.69	1.40	-1.19
	Large	1.66	0.71	-0.53
SOLAR	Small	9.04	3.63	0.00
	Medium	6.30	2.95	0.03
	Large	3.25	1.61	0.03
INCOMING WATER TEMPERATURE	Small	0.16	1.89	2.90
	Medium	5.02	5.01	7.04
	Large	9.34	8.87	9.46
WIND SPEED	Small	-1.49	-0.55	0.40
	Medium	0.13	.006	-0.02
	Large	0.42	0.22	0.02
STREAM DEPTH		Sensitivity of diurnal range = -2.47		

Table 4.4 Model sensitivity values of the TEMP-86 model.Values indicate the relative sensitivity value of each parameter, not an actual change in temperature.

PARAMETER	Stream Size	SENSITIVITY VALUE		
		Maximum Temp	Mean Temp	Minimum Temp
AIR TEMPERATURE	Small	0	0	0
	Medium	0	0	0
	Large	0	0	0
GW INFLOW RATE	Small	0	0	0
	Medium	0	0	0
	Large	0	0	0
HUMIDITY	Small	0	0	0
	Medium	0	0	0
	Large	0	0	0
SHADE	Small	-0.97	-0.24	0.08
	Medium	-0.40	-0.10	0
	Large	-0.15	-0.04	-0.01
SOLAR	Small	0	0	0
	Medium	0	0	0
	Large	0	0	0
STARTING MAX WATER TEMP	Small	16.00	8.03	0.46
	Medium	16.27	8.13	0.27
	Large	16.42	8.18	0.15
STARTING MIN WATER TEMP	Small	0	5.27	10.0
	Medium	0	5.27	10.2
	Large	0	5.27	10.4
WATER VELOCITY	Small	0.97	-0.03	0.79
	Medium	-0.12	0.26	-0.39
	Large	0	0	0
PERCENT POOL	Small	0.09	-0.04	-0.02
	Medium	-0.02	-0.02	-0.04
	Large	-0.02	-0.03	-0.03
POOL DEPTH	Small	-1.07	-0.25	0.04
	Medium	-0.59	-0.13	0
	Large	-0.24	-0.04	0
STREAM DEPTH†		Sensitivity of diurnal range = -1.49		

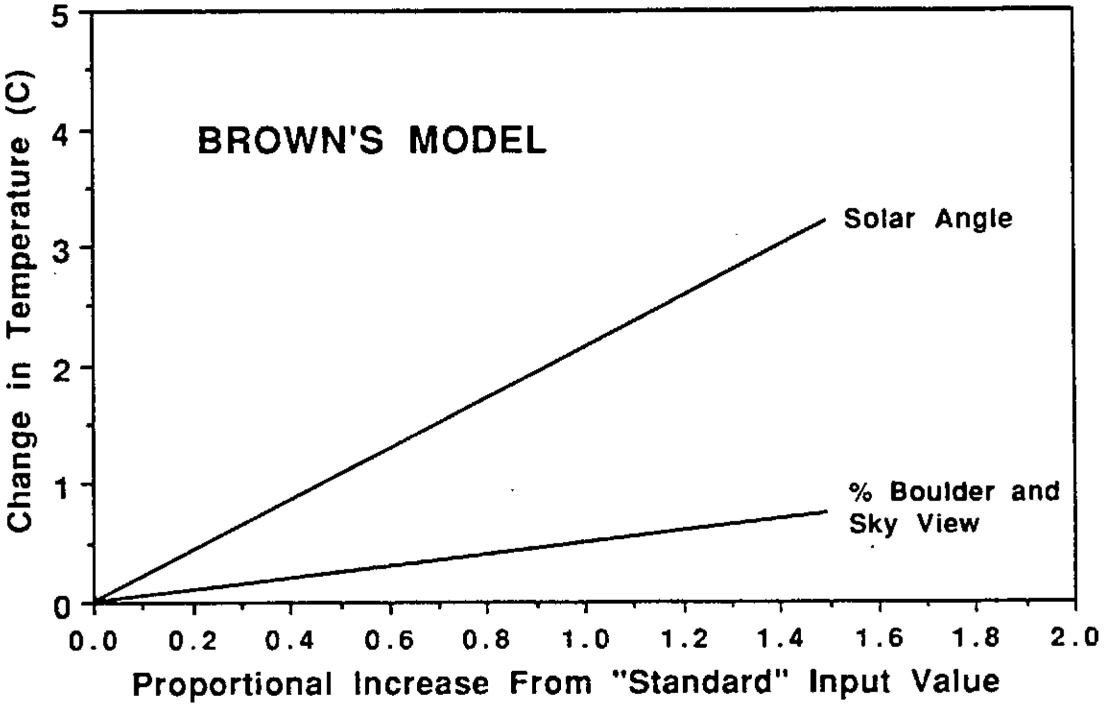
† This model uses stream width as an input variable. Depth was calculated as a function of stream width.

radiation as being of high importance (Crittendon, 1978). While solar radiation does significantly affect maximum water temperature predictions for smaller streams (Brown 1969), the overall importance of this variable for larger streams and for mean stream temperatures may have been somewhat overstated in the past.

Sensitivity analysis demonstrated that stream response is as much a function of air temperature as other variables that are changing concurrently over the course of a day. It should be noted that solar radiation also affects the air temperature, which a stream is seeking to come into equilibrium with, and thus exerts both a direct and indirect effect on stream temperature.

Model predictions were also quite sensitive to relative humidity. Evaporation heat exchange is a function of water vapor pressure, which in turn is dependent on humidity at a given air temperature. While the water vapor pressure is a function of atmospheric weather conditions, the relative humidity for the amount of water present in the atmosphere is a function of the air temperature. For modeling purposes, a good understanding of how relative humidity fluctuates with air temperature is necessary to select appropriate input values.

Figure 4.5 Sensitivity analysis for change in predicted maximum water temperature with variables in small streams with Brown's model



Future field data collection efforts should be minimized for variables showing little sensitivity. These include wind, groundwater, dust reflectivity and ground transfer coefficient values. However a good understanding of the stream being modeled is necessary to be sure these variables are not specified with extreme values which might affect predictions in spite of low sensitivity. Starting water temperature was important for large streams but not for smaller streams. The TWG study sites were mostly streams less than 0.5 meters in depth and thus would not be particularly sensitive to starting water temperatures. Shade values were of comparable importance for TEMPEST and SSTEMP models. Maximum temperatures in small streams were most affected. Mean water temperatures were somewhat affected, because less shade provides an increase in the net energy input to the stream. However, the effect on daily mean temperature is reduced since a greater energy loss occurs during nighttime with reduced shade values.

Table 4.5 Model sensitivity values for Brown's Equation.Values indicate the relative value of each parameter, not an actual change in temperature.

PARAMETER	STREAM SIZE	SENSITIVITY VALUE for MAX TEMP
BOULDER (%)	Small	0.52
	Medium	0.18
	Large	0.07
STREAM ANGLE	Small	0
	Medium	0
	large	0
SOLAR ANGLE	Small	2.09
	Medium	0.76
	Large	0.31
SKY VIEW FACTOR (Shade)	Small	0.71
	Medium	0.50
	Large	0.07

Model Reliability Analysis

The reliability of model predictions is dependent on both the model's sensitivity to input variables and the modeler's ability to provide correct values for those variables. The amount of effort required to generate correct values is dependent on the actual variability of the parameter, and on it's rate of change over time. Nearly all variables to which water temperature is sensitive to vary in nature. The single daily estimate required by most models will be only an approximation of the central tendency of the variable. Hourly, daily and/or geographic variability may exist. If a model were sensitive to a variable that changes hourly and is difficult to estimate then the reliability of the predicted temperatures will be reduced. Use of regional estimates for a sensitive parameter will only produce reliable results if the actual value does not vary significantly than the estimate for the region. Reliability analysis is an evaluation of model sensitivity in relation to parameter variability.

Analysis Steps

The means and standard deviations of model input values for the 33 primary sites were calculated. Since these sites covered a broad geographic range, it was felt that this data adequately described the range of input values likely to be encountered in Washington for T/F/W purposes. Regional NOAA data was used for air temperature, wind speed and humidity values since the longer period of record better describes regional trends and the true range of variability. The model sensitivity values (section 4.2.1) are the slope of the regression of predicted temperature response to a change in the input value. Changes in input values were expressed as a percentage of a "standard" input value. For reliability analysis, maximum, minimum and mean values for each input parameter were expressed as a percentage of the "standard" value used in sensitivity analysis. The mean value for each parameter expressed as a percentage of the "standard" was then subtracted from the percentage values corresponding to the maximum and minimum observed parameter values. This was necessary so that maximum and minimum input values expressed as percentages centered about the true mean rather than the "standard". The following example is provided for clarification/

For Coastal Washington during the study period:

Maximum observed wild speed = 3.66 m/s

Mean observed wind speed = 2.49 m/s

Standard value wind speed = 3.576 m/s

Sensitivity value wind speed = 0.506

Reliability value for wind speed =

$$(-3.576) / 3.576 = 0.02$$

$$(-3.576) / 3.576 = -0.30$$

$$-(-0.3) * 0.506 = 0.17$$

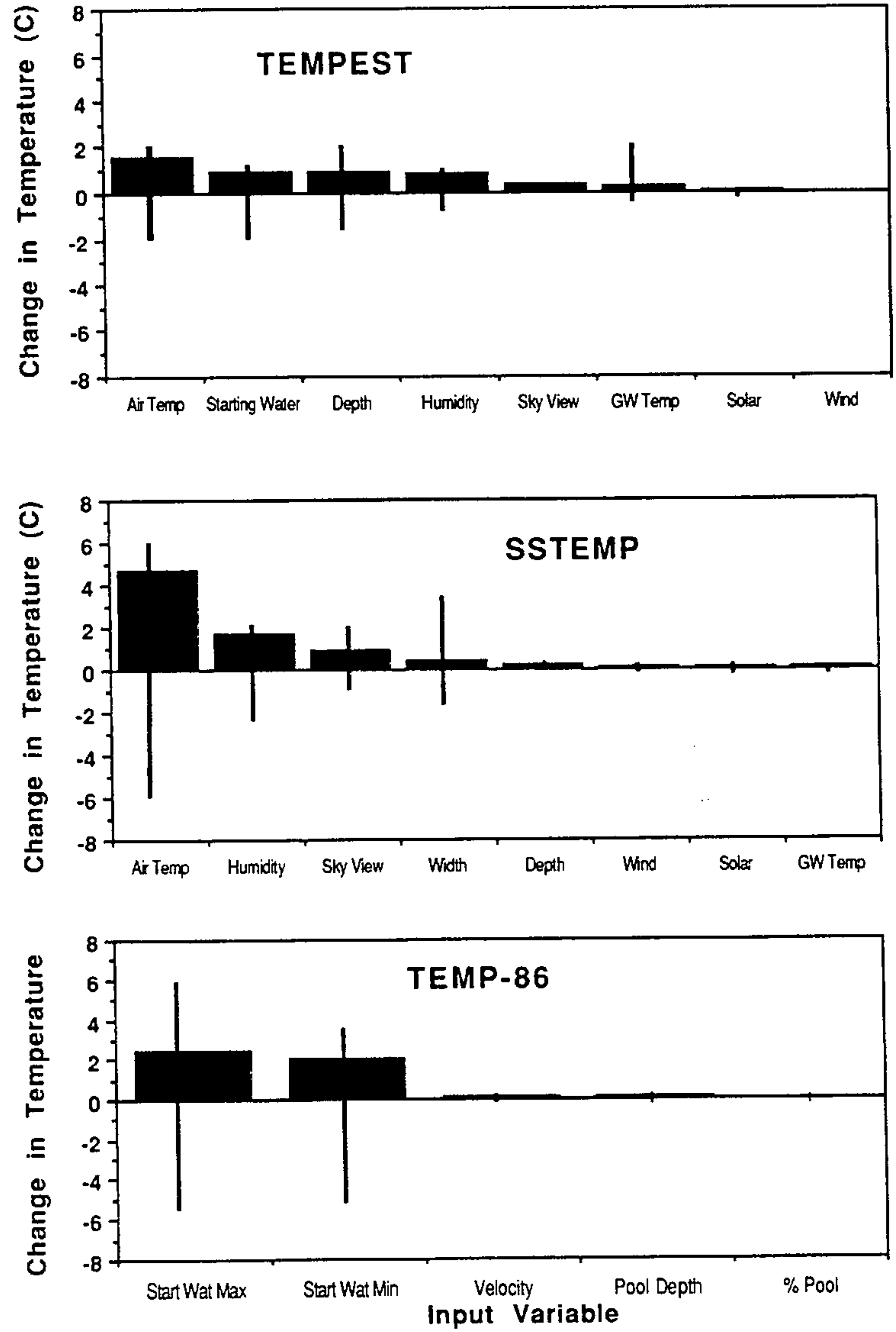
One standard deviation was also calculated for each parameter and this value was expressed as a percentage of the mean parameter value.

Mean, maximum, minimum and standard deviation values (all expressed as a percentage of the mean parameter value) were used in the regression equations from the sensitivity analysis to solve for the change in predicted temperature. This provided a range of predicted temperatures that would likely be associated with the range of variation for each input variable. Small, medium and large streams for each region were analyzed independently. The mean and standard deviation for depth values was calculated by combining all primary site data for each region.

Results

The change in the predicted temperature associated with one standard deviation of the range of the input variable was calculated. For most variables the calculated range in predicted temperatures was surprising low (Figure 4.6). Possible regional differences in reliability were explored during data analysis because of differences in stream characteristics, but no significant differences were found. Only state-wide results are presented in Figure 4.6.

Figure 4.6 Model reliability analysis results showing the range of the predicted mean temperature associated with the observed range of each input variable. Blocks are the 1st standard deviation and bars are the range.



TEMPEST had the best overall reliability with an average value of 1.12 °C change in predicted temperature for a change of one standard deviation in either of the two most sensitive variables. Temperatures predicted by the model for the range of each parameter varied as much as 2°C for the maximum and minimum and 1°C mean temperature 1°C for air temperature, stream depth, relative humidity, and groundwater temperature. Sky view factor was relatively less important. Predictions with this model were also influenced by the starting water temperature used to initialize the calculations. (TEMPEST begins calculations for the period at a specified temperature, eventually reaching the equilibrium temperature. For small streams this takes only a few hours, while for larger rivers it may take one-day or longer. Thus, temperatures predicted before the model is calibrated may be lower than observed temperature.)

SSTEMP varied relatively little with most parameters, but air temperature had a strong influence on predictions (Figure 4.6) Predicted temperature varied as much as 6°C over the range of air temperatures used in this analysis. Stream width, the shade density and relative humidity were also important. Wind speed, solar radiation, and groundwater temperature were relatively less important. Depth is calculated by the model. Changes in the calculated depth led to modest changes in the stream temperature

TEMP-86 predictions were strongly influenced by the starting maximum and minimum water temperatures provided as input values (Figure 4.6). Predicted maximum and minimum temperature varied as much as 6°C and mean temperature as much as 2°C for the range of water temperatures provided. Variability in other parameters had relatively little effect on predictions.

Discussion

The reliability analysis showed promising prospects for the use of regional estimates for input parameters, which would greatly reduce costs associated with temperature modeling. Starting water temperature for all models needs to be carefully evaluated when modeling streams greater than 0.4 meters in depth. Effort expended in data collection for temperature modeling in most streams would best be spent on air temperature data. Using regional values for difficult to measure parameters such as humidity would likely produce acceptable results when predicting mean temperatures. Reliability analysis for TEMPEST indicated one could use regional values for humidity and effect mean temperature by less than 1.0°C ninety percent of the time, provided other input parameters are correct.

Analysis also showed that regional values for groundwater would be acceptable in most cases when modeling summer low flow conditions in Washington. However, knowledge of the stream's geology is important. Lower than expected temperatures as some of the TWG study sites were attributed to higher groundwater inflow volumes than normal, based on observations of seeps, and springs in the area. Using a regional groundwater value for TEMPEST input versus the observed value for sites with high groundwater could change the mean predicted water temperature by as much as 3.8°C. In using the model, some local knowledge of sites would be helpful in deciding whether regional values can be used.

This reliability analysis only reviewed mean water temperature predictions. The ranges shown in reliability graphs (Fig. 4.6) are for the potential range in mean water temperature predictions given the range for each parameter. The results from this analysis should therefore be applied only to Washington streams similar to the primary site streams. The necessary range of input values might be considerably different in another geographic area.

SITE MODEL EVALUATION

Selecting a TFW site temperature prediction model required running the four reach models through a series of testing steps that evaluated model performance and developed the most cost-effective application of the selected TFW method. Technical aspects of model performance were considered to maximize each model's predictive ability when extensive, on-site data was available. These results, along with practicality criteria formed the basis for model selection. Once a model was selected, a further series of simulations were performed where data input was varied to reflect realistic levels of information that would be available for TFW use of the model. As a result of this testing series, the recommended model and field procedures represent a balance between data required for good model performance and practical application in TFW forest management.

Model performance was evaluated by running each of the models for a forty-day consecutive period at each of the thirty three primary sites where field measurements were available. Model-testing sites were chosen to cover as wide a range of stream sizes, stream-shading, and regional locations as possible. Daily predicted values of maximum, mean, and minimum water temperature were compared to observed values using several descriptive statistics. The forty-day period was intended to contain all weather conditions present at a site during the summer testing period, including both sunny and cloudy days. Except for Brown's equation, each of the models was expected to predict temperature under all normally occurring ambient weather conditions, since such factors as cloudiness are accounted for in energy balance calculations. (Because Brown's equation has no accounting for cloudiness, this model's predictions were evaluated only on sunny days. Although TEMP-86 was intended to be used only on sunny days, the model was predicting so accurately that is was decided to evaluate performance over the entire testing period.)

This model testing design represented a evaluation of realistic weather conditions during the hottest times of the year and was not weighted to predicting hot days exclusively, as is often done in temperature prediction. This was considered important if model predictions were to be used to assess practices under regulations that use biologic temperature defined as consecutive exceedence of temperatures over a time interval.

The modeling period varied by site and was chosen to center around the time of the field crew visit so that estimated values of stream flow and other parameters that vary slowly in time would be as accurate as possible. To the extent possible, the time period was also selected to include the warmest summer periods which generally occurred from late July to August.

Methods

Analysis Steps

The first step in model evaluation required finding the best estimation method for those input variables where there was some user discretion in determining methods (*Model Iteration*). There were several input variables that could conceivably be estimated in any of several ways, including some that would prove more cost-effective than the methods recommended in user's instructions provided with each model. Several SSTEMP and TEMPEST model runs were made using each of the estimation methods to determine whether model accuracy was better or worse with non-standard values. These iterative runs represented the only effort at data "tweaking" performed during model evaluations. Once the best variable estimation method was identified, all further model runs were made using it. Recommended methods were followed for other input variables.

The next step in model evaluation involved running each of the models over a forty-day testing period and determining its accuracy in predicting a variety of temperature characteristics as described in the statistical analysis section (*Model Testing*).

Once model performance was determined, the best predictive model was selected (*Model Selection*). While good performance was an essential basis for the selection decision, practical considerations such as cost of routine application, model user-friendliness and reliability were also considered important. Rating criteria were developed for model performance (drawn from the model-testing results), reliability (drawn from the sensitivity analysis) and practicality (based on the TWG's experience) and applied to each. The model was selected based on total score.

One final evaluation step was needed to develop the selected model for TFW application (*Model Optimization*). While site models were tested rigorously with comprehensive data collected at each site, such detailed information will not be available for routine TFW use. Importantly, it will not be feasible to measure the climatic data that models are sensitive to, such as air temperature and relative humidity, at all sites throughout the state where the model may be applied. In Chapter 7, the selected model was run through a series of simulations where data input was varied and estimated values substituted for measured values to reflect realistic constraints on operational use of a temperature prediction model. The best balance of model accuracy and cost effectiveness was identified. Based on these results, a model and procedures for use are recommended for TFW application (Chapter 7: *Recommendations*).

Data Processing

Actually running the four site models and three basin models to generate the predicted daily values was an immense task. Each of the models requires a mix of site-specific variables, constants, and parameters estimated from regional data (see Table 2.3). Using this array of data to predict temperature for a large number of sites over long periods of time appears to be an unprecedented use of the these models. The testing design stretched data input and output procedures well beyond those originally designed by the model authors. (Most of the models were intended to predict temperature for one day at a time with data entered in a menu-driven format.) Complex data handling procedures were developed by the TWG to streamline data input and output and manage the large volumes of data generated by the TWG and study cooperators. (Temperature measurements alone accounted for over 300,000 data values analyzed in this study!)

A general schematic indicates the type of data and its use in the study (Figure 4.7) Measured stream, water and air temperature and climatic information were used both as input to the models as well as for determining characteristic temperature regimes for Washington streams and rivers (Chapter 6). How data was measured or estimated is described in Chapter 2.

Input parameters can be categorized by their variability in time. Static parameters such as site latitude, site elevation, and riparian character, were constant during the 40-day modeling period. Most of these data were derived from maps, except for riparian characteristics which were measured at each site.

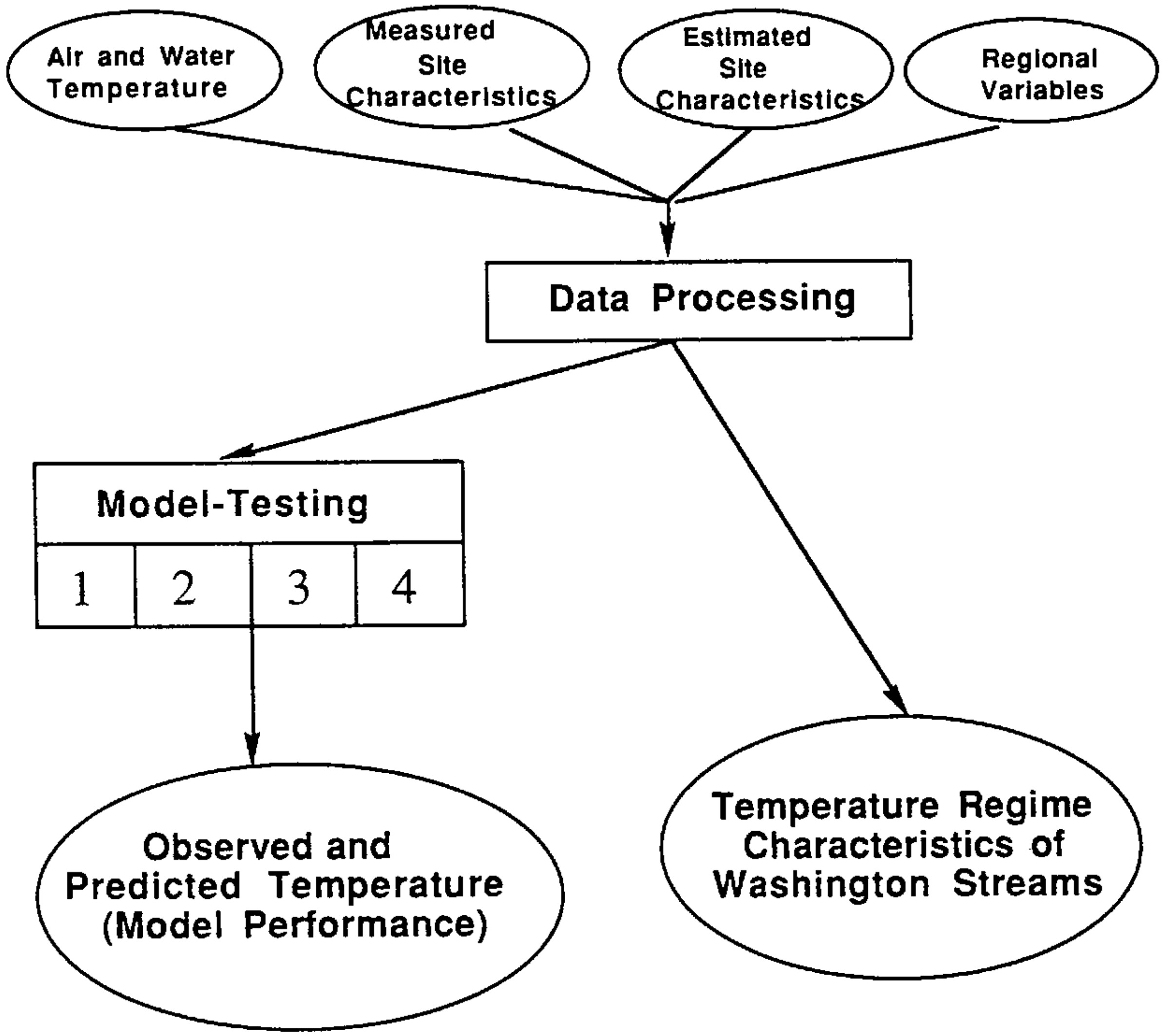
Field measurements, and data generated from maps were entered into a series of personal computer databases. Due to differences in data structure riparian shading data, channel morphology data, hydrology data, and site location data were each kept in separate databases. Summary statistics from the riparian and channel morphology databases were combined with the hydrologic and location data to form a data array for all sites that was stored as a spreadsheet.

Dynamic parameters varied significantly over the modeling period. Some time-dependent input values varied daily or hourly such as air temperature, solar radiation, cloud cover, and relative humidity. Hourly or daily estimates of these variables were used in the models. Air temperature data was collected at each site while other climatic information such as sky cover, wind speed, and relative humidity was collected at one of five regional National Oceanic and Atmospheric Administration (NOAA) climate stations.

Data used as input variables were maintained in several independent databases on both mainframe and personal computers. Hourly observed air and/or water temperatures for the summer period were maintained in a mainframe time-series database. The forty-day test period data sets were down-loaded from this database. Daily values of air and water temperature maximums, minimums, means, and ranges were calculated from the sets of observed hourly values. Summaries of observed values for the forty-day test periods were then extracted from these files. Selected weather data from local NOAA local climatological data stations were entered into a series of personal computer spreadsheets. Metric conversions were made and the spreadsheets combined into one large climate data array. The forty-day test period data sets were extracted from this array.

The observed temperature data for all sites and the NOAA weather data was also used to determine temperature regimes in streams and rivers of Washington (Chapter 6).

Figure 4.7 Data processing schematic for the study.



Some parameters, such as stream depth, water velocity, streamflow, groundwater discharge, and groundwater temperature do vary slowly over the summer period but were assumed to be static during the 40-day simulation intervals. This was probably a good assumption during the summer low flow months but might not be appropriate for modeling other time periods. This data was stored in the large site database.

Each of the models tested had unique data needs in terms of data format, units of measure, and parameter values. A series of file formatting programs were written to merge, edit, or extract model input parameters from the various files and spreadsheets listed above to run all four models for the forty-day test period for each of the thirty-three primary sites at the same time. SSTEMP, TEMPEST and TEMP86 were run as they were designed, and Brown's equation was developed and run in a spreadsheet format. The input and output sections of the TEMPEST and the SSTEMP models were modified to facilitate data importing and archiving of simulation results. (These modifications are noted in the program listings in Appendix C.)

All of the models' output was stored on a mainframe computer, and each site's predictions for the four reach models were combined in a file. The model results for each site were compared with the observed temperatures for each site, also kept on mainframe. Input parameter sets for each model testing iteration, as well as all model outputs and statistics calculations, were archived on floppy disk.

Statistical Analysis

Model performance was determined by carefully examining daily temperature predictions for accuracy, precision, consistency and bias.

Accuracy. Accuracy reflects how close the prediction is to the true value and is a measure of the correctness of the result. Accuracy is usually dependent on how well systematic errors in either predicted or observed values can be controlled. The observed temperature was assumed to be the best estimate of the true value, although this assumption may not always be correct. (The observations of temperature themselves could contain systematic error or bias due to instrument drift. Different thermographs measure temperature with varying levels of accuracy.)

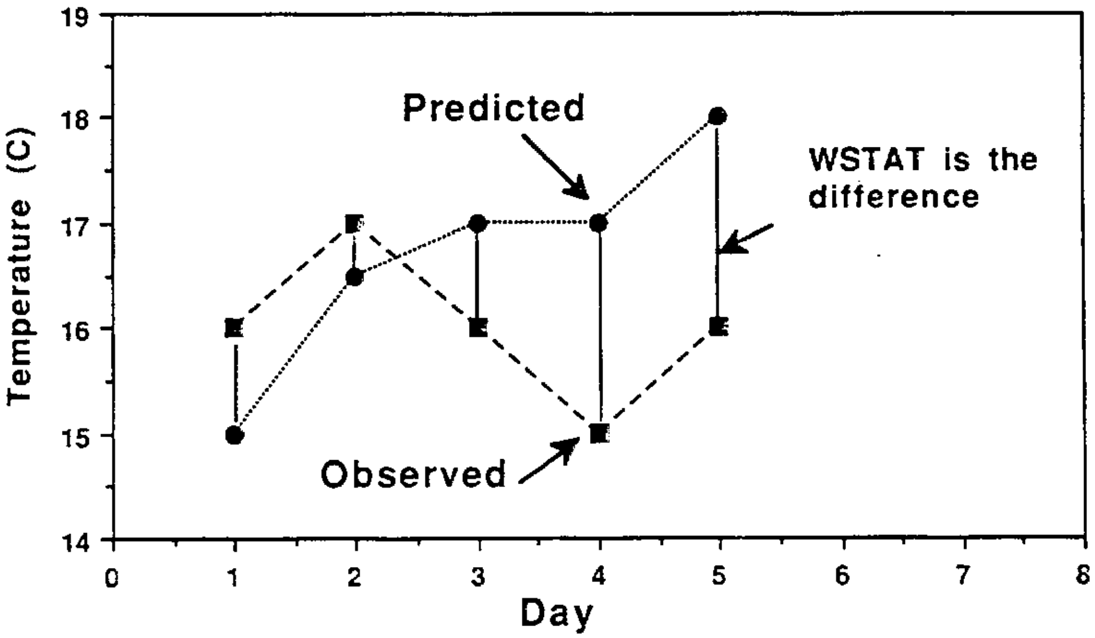
The measure of accuracy used throughout the model-testing analysis is the difference between the predicted and observed temperature, referred to in graphs and tables as the WSTAT, or W-statistic for convenience. For most analyses, the daily WSTAT is averaged over the number of days in the modeling period. Hence,

Accuracy:

$$\text{WSTAT} = \frac{\sum(\text{Predicted Temp-Observed Temp})}{n} \qquad (4.1)$$

A positive WSTAT indicates that the model predicted a higher temperature than actually occurred and the value indicates the number of degrees. (A schematic of this measure is shown in Figure 4.8) A negative number indicates that the model predicted a lower temperature than actually occurred. This measure represents an easily interpreted number indicating model accuracy: if the model predicts well, the average of the daily WSTAT should equal 0.

Figure 4.8 Schematic depicting the method of analysis of model prediction results. WSTAT is calculated as predicted-observed temperature.



H_0: The model is accurate if the average of the daily WSTAT equals 0.

H_1: The model is not accurate (biased) if the average WSTAT is eithergreater than or less than 0.

This accuracy measure is equivalent to residuals analysis of linear regression (Chatterjee and Price 1977, and most statistical texts) although in this case the predictions are based on the physical model rather than on an empirical relationship described by a linear equation. Residuals analysis is useful for uncovering hidden structures caused by systematic error in the data. (It is especially intuitively appealing as used here because it clearly expresses model capability, showing the difference in degrees between the predicted temperature and the observed.) The assumption of residuals analysis is that if prediction errors are random, then the residuals and standardized residuals defined as,

$e_i = y_i - y_i$ (residuals)

e_i/s (standardized residuals)

where y_i=observed and y_i =predicted, and s is the ith standard deviation of residuals, should be normally distributed with a mean of zero and unit standard deviation. By the same reasoning, WSTAT should be normally distributed with a mean of zero. These measures lend themselves to simple statistical tests based on normally distributed populations such as Student's T-tests to ascertain reliability of prediction results, sample differences, and so forth.

Precision. Also important in model performance is the precision or variability of model predictions. Precision is a measure of how exactly the result is determined, its reproducibility, and is therefore an indicator of confidence in model results. The precision is dependent on how well random errors can be overcome and analyzed (Bevington, 1969). Although the average W-statistic over time was expected to equal 0 if models were predicting accurately, the prediction on any day could be significantly higher or lower than the observed temperature due to random or unsystematic errors. Primary sources of such random error reflect the ability to measure climatic and site characteristics and to estimate regional values required by the models. Undoubtedly the accuracy of these estimates also varied between sites.

The primary measure of precision used in this analysis was the "average error", calculated as the absolute value of W-statistic summed over the testing period and divided by the number of days.

Precision:

$$\text{Average Error} = \frac{\sum_{i=1}^{n} |\text{WSTAT}|}{n} \quad (4.2)$$

where n is the number of days in the sample period.

The average error provided an estimate of how closely the temperature was predicted each day. For example, an average error of 2 indicates that the predicted temperature was usually within 2 degrees of the observed value, but ignores whether the model prediction was higher or lower than observed temperature. Other measures of precision used in statistical analyses during model-testing include the standard deviation and variability of WSTAT. For most illustrative purposes, however, the primary measure of precision for analyzing temperature models is the average error. This number was felt to have greater intuitive value because it indicates the actual number of degrees that predictions were in error.

For a model to achieve good performance ratings, the W-statistic would need to be small (the model is accurate) and the average error would need to be low (the model is precise). It was not assumed that a model would predict all temperature characteristics with the same accuracy because the models all calculate temperature somewhat differently. For example, a given model may predict daily mean temperature well but predict diurnal fluctuations poorly. Therefore, all temperature characteristics were evaluated separately.

Consistency. Not only was overall model performance evaluated considering averages of all the sites tested, but the actual accuracy of each site's performance was tracked as a measure of consistency. Because a temperature prediction model could be used for developing site-specific management prescriptions, the reliability of site prediction needed to be indexed. How often did the model adequately or correctly predict temperature when it was applied?

How often was it wrong? Consistency was evaluated as the percentage of sites that were adequately or correctly predicted, depending on the criteria applied in any given model-test. This also allowed identification of sites with faulty instrumentation although none were encountered.

Bias. Also of concern were possible systematic errors (bias) in temperature prediction indicated by patterns in the W-statistic that were consistently positive or negative. While there are many possible sources of systematic error, the TWG was particularly concerned that models perform equally well in all stream sizes and in all riparian conditions. Bias in predictions based on these site characteristics would negate a model's suitability for use in TFW applications since good estimates are essential if management prescriptions are to be altered based on them. Also of interest was whether models performed equally well over the range of temperature values measured throughout the state, since there are differences in climatic conditions throughout the state. Bias was evaluated by examining the W-statistic relative to site and temperature characteristics with linear regression.

Model Evaluation Results

Model Iterations

The model authors recommend methods for estimating input values (termed "standard values" in this report). In some cases, there is opportunity for the user to exercise some discretion and use other estimation methods that may be more feasible, or more cost-effective. The TWG wanted to explore if, and how, using different estimation methods for some input variables would affect model performance. For a few key input variables, alternate estimation methods were used and model results were compared with the intent to identify the best estimation method and to explore the effects of using different input estimates on model performance. Model performance was evaluated using the W-statistic and choices were then made on how to calculate key input values for the next model-testing step.

Input variables tested included groundwater inflow rate, riparian shading, length of stream reach, and the initial water temperature value (listed in Table 4.6). Although all four reach models have these input variables, only the TEMPEST and SSTEMP models were studied due to practicality considerations. (TEMP-86 and Brown's equation were both cumbersome and time-consuming to use, precluding completion of this kind of exploration in a timely manner.)

Input Variable Comparisons

Groundwater Inflow Rate. The amount of groundwater inflow to a stream reach is extremely difficult to measure accurately. Sensitivity analysis showed both SSTEMP and TEMPEST to be fairly insensitive to groundwater inflow rate at summer low flow conditions in typical Washington streams, so errors in estimation may not have a significant effect on model prediction capability. The SSTEMP model recommends estimating groundwater inflow by measuring streamflow and comparing the difference between two measurements taken at the upstream and downstream ends of a study reach. Generally, stream gaging techniques are only accurate to within 10-20%, so small increases in flow within a reach may be difficult to detect. TEMPEST's author recommends that the inflow rate be derived from a summer low flow or baseflow estimate, divided by the length of perennial stream in the basin, which can be derived from maps.This test explored the difference in predictions between the two groundwater estimation techniques.

Streamside Shading. The effects of changes in stream shading on water temperature are an important TFW concern. Both the SSTEMP and TEMPEST models are sensitive to changes in the shade input value, but their recommended methods to estimate shading vary significantly. TEMPEST recommends estimating the total stream openness ("View-to-Sky" factor), which can be done as a visual (subjective) estimate, or measured with a densiometer. On the other hand, SSTEMP uses a program subroutine (SRSHD) to compute the stream shading value from a detailed array of topographic and riparian zone measurements. (Shading and openness are merely the inverse of one another. Reference to shade or openness reflects preference of the authors for communicating the concept.) The SRSHD model produces a total stream shading value similar to the view factor estimated directly in the field. The TWG wanted to explore whether a simple measure of the shade value would suffice for the SSTEMP model, instead of the detailed measurements called for by the authors. This simpler method would be more conducive for using this model to predict the effects of alternative silvicultural prescriptions. This alternative method of estimating shading was only tested for the SSTEMP model.

Input Water Temperature. In order to start modeling calculations that are generally expressed as differential equations varying with time, SSTEMP and TEMP86 require an input water temperature value at the start of each modeling time-step (one hour for TEMP86, and twenty-four hours for SSTEMP). Sensitivity analysis showed that TEMP86 and SSTEMP are sensitive to the input water temperature value, depending on stream size. TEMPEST is also sensitive to input water temperature values, but only for the first twenty-four hours of its multi-day modeling period. (Although not usually required, the TEMPEST program was modified to accept an input daily water temperature value for this test.)

Clearly, hourly water temperature are not a variable that will be generally available when a model is used in a TFW application for predictive purposes prior to riparian zone management. This model iteration tested to see if a significant difference in modelingaccuracy occurs if an input water temperature is randomly specified from a range of regionally appropriate values as opposed to the measured water temperature that was available from the study sites. If the model performance was not affected by a less-accurate estimate of starting water temperature, use of regional values for input water temperature could be used in TFW applications.

Reach Length. The standard length of study stream reaches where models were tested was approximately 600 meters. For the range of stream velocities observed in this study, water should be routed through each reach in only a few hours. SSTEMP uses a twenty-four hour timestep for its daily calculations, and essentially back-calculates water temperatures upstream for a twenty-four hour period. The TWG was concerned that use of the 600-meter reach might inadvertently introduce error into the SSTEMP model predictions. Therefore, an alternate reach length was calculated as the length of stream that water would travel through in a 24-hour period, based on the water travel time measured at each site. This tested whether SSTEMP might require some adjustments to the reach length value in the smaller, shorter stream reaches in order to model accurately. No reach length adjustments were necessary for the other models.

Table 4.6 Description of standard and alternative methods for estimating variables tested in model iterations.

MODEL	VARIABLE	STANDARD	ALTERNATIVE
USF&WS--SSTEMP	**Groundwater Inflow**	Field measurement	Basin estimate
	Riparian Shade	USF&WS SRSHD	View-to-sky--% total sky view
	Reach Length	600 meters	24-hour travel time
	Starting Water Temperature	Measured at upstream and downstream end of reach	Randomly selected from observed range
TEMPEST	**Groundwater Inflow**	Basin estimate	Field measurement
	Starting Water Temperature	Measured	Randomly selected from observed range

U.S. Fish &Wildlife Service SSTEMP

In several cases, alternatives to model input values did change the model prediction results, especially for maximum and minimum temperatures. On a site by site basis, no input set consistently predicted all three temperature characteristics better than standard methods, although some methods improved either maximum, mean, or minimum temperature estimates. W-statistics and errors are summarized for all sites by iteration method in Figures 4.9 and 4.10, while W-statistics and average errors for maximum temperature are provided by site in Table 4.7.

Estimated Groundwater vs. Standard. The SSTEMP "Standard" input set used the two on-site flow measurements to estimate groundwater, and the basin groundwater alternate set used the map-estimated value (Table 4.6). The SSTEMP standard yielded superior predictions than the alternative input set (Figure 4.9, 4.10). While the mean W-statistic was similar for both methods, the maximum and minimum temperature estimates were much worse using the alternate method. The SSTEMP "standard" method was used in model tests to estimate this parameter.

Sky View Estimate. The SSTEMP "Standard" input set contained shade values calculated by the SRSHD program, as recommended by the authors, and the "Sky view" alternative input set contained the measured densiometer reading from the site. Interestingly, the model estimated maximum and minimum temperatures better with the sky view than the standard method ($p<0.01$),while predicting the mean temperatures about equally well. Model precision, indicated by the average error, was similar for the maximum and minimums, although the View-to-Sky set was a little less precise in predicting the means. When compared, the calculated total view

Figure 4.9 A comparison of the W-statistics computed for iterations of the SSTEMP reach model (averaged for all sites).

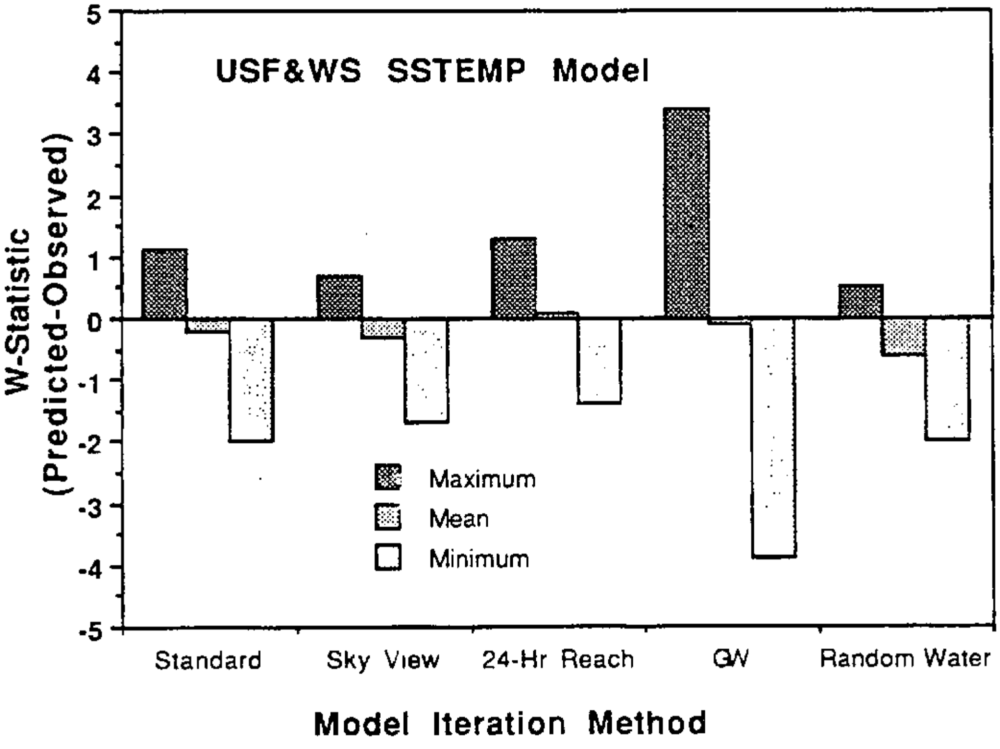


Table 4.7 W-statistics and average error of the maximum temperature for each site with different iterations of input vairables for the USF&WS SSTEMP model.

	W-STATISTIC (PREDICTED-OBSERVED)					ABSOLUTE ERROR				
SITE	Standard	Sky View	Reach	Basin GW	Water Temp	Standard	Sky View	Reach	Basin GW	Water Temp
AA	1.0	1.0	2.8	6.3	1.1	1.2	1.2	2.9	6.3	1.6
AB	1.4	2.0	2.0	3.5	2.0	1.6	2.2	2.8	3.8	2.3
AC	0.3	0.3	-1.1	0.3	0.5	0.4	0.5	1.2	0.5	0.8
AD	0.0	-0.2	0.2	2.6	-0.2	0.4	0.5	0.7	2.6	0.9
AE	0.1	0.3	-1.1	0.8	0.8	0.5	0.6	1.5	1.3	1.7
AF	0.3	-0.3	1.3	3.5	-0.2	0.6	0.7	1.8	3.6	1.8
AG	0.9	1.2	2.3	4.5	1.3	1.0	1.3	2.5	4.7	1.8
AH	1.6	-0.1	1.4	3.3	0.0	1.8	0.9	2.2	3.6	1.5
AI	0.4	0.0	-0.4	1.6	-0.4	0.8	0.8	1.1	1.9	1.7
AJ	-0.9	-1.3	-0.7	3.0	-1.7	1.1	1.4	1.0	3.1	2.2
AK	-0.8	-1.0	-1.4	1.9	-1.2	1.0	1.2	1.5	2.0	1.9
AL	-0.2	-0.6	0.8	3.9	-0.2	0.9	1.1	1.5	4.0	1.8
AN	1.2	0.3	3.1	4.7	0.3	0.1	0.6	3.2	4.7	1.0
AO	3.2	1.9	4.3	5.6	2.0	3.2	2.0	4.5	5.6	2.1
AP	-1.0	-1.0	-2.9	-0.5	-1.4	1.1	1.1	2.9	0.7	2.1
AQ	0.8	0.9	0.7	2.1	0.9	1.1	1.2	1.7	2.7	1.7
DA	0.5	1.0	-0.4	2.9	1.0	0.9	1.1	1.7	2.9	1.6
DB	0.9	0.8	-1.7	1.1	0.7	0.9	0.9	2.3	1.2	1.1
IC	0.1	0.9	-1.1	1.2	0.9	0.9	1.2	1.5	3.1	1.2
ID	0.6	0.5	0.7	3.1	0.4	0.9	0.8	1.9	3.2	1.8
HC	2.0	1.7	3.5	5.6	1.2	2.0	1.7	3.7	5.6	1.6
HG	1.9	1.3	2.1	3.6	0.9	2.0	1.4	2.5	3.7	1.4
BC	4.3	3.4	4.7	5.4	3.2	4.3	3.4	4.8	5.4	3.3
BD	0.1	0.1	-1.0	2.5	-0.1	0.8	0.8	1.4	3.0	1.1
BE	0.1	-0.2	-2.0	-0.9	-0.1	0.5	0.5	2.0	1.0	0.7
GA	2.7	1.9	4.0	6.5	1.9	2.9	2.2	4.2	6.6	2.2
CA	3.3	1.8	5.4	7.7	1.7	3.3	1.8	5.4	7.7	1.7
CB	4.3	1.7	6.8	7.4	1.7	4.3	1.7	6.8	7.4	1.8
CC	2.1	1.3	4.5	5.0	1.2	2.1	1.2	4.5	5.0	1.4
CD	2.5	1.4	5.5	6.4	1.3	2.5	1.4	5.5	6.4	1.6
EA	1.7	2.7	0.5	2.6	2.8	1.7	2.8	1.8	2.9	2.9
EB	-0.4	-0.6	-0.9	2.1	-5.6	0.9	0.9	1.2	2.4	5.8
AVERAGE	**1.1**	**0.7**	1.3	**3.4**	**0.5**	**1.5**	**1.3**	**2.6**	**3.6**	**1.8**

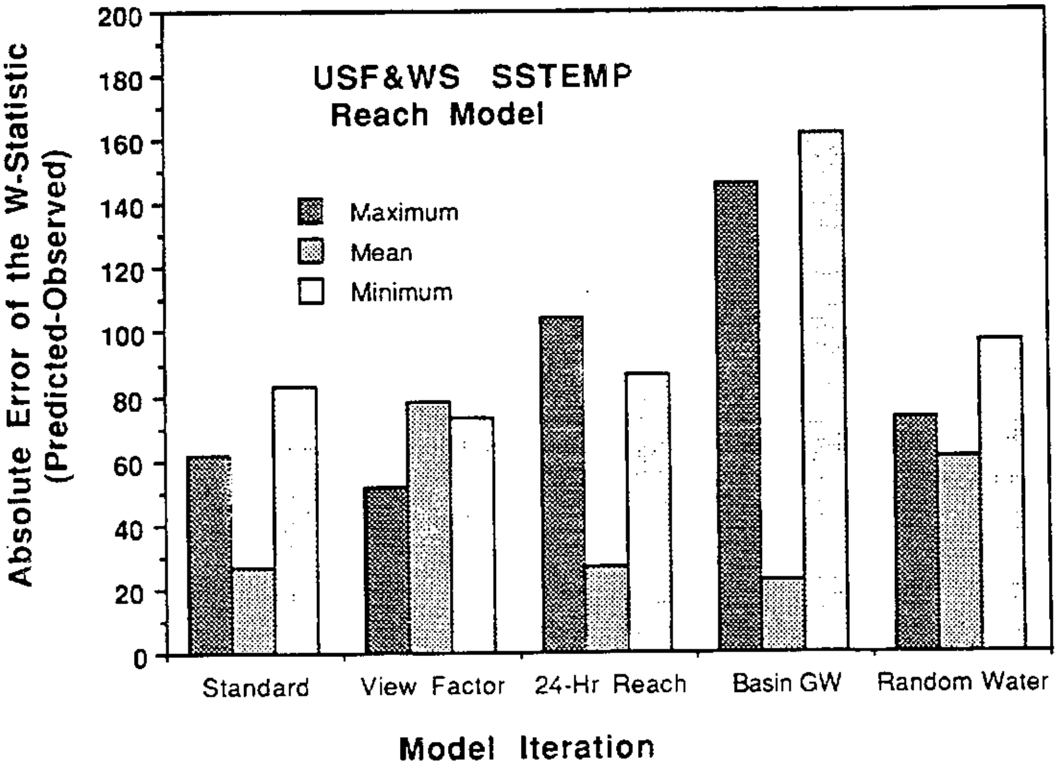
from the SRSHADE model tends to be greater than the measured view (Chapter 3), thus accounting for the tendency for temperature estimates to be greater with the calculated value.

These results suggest that the level of detail required in measuring riparian vegetation by the SRSHD model does not appreciably improve temperature prediction. This is important in considering application of this model. Use of the simpler View-to-Sky estimate measured with a densiometer would significantly decrease field data requirements and considerably increase flexibility in using the SSTEMP model as a gaming tool to evaluate alternative management prescriptions.

Although model performance was actually improved by substituting the measured view with the calculated view, the TWG decided to use the SRSHD calculated shade estimate in model-tests. Not doing so would represent such a large departure from normal model use that it was feared that the change might trigger criticism that a fair test was not performed. The TWG feels, however, that users of this model can substitute a total sky view (or shade) measured at the site with a densiometer for the more complex measurements required to run the SRSHADE model.

24-Hour Reach Length vs Standard (600 meters). The "standard" SSTEMP input set contained the 600 meter reach length, and the "24-Hour Reach" set contained the longer reach lengths determined by travel distance in 24-hours for each site. Because of the routing calculations used in SSTEMP, it was hypothesized that the standard, 600-meter reach length would yield poorer predictions than the longer, 24-hour reach length. That was not the case. There was no statistically significant difference between the W-statistics for either input parameter set for the maximum, mean or minimum temperatures. The average error was better for the standard on maximum temperature, and the same for both sets for mean and minimum temperature.

Figure 4.10 A comparison of the sum of the absolute value of the difference between predicted and measured water temperature (absolute error) computed for iterations of the IFIM reach model averaged for all sites.



Because there seemed to be little difference between the two sets of results, the measured reach length of 600 meters rather than the artificial "24-hour" reach length was used in model tests. This was felt to be most appropriate, especially in the headwater streams where a "24- hour" distance often did not exist upstream of the study site.

Random Input Water Temperature vs. Standard. The "Standard" input set contained measured water temperature values, and the "Random Water" input set contained the randomly specified values for each site. Overall model performance using the random water input values was similar to the standard set. The standard model was significantly less accurate at predicting maximum temperatures ($p<0.01$), while predictions of mean and minimum temperature were the same with the two methods (Figure 4.9). Model precision was also similar.

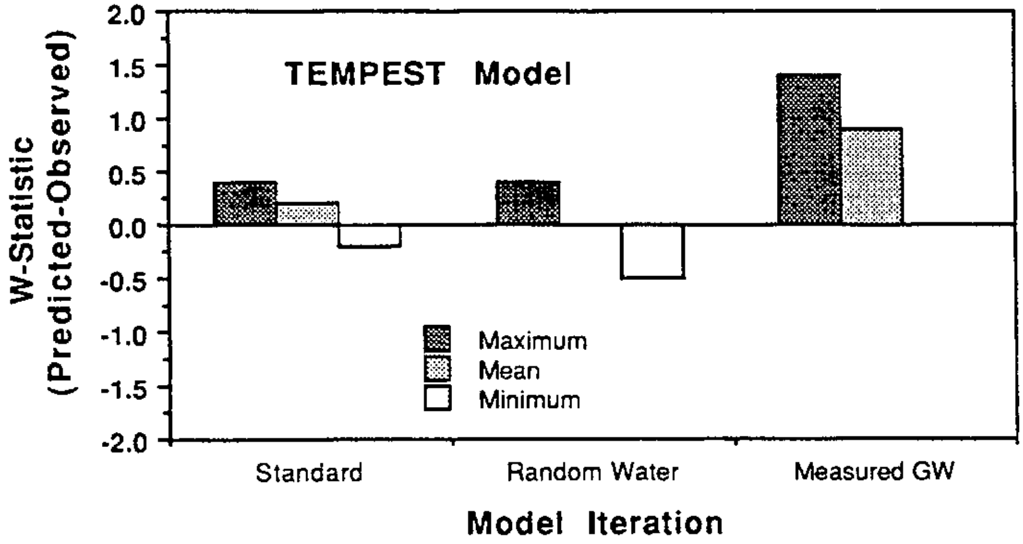
These results indicated that estimating the water temperature input would be acceptable. It is possible that this result could be partly caused by the size of streams in this study. Most of the study sites had average depths less than 0.5 meters. Sensitivity analysis for the SSTEMP and TEMPEST models showed only larger streams (greater than 0.4 meters in depth) to be sensitive to initial water temperature. While it may prove cost- effective to use a regionally averaged initial water temperature value in a TFW application of this model, it may be necessary to rely on observed temperatures when modeling larger streams.

Although some alternative methods for estimating input variables did result in improvements in the SSTEMP performance, in no case was improvement significant enough to justify changing input estimates for the model-testing step. The TWG felt it was best to stay as close as possible to the authors' recommendations for model-testing to provide the fairest tests. Therefore, the SSTEMP model tested contained a parameter set including SRSHD estimates of riparian shading, groundwater inflow values derived from field measurements, a 600-meter stream reach length, and actual measured values of starting water temperature, among the other required variables. However, the results of these model input variable tests suggest that several variables may be estimated more easily than current model recommendations without loss of predictive capability. It was recognized that results from this test of alternatives would be used to develop alternative recommendations should this model be used in TFW applications.

TEMPEST

Alternatives for two input variables, groundwater inflow rate and random water temperature, were tested for the TEMPEST model. Results of the tests are presented by site in Table 4.8 and in summary in Figure 4.11 and 4.12. Although results vary by site, TEMPEST, predicted quite accurately on average

Figure 4.11 A comparison of the w-statistic calculated for iterations of the TEMPEST model averaged for all sites.



using the standard variable input sets. No alternative input set predicted significantly better than the standard for all temperature characterisics.

Measured Groundwater vs. Standard. For TEMPEST, the "Standard" input set used the inflow rate derived from basin characteristics, while the the "Measured Groundwater" alternate set used the rate calculated from flow measurements. Model performance using the measured groundwater was worse than the standard when predicting maximum and mean temperatures, but was better at estimating minimum temperatures (p=0.03). Model precision was lower in all cases when the measured groundwater value was used.

Random Water Temperature vs. Standard. Overall model performance using the random water inputs was as good or better than the standard model. The maximum and minimum were not significantly different, but the prediction of the mean was significantly improved (p= 0.04). The average error tended to be a little higher with the random water inputs, but was not statistically different.

For the TEMPEST model, the TWG concluded that the basin estimate of groundwater, which is much more easily derived than the measured estimate, provided a quite adequate estimate. While it was decided to use the observed input water temperature values for the model testing step, it was recognized that, if an appropriate range of regionally derived values could be specified, modeling performance would not be decreased significantly. Because the input water temperature value only affects the TEMPEST model for the first 24 hours of the modeling period, greater care in specifying this value is probably not necessary. Sensitivity analysis indicates that for streams with an average depth greater than 0.5 meters, this model may require a more accurate starting water temperature value. These considerations are addressed in developing the TFW application recommendations for these models.

For the model testing step, the TEMPEST model was run using the basin estimates of groundwater inflow rate, as recommended by the authors, and measured starting water temperature values as described in Table 4.6.

Figure 4.12 A comparison of the sume of the absolute value of the difference between predicted and measured water temperature (absolute error) computed for iterations of the TEMPEST model averaged for all sites.

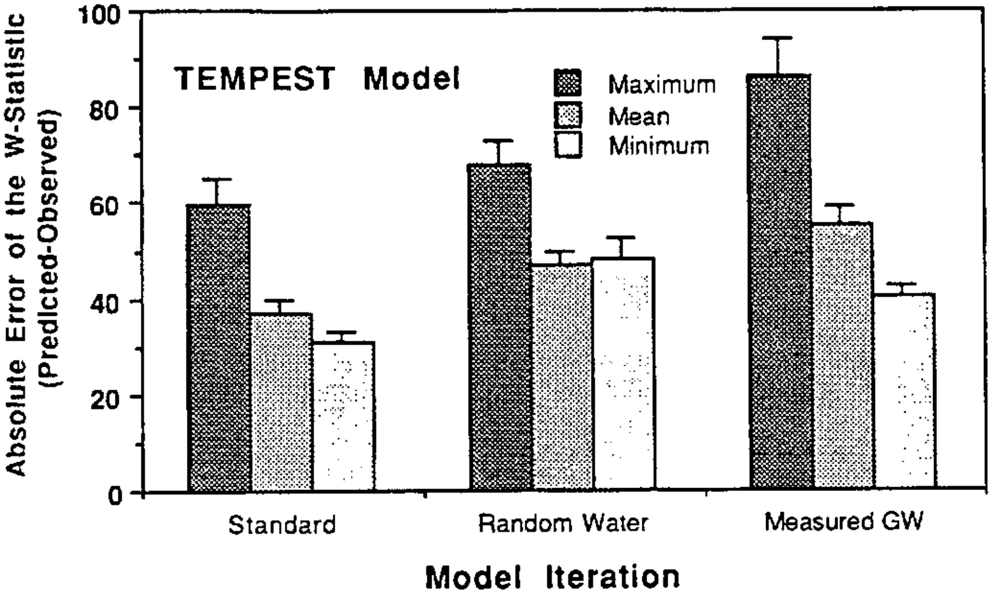


Table 4.8 W-statistics and average daily error for the maximum daily temperature for TEMPEST model iterations.

SITE	W-STATISTIC (PREDICTED-OBSERVED)			AVERAGE ERROR		
	Standard	Random Water Temp	Groundwater	Standard	Random Water Temp	Groundwater
AA	-0.3	0.1	2.6	1.8	1.7	3.2
AB	-0.5	-0.7	-0.4	2.2	2.4	1.9
AC	1.2	1.3	3.3	1.3	1.3	3.3
AD	-0.8	-0.6	2.4	0.9	0.9	2.5
AE	0.9	1.4	2.4	1.5	2.2	2.7
AF	0.0	0.1	0.1	1.3	1.7	1.1
AG	1.6	1.9	2.9	1.9	2.2	2.9
AH	-0.8	-0.5	-0.7	1.0	1.4	1.2
AI	-0.5	-0.6	-0.2	0.9	1.2	0.9
AJ	-0.4	-0.4	0.9	0.9	1.3	1.1
AK	-1.3	-1.2	-1.2	1.3	1.7	1.4
AL	-1.0	-1.0	-1.1	1.0	1.9	1.3
AN	0.4	0.6	0.9	1.0	1.2	1.2
AO	1.5	1.5	2.2	2.1	2.3	2.4
AP	-0.4	-0.1	0.9	0.9	1.2	1.2
AQ	-0.8	-0.3	-1.5	2.4	2.3	1.9
BC	2.0	2.1	3.1	2.3	2.4	3.2
BD	-1.2	-1.2	-1.5	1.3	1.5	1.5
BE	-0.5	-0.4	0.7	0.6	0.7	1.0
CA	2.6	2.6	4.0	2.9	2.9	4.0
CB	1.7	1.8	3.7	1.8	1.9	3.7
CC	0.7	0.6	1.3	1.7	1.7	1.6
CD	1.4	1.3	2.8	1.9	2.0	2.8
DA	-0.3	-0.3	1.5	0.6	1.3	1.9
DB	0.3	0.4	2.0	0.8	0.9	2.2
EA	4.0	4.2	5.5	4.1	4.3	5.6
EB	0.9	-1.2	-0.7	2.5	2.2	1.5
GA	0.3	0.4	2.5	1.0	1.1	2.5
HC	1.1	1.0	1.6	1.2	1.2	1.7
HG	-0.1	-0.5	0.4	0.6	0.9	1.3
IC	1.3	1.3	2.7	1.4	1.4	2.8
ID	0.2	0.2	1.9	1.4	1.3	2.0
AVERAGE	**0.4**	**0.4**	**1.4**	**1.5**	**1.7**	**2.2**

Comparison of Model Performance

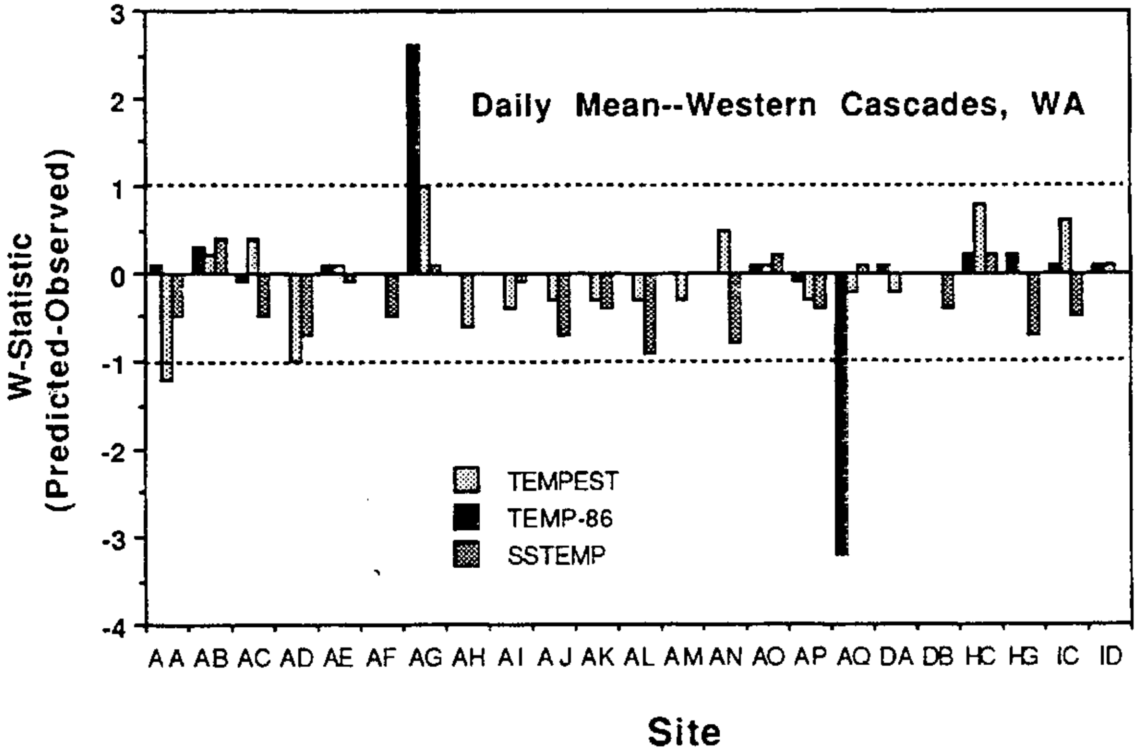
In order to test the performance of the reach models, the best available estimated or measured parameter values at the thirty-three primary study sites were used for model inputs. In a T/F/W context, the model test delineates the "upper limit" of modeling ability by using site-specific stream data and actual measured air and water temperatures. Typically, air and water temperatures will not be available for routine use of a prediction model in TFW applications, although these variables are shown in the sensitivity analysis to be important to correct prediction of temperature. Methods to estimate climatic and stream data will be developed in the TFW simulation section of this chapter, and results using estimated values compared to this those in the model test described here.

Models were examined for accuracy, precision, consistency and bias in predicting maximum, mean and minimum temperatures and the diurnal flux. The W-statistic formed the basis for all comparisons. Results were examined on a site-by-site basis, and in aggregate yielding an overall evaluation of model performance as an average of all sites.

Examining W-statistics for the mean stream temperature at the thirty-three sites illustrates general patterns in model performance from site to site (Figures 4.13 and 4.14; for those interested in performance of an individual site, a list of stream names represented by the site codes shown in the figure can be found in Table 2.1). Generally, all of the models predicted temperature fairly well, although none of the models predicted well at every site. For many sites, the average difference between observed and predicted values (the W-statistic) fell within ±1°C. Since some equipment used in the study cannot measure temperature with greater accuracy than ±1°C, predictions within this range were considered by the TWG to be essentially the same as the observed temperature.

All models occasionally predicted temperature very

Figure 4.13 Average w-statistic for mean water temperature predicted for each site in the western Cascades, Puget Sound region.



badly, but none did so consistently. (Input data were carefully re-examined at all sites where estimates were very poor. If no errors were detected, the poor estimate was allowed to stand and was viewed as part of the unexplained variability in model performance.) No site was predicted poorly by every model, which was viewed as an indication that no site's observed temperature data were extremely inaccurate.

Although W-statistics vary by site, general trends in model performance are easily observed in Figures 4.13 and 4.14. The W-statistic for TEMP-86 is very close to zero at most sites (nearly perfect prediction). TEMPEST also tends to predict well, but is more variable. The SSTEMP model is more variable than both of the other two models, and tends to under-predict temperatures. Similar general performance traits can be observed in maximum, mean, minimum and diurnal fluctuations, whose site averaged values are provided in Tables 4.9, 4.10, 4.11 and 4.12.

Figure 4.14 Average w-statistic for mean water temperature predicted for each site in eastern and coastal Washington.

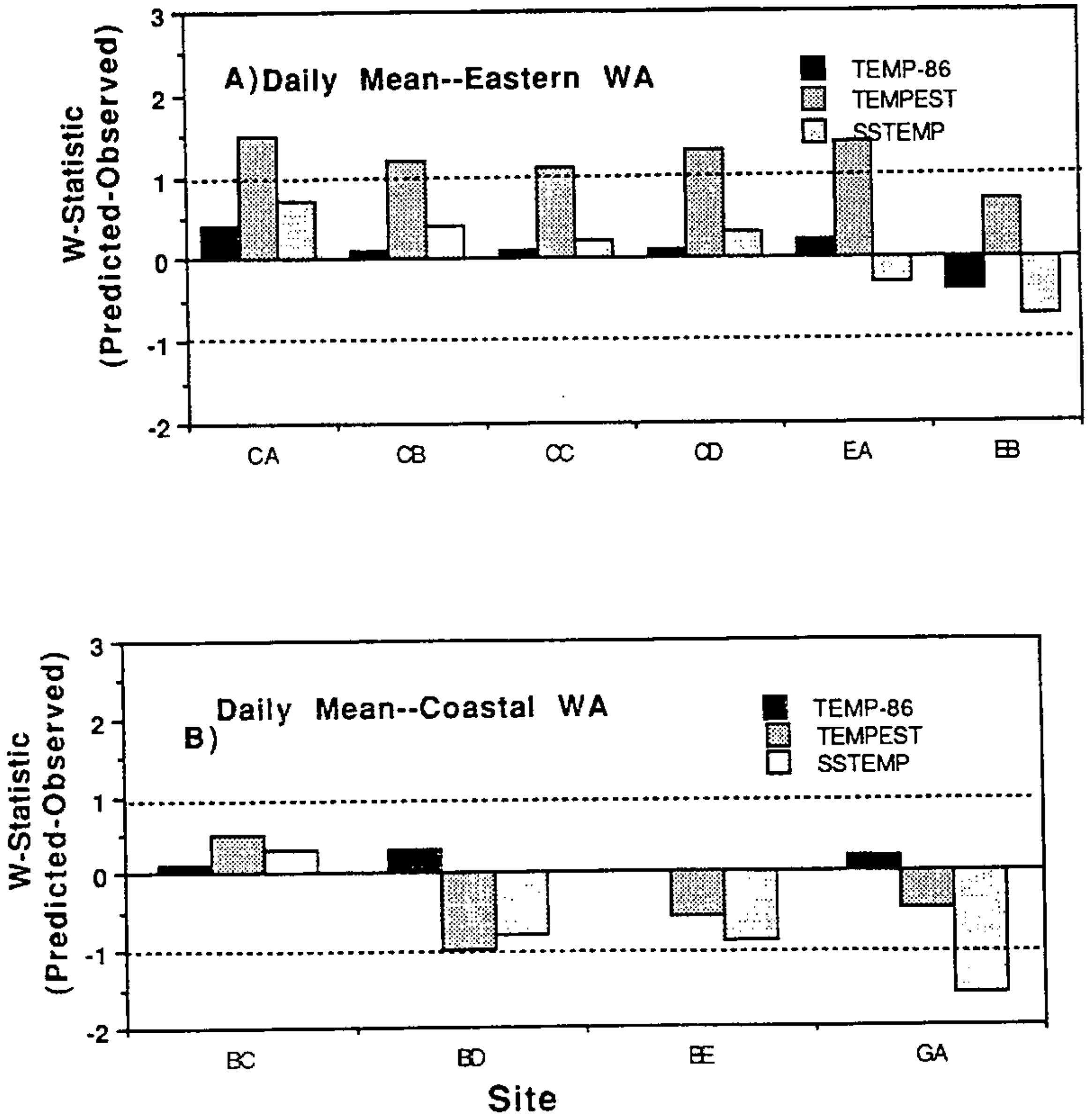


Table 4.9 Average w-statistic and daily error for predicted maximum temperature by site.

	W-STATISTIC (PRE-OBS)				AVERAGE ERROR			
SITE	**TEMP-86**	**TEMPEST**	**SSTEMP**	**BROWN**	**TEMP-86**	**TEMPEST**	**SSTEMP**	**BROWN**
AA	0.0	-0.3	1.0	-1.3	1.0	1.8	1.2	1.3
AB	0.5	-0.5	1.3	-0.3	0.9	2.2	1.5	0.8
AC	-0.1	1.2	0.3	6.4	0.4	1.3	0.4	5.5
AD	0.0	-0.8	0.0	-0.5	0.5	0.9	0.4	0.7
AE	0.1	0.9	0.1	0.4	0.6	1.5	0.5	0.7
AF	-0.2	0.0	0.3	-5.7	0.8	1.3	0.6	6.5
AG	3.4	1.6	0.9	-3.4	3.2	1.9	1.0	3.9
AH	-0.2	-0.8	1.6	-4.8	0.8	1.0	1.8	5.4
AI	-0.1	-0.5	0.4	-5.0	0.9	0.9	0.8	5.7
AJ	-0.1	-0.4	-1.0	-4.5	1.0	0.9	1.1	5.1
AK	-0.3	-1.3	-0.8	-5.3	0.9	1.3	1.1	5.0
AL	-0.2	-1.0	-0.2	-5.4	1.0	1.0	0.9	5.1
AM	-0.1	-0.2	0.9	-2.9	0.4	0.9	1.3	2.7
AN	-0.2	0.4	1.2	-5.2	0.7	1.0	1.3	4.8
AO	0.3	1.5	3.2	-3.8	0.8	2.2	3.2	3.8
AP	-0.3	-0.4	-1.0	-3.2	0.6	0.9	1.1	3.6
AQ	-6.8	-0.8	0.8	-7.3	6.5	2.4	1.1	7.3
BC	0.9	2.0	4.3	0.0	0.9	2.3	4.3	0.5
BD	0.6	-1.2	0.1	0.0	0.9	1.3	0.7	1.1
BE	-0.1	-0.5	0.1	-1.8	0.5	0.6	0.5	1.9
CA	1.0	2.6	3.3	-2.8	1.0	2.9	3.3	2.8
CB	0.0	1.7	4.3	-3.6	0.6	1.8	4.3	3.6
CC	0.2	0.7	2.1	-5.8	0.7	1.7	2.1	5.9
CD	0.1	1.4	2.5	-5.2	0.6	1.9	2.5	5.2
DA	0.0	-0.3	0.5	-2.8	0.7	0.6	0.9	0.7
DB	0.1	0.3	0.9	-1.7	0.4	0.8	0.9	0.9
EA	0.1	4.0	1.7	-1.3	0.5	4.1	1.7	1.8
EB	-0.1	0.9	-0.4	-7.1	0.3	2.5	0.9	10.9
GA	1.1	0.3	2.7	-0.9	1.1	1.0	2.8	0.7
HC	0.3	1.1	2.0	-2.6	0.6	1.2	2.0	2.9
HG	0.2	-0.1	1.9	-3.5	0.7	0.6	2.1	3.9
IC	0.1	1.3	0.1	-1.3	0.4	1.4	0.9	1.7
ID	0.1	0.2	0.6	-5.4	0.9	1.4	0.9	6.8
AVE	**0.0**	**0.4**	**1.1**	**-3.0**	**1.0**	**1.5**	**1.5**	**3.6**

Table 4.10 Average w-statistic and daily error for predicted mean temperature by site.

	W-STATISTIC (PRE-OBS)			AVERAGE ERROR		
SITE	TEMP-86	TEMPEST	SSTEMP	TEMP-86	TEMPEST	SSTEMP
AA	0.1	-1.2	-0.5	0.6	1.3	0.8
AB	0.3	0.2	0.4	0.5	1.3	0.5
AC	-0.1	0.4	-0.5	0.4	0.5	0.5
AD	0.0	-1.0	-0.7	0.4	1.1	0.7
AE	0.1	0.1	-0.1	0.4	1.0	0.4
AF	0.0	0.0	-0.5	0.5	0.8	0.7
AG	2.6	1.0	0.1	2.4	1.1	0.4
AH	0.0	-0.6	0.0	0.6	0.8	0.7
AI	0.0	-0.4	-0.1	0.8	0.7	0.8
AJ	0.0	-0.3	-0.7	0.7	0.7	0.8
AK	0.0	-0.3	-0.4	0.6	0.4	0.7
AL	0.0	-0.3	-0.9	0.8	0.5	1.0
AM	0.0	-0.3	0.0	0.1	0.6	1.2
AN	0.0	0.5	-0.8	0.5	0.7	0.9
AO	0.1	0.1	0.2	0.5	1.0	0.4
AP	-0.1	-0.3	-0.4	0.5	0.7	0.6
AQ	-3.2	-0.2	0.1	3.2	1.4	0.7
BC	0.1	0.5	0.3	0.3	1.0	0.6
BD	0.3	-1.0	-0.8	0.6	1.0	0.8
BE	0.0	-0.6	-0.9	0.5	0.7	0.9
CA	0.4	1.5	0.7	0.5	1.5	0.7
CB	0.1	1.2	0.4	0.5	1.2	0.5
CC	0.1	1.1	0.2	0.5	1.2	0.5
CD	0.1	1.3	0.3	0.4	1.3	0.5
DA	0.1	-0.2	0.0	0.4	0.4	0.4
DB	0.0	0.0	-0.4	0.4	0.7	0.4
EA	0.2	1.4	-0.3	0.5	1.5	0.4
EB	-0.4	0.7	-0.7	0.6	1.6	0.9
GA	0.2	-0.5	-1.6	0.3	0.8	1.7
HC	0.2	0.8	0.2	0.5	1.0	0.5
HG	0.2	0.0	-0.7	0.4	0.4	0.7
IC	0.1	0.6	-0.5	0.4	0.7	1.0
ID	0.1	0.1	0.0	0.4	0.9	0.4
AVE	**0.0**	**0.1**	**-0.3**	**0.6**	**0.9**	**0.7**

Table 4.11 Average w-statistic and daily error for predicted minimum temperature by site.

	W-STATISTIC (PRE-OBS)			AVERAGE ERROR		
SITE	TEMP-86	TEMPEST	SSTEMP	TEMP-86	TEMPEST	SSTEMP
AA	0.1	-1.4	-2.5	0.0	1.4	2.5
AB	0.0	0.1	-1.8	0.0	0.7	1.8
AC	-0.1	-0.3	-1.2	0.0	0.6	1.3
AD	0.0	-1.1	-1.5	0.0	1.1	1.5
AE	0.1	-0.3	-0.2	0.0	0.7	0.5
AF	-0.1	-0.1	-1.7	0.0	0.4	1.7
AG	1.9	0.5	-0.8	0.1	0.6	0.9
AH	0.1	-0.4	-2.0	0.0	0.8	2.2
AI	0.1	-0.2	-0.8	0.0	0.6	1.2
AJ	0.0	-0.2	-0.6	0.0	0.6	0.7
AK	0.1	0.4	-0.4	0.0	0.5	0.7
AL	0.2	0.1	-1.9	0.0	0.4	1.9
AM	-0.1	-0.5	-0.9	0.0	0.7	1.7
AN	0.1	0.6	-3.0	0.0	0.7	3.0
AO	0.0	-1.5	-3.3	0.0	1.5	3.3
AP	-0.1	-0.3	0.2	0.0	0.6	0.5
AQ	-0.5	-0.2	-1.6	0.2	0.6	1.8
BC	-0.2	-1.3	-4.2	0.0	1.3	4.2
BD	-0.2	-1.2	-2.3	0.0	1.1	2.2
BE	-0.1	-0.7	-2.0	0.0	0.8	2.0
CA	-0.1	-0.1	-2.8	0.0	0.4	2.8
CB	0.0	0.5	-3.9	0.0	0.6	3.9
CC	0.2	1.1	-2.3	0.0	1.1	2.3
CD	0.1	1.1	-2.2	0.0	1.1	2.2
DA	0.1	-0.1	-0.6	0.0	0.4	0.9
DB	0.0	-0.5	-1.7	0.0	0.7	1.7
EA	0.1	-0.7	-2.5	0.0	0.9	2.5
EB	-0.5	0.1	-1.4	0.0	0.8	1.5
GA	-0.1	-1.1	-5.9	0.0	1.1	5.9
HC	0.2	0.4	-1.7	0.0	0.9	1.7
HG	0.1	0.0	-3.6	0.0	0.5	3.6
IC	0.1	0.0	-1.2	0.0	0.5	1.6
ID	0.1	-0.8	-1.8	0.0	0.8	1.9
AVE	**0.0**	**-0.3**	**-1.9**	**0.6**	**0.8**	**2.0**

Table 4.12 Average w-statistic and daily error for predicted diurnal fluctuation by site.

	W-STATISTIC (PRE-OBS)			AVERAGE ERROR		
SITE	TEMP-86	TEMPEST	SSTEMP	TEMP-86	TEMPEST	SSTEMP
AA	-0.1	1.1	3.5	1.2	2.3	3.5
AB	0.5	-0.6	3.1	1.0	2.0	3.3
AC	-0.0	1.6	1.5	0.3	1.6	1.5
AD	-0.0	0.2	1.5	0.6	0.7	1.5
AE	-0.0	1.2	0.2	0.5	1.4	0.6
AF	-0.1	0.1	2.0	0.9	1.3	2.1
AG	1.5	1.1	1.7	1.6	1.6	1.7
AH	-0.3	-0.4	3.6	0.7	0.8	3.7
AI	-0.1	-0.3	1.2	0.7	0.8	1.4
AJ	-0.1	-0.2	-0.4	1.0	0.7	0.8
AK	-0.3	-1.7	-0.5	1.0	1.7	1.0
AL	-0.3	-1.1	1.7	0.9	1.1	1.7
AM	0.0	0.2	1.8	0.3	0.8	1.9
AN	-0.3	-0.2	4.2	0.8	1.0	4.2
AO	0.3	2.9	6.5	0.9	3.0	6.5
AP	-0.2	-0.1	-1.2	0.7	0.5	1.2
AQ	-6.4	-0.6	2.3	6.5	2.2	2.7
BC	1.1	3.3	8.5	1.1	3.3	8.5
BD	0.9	-0.1	2.4	1.1	0.7	2.4
BE	-0.0	0.2	2.1	0.8	0.4	2.1
CA	1.1	2.8	6.1	1.1	3.1	6.1
CB	0.0	1.2	8.2	0.6	1.6	8.2
CC	0.0	-0.4	4.3	0.8	1.8	4.3
CD	-0.0	0.3	4.6	0.7	1.7	4.6
DA	-0.1	-0.2	1.2	0.7	0.6	1.4
DB	0.1	0.8	2.6	0.6	0.9	2.6
EA	0.0	4.7	4.2	0.5	4.8	4.2
EB	0.4	0.8	1.0	1.1	2.5	1.2
GA	1.2	1.4	8.5	1.2	1.4	8.5
HC	0.1	0.7	3.7	0.6	0.8	3.7
HG	0.1	-0.2	5.6	0.6	0.8	5.6
IC	-0.0	1.3	1.3	0.3	1.4	1.4
ID	0.0	0.9	2.4	1.1	1.7	2.7
AVE	0.0	0.6	3.0	1.0	1.5	3.3

Maximum Temperature

Predictions of maximum temperature relative to observed showed different patterns for the four models. Site-averaged predicted temperature is shown relative to observed temperature for the four models in Figure 4.15. TEMP-86 showed little variability in relationship between predicted and observed temperature (except for several outliers), and the regression slope was near 1. (Perfect prediction should have 1:1 correspondence with observed temperature.) TEMP-86 tends to slightly over predict temperature at higher average site temperatures and under predicts at sites with lower temperatures. TEMPEST has wider variability in the relationship in general, but has less discernible patterns in predictions with average site temperature characteristics. SSTEMP is also more variable than either TEMP-86 or TEMPEST, and shows a distinct bias to over predicting temperature at most sites. Brown's predictions were also highly variable and tended to under predict at higher site temperature.

When model performance was evaluated for all sites, TEMP86, SSTEMP, and TEMPEST all predicted maximum temperature accurately, that is, close to or within the range of instrument precision. (Summary statistics for the W-statistic, average error and consistency of model performance are shown by model in Figure 4.16. Average W-statistic and error are listed by site in Table 4.9.) Brown's equation showed inconsistent results, and almost always under-predicted maximum temperature. TEMP86 was the most precise model, as indicated by the average.error, averaging about 1°C error per day. TEMPEST, SSTEMP and Brown's equation were somewhat less precise, with an average error of approximately 1.5°C per day. Consistency of model performance was good for the three computer models but not as good for Brown's equation. TEMPEST and TEMP86 predicted 93% of all sites accurately (site accuracy was defined as the average w-statistic within 2°C), while SSTEMP predicted 78% and Brown's equation correctly predicted only 33% of the sites.

Figure 4.15 Relationship of observed to predicted daily maximum temperature by site models.

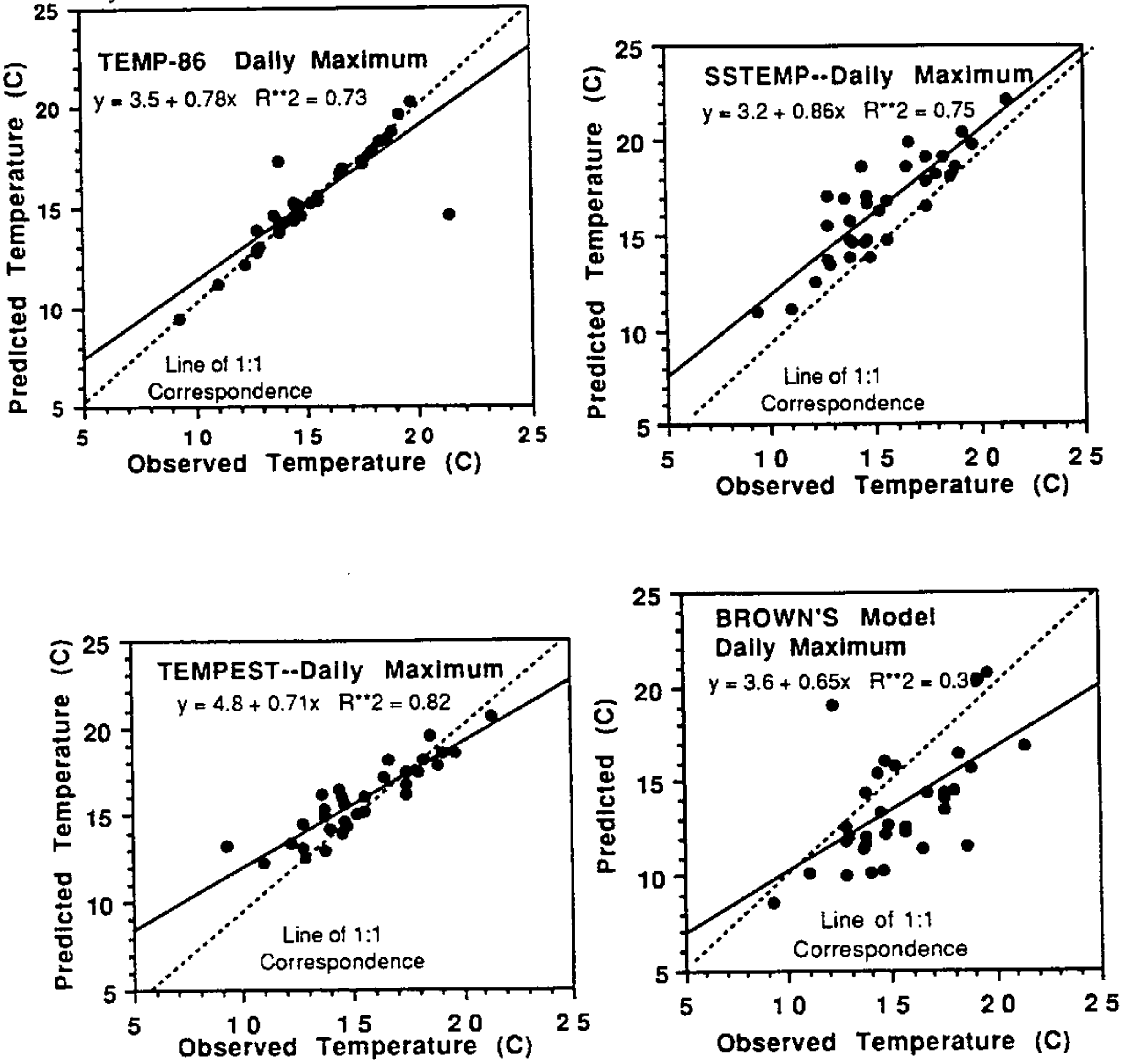
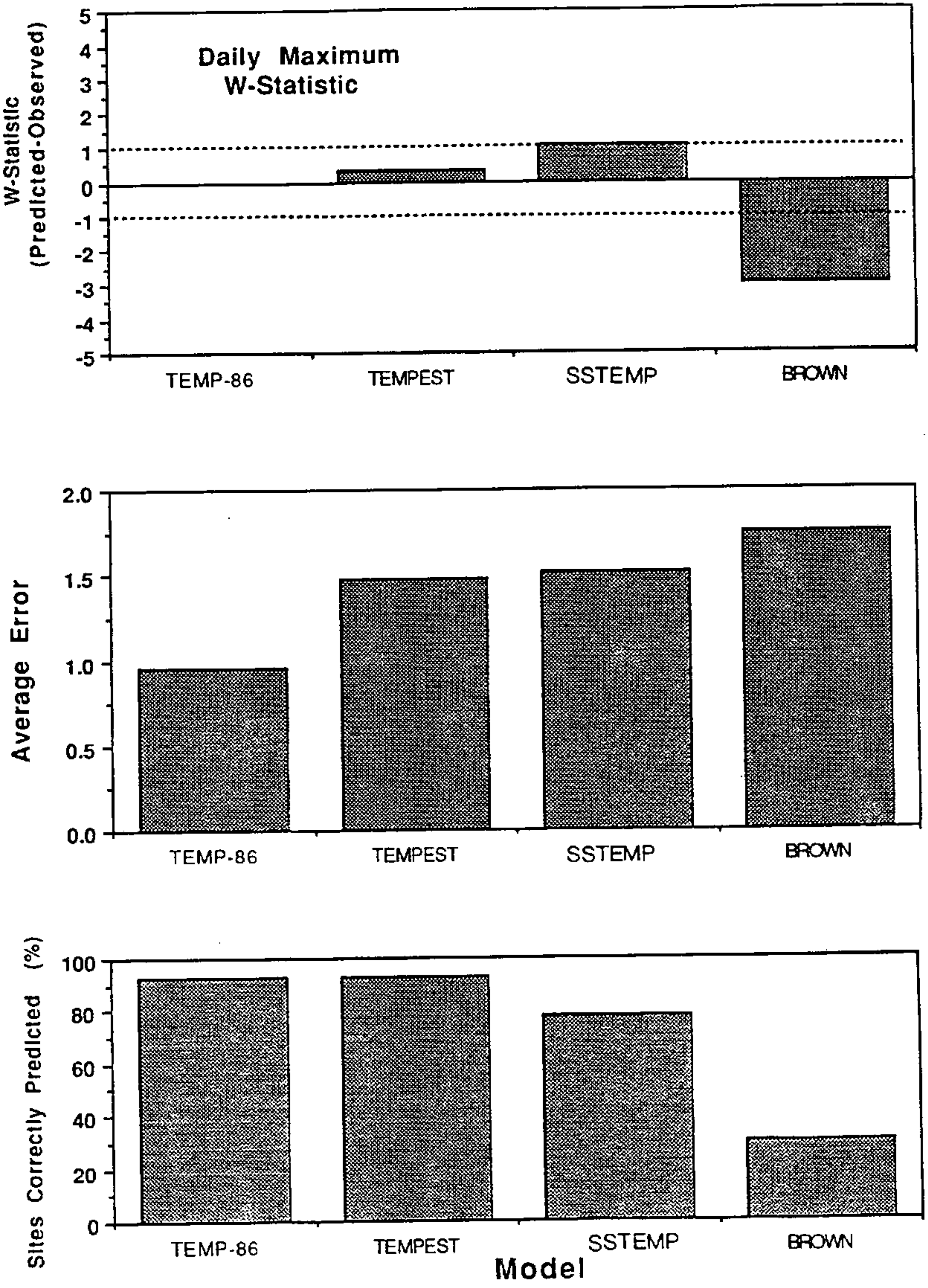


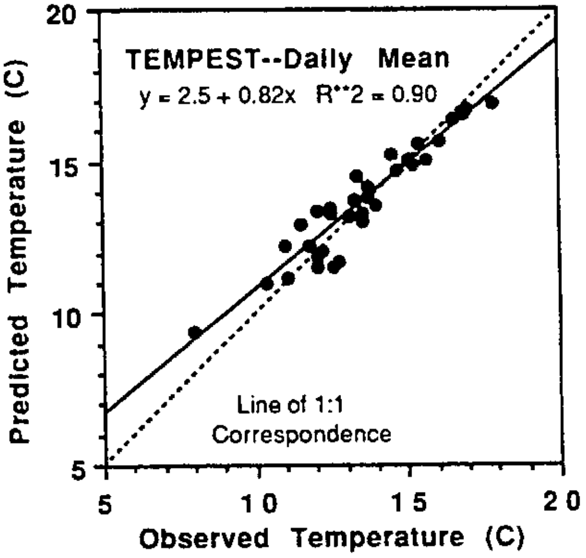
Figure 4.16 Summary performance statistics for maximum temperature based on averages for all sites (n=33).

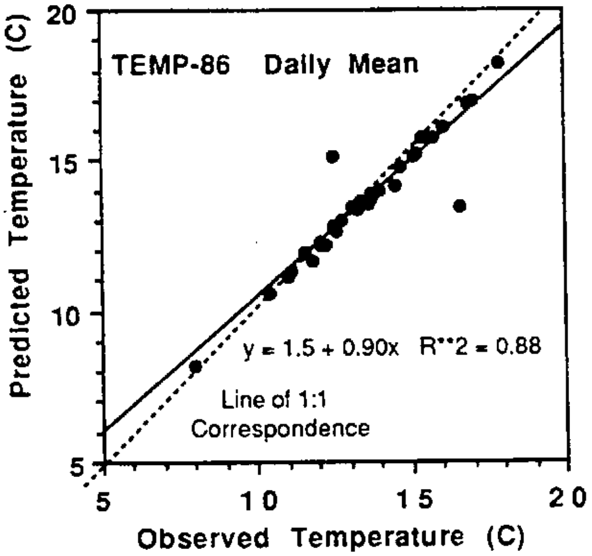


Mean Temperature

In general, all three of the computer models predicted mean daily temperature more accurately than they predicted the maximum temperature. Site-averaged predicted mean temperature is shown relative to observed mean temperature for the three models in Figure 4.17. (Brown's model does not predict mean or minimum temperature.) For all models, the predicted mean temperature was close to the observed temperature, with a regression slope of nearly 1 (perfect correspondence). Also, there was little evidence of bias with average site temperature and relatively low variability in the predictive capability from site to site.

When model performance was evaluated for all sites, TEMP86, SSTEMP, and TEMPEST all predicted mean temperature very accurately, and better than other temperature characteristics. (Summary statistics for the W-statistic, average error and consistency of model performance for predicting mean daily temperature are shown by model in Figure 4.18. Average W-statistic and error for the mean temperature are listed by site in Table 4.10.) All three models were very accurate, and showed similar precision levels. All three models predicted quite consistently, with TEMPEST and SSTEMP predicting 100% of the sites well, and TEMP86 predicting 93%. TEMP-86 generally performed well, but overall performance was marred by two outlier sites where the model inexplicably performed poorly.





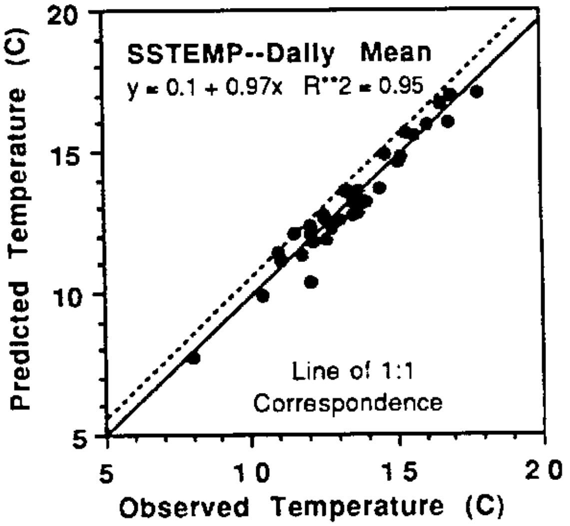
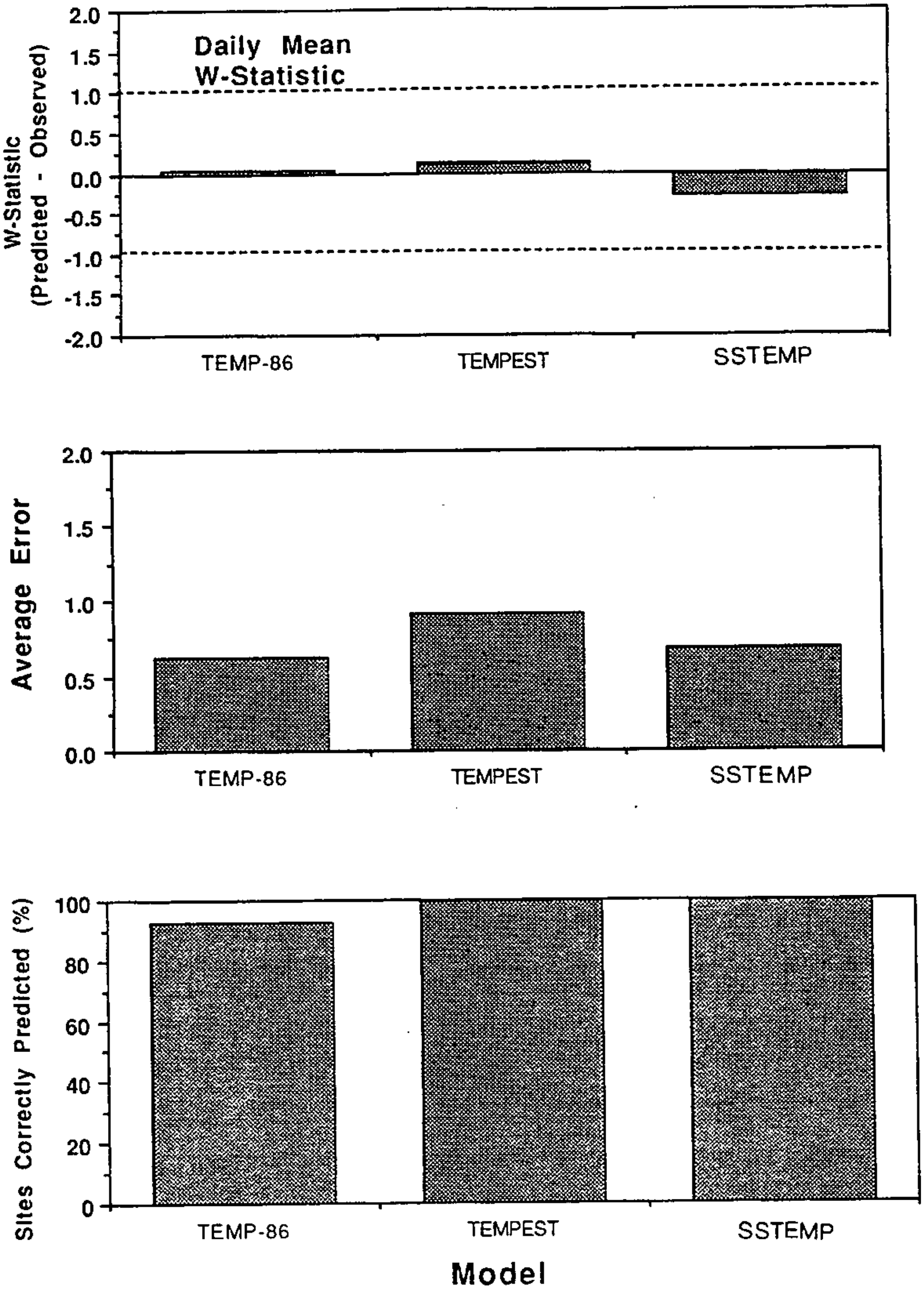


Figure 4.17. Relationship of observed to predicted daily mean temperature by site models.

Figure 4.18 Summary performance statistics for mean temperature based on averages for all sites (n=33).



Minimum Temperature

TEMP86 and TEMPEST continued to show good performance, predicting minimum temperatures very well, on average, for most sites tested. Site-averaged predicted minimum temperature is shown relative to observed minimum temperature for the three models in Figure 4.19. SSTEMP performed poorly, and showed a trend of under-predicting the observed minimums.

When model performance was evaluated for all sites, TEMP86 and TEMPEST predicted minimum temperature accurately. (Summary statistics for the w-statistic, average error and consistency of model performance for predicting minimum daily temperature are shown by model in Figure 4.20. Average w-statistic and error for the minimum temperature are listed by site in Table 4.11.) While TEMPEST and TEMP86 showed similar levels of precision, SSTEMP was less precise than the other two models. TEMP86 and TEMPEST adequately predicted minimum temperature at 100% of the sites, while SSTEMP was less consistent, predicting only 64%.

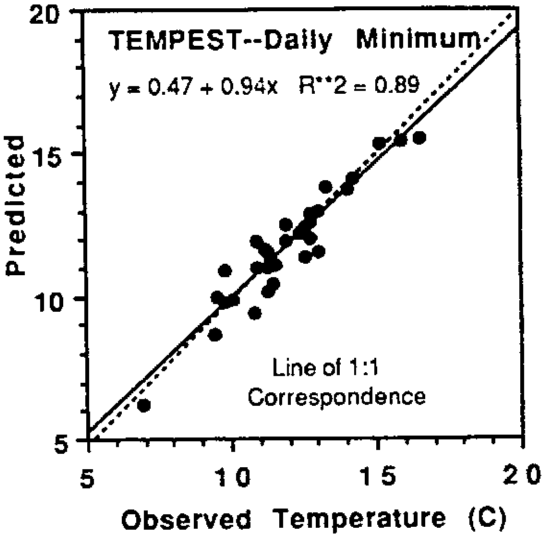
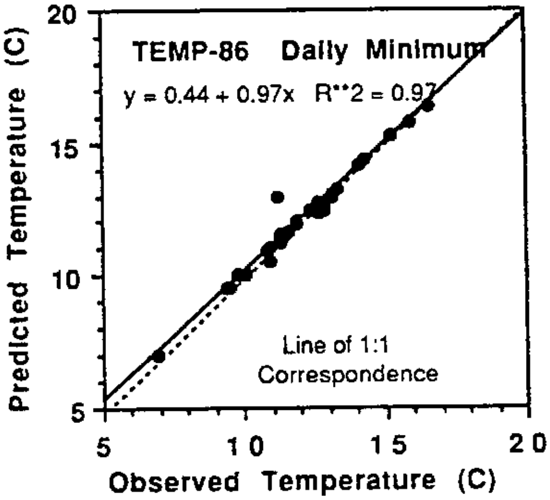


Figure 4.19 Relationship of observed to predicted daily maximum temperature by site models.



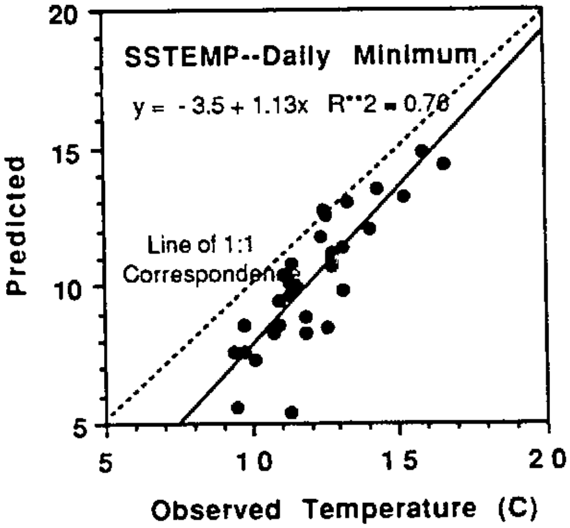
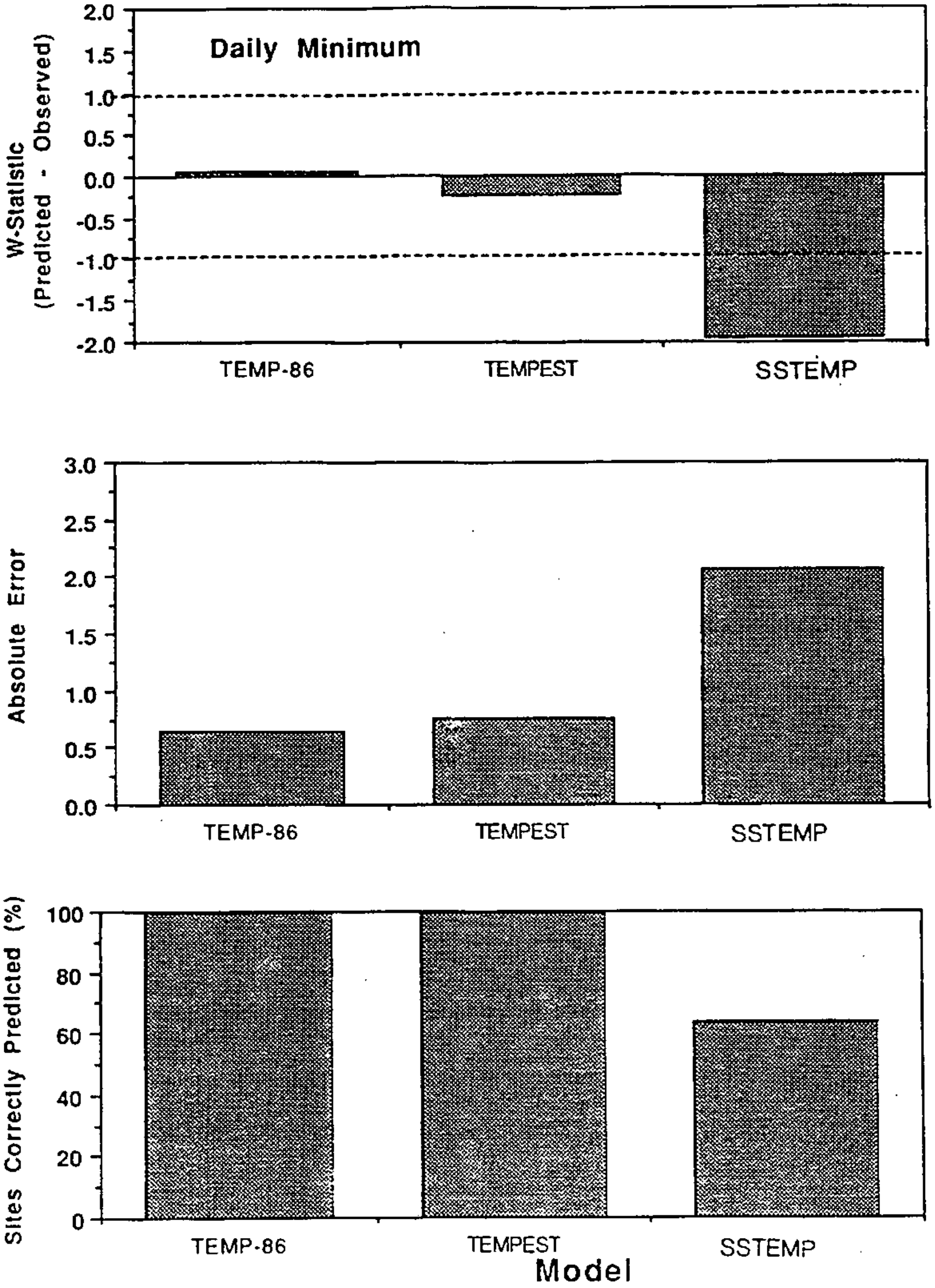


Figure 4.20 Summary performance statistics for minimum temperature based on the average of all sites (n=33).



Diurnal Fluctuation

Prediction performance for diurnal flux follows that of the maximum and minimum temperature. Models that predicted these characteristics accurately tended to also predict the diurnal flux accurately, although for all models the ability to predict diurnal flux was worse than for predicting maximum or mean temperature. Site-averaged predicted minimum temperature is shown relative to observed minimum temperature for the three models in Figure 4.21. TEMP86 predicted diurnal flux well, on average, for most sites modeled. TEMPEST and SSTEMP were more variable, with SSTEMP doing a generally poor job in predicting diurnal flux with a significant tendency to over-predict. This is consistent with the results shown above, where the poor predictions by SSTEMP of the minimum temperatures mean poor predictions of the flux.

Figure 4.21 Relationship between observed diurnal fluctuation and that predicted by the TEMPEST model, averaged by site.

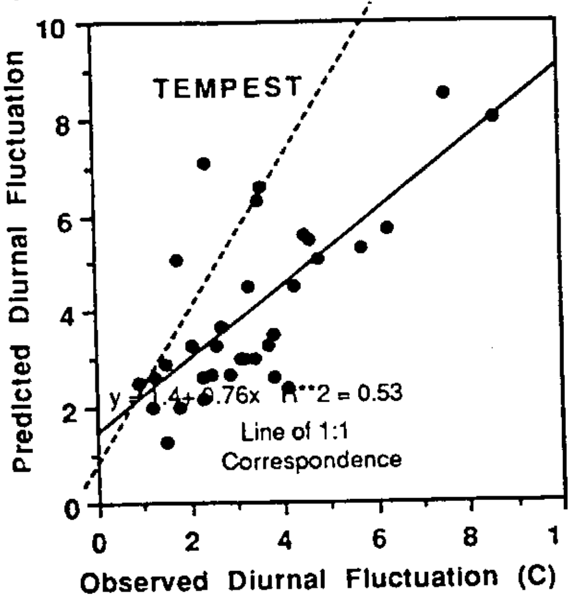
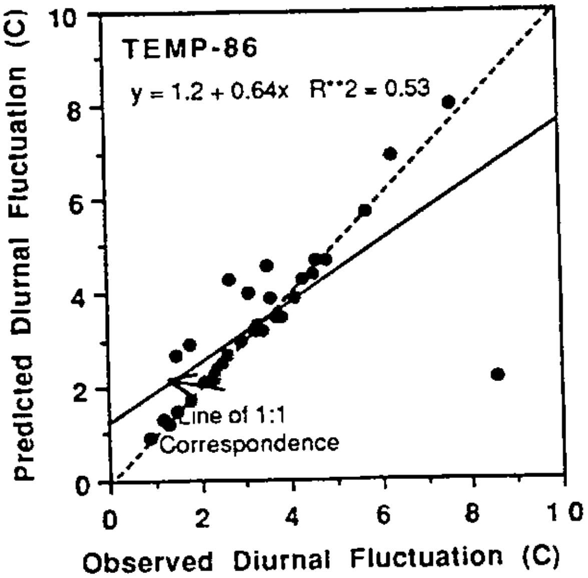
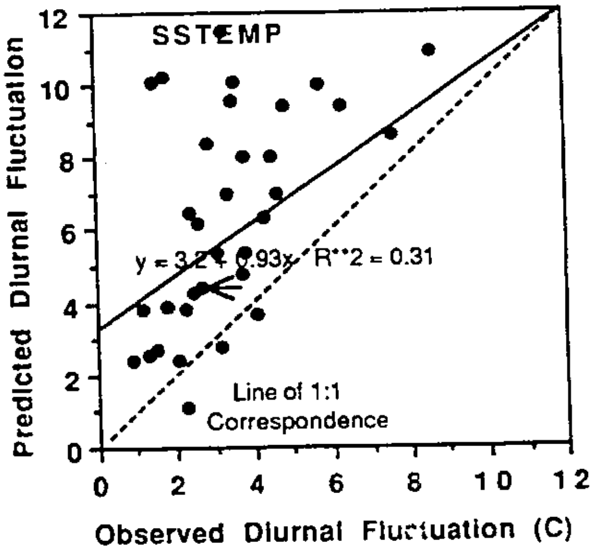


Figure 4.21 Relationship between observed diurnal fluctuation and that predicted by the TEMP-86 model, averaged by site.

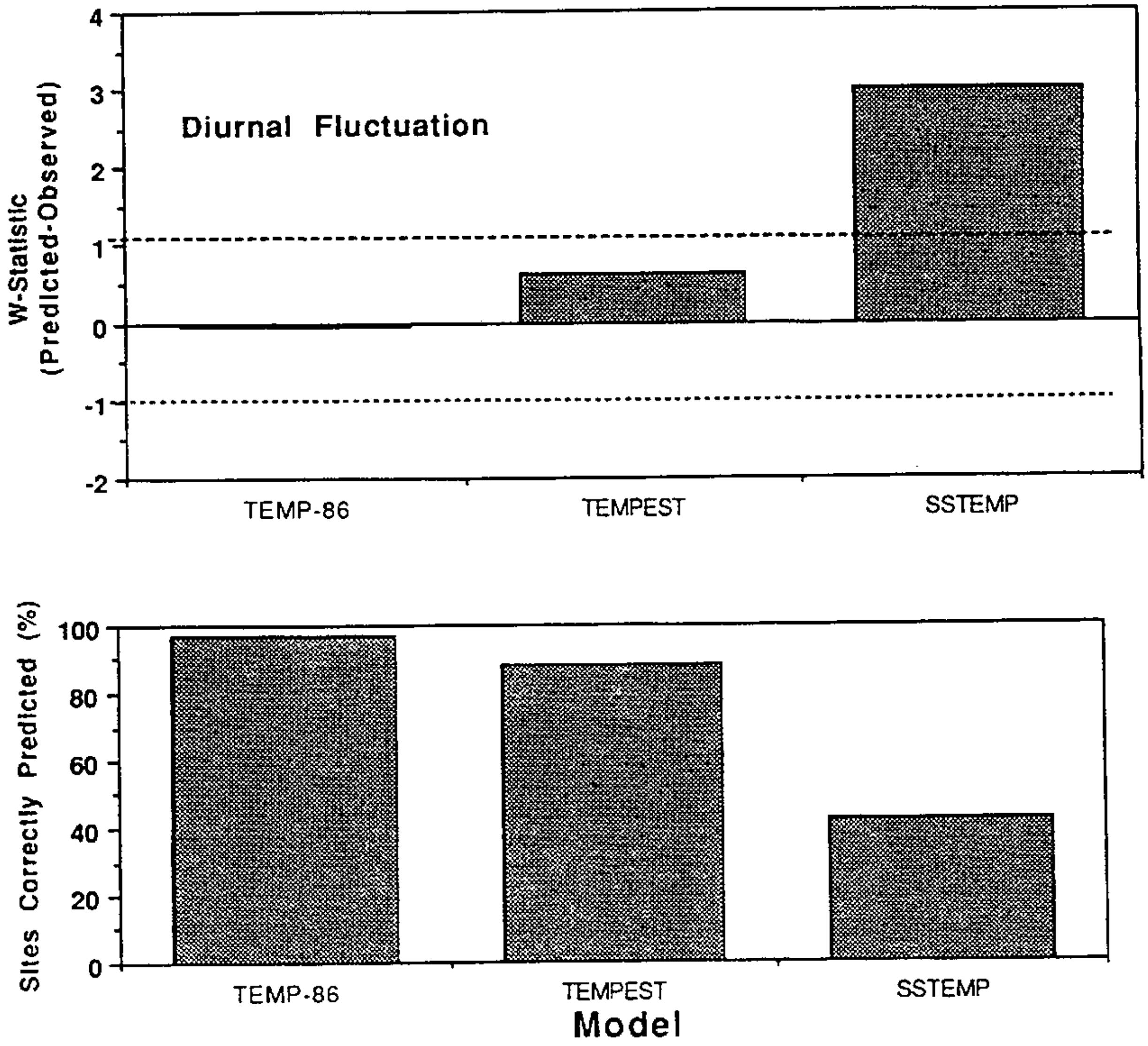




When model performance was evaluated for all sites, TEMP86 and TEMPEST predicted diurnal fluctuation accurately. (Summary statistics for the W-statistic, average error and consistency of model performance for predicting diurnal temperature fluctuation are shown by model in Figure 4.22. Average W-statistic and error for the minimum temperature are listed by site in Table 4.12.)

TEMP86 performed well in predicting diurnal fluctuation in general, as did TEMPEST. SSTEMP showed poor precision. The TEMP86 model again was the most consistent, predicting 97% of all sites within 2°C. TEMPEST correctly predicted 88% of the sites while SSTEMP predicted only 42% of the sites accurately.

Figure 4.22 Summary performance statistics for diurnal temperature fluctuation based on the average of all sites (n=33).



Patterns and Trends in Performance

Model performance was analyzed for possible bias in prediction with different riparian vegetation shade (expressed as the percent of sky that could be viewed from the stream), as well as over the range of stream sizes studied (expressed as basin area). Model predictions over the range of observed maximum temperatures were also analyzed to see if the models themselves performed differently at different temperatures.

None of the models showed significant bias in predictions over the ranges of observed riparian canopy categories. Each site's average W-statistic compared to its riparian shade density is shown in Figure 4.23. Regression statistics for simple linear equations fitted to these relationships for maximum, mean, minimum and diurnal fluctuation characteristics are provided in Table 4.13. Regression slopes significantly different than zero, indicating bias in temperature prediction as a direct function of riparian density was not observed for any model for any temperature characteristic.

Comparing the W-statistic over the ranges of stream sizes studied suggested that all of the models tended to be less accurate for small streams, which make up the majority of the streams in this sample (Figure 4.24). TEMP86 and SSTEMP showed no significant level of bias (Table 4.14). TEMPEST, however, tended to show a bias for predicting higher minimum temperature with stream size (p=0.02), and lower diurnal fluctuation with stream size (p=0.07). TEMPEST did not show bias in predicting the maximum or mean temperatures.

All models showed a prediction bias across the observed temperature range, consistently under-predicting at higher temperatures and over-predicting at lower temperatures (Figure 4.25). This could be due to changes in the rate of some temperature processes at higher temperatures, particularly evaporation, that are not adjusted within the models. Because the higher temperatures where the prediction error was most pronounced was rarely observed in the streams under study, the TWG noted this result but did not pursue it further.

Figure 4.22 Continued

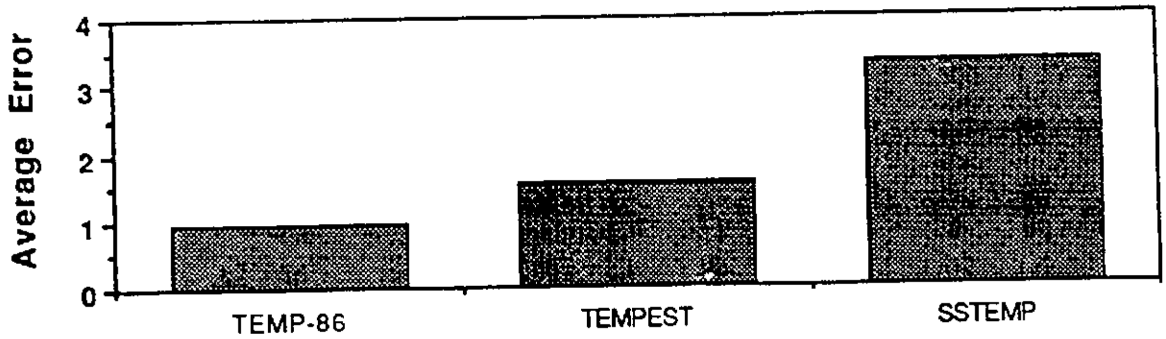


Table 4.13 Regression statistics testing bias of model temperature predictions with variability in sky view factor (0-100%) ((Temp=f(View)).

TEMPERATURE CHARACTERISTIC	MODEL	SLOPE	INTERCEPT	R^2	Pr>T FOR SLOPE
MAXIMUM	TEMP-86	-0.008	0.5	0.02	0.44
	TEMPEST	0.001	0.4	0.00	0.90
	SSTEMP	0.013	0.3	0.05	0.20
MEAN	TEMP-86	-0.004	0.3	0.02	0.48
	TEMPEST	0.004	-0.1	0.02	0.45
	SSTEMP	0.004	-0.5	0.03	0.33
MINIMUM	TEMP-86	0	0.04	0.00	0.92
	TEMPEST	0.002	-0.36	0.01	0.62
	SSTEMP	-0.014	-1.08	0.07	0.14
DIURNAL FLUCTUATION	TEMP-86	-0.009	0.47	0.02	0.35
	TEMPEST	-0.002	0.75	0.00	0.87
	SSTEMP	0.027	1.38	0.07	0.14

Table 4.14 Regression statistics testing bias of model temperature predictions with variability in basin area (Temp=f(BA)).

TEMPERATURE CHARACTERISTIC	MODEL	SLOPE	INTERCEPT	R^2	Pr>T FOR SLOPE
MAXIMUM	TEMP-86	0	0.01	0	0.93
	TEMPEST	-0.001	0.56	0.02	0.48
	SSTEMP	-0.002	1.31	0.04	0.29
MEAN	TEMP-86	0	0.08	0	0.74
	TEMPEST	0	0.08	0.02	0.40
	SSTEMP	0	-0.24	0	0.93
MINIMUM	TEMP-86	0	0.09	0.02	0.48
	TEMPEST	0.002	-0.42	0.17	0.02
	SSTEMP	0.002	-2.11	0.03	0.32
DIURNAL FLUCTUATION	TEMP-86	0	-0.08	0	0.88
	TEMPEST	-0.004	0.97	0.10	0.07
	SSTEMP	-0.004	3.41	0.04	0.27

Figure 4.23 W-Statistics for the model predictions in relation to riparian canopy.

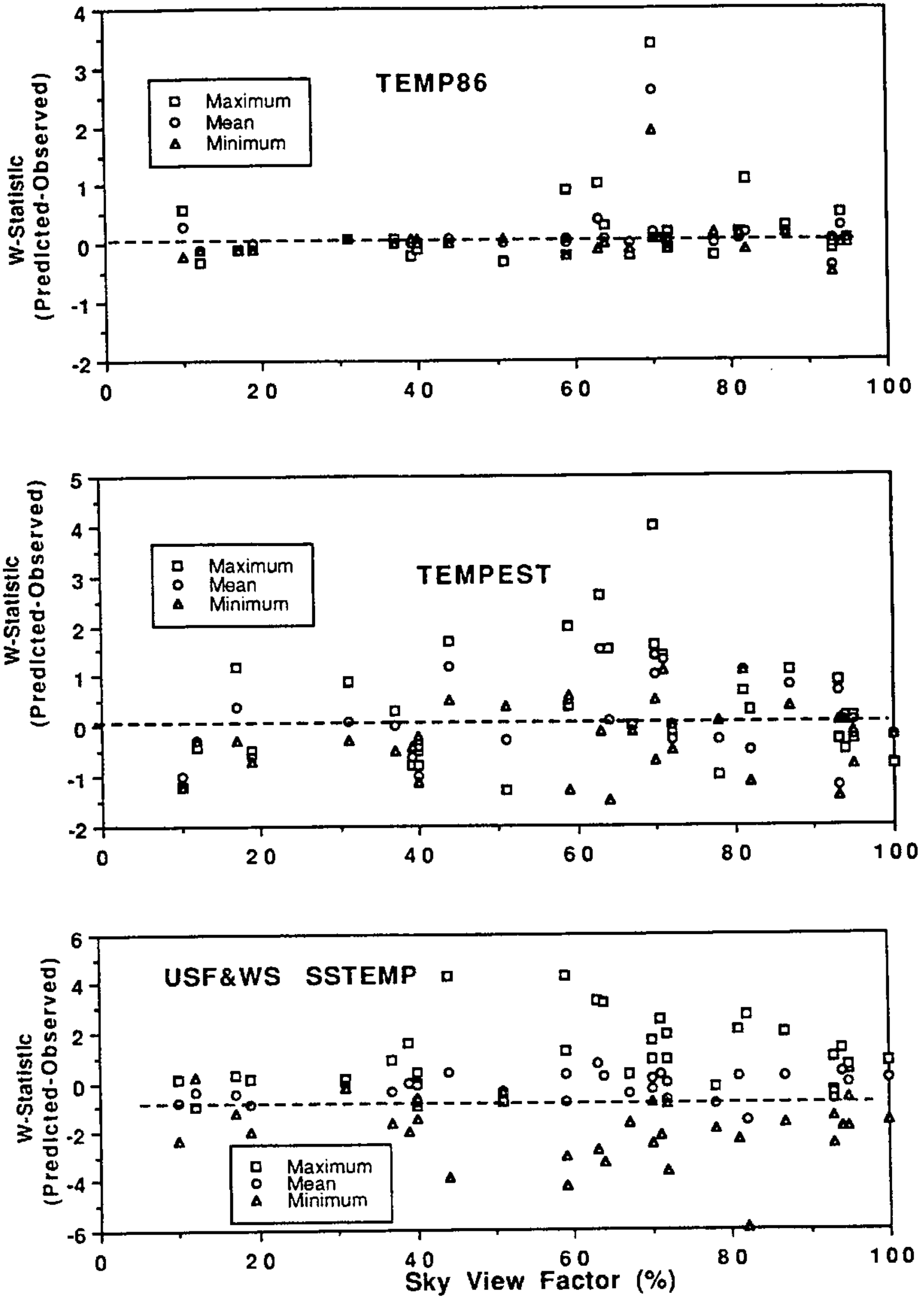
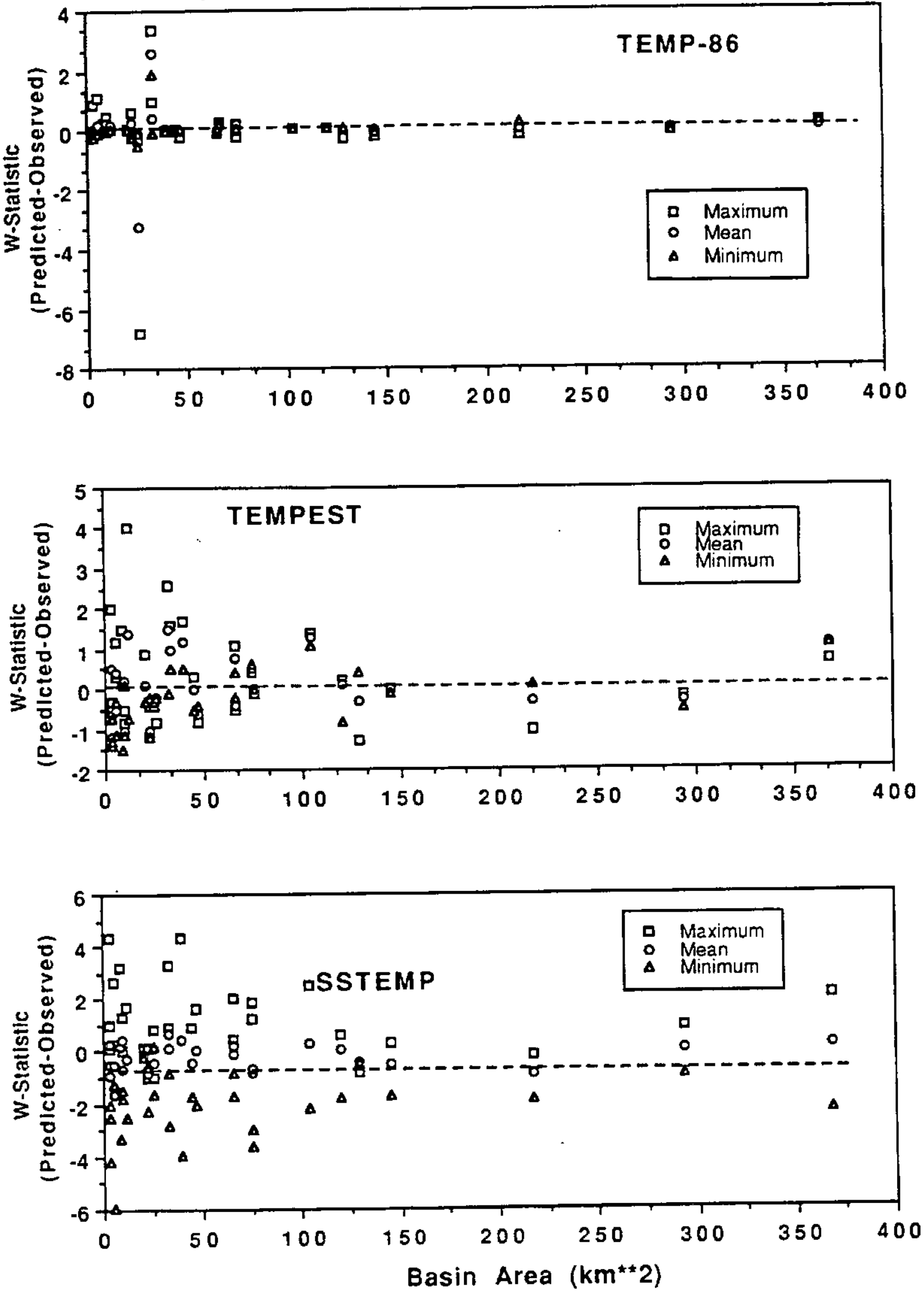


Figure 4.24 W-statistics for TEMP86 model predictions as a function of stream size indexed by basin area.



General Observations and Conclusions

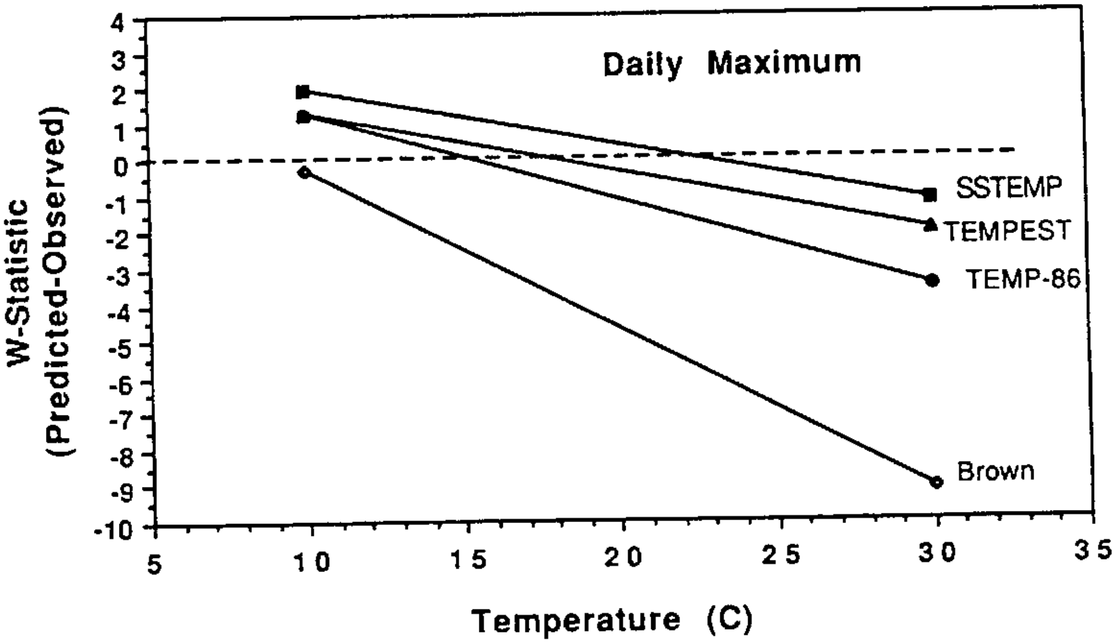
TEMPEST and TEMP86 predicted all temperature characteristics quite well. SSTEMP predicted mean water temperatures well, and did much more poorly in predicting temperature ranges. Three of the four models tested predicted well enough, with this level of input data, to be considered for further development in TFW applications. None of the models showed major bias with stream size or riparian category, although all of the showed a tendency to under-predict at higher temperatures.

The reasons for the difference in results between models even though they used the same data, may relate to model structure. While TEMP86, TEMPEST and SSTEMP are all steady-state models, they route the heating equations through time steps differently. SSTEMP relies on a 24-hour time step using 24-hour averages of input values to predict the mean daily temperature. To calculate the daily maximum, the model begins with the 24-hour mean value at solar noon, and models the stream's response up to solar sunset, predicting the maximum.

To estimate the minimum, the model makes a mirror image of the curve between the mean and the maximum by subtracting their difference from the mean. Low accuracy in predicting minimum and diurnal fluctuation by SSTEMP may result because minimum stream temperatures are more strongly affected by factors such as groundwater temperature and mean air temperature than by solar insolation, which affects maximum temperatures more strongly.

The good performance of TEMPEST and TEMP86 may stem from these model's reliance on a shorter, one-hour time step for calculating heat loading, and both models require a new air temperature value input each hour. TEMPEST generates hourly water temperature predictions, but TEMP86 also requires a new water temperature input each hour. This may be why these two models estimate the maximum, minimum and flux more accurately than SSTEMP, since the time step the model can run before recalibration with new input data is shorter. The need of TEMP86 to have a value supplied as input (water

Figure 4.25 W-statistics (predicted - observed temperature) for maximum temperature predictions as a function of temperature.



temperature) which is also output one hour later is probably the reason for the good model performance. The TWG does not know if this good performance would hold up without measured water input values, or using hourly values estimated from measured maximum and minimum temperatures.

Accuracy of climate variables used as input could also affect model performance. For the more moderate climates of the Western Cascades and Washington Coast, NOAA station estimates of relative humidity and wind speed, used to estimate conditions at the study sites, might be closer to those actually existing at the stream reach than east of the Cascades. For the Eastern regions, it could be hypothesized that relative humidity and wind speed conditions in a riparian zone could differ more from the conditions at the NOAA index station. A less-accurate estimate of the regional climate parameters could affect model performance. The extent to which regional estimates of climate characteristics affected model performance at any site is not known.

Model Selection Criteria and Conclusions

Following the numerical tests and sensitivity analyses, the models were evaluated for their overall effectiveness as a TFW management tool. Although good temperature prediction capabilities were considered essential in the model selected, other practical factors influencing effective TFW implementation such as cost effectiveness and data requirements were also considered important. Where temperature prediction capabilities were comparable between models, the most practical would be considered superior. Furthermore, after developing a thorough understanding of model performance relative to the required input data parameters, the TWG felt that a rating reflecting their perception of a model's reliability was also an important consideration in model selection.

Evaluation criteria included model performance in temperature prediction, model reliability based on the data required to run them, and practical considerations such as cost and personnel. The criteria categories received initial weightings reflecting the TWG's consensus of their relative importance. Of the total possible score, 40% was based on performance, 25% was based on reliability, and 35% was based on practicality considerations. A number of criteria to be applied to each model were developed for each of the three categories. Each criteria's rating was designed to provide the highest score to the best performance or most desirable features. The score for each criteria varied reflecting the TWG's perceptions of its relative importance, as shown in Table 4.15. Each model's overall score was the basis for model selection.

Model Performance Criteria

Performance criteria characterized how well the model predicted temperature by appraising the accuracy, precision, consistency and bias of model results. Performance criteria were evaluated individually for each of the temperature characteristics: daily maximum, mean, minimum and diurnal fluctuation. For each temperature characteristic, an overall model rating was estimated based on the mean value of all sites (33). An evaluation of excellent, good and poor performance as defined below was applied and an overall performance score was computed by summing all ratings.

Accuracy. Model predictions were considered accurate when the difference between the daily observed temperature and the predicted temperature (W-statistic) was small. *Rating:* 10=Excellent (W-statistic<=1.0); 6=Good (1.0<W-statistic<=2.0) 0=Poor (W-statistic>2.0) .

Precision. Model predictions were considered precise when the difference between the observed and predicted temperatures (Average Error),either positive or negative, was consistently low. This was evaluated by determining the average error for each site, and then determining the overall average for all sites. *Rating:* 10=Excellent (Average Error<=1.0); 6=Good (1.0<Average Error<=2.0); 0=Poor (Average Error>2).

Consistency. A model was considered consistent if it accurately predicted temperature at most of the test sites. A site prediction was considered accurate if the average difference in predicted and observed temperature was less than or equal to 2.0°C. (W-statistic <= 2.0.) *Rating:* 10=Excellent (More than 90% of the sites were accurately predicted); 5=Good (81-90% of sites accurately predicted); 0=Poor (Less than 80% of sites accurately predicted) .

Bias. Significant trends in high or low temperature predictions relative to stream size or riparian conditions was used as an indicator of model bias considered important for TFW applications. Bias was determined by examining the W-statistic relative to basin area and riparian vegetation density with linear regression. *Rating:* 5=No bias 0=Yes.

Table 4.15 Weighting factors for model selection criteria. (To compute total points each model's score for each criteria (shown in Table 4.17 is multiplied by the weighting shown here.)

CATEGORY	CRITERIA	WEIGHTING
PERFORMANCE	Accuracy--Maximum	10
	Accuracy--Mean	10
	Accuracy--Minimum	10
	Accuracy--Daily Flux	10
	Precision--Maximum	10
	Precision--Mean	10
	Precision--Minimum	10
	Precision--Daily Flux	10
	Consistency--Maximum	10
	Consistency--Mean	10
	Consistency--Minimum	10
	Consistency--Flux	10
	Bias (Size)--Mean	5
	Bias (Size)--Flux	5
	Bias (Riparian)--Mean	5
	Bias (Riparian)--Flux	5
RELIABILITY	Number of Variables	15
	Model Response	15
	Variable Measurability	15
	Parameter Sensitivity	30
PRACTICALITY	Field Personnel	15
	Field Equipment	6
	Field Training	9
	Field Data Collection	24
	Data Management	9
	Model Run Cost	6
	Computer Costs	3
	Computer Training	3
	Operation Mechanics	6
	Product Support	3
	Output	6
	Model Friendliness	15

Model Reliability Criteria

Evaluation of model reliability was based primarily on the results of the sensitivity analysis where temperature predictions were related to variation in specific model input variables. These analyses identified which variables were most important in determining each model's the water temperature predictions and suggested the reliability of variable measurement or estimation required to minimize prediction errors. Models were considered to be less reliable if they were sensitive to many variables, or to variables that are difficult to measure. Most of the models require an estimate of water temperature as a starting point for the temperature calculation. Since water temperature is both an input and an output variable, a high degree of sensitivity to, or reliability on, this variable was considered especially undesirable.

Number of Variables. A model's complexity increases with the number of input variables it requires. Ideally, only variables necessary to yield good predictions without compromising the model's application as a management tool should be required for input. Models were evaluated on the number of input variables and the importance of these variables in producing reliable results. Requiring four or more input variables which do not actually significantly affect a model's predicted maximum or mean temperatures was considered undesirable (poor=0). Models for which the majority of input variables are readily understood and make significant differences in predicted temperatures were rated good (5). Models requiring fewer than five input variables, for which information is readily available from pre-existing sources were considered desirable (excellent=10).

Variable Measurability. Many environmental parameters can only be estimated due to difficulty in obtaining measurements or rapidly changing values. Models whose input requirements can be met by use of regional databases scored 10 points. If one or more variables can only be measured with moderate difficulty, a score of 5 points was given. Models with input variables that can not be readily measured scored zero.

Model Response. It is desirable for a model to be responsive to input parameters. However, this sensitivity should match the precision with which variables can be measured or estimated. High sensitivity to parameters that are both difficult to measure and showed wide variation between study sites within a single region decreases the model's applicability. Good site data will seldom be available for TFW model applications. It was considered desirable for sensitivity to be compatible with regionalized estimates for input variables and essential that sensitivity be compatible with our ability to measure fluctuation parameters such as humidity.

Mean values and standard deviations for each parameter were calculated for the study site data with the sites grouped regionally. Sensitivity values were used to calculate the range in predicted mean temperature associated with one standard deviation for the input parameter. This model response was analyzed for different stream sizes and for different regions for each model's two most sensitive parameters (*Reliability Analysis*, Chapter 4). Models with the range in the predicted mean temperature being less than ±1.5 °C rated good (10 points). A rating of fair (5 points) was awarded if the change in one of the sensitive input variables resulted in an average range in predicted mean temperature between ±1.5 to 2.5 °C. A poor rating (0 points) was given to models with the average predicted range greater than ±2.5 °C.

Parameter Sensitivity. This rating indexed the relative reliability of the model based on the key variables that determine temperature predictions. If model output is most sensitive to a similar input variable, referred to as output dependent, the rating was poor (0 points). If model results are output-independent but are sensitive to variables it is impossible to measure, the rating was good (3 points). If results are sensitive to measurable variables and are output-independent, the rating is excellent (8 points). An additional two points was awarded to models sensitive to variables important in TFW management, such as shade.

Practicality Criteria

Practicality criteria considered both cost of model application and the user-friendliness of the model. Costs include equipment and personnel needed to collect, collate and enter data into the computer. It should be remembered that field data collected at a site could represents only a portion of the necessary data for some models and considerable effort could still be required in the office to gather the necessary information to run the model. The estimates of time and level of expertise required to perform tasks were based on documentation of time expended by the Temperature Study field crew and experience of the TWG in performing this study. Data acquisition and management costs for the model testing and simulation runs were evaluated by determining the time required to collect the specific information used in each analysis. It should be noted that the costs listed here do not necessarily represent those estimated for future TFW application, since the committee will develop some modifications to both models and input data requirements to facilitate model use in routine management operations. These projected costs will be discussed in following sections of this report. The intent of this section is to evaluate the costs and practicality of "off-the-shelf" models.

Costs

Field Personnel. The level of expertise of personnel required to gather the data necessary to run the model. *Rating:* 10=Technician 5=General Professional 0=Technical Advisor. (A technical advisor is defined as a professional with extensive experience, and a specialty in this type of modeling. A general professional has a scientific background but does not necessarily have any experience with temperature measurement or modeling.)

Field Equipment. Equipment required to gather data required by the model. *Rating:* 10=Low (<$100) 5=Medium ($100-$500) 1=High (>$500) .

Field Training. The level of field personnel training required to collect data. *Rating*: 10=No additional training beyond materials provided with the model is required 3=Additional training in a classroom or field setting is required.

Field Data Collection. Personnel costs based on estimates of field time (excluding travel time) required to collect data at one site. Rating: 1=Stream traverse is required, as well as collection of measured air and/or water temperatures requiring multiple site visits; 5=A stream traverse, and one-time visit is all that is required. 10=All needed information to use the model is available from current sources: air-photos, maps, GIS, regional climate or other databases.

Data Management. Office personnel costs based on estimates of time required to get all necessary data into the appropriate format. Rating: 10=Files used for input can be easily generated from commonly used spreadsheets. 5=The model requires a separate computer generated data file; 1=Each input value must be entered manually using program menus.

Model Run Cost. Personnel costs based on time required to sit at the computer and run the model. (This task as been rated separately since the models differ significantly in computer run time.) Rating: 10=Model runs entire simulation period (30-40 days) from one input data set; 0=Model requires daily iterations necessitating re-entry of all input values for each day modeled.

Computer Equipment. Is a computer required to run the model? *Rating:* 5=No 0=Yes.

User-Friendliness

The user-friendliness of the model was defined as the level of training required to run the model and the extent to which unsolvable computer problems were encountered as the models were run. Tied to the extent that problems occurred was a consideration of the quality of product support to solve those problems. Because many problems were encountered by the TWG in performing model tests, this aspect of using the models was considered important in finding a satisfactory model for TFW use. (Since Brown's model was not computer-based, it was awarded the maximum points where specific criteria were applied.)

Training. The degree of operator training required to run the model. *Rating:* 10=No additional training is required beyond use of materials provided as model documentation; 3=Additional training in a classroom setting is required to effectively use the model.

Operation Mechanics. The occurrence of recoverable and nonrecoverable errors (requiring exiting the model or starting again) during model operation. Non-recoverable errors are those where the program ceases to run with no recourse. The occurrence of recoverable errors was considered, as well as how well the model checked for errors and informed users. 10=Model performs error check on data entry, and clearly explains errors; 5=Model contains recoverable errors, or allows some user information; 0=Occurrence of unexplained, unrecoverable, or undocumented errors.

Product Support. Was help available if problems with the model were encountered during its use? *Rating:* 10= The model was fully supported by phone, access to qualified personnel and had documentation; 5=Limited model documentation, or some source code was available, but no phone support; 0=No help was available and documentation was very limited.

Output. The manner in which model output is generated determines the ease with which output can be used in for management decision-making. *Rating:* 10=The model generates graphic output, and/or values that can be easily imported into a spreadsheet;

5=The model generals a file which requires extensive edition to obtain needed information; 0=No computer output is generated.

Model Friendliness. Subjective rating of the overall ease of model use based on the experience of TWG after extensive model testing. The rating ranges between 0 and 10 where 10=Friendly and 0=Hostile.

Results of Applying Criteria

Performance. Two of the four site models were found to predict temperature particularly well. (Ratings and scores are provided in Table 4.16 and depicted graphically in Figure 4.26) Remarkably, TEMP-86 scored all of the possible 1300 points while TEMPEST was a close second scoring 1180. These two models consistently predicted all temperature characteristics accurately and with good precision. Although all site models were expected to perform fairly well at the outset of this study, the very good accuracy of these two models over such a wide range of conditions was both surprising and promising in suggesting that a satisfactory model could be identified for TFW application.

The other two models did not predict temperature nearly as well. The SSTEMP model did a good job of predicting mean daily temperature, but performed poorly in predicting maximum, minimum and diurnal fluctuations. SSTEMP's poor prediction of diurnal fluctuations may result from the way that thi characteristic is mathematically computed. The overall performance score for SSTEMP was only 58 of 1300 points.

Brown's model received a very low performance scor (60 of 1300), largely because the model only predict maximum temperature and does not predict most of the temperature characteristics that were included in the selection criteria. Even so, the model was not consistent in predicting the maximum temperature, predicting well at some sites and poorly at others.

No model was found to have significant bias in accuracy of temperature prediction relative to stream size or shading conditions. This was also a positive result for future TFW applications.

Figure 4.26 Performance scores based on model-testing results for four site models. Scores are computed based on criteria described in the text. The total possible score for each model was 1300.

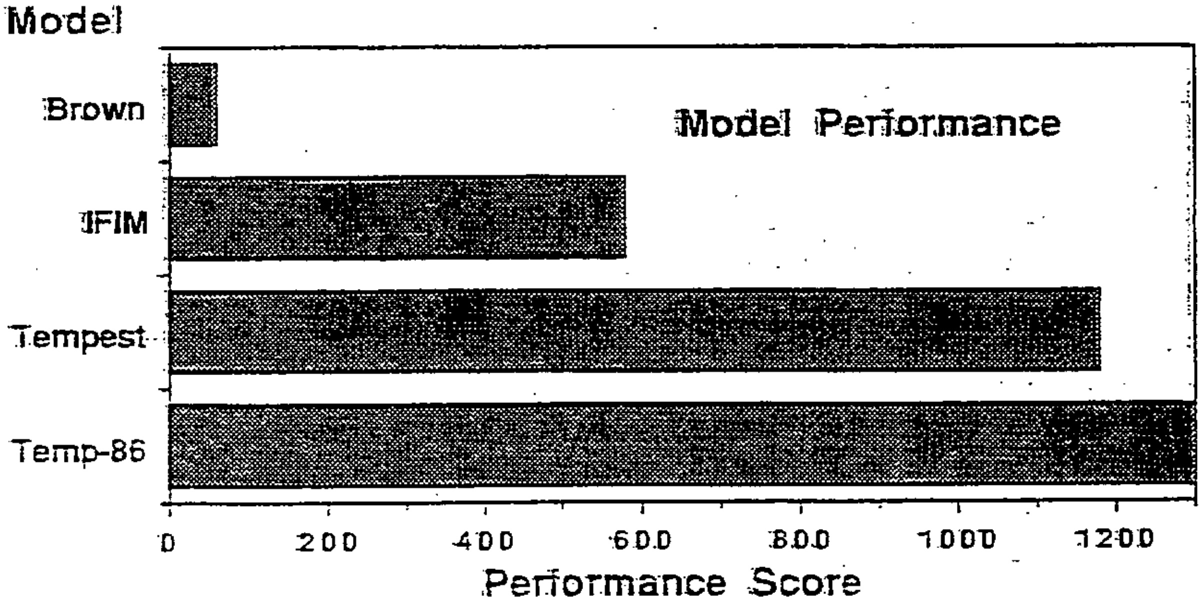


Table 4.16 _ Performance statistics for site temperature models and scores shown in the upper right hand box. (Scores are calculated based on the ratings described in the text multiplied by the criteria weighting in Table 4.15 .)

CRITERIA	Temp-86		TEMPEST		SSTEMP		Brown	
Accuracy--Maximum	0.01	100	0.39	100	1.08	60	-2.96	0
Accuracy--Mean	0.05	100	0.13	100	-0.26	100	0	0
Accuracy--Minimum	0.05	100	-0.25	100	-1.94	60	0	0
Accuracy--Diurnal Flux	-0.03	100	0.63	100	3.00	0	0	0
Precision--Maximum	0.96	100	1.48	60	1.51	60	1.75	60
Precision--Mean	0.62	100	0.92	100	0.68	100	0	0
Precision--Minimum	0.64	100	0.76	100	2.06	0	0	0
Precision--Flux	0.95	100	1.54	60	3.31	0	0	0
Consistency--Maximum	93%	100	93%	100	78%	0	30%	0
Consistency--Mean	93%	100	100%	100	100%	100	0	0
Consistency--Minimum	100%	100	100%	100	64%	0	0	0
Consistency--Flux	97%	100	88%	60	42%	0	0	0
Bias (Size)--Mean	No	25	No	25	No	25	0	0
Bias (Size)--Flux	No	25	No	25	Yes	0	0	0
Bias (Riparian)--Mean	No	25	No	25	No	25	0	0
Bias (Riparian)--Flux	No	25	No	25	No	25	0	0
Performance Score	*1300*		*1180*		*555*		*60*	

It is important to note that the excellent results of the TEMP-86 model in this test may have been something of an artifact of the way in which the test was run. Sensitivity analysis showed that TEMP-86 is very sensitive to input water temperatures. Since hourly measured values of water temperature are required as input to the model, it stands to reason that the model would predict temperature quite well since the model can only adjust the temperature slightly over a one-hour period. Thus, the model prediction is "corrected" hourly based on observed data. Very low errors would be expected with such a short prediction period. The other models were challenged to predict the real temperature with no such correction. The TWG was not sure that the excellent performance of TEMP-86 would hold up when no measured water temperature data would be available to run it. In that case, the investigator's ability to estimate the temperature would determine the model's accuracy. These concerns were expressed in the reliability scores.

Reliability. Reliability of model results reflected the importance of input variables required by the models and their effect on predicted temperature. Three of the models were rated to have good reliability, including Brown's, SSTEMP and TEMPEST. (Reliability scores are provided in Table 4.17 and shown graphically in Figure 4.27). Only TEMP-86 scored low in this category, largely due to the large effect on input water temperature on prediction results. A rating of good was given to SSTEMP model even though it requires a number of variables that do not significantly affect results since suitable default values are provided for many stream conditions.

Generally, the simplest models requiring the fewest input variables scored the highest (Figure 4.27.) Brown's model and TEMPEST each require relatively few variables to run them. It should be noted, however, that requiring few variables does not necessarily ensure good model performance as indicated by the results of the performance scores (Figure 4.26). The SSTEMP model scored slightly lower than Brown's or TEMPEST, largely because of the large number of variables required by the model that add relatively little to its predictive capability.

Practicality. Practicality criteria weighed such factors as personnel requirements and costs to run each model. Tracking of costs and time expended during field data collection and model runs served as the basis for this analysis. As with the reliability criteria, the simplest models tended to score the highest in practicality. (Practicality scores are provided in Table 4.17 and shown graphically in Figure 4.28).

Brown's model was the most practical, requiring little effort in the field and not necessarily demanding computer equipment or skills. However, running this model over longer time frames than a single day significantly increased the difficulty of its use. TEMPEST rated nearly as high as Brown's model in practicality, largely because field data collection is relatively simple, and the computer modeling aspects of data input needs and model output format were considered easy to use. Based on the extensive

Figure 4.27 Reliability scores for four site models based on model-testing results. Scores are computed based on criteria described in the text. The total possible reliability score for each model was 750.

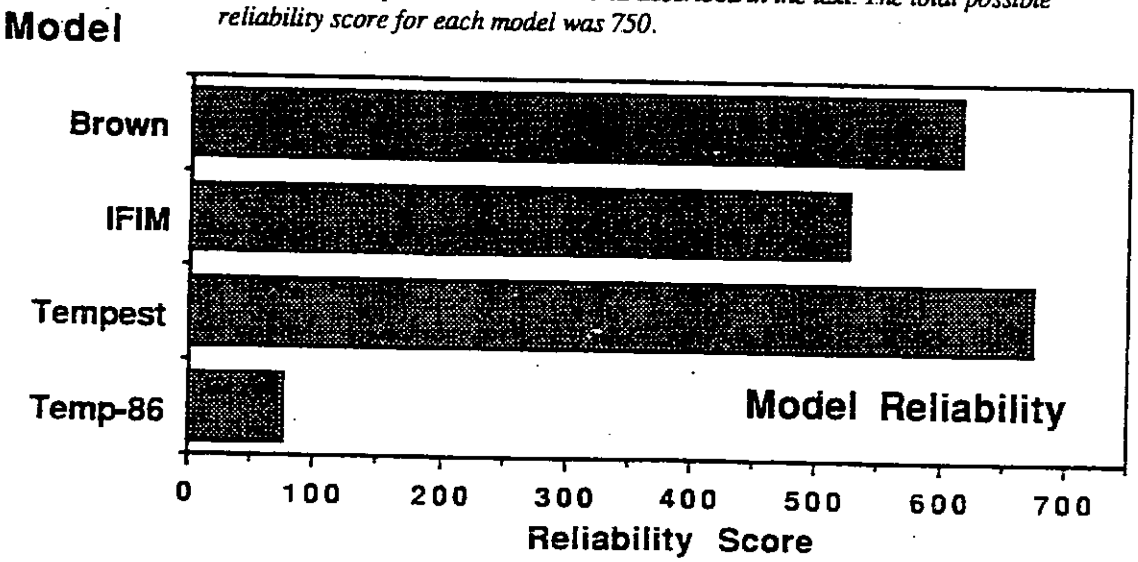


Table 4.17 *Reliability and practicality statistics for site temperature models. Actual ratings as described in the text are shown in the main box and the scores calculated based on the rating multiplied by the criteria weighting in Table 4.15 are shown in the upper right hand box.*

CRITERIA	Temp-86		TEMPEST		SSTEMP		Brown	
Number of Variables	0	0	10	150	5	75	10	150
Model Response	5	75	10	150	0	0	5	75
Variable Measureability	5	75	5	75	5	75	10	150
Parameter Sensitivity	0	0	10	300	10	300	8	240
RELIABILITY SCORE	150		675		450		615	
Field Personnel	5	75	5	75	5	75	10	150
Field Equipment	1	6	1	6	1	6	10	60
Field Training	3	27	10	90	3	27	10	90
Field Data Collection	1	24	1	24	1	24	10	240
Data Management	1	9	10	90	1	9	1	9
Model Run Cost	0	0	10	60	0	0	0	0
Computer Equipment	1	3	1	3	1	9	10	30
Computer Training	10	30	10	30	10	30	5	15
Operation Mechanics	0	0	5	30	10	60	0	0
Product Support	5	15	5	15	5	15	5	15
Output	0	0	10	60	5	30	0	0
Model Friendliness	1	15	8	120	5	75	5	75
Practicality Score	204		603		360		684	
Total	*1654*		*2458*		*1390*		*1359*	

number of modeling runs performed by the TWG, TEMPEST was considered to be the most user-friendly of all the models.

The SSTEMP and TEMP-86 models scored lower in practicality because of the large volumes of data required for input, and relatively awkward handling of data as input and output. It was clear during modeling exercises that the authors of these models did not anticipate the long modeling periods used by the TWG in model-testing, and their use in this way represents a deviation from their standard application. For applications outside of TFW, the practicality criteria might have rated differently for these two models and users might find them more practical than we did. For TFW's purposes, however, these models were considered moderate to difficult to use.

Conclusions and Recommended Site Model

When the performance, reliability and practicality categories of selection criteria were summed, there was a clear best choice (Figure 4.29). TEMPEST scored nearly 2500 of the total possible 3100 points and 800 points in front of the nearest rival. It should be noted that there was always competition between two or more models within each category (Figures 4.26, 4.27, and 4.28), and that each of the models scored well in at least one category. However, only TEMPEST scored well in all three categories rating performance, reliability and practicality, accounting for its relatively large score. In contrast, each of the other models scored poorly in at least one category.

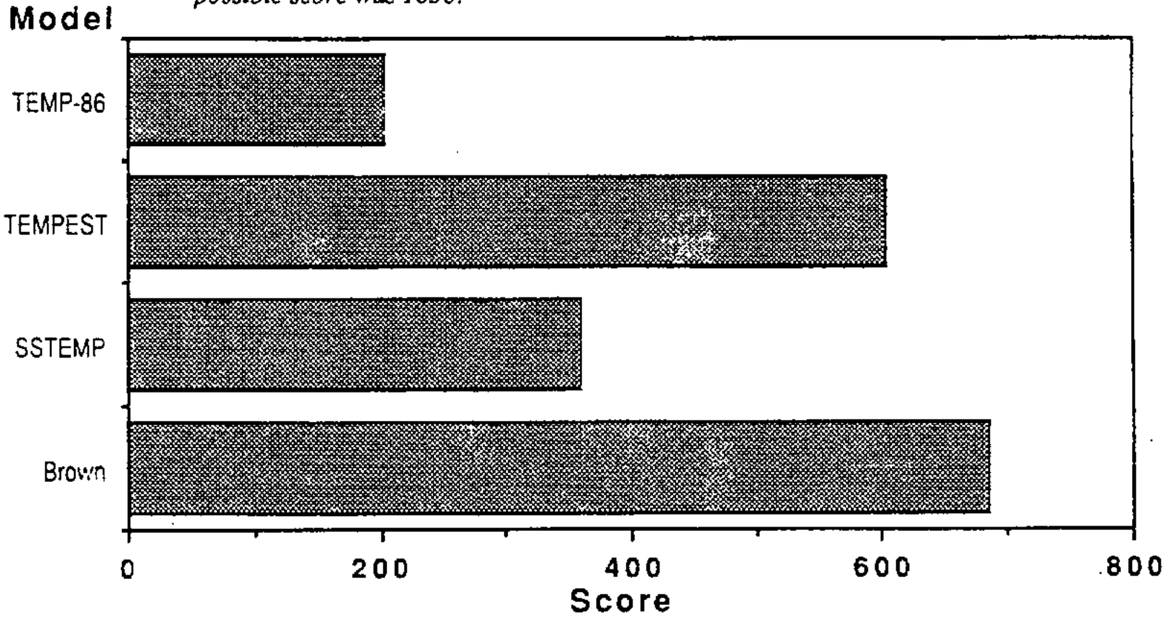
Because of its good performance and user-friendliness, the TWG recommends TEMPEST as the best site temperature prediction model for TFW applications.

This recommendation is based on selection criteria specific to proposed TFW application of site temperature models. The proposed use of the model (described in later sections) is to simulate temperature for a thirty-day time period from July 15 to August 15 when the warmest stream temperatures occur. The prediction will be evaluated to determine whether post-treatment stream shading will be sufficient to ensure that current temperature criteria will be met.

For temperature model users outside the TFW forest management environment, the results of this model-testing study may be of use in comparing model performance. However, each user's final selection criteria may vary from that used by the TWG and their conclusions on the best model for their purposes could vary from those of this study. Since several of these models are already used extensively in project applications and are familiar to some TFW participants, we summarize our general impressions of these models:

The SSTEMP model performs well in predicting mean temperatures but was disappointing in its ability to accurately estimate the maximums and minimums. These temperature characteristics are

Figure 4.28 Practicality scores for site models based on model-testing results. Scores are computed based on practicality criteria described in the text. The total possible score was 1050.

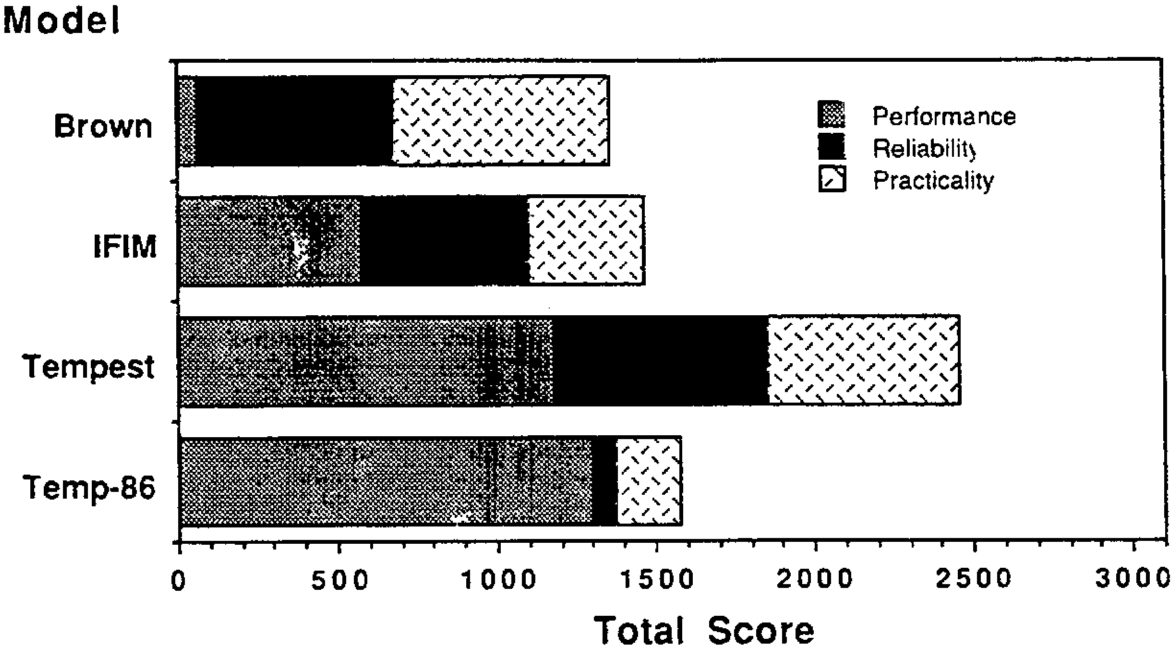


considered important to aquatic life and their accurate prediction is an important aspect of model performance that could be improved. The model is user-friendly and is well supported by its authors. The auxiliary solar calculation model (SSSOLAR) is well-suited for use by TFW. The shade model (SRSHADE) is easy to use, but requires extensive field measurements. Importantly, the model-testing results clearly showed that the model predicts temperature as well or better when a more simplified total sky view factor that is directly measured in the field with a densiometer is substituted for the SRSHADE output. This substitution allows greater flexibility in using the model for predictive game-playing and greatly simplifies its field use.

TEMP-86 appears to be an excellent temperature predictor when sufficient water temperature data is available as input. (Both maximum and minimum water temperatures and their time of occurrence are required inputs) The TWG was concerned about the sensitivity of the model to input water temperature, but did not extensively explore whether this would be a serious flaw in its general application. We recommend that users of this model satisfy themselves that model results are acceptable given the level of input data they have available. The model has many programming bugs, making it frustrating to use, and it is not well supported.

Brown's model is very simple to use and may provide a reasonable index of change in the maximum temperature with a change in stream shading. (It does require an estimate of pre-treatment conditions.) However, the model is inconsistent in its performance and may result in large errors at some sites while predicting well at others. It is noted that it was a precursor to all of the models tested and predates the current ready-availability of personal computers. Many of the advantages it once held are now a less important consideration in practical model applications.

Figure 4.29 Total score for site temperature models based on model-testing results.



CHAPTER 5
BASIN MODEL EVALUATION

INTRODUCTION

Two elements of basin-scale temperature concerns related to forest management must be addressed by basin temperature models. First, what is the magnitude and extent of downstream temperature response to a forest management activity occurring at an upstream location? In assessing the potential effect of a forest practice, it is important for managers to have the capability to predict how far downstream, and to what degree, temperature changes from that activity will be significant. Defining the distance downstream that a stream can be expected to show a response to a change caused by a forest practice will help managers to identify specific areas of concern and fully assess the risk associated with the proposed activity. Reach models can predict the change in temperature along a stream segment where the activity is planned, but cannot determine the downstream zone of influence. Second, what is the cumulative effect of multiple forest practices within a single basin?

The TWG envisions the use of basin models, (if any are found to work well enough in a TFW context) to be primarily in evaluating alternative management strategies, defined here as "gaming". Two examples of gaming include the definition of the length of a downstream impact zone from a timber harvest practice, if one exists, and the use of a basin network model in annual timber harvest planning.

The three basin models tested were QUAL2E, SNTEMP, and MODEL-Y. (See Chapter 1 for description of these models.) Two of these models, SNTEMP and MODEL-Y have counterpart reach models (respectively, SSTEMP and TEMPEST, discussed in Chapters 1, 2, and 4.). The three models vary in the manner that data is entered, heat transport is modeled, and the stream network that is constructed for calculation steps. Major considerations in evaluating these basin models was their ability to simulate a host of different management options in the basin, and of even greater fundamental importance, their ability to reliably predict temperature given the realistic constraints imposed by their expected use within TFW.

The basin models were far more complex to use than the reach models. Data and modeling requirements were intense, and it should be anticipated that general managers are not likely to be able to routinely commit the time or resources required to run a basin model. While documentation is available for the three basin models, they require considerable technical background to successfully generate useful information. Model-users are likely to be specialists requiring field and classroom training, and preferably possessing previous experience. For these reasons, it should be understood at the outset that use of a basin model in TFW is likely to be much more limited than reach models, which were simple to use and understand and very reliable for many applications.

METHODS

Basin Study Sites

The basin models were tested in three basins where co-operators were able to group study sites. Basin model tests were performed on watersheds which met the following criteria: (1) There were at least three primary study sites representing typical conditions within the basin, (2) There was a thermograph site at the lowest point of simulation. (Individual sites within the study basins were also included in the site-model evaluation described in Chapter 4.) Study basins included the Little Natches River in the southeastern Cascades (Figure 5.1; 4 sites), the Coweeman River in the south western Cascades (Figure 5.2; 7 sites), and the Deschutes River in the central Cascades (Figure 5.3; 6 primary sites and 3 secondary sites). Site characteristics are provided in Table 5.1.

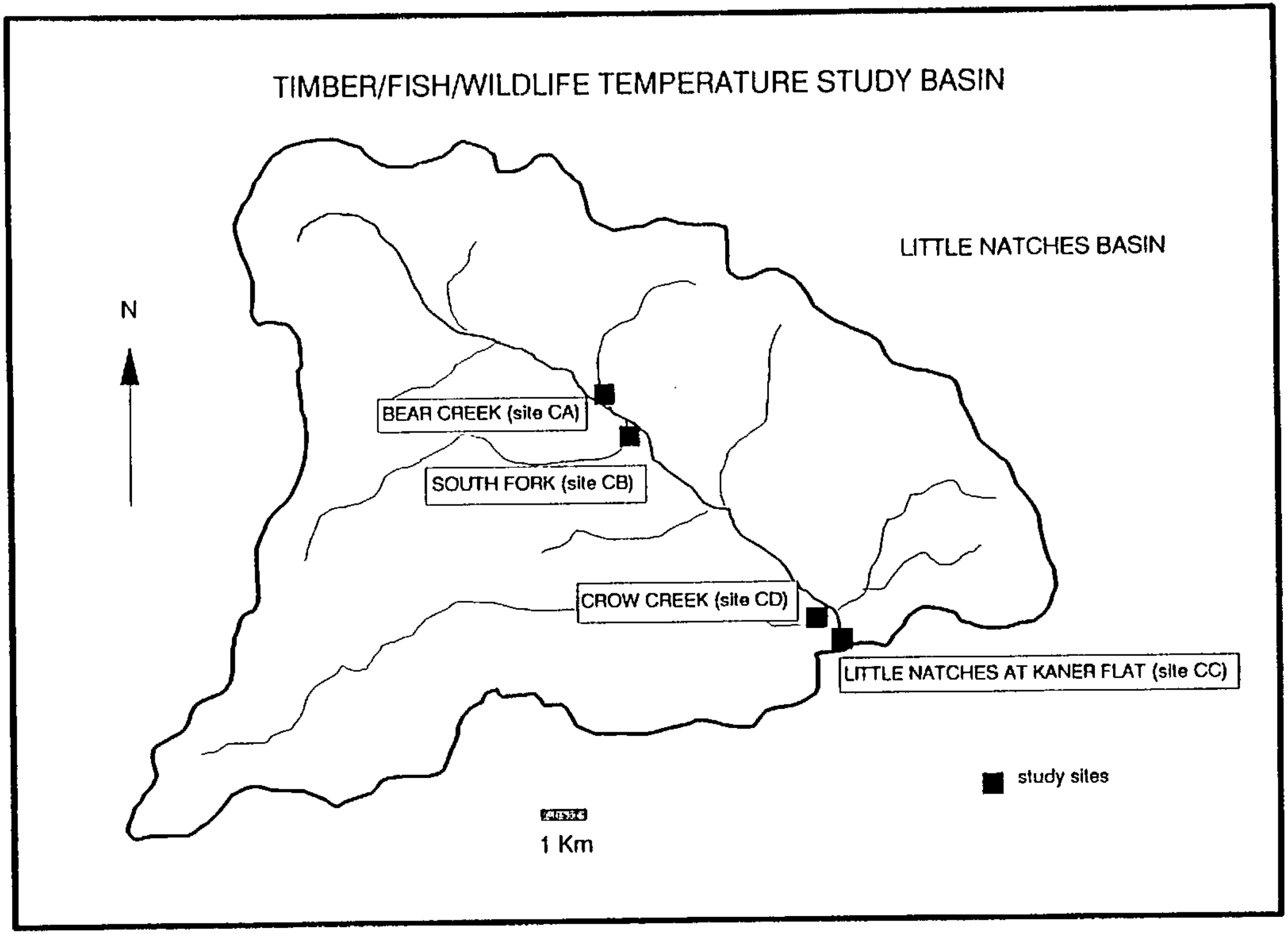


Figure 5.1 Little Naches Study Basin

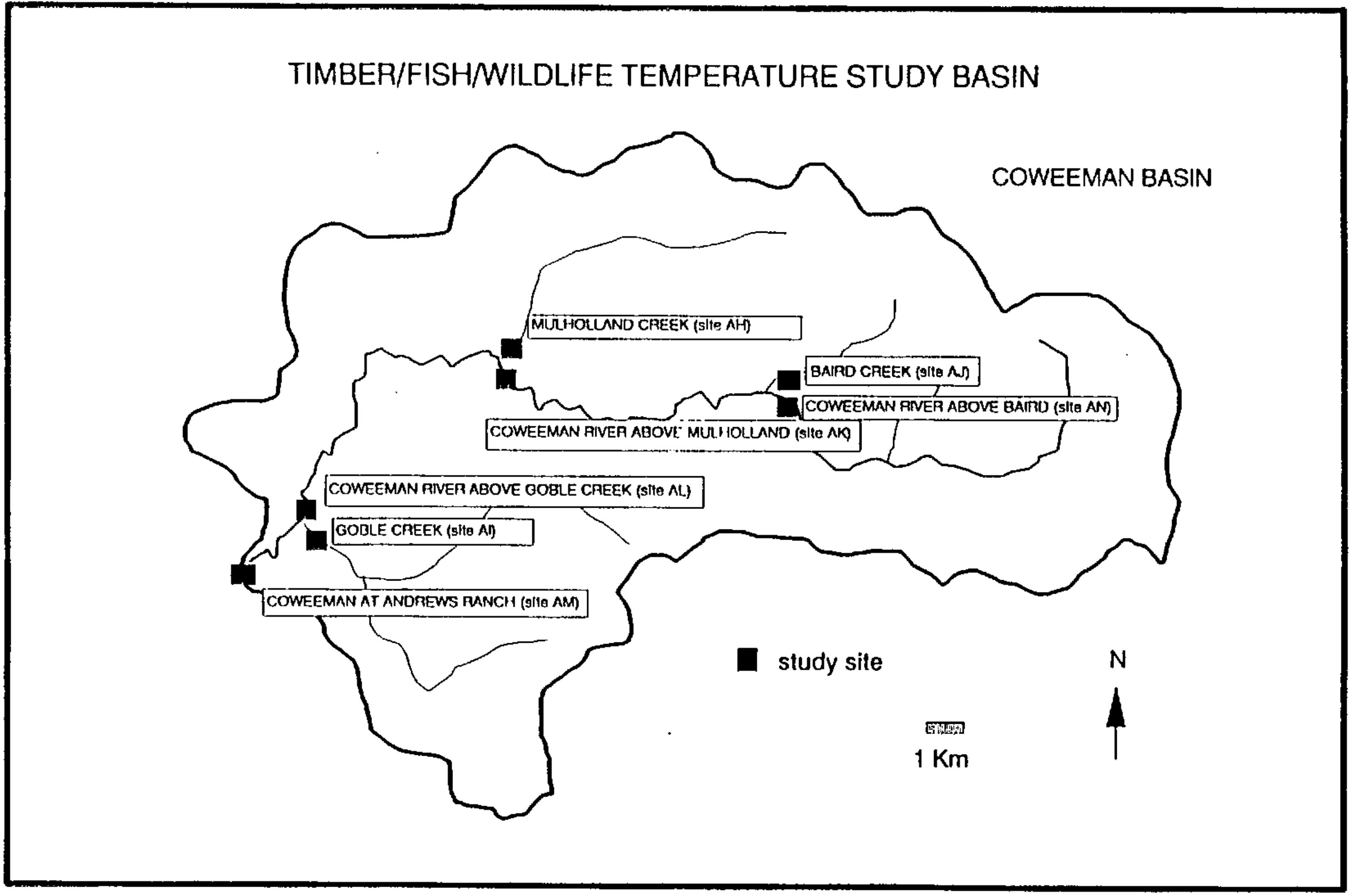


Figure 5.2 Coweeman Study Basin

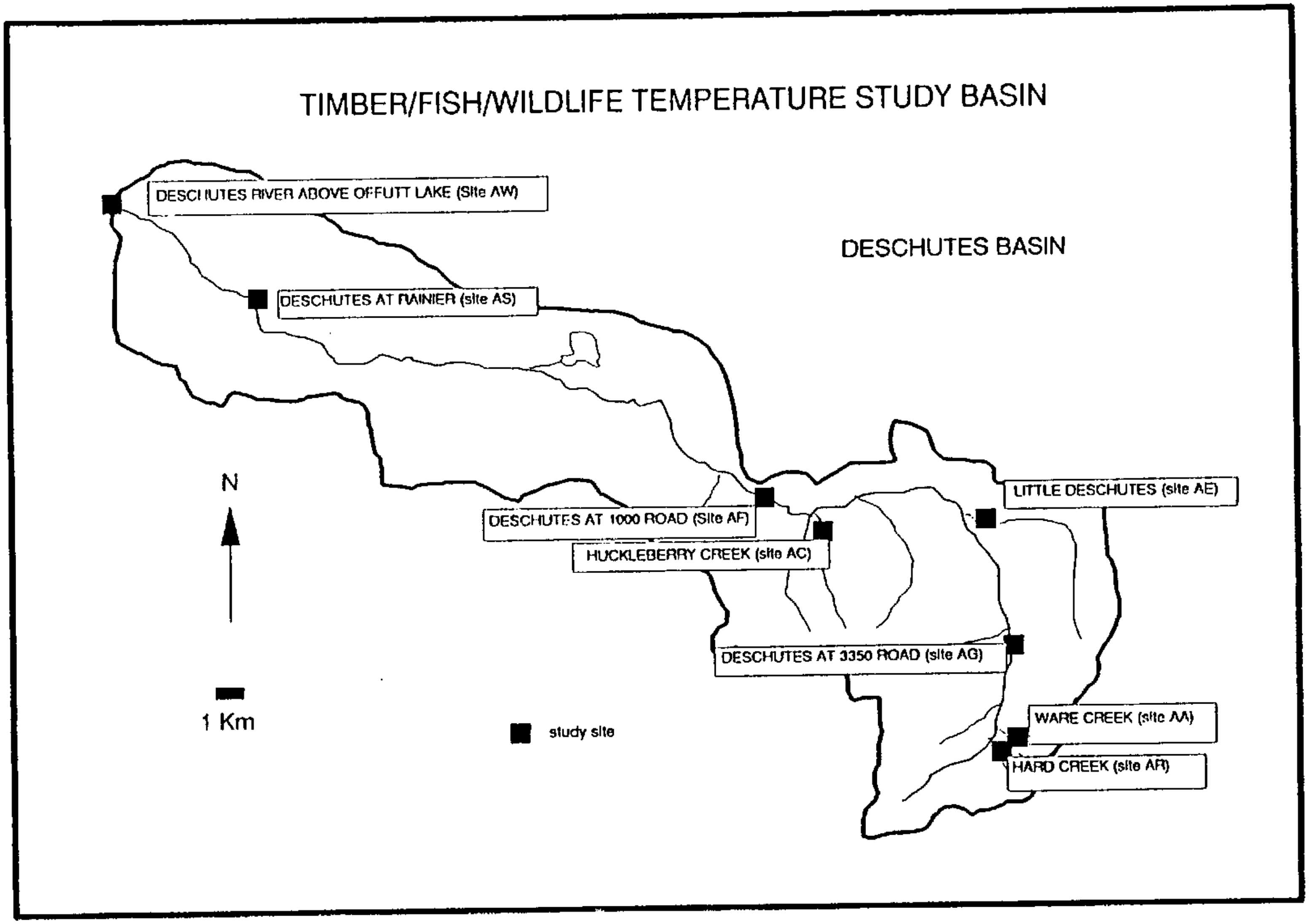


Figure 5.3 Deschutes Study Basin

Table 5.1 Characteristics of sites used in basin temperature model analysis. Stream and vegetation characteristics were measured at primary sites (see table 2.1). Characteristics were estimated at secondary sites (indicated as [a]).

Basin	Site Code	Site Name	Elev (m)	Sky View (%)	Distance (km)	Discharge (m^3/s)	Depth (m)	Bankfull Width (m)
Little Natches River								
	CA	Bear Creek	956	63	7.9	0.07	0.24	7.3
	CB	S.Fork Little Natches River	949	44	16.2	0.16	0.26	9.1
	CD	Crow Creek	827	71	27.8	0.60	0.34	10.1
	CC	Little Natches River at Kaner	813	81	30.0	1.32	0.37	24.4
Coweeman River								
	AJ	Baird Creek	216	40	7.9	0.28	0.28	10.1
	AH	Mulholland Creek	111	39	13.7	0.16	0.30	13.7
	AI	Goble Creek	48	40	12.9	0.27	0.30	12.8
	AN	Coweeman River (above Baird) (	209	59	17.4	0.78	0.35	12.2
	AK	Coweeman River (above Mulholland)	115	51	29.1	1.12	0.44	21.3
	AL	Coweeman River (above Goble)	43	78	40.7	1.63	0.59	22.9
	AM	Coweeman River (above Andrews)	27	72	43.8	1.57	0.54	30.2
Deschutes River								
	AR	Hard Creek	450	0-25[a]	1.9	.	16-25[a]	.
	AA	Ware Creek	436	93	3.0	0.03	0.16	10.7
	AC	Huckleberry Creek	197	17	5.8	0.03	0.13	.
	AD	Thurston Creek	292	40	5.2	0.12	0.22	.
	AE	Little Deschutes Cr.	269	31	9.4	0.07	0.23	9.3
	AG	Deschutes River (RK75.5)	342	70	9.8	0.48	0.34	15.2
	AF	Deschutes River (RK60.2)	168	67	26.5	1.14	0.29	16.8
	AS	Deschutes River (RK 41.7)	.	75-100[a]	43.6	.	.41-.60[a]	.
	AW	Deschutes River (near Offut Lake)	20[a]	75-100[a]	85.6	.	.	.

Stream System Description

The most difficult aspect of basin temperature modeling is describing the stream system in sufficient detail to accurately predict water temperature. Basin temperature models require the division of the stream system into a series of discrete segments, referred to as "computational elements" (Figure 5.4). The energy-budget equations are solved to calculate the net heat change for each computational element and calculate temperature, and the result is numerically transported to the next element downstream, where the process is repeated. The models use a complex series of data arrays to manage data between timesteps and in routing the temperature from one segment to the next. Calculated temperatures for each computational element are extracted from the data arrays and provided to the user. Depending on the detail used in dividing the stream system into computational elements, a large array of information must be generated, managed, and manipulated to effectively use a basin model. Even for the relatively few sites per basin used in this study (for example, 8 for the 450 km^2 Deschutes basin), the computational and data requirements were quite large.

The basin models further characterize a watershed as a skeleton of reaches and nodes. Reaches are lengths of stream where the environmental parameters of shading, climate, hydrology, and stream geometry are assumed constant. Each reach (containing a number of computational elements) begins and ends with a node defining a designated location where a particular type of computation is performed. Typically nodes are designated as either initializing points, where calculations are initialized with beginning assumptions, or locations where physical conditions change such as where tributary streams enter the skeleton, or where changes in the riparian, climate, or channel-geometry conditions occur. Node types generally needed for TFW simulations are: 1) headwater nodes (the first node on a stream); 2) branch nodes (indicating the presence of a tributary); 3) junction nodes (the first node below a tributary indicating mixing of flows); 4) change nodes (indicating a change in environmental parameters), and 5) the termination node (the most downstream node in the basin).

Stream Network Definition. The first step in model testing required definition of the stream network for the three basins. This was a challenging process that required balancing the need to describe the system in as simple a manner as possible to facilitate modeling against the need for sufficient description to accurately represent the highly complex basin conditions. Complicated network descriptions that closely match the real basin drainage pattern can be built, but they may exceed the capacity for model calculations (not to mention an organization's resources to collect the required input data). Conversely an overly simplified network may lack the needed precision and resolution for good simulation.

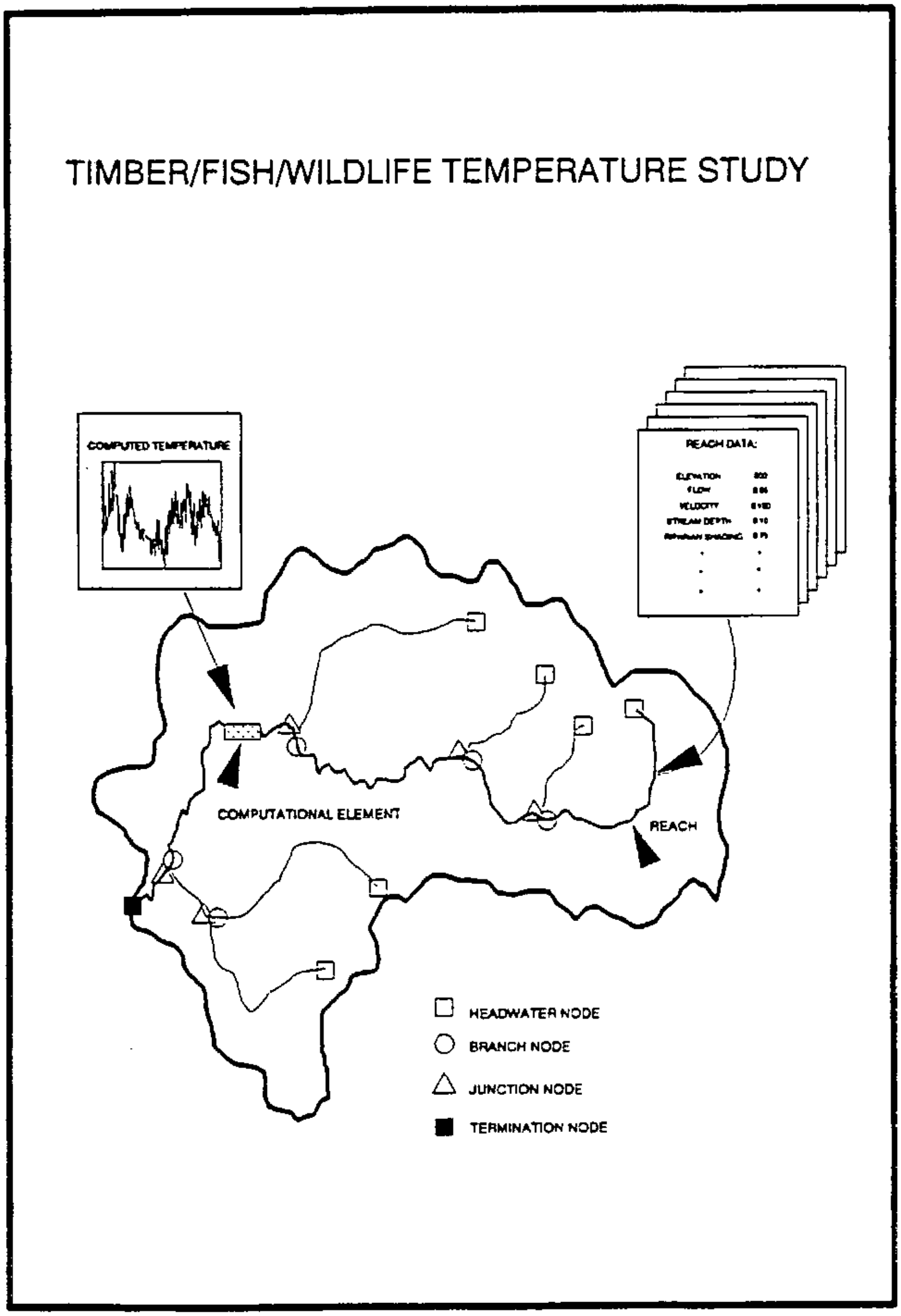
The Deschutes basin network was derived from a PC-ARC-INFO® 1:24,000 scale geographical information system coverage. The networks for the Coweeman and Little Natches watersheds were digitized from USGS topographic maps at a scale of 1:100,000 and 1:62,500 respectively, since ARC-INFO information was not available for these areas. The ARC-INFO coverage, developed by the Puget Sound River Basins Team, contained TFW water types 1 through 5 over the entire Deschutes watershed. The stream segment lengths and node attributes were exported from PC-ARC-INFO® and edited to form the stream network skeleton needed for developing the model-specific stream network. The editing included sorting the reaches into downstream order and deleting those tributaries not contributing at least 10% flow.

Once this base network was developed the model specific networks were built. The QUAL2E network was developed first. This model limits the tributaries to six. (This feature was considered a limitation in TFW applications, since most watersheds of interest to TFW have a greater number of tributaries that would significantly affect temperature). This and other restrictions dictated the configuration of the network to some extent. All tributaries were treated as point sources.

The SNTEMP network was developed next. This required adding tributaries, branch, junction, and riparian change nodes to the basic skeleton network. The reach lengths and tributary mileposts (along the main channel) were determined. The same network was used for MODEL-Y, although the reaches were broken at locations corresponding to the distance water travels in one timestep (typically one hour). (The average velocity function presented in Chapter 3 was used to split reaches into the one-hour long computational elements.) A spreadsheet containing lookup-values based on the travel time function was used to calculate milepost points for standard computational-element nodes.

The procedure was to move downstream along the mainstem starting from a headwater node at 1 km from the drainage divide. A 'branch node' was entered when a tributary was encountered. Before moving downstream, the model computed the temperature of the tributary by backing up to the headwaters using timesteps determined as above, initializing temperature at the

Figure 5.4 Basin temperature model system description.



source, and calculating temperature downstream to the junction. Tributary temperature was recorded at the branch node, and then flow from the tributary and the mainstem was mixed. The new temperature was recorded at the next timestep at a junction node identified at the end of the next downstream reach. Predicted temperature can be reported at any computational element or node.

Data Requirements

One the system skeleton of reaches and nodes basin temperature models was constructed, the arrays of environmental data satisfying model input requirements was created. Input parameters included: shading, streamflow, groundwater inflow, relative humidity, wind movement, air temperature, channel depth and width, elevation, and basin latitude (see Table 2.3 for parameter list). Although these data were needed for each computational element, they are specified at the reach or basin scale.

Hydrology. Streamflow data are important for calculating the transfer of the heat from one reach to another. In addition, tributary inflow must be accounted for as cooler or warmer streams merge. A simple flow mixing equation was used for tributary inflow following Brown and others (1971):

$$T3 = \frac{(T1*Q1) + (T2*Q2)}{Q1 + Q2}$$

Where: T1 and T2 are the temperature of the two stream reaches joining. Q1 and Q2 are the respective stream flows of the adjoining reaches, and T3 is the resultant stream temperature immediately downstream of the junction.

Streamflow was assumed to be constant over the modeling period. Headwater flows were initialized at zero, and increased with distance by the relationship described in Chapter 3. Streamflow was assumed one-directional with uniform mixing.

Groundwater inflow was treated as a residual in the flow mass balance of QUAL2E and SNTEMP. Groundwater influx was held constant at the median value from all sites in the temperature study for MODEL-Y. Groundwater temperature was approximated by a relationship to mean annual air temperature as described in Chapter 3.

Climatological Data. Basin models required data to describe the climate of the watershed including solar radiation, relative humidity, air temperature, cloud cover, wind speed, and mean annual air temperature. Each model's specific requirements were somewhat unique. QUAL2E demanded the most detailed climate data, accepting values of cloudiness, dry-bulb temperature, wet-bulb temperature, barometric pressure, and wind speed every three hours. These data were obtained from the NOAA Local Climatological Data for Washington for Olympia and Yakima (NOAA 1988).

SNTEMP required mean daily air temperature, mean daily wind speed, mean daily relative humidity, and mean daily percent possible sun. These data were supplied from the NOAA Local Climatological Data sites.

MODEL-Y utilized internal climatologic and solar profiles developed from regional data collected during this study. Derivation of hourly air temperature profiles is described in Chapter 3. Regional daily values of relative humidity (corrected to 25°C) and sky cover were derived from Quillayute, Olympia, and Yakima NOAA climatological stations. Solar values for MODEL-Y were calculated using the USF&WS SSSOLAR model using median values for input parameters. These values were then corrected to observed data published by Cinquemani and others (1978), and Critchfield (1978).

Channel geometry. Channel geometry data are required to describe the channel width, depth, roughness and average stream velocity. The velocity and roughness affect the routing of heat downstream; the channel width and depth effect the heat balance of the computational element.

Each of the models have somewhat different requirements for describing the hydrologic budget and the shape of the stream channel. QUAL2E offers two options for describing average velocity and channel depth. One is the trapezoidal channel shape method and the other is the discharge coefficients method. The coefficient method was used with the slope set to 0.0 and the intercept was the measured field value for velocity and depth. (This assumed constant flow over the modeling period). SNTEMP also used this coefficient method. MODEL-Y used channel depth as a direct measure of flow geometry appropriate for heat transfer relationships. Depth was determined from the relationship between depth and the distance downstream from the watershed divide developed in Chapter 3. MODEL-Y also assumed depth was an adequate surrogate for flow in the tributary flow mixing equation.

Riparian and Topographic Shading. Values for shading were obtained by measurement in the primary study sites within the study basins. No attempt was made to measure shade conditions of other reaches, although shade values for unmonitored sites were estimated from primary sites with similar size and riparian cover. Shade values for SNTEMP were calculated with the USF&WS SRSHD reach model as described in Chapter 4. Shade values for MODEL-Y were the view-to-the-sky factor measured at primary study sites within the study basins. QUAL2E does not require a shading factor.

Water Temperature. Values for water temperature were needed as estimates for initial conditions, point discharges, and calibration of the QUAL2E model. The headwater nodes were initialized at groundwater temperature, and tributary streams were treated as point discharges. Mean water values for the modeling period were used as the tributary temperature values.

Model Tests

Calibration. Several of the basin temperature models were designed to be used with a calibration step. A typical calibration step would consist of changing model input parameters to force model output to match observed temperature values at locations where water temperature has been measured. The question of model calibration poses difficult problems for model use in TFW applications since regional or site-specific stream characteristic input values could be available, but observations of water temperature would probably not be. (This might not be the case for experimental basins where water temperature data could be gathered before running models.) For this test, the models were run using the best available input data, but were not calibrated to observed values. The TWG recognized that this represented a departure from normal use of QUAL2E and SNTEMP and probably does not fully express predictive ability of these two models. However, this test does adequately represent realistic limitations in the models' envisioned use in TFW.

Data processing and simulation. All data manipulation was performed with personal computers. A combination of programs supplied with the models supplemented with customized file-handling programs developed by the TWG were used for file-building and to reformat model output for statistical analysis.

RESULTS

Sensitivity Analysis

Two of the basin models are constructed from reach prediction models, simply adding heat transfer calculations to transport heat downstream. SNTEMP uses the same energy-balance algorithms as the SSTEMP reach model. MODEL-Y is derived from TEMPEST. Results of the sensitivity analysis of environmental factors on predictions that were performed on SSTEMP and TEMPEST (Chapter 4) were assumed applicable to their corresponding basin models. Using similar methods, sensitivity analysis for QUAL2E was performed using input parameters listed in Table 5.2. The sensitivity of predicted maximum,

Table 5.2. Sensitivity input values for for the basin model QUAL2E

Variable	Standard Value	Range
Air Temperature (°C)	18.72	9.36-37.44
Humidity (%)	15	0 - 100
Groundwater Inflow Rate ($m^3/s/km$)	0.00303	0.00003 - 0.01515
Clouds (% of sky)	100	1 - 100
Starting Water Temp. (°C)	16.4	14.1 - 32.8
Stream Velocity (m/s)	0.24	0.02 - 1.2
Stream Depth (m)	0.31	0.16 - 1.5

mean, and minimum temperatures to input variables was performed for small, medium and large streams (depths 0.16 m, 0.4 m, 1.0 m respectively). The sensitivity of predictions to depth was interpreted from the model's response in diurnal temperature.

As with the reach models, QUAL2E was most sensitive to air temperature and starting water temperature (Figure 5.5 and Table 5.2). The temperature of larger streams was more sensitive to starting water temperature than smaller streams. QUAL2E was more sensitive to starting water temperature than SSTEMP and TEMPEST, but less sensitive than TEMP86. Other environmental factors such as humidity and cloudiness had little effect on temperature predictions.

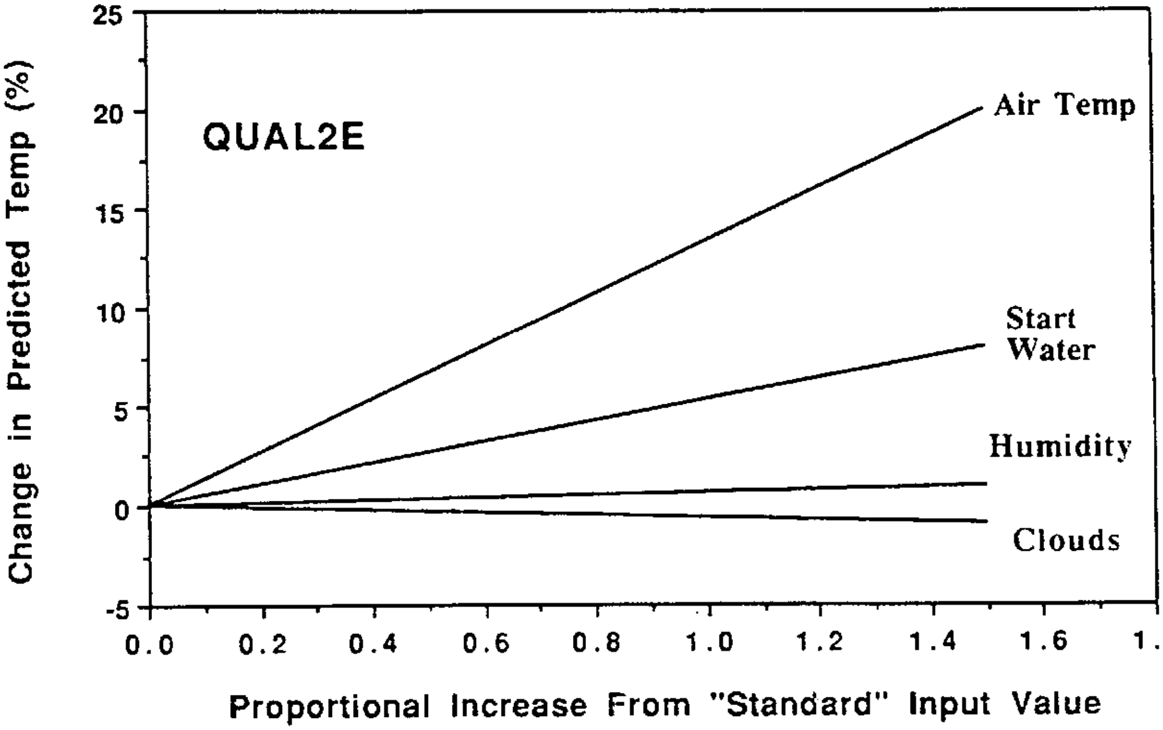
Sensitivity of the basin models to network factors (as opposed to environmental factors) were of interest to the TWG but were not thoroughly explored. All basin models use similar flow mixing equations in transport heat downstream. The sensitivity of predicted temperatures at a downstream point to changes in input parameter values in upstream reaches was not tested. The minimum size tributary to include in basin networks was also of interest. Generally, tributaries with less than 10% of the mainstem flow are neglected.

An estimate of the effect of tributary mixing (assuming a temperature of 10°C for the incoming stream) at various proportions of total streamflow and temperatures of the mainstem are shown in Figure 5.6. Tributaries contributing 10% of the flow reduce temperature by 1°C, suggesting that this is a good assumption.

Model Evaluation

As a consequence of the complex process of running and interpreting basin model results, the TWG concluded that the evaluation criteria would necessarily have to more subjective than for the site model-testing. Many factors were difficult to account for or quantify. Using these models turned out to be something of an art compared to site models, which were simple to use and understand. For the most part, the TWG found the basin models to be far more frustrating and less insightful for TFW applications then was hoped when testing began. The TWG evaluated model performance, reliability and practicality considering the TFW user as was done for the site models (Chapter 4). However,

Figure 5.5 Sensitivity analysis of environmental variables in QUAL 2E predicting mean temperature for medium size streams.



most of the criteria used for the site models had to be relaxed considerably for the basin models. In fact, few strict criteria were specified. Performance is judged based on general trends in predictions within basins, and practicality and reliability are discussed based on the experience of the group. The models were not formally rated.

Performance

Basin model performance was tested in much the same manner as the reach models. (An in-depth discussion of the statistical strategy can be found in Chapter 4). The difference between predicted and observed temperature (W-statistic) was used to evaluate each model's ability to accurately maximum, mean, and minimum temperatures, and the daily diurnal fluctuation. The accuracy, precision, consistency and bias of model predictions were considered as described in Chapter 4.

Overall performance of the models where all sites are averaged are summarized in Figure 5.7. Statistics computed for each site within the three basins are shown by model and basin in Figures 5.7-5.15.

(No overall basin performance was determined.) Trends in performance were examined relative to riparian shading levels, stream size, elevation, or position of the site in the stream system. This latter analysis was to determine if the model predictions systematically gained or lost errors from node to node irrespective of stream conditions.

QUAL2E

QUAL2E does not consider stream shading in the calculation of heat transfer, and so would not be expected to perform well in predicting the temperature of headwater streams where shading is known to significantly affect temperature. Not unexpectedly, the model poorly predicted all temperature characteristics in the upper reaches of both the Coweeman (Figure 5.8) and Deschutes Basins (Figure 5.9). Maximum temperatures tended to be more than 6°C too high at the most upstream locations in the watersheds (both are approximately 16 km from the watershed divide.)

Figure 5.6 Temperature effects from tributary mixing. The calculation assumes that tributary water temperature is 10 deg C.

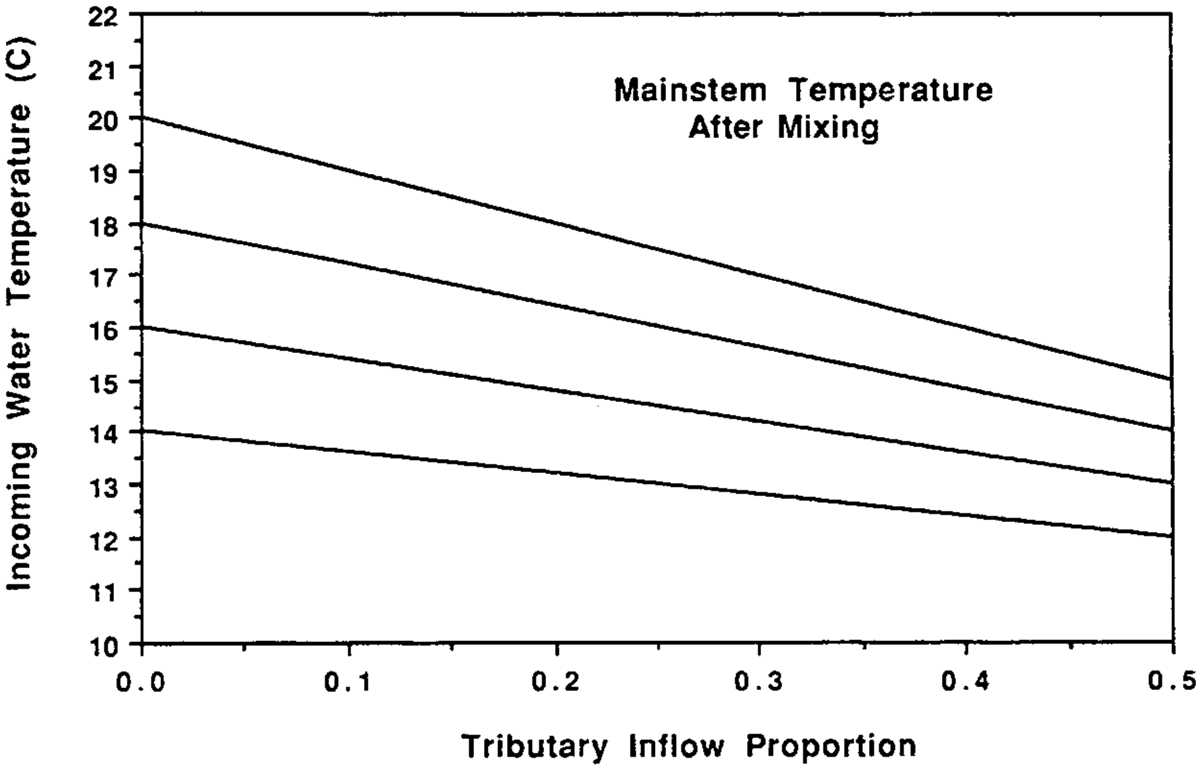
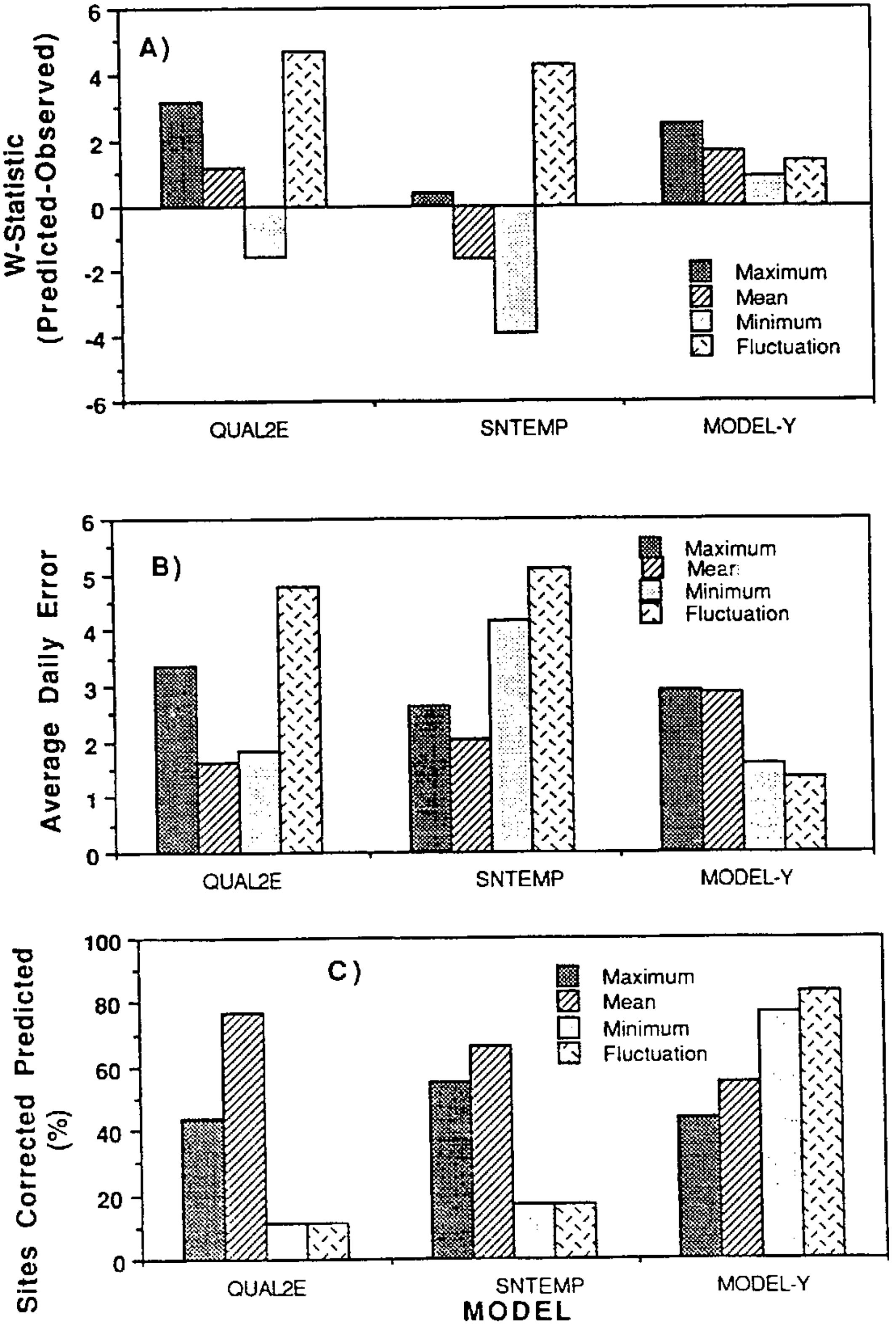


Figure 5.7 Performance statistics for basin model-testing averaged for all sites (A) w-statistics (predicted-observed), B)Average daily error , C) sites correctly predicted. sites tested.



The model performance improved progressively in the downstream direction where presumably shading had less influence on the temperature. In lower reaches, the model predicted maximum and mean temperature better than in the upper reaches, although it continued to underpredict the minimum temperature and diurnal fluctuation. Temperature predictions in the lower reaches of the river were well within acceptable levels (generally within 1-2°C). Because of the poor performance in headwater streams, the overall performance statistics of the model were only poor to fair (Figure 5.7). Maximum temperature was predicted correctly (within 2°C) at only 40% of the sites, although mean temperature predictions were better (77% of sites).

This model would appear to be a good performer in larger rivers where shade is not an influence on temperature, but would be a poor performer for TFW applications where the purpose for using the model is to predict the effects of forest management on shade.

SNTEMP

The overall performance of the USF&WS basin model appeared far better when averaged for all sites (Figure 5.7) then it was within any of the basins (Figure 5.10, 5.11, and 5.12.) Although the average W-statistic for the maximum temperature was 0.40 (better than in the site model test), the maximum W-statistic within basins ranged from large and positive in the Deschutes basin (model overpredicts) to large and negative in the Coweeman basin (model grossly underpredicts.) Results varied in the Little Natches Basin (Figure 5.12) where the model tended to predict high in the smaller streams and low in the larger river. The overall consistency of model predictions from site to site was on 15 to 70% correct, varying with temperature characteristic. The SNTEMP basin model was not consistent from site to site, but it did tend to show similar trends within the same basin. For example, the model underpredicted all characteristics at all sites in the Coweeman Basin (Figure 5.10). Predictions varied in the Deschutes Basin, but tended to be in the same throughout the basin (Figure 5.11)

Figure 5.8 W-STATISTIC for QUAL2E in the Coweeman Basin

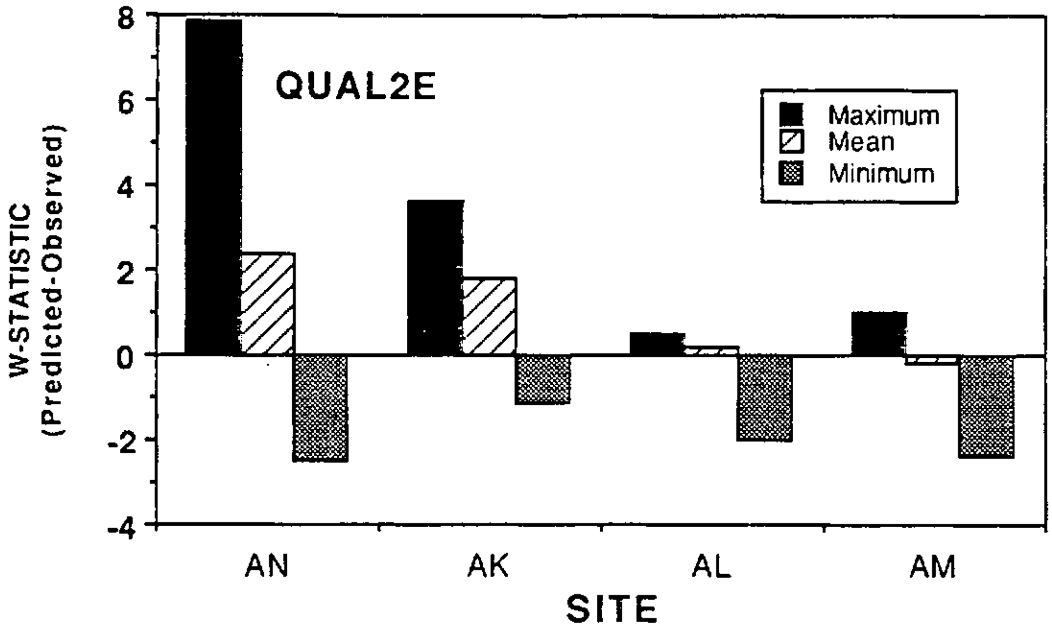
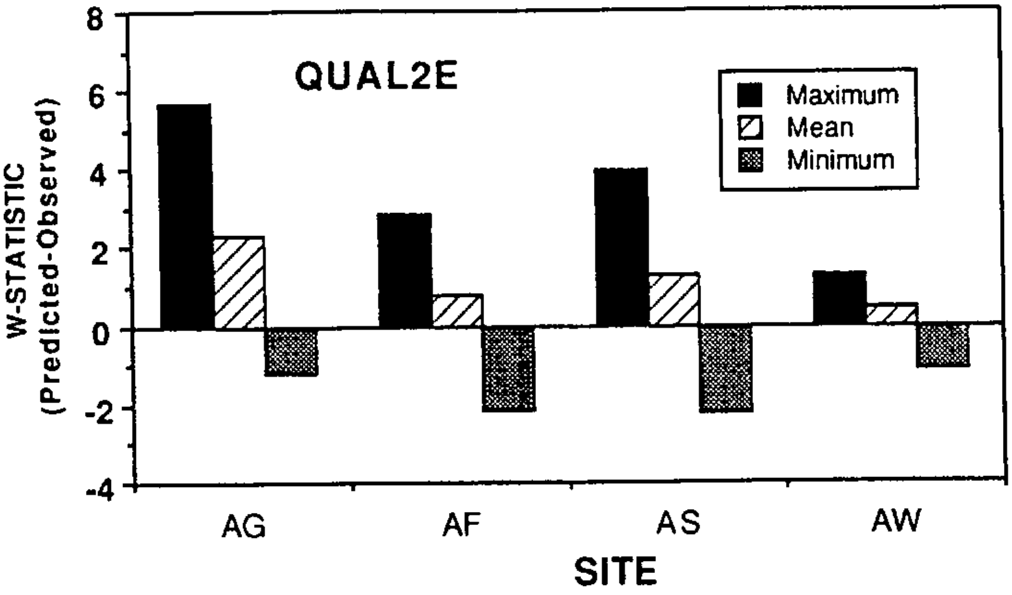


Figure 5.9 W-STATISTIC for QUAL2E in the Deschutes Basin.



The general performance of the models relative to maximum and minimum temperatures was somewhat surprising, given the results of the site model test. SSTEMP reach model calculates maximum temperature, and simply assumes minimum temperatures the be the same amount below the mean. As a result, when maximum temperatures were in error, minimum temperatures were typically in error an equal amount and in the opposite direction, explaining why the model was such a poor predictor of diurnal temperature fluctuation. Although a similar relationship was expected with the basin model, it was not observed. The TWG does not know whether model mechanics vary in calculating these temperatures between the reach and basin models.

Although the SNTEMP basin model predictions for maximum, and mean temperature were fairly good considering the estimates that go into running the model, the TWG felt that the performance as too inconsistent to recommend it for routine application. Many factors could have contributed to our inconsistent results, although we do not understand precisely why the model performed as it did. No calibration step was performed, which could certainly have affected overall performance within a basin. No calibration step would be possible in TFW application. We were unclear as to whether the number of measured sites within each of the basins was sufficient to provide the model enough calculating points, although maintaining 8 to 9 sites within one watershed was an intensive field effort requiring considerable resources including labor and equipment. We were also not sure that our basins were actually too small to achieve good results from the model, although we saw no consistent improvement in performance in the lower reaches of the rivers as we did with QUAL2E.

Figure 5.10 W-STATISTICS for SNTEMP for the Coweeman Basin

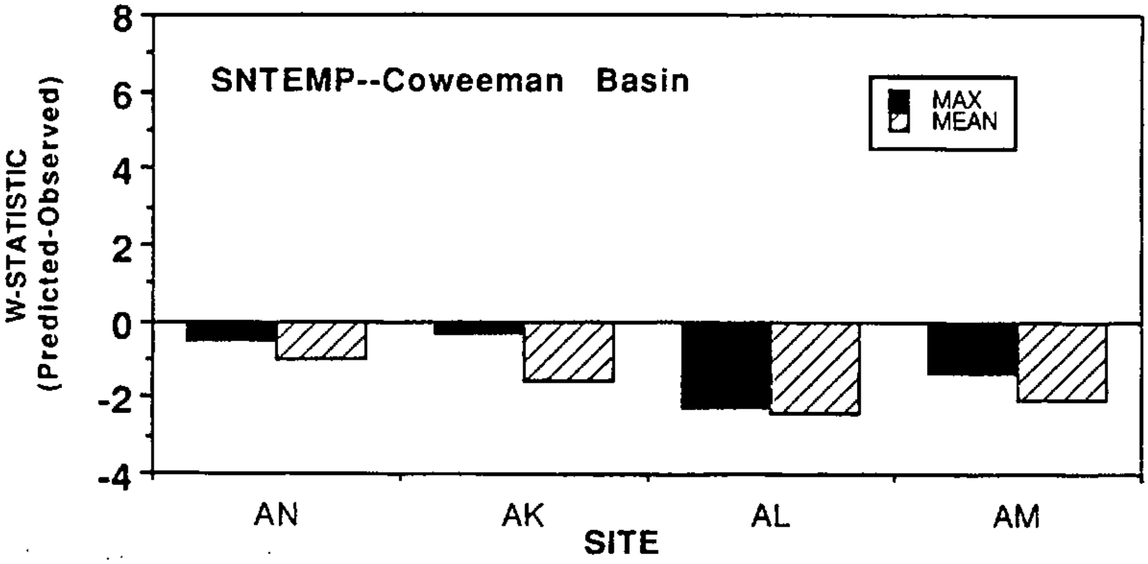


Figure 5.11 W-STATISTIC for SNTEMP for the Deschutes Basin.

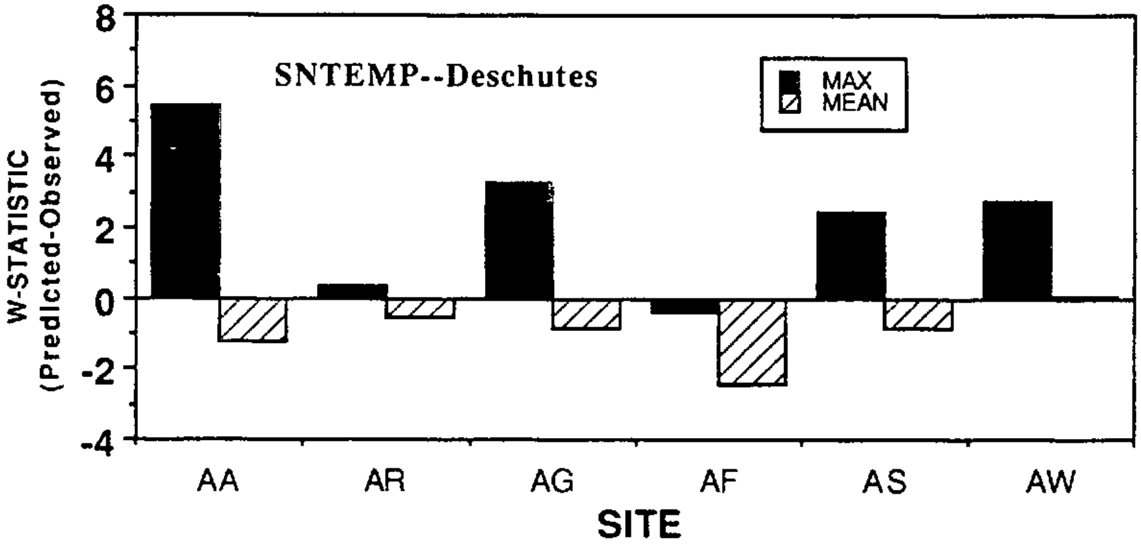
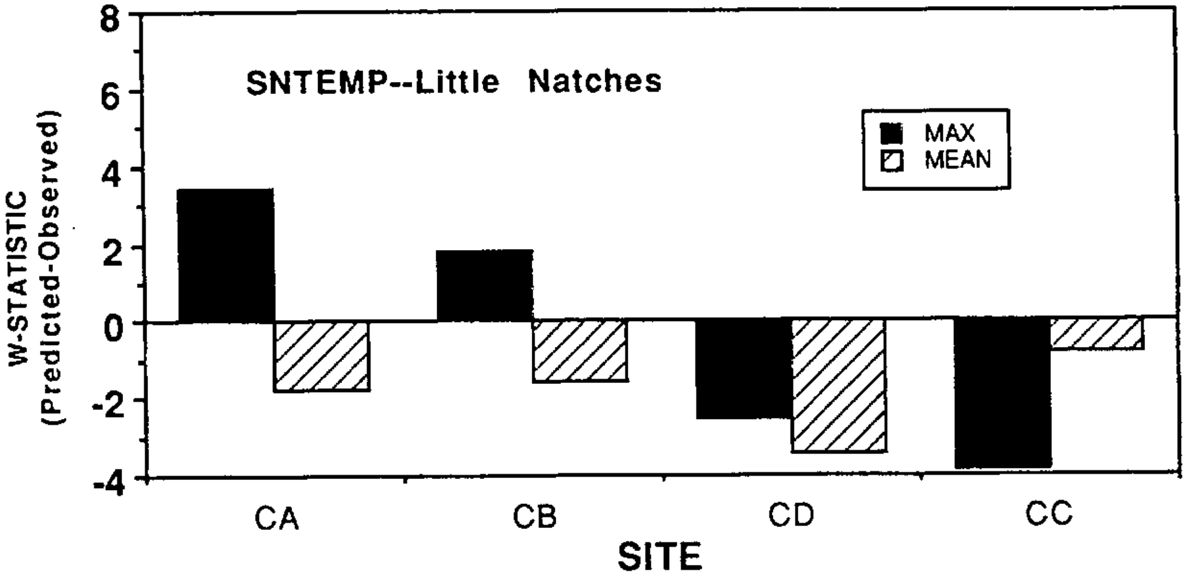


Figure 5.12 W-STATISTIC for SNTEMP for the Little Natches Basin.



MODEL-Y

MODEL-Y was the best overall performer (Figure 5.7) although it did not predict maximum temperatures as well as the SNTEMP basin model on average. The model was particularly accurate in the Coweeman Basin (Figure 5.13), fair in the Deschutes Basin (Figure 5.14) and poor in the Little Natches Basin (Figure 5.15). (The reach model TEMPEST also performed poorly at the sites in the Little Natches Basin so poor predictions here were not surprising.)

The model showed similar behavior as the site model, but predictions were less accurate. This can probably be attributed to the fact that most of the input values to MODEL-Y were estimated from regionalized relationships rather than measured as they were in the model tests. Neither MODEL-Y or SNTEMP were expected to predict temperature with the degree of precision that was observed in the site model tests. (For that matter, TEMPEST and SSTEMP would not be expected to predict as accurately if input data that the model is sensitive to is estimated rather than measured).

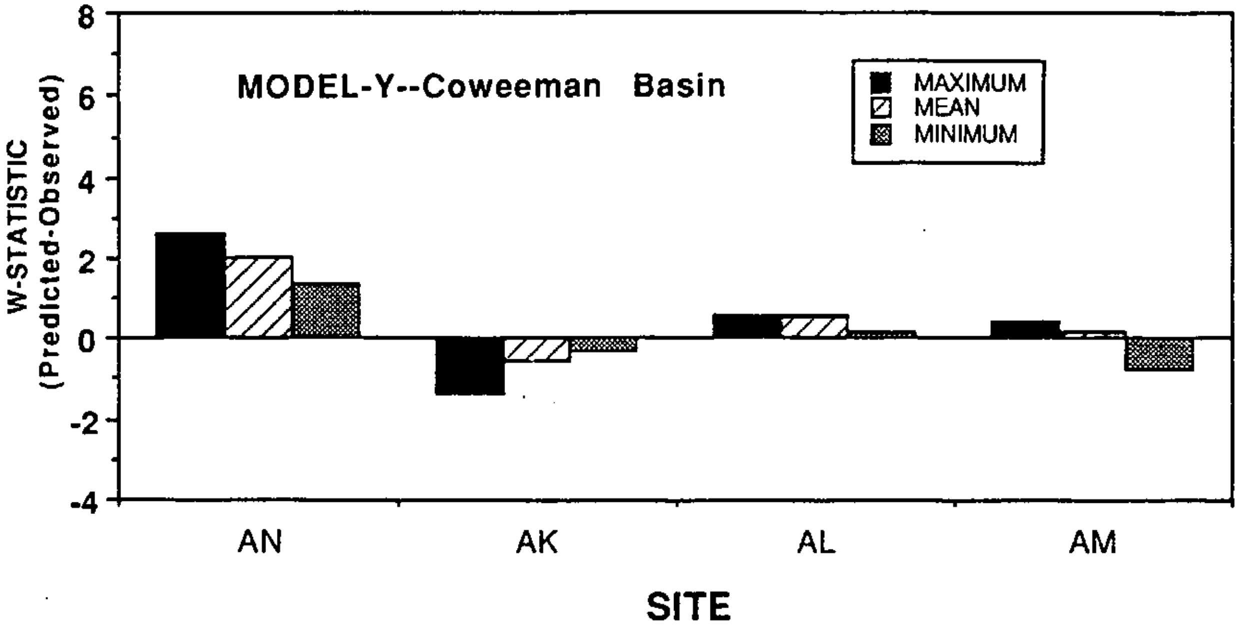
MODEL-Y was the most consistent model, both in predicting all temperature characteristics, and in the number of sites predicted accurately. However, maximums and means in particular were not predicted as well on average as with the SNTEMP model. Only about 50% of the sites were predicted within 2°C (Figure 5.7). Although this model shows promise, the TWG felt that it also did not perform well enough at this time to recommend its use.

Comparison Between Site and Basin Model Predictions

Reach models were shown to predict temperature accurately, even though only about 600 meters of stream characteristics were described as input values and basin conditions upstream of the sites were not quantified (Chapter 4). Reach modeling results suggested that water temperature could be considered a local phenomenon, dependent primarily on relatively close-by stream and riparian conditions (although the spatial influence was not identified.) Nevertheless, heat moves downstream with flow and important questions remain as to how far, and to what extent riparian conditions in upstream reaches influence temperature in downstream reaches. Indeed, this is the primary motivation for attempting to use the inherently more complex and difficult basin models.

It was hoped that differences in the predictions generated from the basin and site models could be used as an

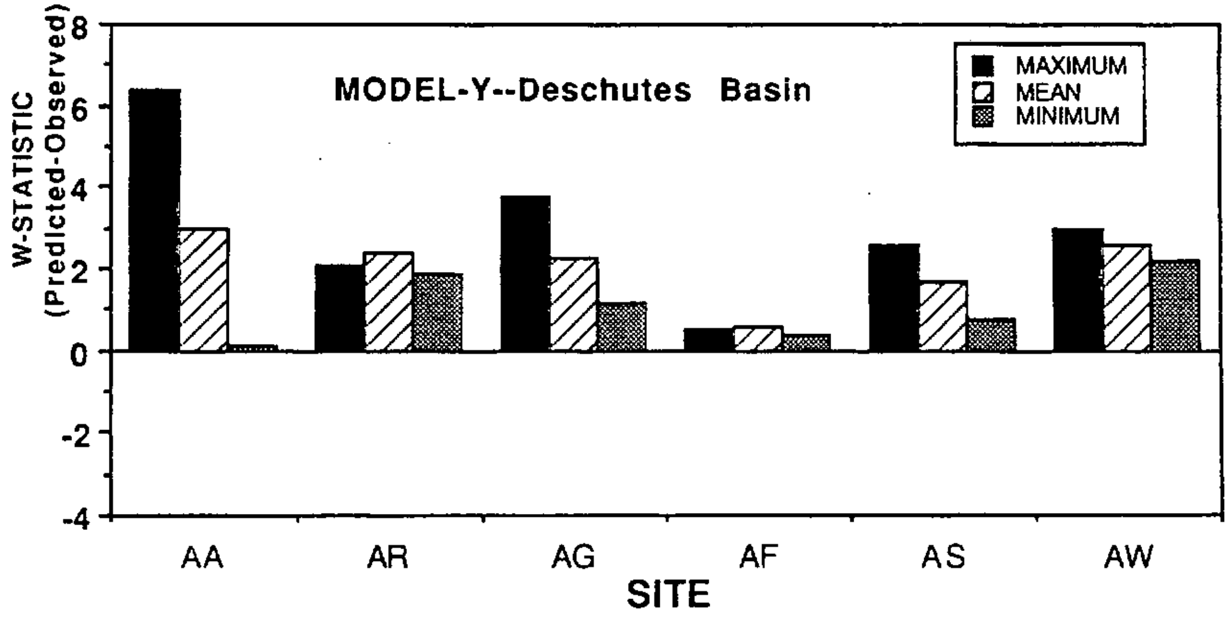
Figure 5.13 W-STATISTIC for MODEL-Y for the Coweeman Basin.



indicator of the relative importance of watershed conditions beyond the immediate reach. Improvement in predictions by basin models could be interpreted as indicating that offsite effects were significantly influencing the site. However, model results were so much less accurate in the basin test because so much of the data was estimated rather than measured, that it was impossible to draw definitive conclusions.

It can be said that basin models were imprecise, and only gross differences in temperature would be detectable using them. It was also shown that site models predicted well without characterizing much of the basin, although this is not helpful for interpreting

Figure 5.14 W-STATISTIC for MODEL-Y for the Deschutes Basin.



the near-site downstream effects of a timber harvest activity.

Sensitivity and Reliability

No specific tests were performed on the basin models to determine their reliability relative to ranges of input variables for various parameters. Although these tests were performed on the site models, it is not clear that they are directly applicable for the basin models. Predictions from both the SSTEMP and TEMPEST models were shown to vary over the naturally occurring range of the input variables, although SSTEMP tended to more sensitive than TEMPEST (Chapter 4; Figure 4.6). Since many of these parameters were not measured as they were for the basin tests but estimated from regional relationships, it was likely that the models would perform less reliably. The SSTEMP model was particularly sensitive to air temperature, which was measured for the site test but estimated from regional relationships for the basin test. Estimating these parameters rather than measuring them undoubtedly accounted for some of the decline in performance between site and basin models.

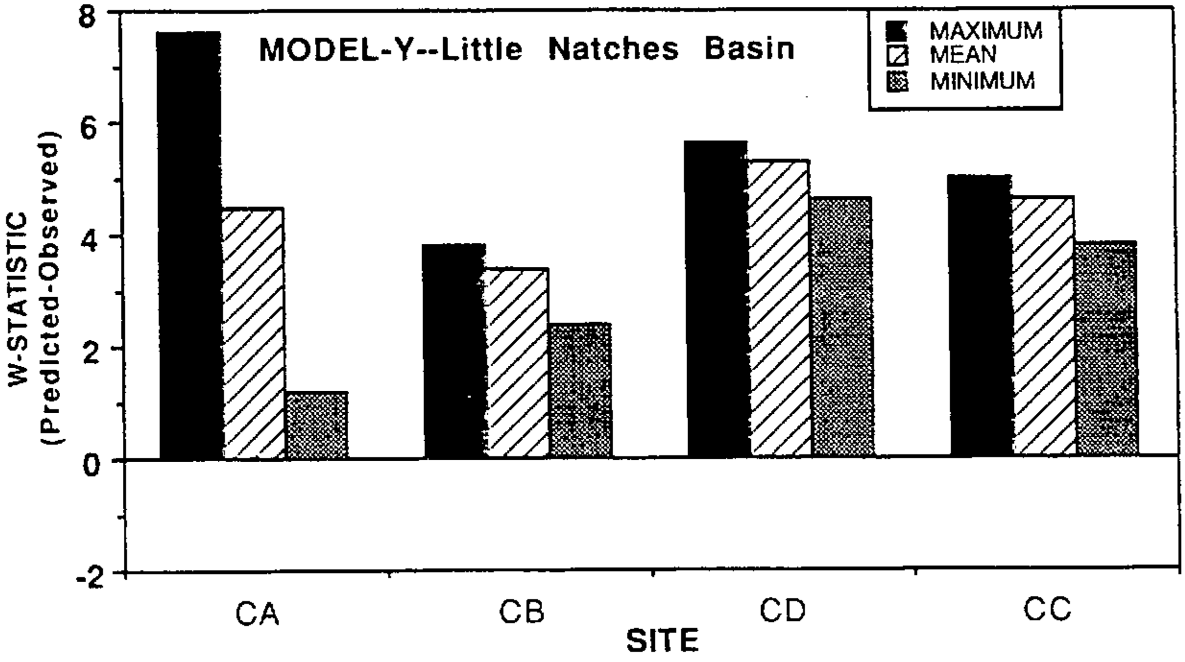
Practicality

Similar practicality criteria were considered for the basin models as for the reach models, including data requirements, model user-friendliness, and field data collections costs (Chapter 4).

Costs

All three models required collection of reach-specific data. MODEL-Y relied on regional estimates for travel time, stream depth, groundwater inflow, climate, and local air temperature, needing only a riparian and topographic view-to-the-sky-factor as the user-supplied reach data (assumed to be estimated in the field). (Improving performance of this model may require increasing the site-measured data input to it rather than relying on gross estimates from regionalized relationships.) QUAL2E required reach-specific channel geometry data, but did not require any shading factors. SNTEMP was the greatest consumer of data with multi-parameter shading information, channel geometry, and hydrology data needed on a reach basis. Gathering this information for more than a limited

Figure 5.15 W-STATISTIC for MODEL-Y for the Little Natches Basin.



number of sites would be a limitation in its routine use, although it may be applicable on an experimental or project basis. A unit cost per basin cannot be easily established without knowing the number of sites that would be required by that basin's unique topography.

Data Management

Data management costs were closely related to the complexity of the model data requirement. Data input and output features were an important consideration. MODEL-Y, with its simple data needs required only one spreadsheet-type data file to run, and output exported into simple spreadsheet-type arrays was easy to handle and interpret. QUAL2E required two carefully formatted, but fairly small, data files to run. However, QUAL2E output was very cumbersome and required a substantial amount of post-simulation processing by custom-built TWG programs to reformat the output into a useful data base. SNTEMP required eight carefully formatted and cross-referenced data files to run it. Although the USF&WS support services offered a very handy file-checking program to assist the user, file building and data management were still fairly tedious. SNTEMP support services also offered a utility program for reformatting the model output into a useful spreadsheet format.

Generally, getting data into the computer and running it through the models was more difficult than using the output. However, if attempting to use a basin model, be prepared to handle an enormous amount of computer information to obtain stream system predictions. For most of the models, gaming of alternative basin prescriptions would require difficult and repeated re-entry of information for each iteration.

Network Flexibility

Satisfaction with a model stems partly from the ability to set up the network in such a way that useful results for interpreting management effects can be generated. The construction of a suitable network was a very important part of the process. Each of the models had certain restrictions that limited the flexibility of the stream network. MODEL-Y is restricted by the travel time distance of the reaches. For example, tributaries must enter the network at a travel-time defined reach breaks. (This limits length to generally 200-500 meters). QUAL2E is probably the most constrained of all the models. It bounds the number of tributaries that can be included to six, the number of headwater nodes to seven, the number of computational elements to 250, the number of computational elements per reach to 20, and further mandates that all computational elements in the network be the same length. SNTEMP allows unlimited network configuration (limited by the available disk space) but places restrictions on the length of reaches and the network at large based on the 24-hour travel time requirements.

User Friendliness

The user-friendliness of the models was defined as the level of training required to run the model, ease of model use, and the extent to which unsolvable computer problems were encountered. The quality of product support was also considered. Given the level of complexity of data management required by basin models, this is a far more important consideration than it was for the site models, which can be run by anyone assuming basic computer skills. None of the basin models were easy enough to run to consider them practical for general use in TFW applications. Using any of the basin models required a higher level of computer skills, training, or specialization (although some were considerably easier to use than others).

Operation Mechanics and Product Support

All three models suffered from lack of error trapping and recovery. Unlike the reach models, none of the basin models contained internal data-range checking and warning information. SNTEMP, through its user support, does offer an external data checking program. Its use is highly recommended. Both SNTEMP and QUAL2E support services offer periodic training seminars. At this point such training is not available for MODEL-Y. SNTEMP support services provided much assistance to the TWG during this modeling effort.

CONCLUSIONS

This review of basin temperature models was based strictly on the need to recommend a model for TFW applications and should not be viewed as a rigorous test of any these model's ability to predict temperature with more controlled testing conditions. However, our experiences during model-testing reflect the hazards likely to be encountered when using basin temperature models in routine forest management decision-making in TFW. Such use imposes many constraints, including: 1) satisfactory performance in relatively small basins, 2) no opportunity for calibration steps, 3) reliance on regional relationships and estimates for some input parameters, and 4) the need to be able to manipulate the model data to provide gaming opportunities for testing alternative prescriptions on temperature at a basin scale.

First, the TWG cautions that use of any basin model is sufficiently complex, and as yet of undemonstrated value, that a general use of basin temperature models does not appear warranted. Furthermore, none of the basin models tested here performed well enough, were sufficiently practical and reliable, or had appropriate gaming capabilities to recommend their use. However, the TWG recognizes the worth of an operational basin model for the gaming and basin planning functions described above and encourages further development of a basin model on a limited experimental basis. Considering the existing strengths and weaknesses of the models, which might be the most appropriate?

QUAL2E does not consider riparian shading and therefore is not useful for TFW applications. Unless future versions of the model add this factor, this model should not be considered further. Additional problems with this model include its unfriendliness to users (it requires unacceptably complex segmentation for nodes and computational elements) and requirements for data that cannot be satisfied (relative humidity functions in particular, are among the most difficult to measure accurately). This model appears to work well in larger rivers, and would probably be a satisfactory choice for applications other than forest management.

SNTEMP: The model is complex, and should only be implemented by a trained and experienced user. The model is well-supported, and training is available, making its use feasible if TFW concerns warrant. However, it would require a specialist to apply it. The model demands a lot of information, and is not particularly suitable for simulating alternative management scenarios since data management is difficult. The basin model is less accurate on average than the reach model, and was inconsistent in its performance. The model performed poorly at some nodes, including those below tributary junctions where it should have performed better. These and other specific aspects of the model's performance remain unexplained, leaving the TWG uneasy about its reliability, especially for decision-making relative to basin layout of harvest plans.

MODEL-Y: This model seems to have the most potential for use in TFW applications since it is user-friendly, requires relatively little data, and has the best capacity of gaming. However, the model does not perform with sufficient reliability at this time to recommend its use. Some continued development of this model on an experimental basis may be warranted. If performance could be improved, the ability to game, or iteratively evaluate different riparian situations could prove extremely useful to TFW. It is likely that performance could be improved by increasing the amount of measured data input to the model.

CHAPTER 6

CHARACTERISTIC TEMPERATURE REGIMES

General trends and patterns of water temperature in relation to forest management and climate are documented in this chapter. Data collected from 92 sites located throughout Washington were used in this characterization of stream temperature from a site and basin perspective. The period of maximum summer temperatures (July to September) were the focus of this analysis, since forest practice regulations specify maximum temperature criteria, and data were readily available and most organizations measure temperature during this time. Eight sites were also measured during the winter months and these data were examined to determine possible changes during the colder months in relation to forest management.

Average summer temperature characteristics of forest streams throughout Washington are described (*Summer Temperature Regimes*). Stream temperature regimes and their relationship to environmental characteristics such as riparian shading are analyzed, and results are used to identify methods to easily characterize stream temperatures based on site and basin conditions (*Relationship to Environmental Factors*). Winter temperature regimes from a limited number of sites are explored (*Winter Temperature*). Characteristic basin temperature patterns are discussed using data collected at sites clustered within three watersheds, as well as by considering all sites in relation to their relative position in the watershed (*Basin Temperature Patterns*).

Temperature characteristics in relation to water quality regulatory standards and the effectiveness of riparian management strategies in protecting stream temperature are presented in Chapter 7 along with TFW temperature modeling recommendations.

AVERAGE STREAM TEMPERATURES OF WASHINGTON

General temporal and spatial temperature characteristics of Washington streams are investigated in this section. Daily maximum, mean and minimum, and diurnal fluctuation are the temperature characteristics considered in various analyses. Although many factors influencing temperature are discussed, the effect of shading by riparian vegetation is emphasized. Average temperature during the warmest 30-day period of the summer (July 15-August 15) are provided along with stream and basin characteristics of sites in Table 6.1. Two definitions of shading considerations used throughout this chapter are important: *view factor* refers to the proportion of the total horizon visible to the stream surface (expressed as percent); *shade* refers to the remaining proportion of the horizon blocked by all elements, including vegetation and topography, (also expressed as percent). The view factor and shade combine to take in 100% of the horizon.

Table 6.1 Site characteristics and average maximum, mean and minimum temperature for the period between July 15 and August 15. Stream and vegetation characteristics were measured at primary sites (see table 2.1). Characteristics were estimated at secondary sites (indicated as ^{a}).

Site Code	Site Name	Maximum (oC)	Mean (oC)	Minimum (oC)	Elev (m)	View (%)	Distance from Divide (km)	Discharge (m^3/s)	Depth (m)	Bankfull Width (m)	Azimuth (degrees)
AA	Ware Creek	16.9	14.5	12.2	436	93	3.0	0.03	0.16	10.7	303
AB	Schultz Creek	19.9	15.7	12.9	540	94	7.3	0.04	0.29	7.0	344
AC	Huckleberry Creek	13.6	12.9	12.4	197	17	5.8	0.03	0.13	.	348
AD	Thurston Creek	14.8	13.5	12.4	292	40	5.2	0.12	0.22	.	4
AE	Little Deschutes Cr.	15.2	14.0	12.8	269	31	9.4	0.07	0.23	9.3	315
AF	Deschutes River (RK60.2)	18.6	16.0	13.8	168	67	26.5	1.14	0.29	16.8	271
AG	Deschutes River (RK75.5)	15.0	13.5	12.0	342	70	9.8	0.48	0.34	15.2	357
AH	Mulholland Creek	18.2	16.1	14.4	111	39	13.7	0.16	0.30	13.7	231
AI	Goble Creek	18.5	16.5	14.8	48	40	12.9	0.27	0.30	12.8	316
AJ	Baird Creek	16.3	14.5	12.8	216	40	7.9	0.28	0.28	10.1	211
AK	Coweeman River (above Mulholland)	18.2	15.7	13.6	115	51	29.1	1.12	0.44	21.3	317
AL	Coweeman River (above Goble)	19.8	17.6	15.6	43	78	40.7	1.63	0.59	22.9	183
AM	Coweeman River (above Andrews)	19.1	17.5	16.4	27	72	43.8	1.57	0.54	30.2	247
AN	Coweeman River (above Baird)	16.2	14.1	12.0	209	59	17.4	0.78	0.35	12.2	273
AO	Herrington Creek	17.1	15.0	13.3	375	64	6.3	0.07	0.19	5.5	276
AP	Porter Creek	15.6	14.4	13.3	109	12	13.2	0.13	0.23	8.2	242
AQ	Hoffstadt Creek	22.0	16.9	12.7	587	100	7.3	0.10	0.23	15.2	237
AR	Hard Creek	12.5	11.0	10.2	450	0-25^a	1.9	.	16-25^a	.	303
AS	Deschutes River (RK 42)	16.8	16.1	15.1	120	50-75^a	43.6	.	.41-.60^a	.	.

Site Code	Site Name	Maximum (oC)	Mean (oC)	Minimum (oC)	Elev (m)	View (%)	Distance from Divide (km)	Discharge (m^3/s)	Depth (m)	Bankfull Width (m)	Azimuth (degrees)
AT	Gobar Creek	17.6	14.6	12.0	.	80^a	5.6	.	0.20^a	.	.
AW	Deschutes River (near Offut Lake)	17.0	15.7	14.6	20^a	50-75^a	85.6	.	.	.	.
BA	Abernathy Creek (Lower)	15.8	13.9	12.0	178	33	7.4	0.20	0.27	11.0	146
BB	Germany Creek (Upper)	17.5	15.2	12.8	184	38	7.9	0.09	0.32	11.0	160
BC	Naselle River	14.4	13.1	12.3	288	59	4.1	0.02	0.18	7.9	267
BD	Smith Creek	20.2	18.5	17.2	67	93	12.8	0.10	0.60	4.3	211
BE	Bear River	14.5	13.5	12.6	92	19	3.5	0.03	0.19	7.0	352
BF	Abernathy Creek (Upper)	16.6	14.9	13.2	.	25-50^a	.	.	.26-.40^a	.	.
CA	Bear Creek	14.2	11.8	10.2	956	63	7.9	0.07	0.24	7.3	154
CB	S.Fork Little Natches River	13.9	11.5	9.9	949	44	16.2	0.16	0.26	9.1	44
CC	Little Natches River at Kaner	17.1	13.9	11.1	813	81	30.0	1.32	0.37	24.4	158
CD	Crow Creek	15.4	12.7	10.1	827	71	27.8	0.60	0.34	10.1	69
CE	Bear Creek Watershed (Baseline)	14.0	13.2	12.5	317	25-50^a	9.8	.	.26-.40^a	.	.
CF	Wind River (Baseline)	14.3	12.8	11.2	341	25-50^a	19.1	.	.26-.40^a	.	.
CG	Trout Creek (Baseline)	13.2	12.8	12.2	341	25-50^a	15.9	.	.26-.40^a	.	.
CH	Trapper Creek (Baseline)	13.6	13.1	12.6	415	25-50^a	7.1	.	.16-.25^a	.	.
DA	Pilchuck River (RK 15.4)	19.1	16.9	15.0	38	95	18.5	1.78	0.50	23.5	177
DB	Pilchuck River (RK 2.7)	16.2	14.6	13.3	49	37	16.5	0.10	0.21	6.4	164
EA	Cee Cee Ah Creek	11.9	10.2	8.8	1048	70	6.1	0.03	0.14	3.7	190
EB	Chamokane Creek	20.1	15.8	12.1	446	93	46.4	0.72	0.28	14.0	216
FB	Norwegian Creek	12.0	10.0	8.0	1154	55	2.4	0.00	0.07	2.4	334
GA	Red Creek (Tributary)	16.2	14.8	13.3	41	15	4.0	0.07	0.21	5.8	258

Site Code	Site Name	Maximum (oC)	Mean (oC)	Minimum (oC)	Elev (m)	View (%)	Distance from Divide (km)	Discharge (m^3/s)	Depth (m)	Bankfull Width (m)	Azimuth (degrees)
GB	Red Creek	19.3	17.5	15.8	61	82	7.6	0.68	0.50	.	300
GC	Red Creek (Site 2)	15.4	15.0	14.7	.	.	.	.	.	.	.
HA	Little Deer Creek	17.6	15.1	12.4	463	77	10.6	0.23	0.41	17.7	173
HB	N. Fork Stillaguamish (up. Deer Cr)	13.5	11.4	9.7	.	40[a]	.	.	0.61[a]	.	.
HC	Squire Creek	13.6	12.3	11.2	792	51	18.0	0.77	0.52	.	325
HD	Higgins Creek	17.3	14.9	13.2	130	87	3.9	0.04	0.36	7.3	316
HE	S. Fork Nooksack River	.	.	.	105	97	26.7	3.94	0.39	.	331
HF	Tributary to S. Fork Nooksack	12.8	12.8	12.8	122	19	6.5	0.01	0.12	6.7	237
HG	N. Fork Stillaguamish (RM 38.8)	16.4	14.9	13.6	275	72	20.5	0.27	0.40	18.0	204
HH	Deer Creek (above Deforest)	19.3	15.4	12.3	487	76	14.0	0.27	0.39	27.7	299
HI	Deer Creek (at mouth)	18.2	16.5	14.7	58	89	38.5	1.37	0.37	30.2	211
HJ	S. Fork Nooksack (Upper river)	18.4	16.7	15.0	.	25	0.5	.	0.50	.	.
HK	Segelson Creek	8.6	8.0	7.4	.	10[a]	.	.	0.08[a]	.	.
HL	N. Fork Stillaguamish (do. Deer Cr)	17.6	15.5	13.2	.	70	.	.	0.46	.	.
IA	Ten Creek	16.1	14.8	13.8	.	.	.	.	.	.	.
IC	S. Prairie Creek (upper)	12.4	11.5	10.8	527	43	7.7	0.21	0.26	9.1	314
ID	Greenwater River	15.7	12.6	10.6	705	95	21.0	0.77	0.25	15.2	297
JA	Snow Creek	.	18.6	.	100[a]	50[a]	8.0	.	0.30[a]	.	.
KA	Wenatchee River (Site 1)	20.0	17.8	16.7	.	100[a]	.	.	.	.	.
KB	Wenatchee River (Site 2)	18.3	16.8	16.0	.	100[a]	.	.	.	.	.
KC	Wenatchee River (Site 3)	18.4	16.6	15.3	.	100[a]	.	.	.	.	.

Site Code	Site Name	Maximum (oC)	Mean (oC)	Minimum (oC)	Elev (m)	View (%)	Distance from Divide (km)	Discharge (m^3/s)	Depth (m)	Bankfull Width (m)	Azimuth (degrees)
KD	Wenatchee River (Site 4)	17.5	16.0	15.3	.	100[a]	.	.	.	.	.
KE	Icicle Creek Bypass	.	.	.	.	100[a]	.	.	.	.	.
LA	Tucannon River (below M.Russels Sp.)	19.4	16.1	13.7	.	100[a]	.	.	.	.	.
LB	Tucannon River (at bridge 14)	.	.	.	.	100[a]	.	.	.	.	.
LC	M. Russels Spring--Tucannon	19.2	15.8	13.4	.	100[a]	.	.	.	.	.
LD	Hartstock Cr--Tucannon	15.1	11.4	8.7	.	100[a]	.	.	.	.	.
LE	Tucannon River (Below Panjab Cr)	12.6	10.3	8.0	.	0[a]	.	.	.26-.40[a]	.	.
LF	Tucannon River (Below Big 4 Lake)	16.8	13.7	10.7	.	95[a]	.	.	.26-.40[a]	.	.
LG	Tucannon River (Below Deer Lake)	18.6	15.1	11.7	.	85[a]	.	.	.26-.40[a]	.	.
LH	Tucannon River (Below Cummings Cr)	18.6	15.1	11.7	.	70[a]	.	.	.15-.25[a]	.	.
LI	Tucannon River (Below Beaver Lake)	18.5	15.2	11.9	.	100[a]	.	.	.41-.60[a]	.	.
PA	Muddy River (Baseline)	10.3	9.5	8.7	366	25-50[a]	19.1	.	.26-.40[a]	.	.
PB	Clearwater Cr. (Baseline)	11.0	10.1	9.2	439	25-50[a]	21.4	.	.26-.40[a]	.	.
PC	Clearwater Creek (at rd. 9300)	15.4	13.5	11.6	.	51-75[a]	22.2	.	.26-.40[a]	.	.
PD	Clearwater Creek (upper)	17.2	13.8	10.3	.	76-100[a]	4.0	.	.	.	.
PE	Clearwater Creek (Bel. M. Brl.)	15.7	12.5	9.3	.	76-100[a]	8.8	.	.16-.25[a]	.	.
PF	Clearwater Creek (at Paradise Falls)	16.3	13.3	10.2	.	75-100[a]	13.0	.	.16-.25[a]	.	.
PG	Hungry Creek (Upper)	11.8	9.5	7.2	.	0-25[a]	1.2	.	.16-.25[a]	.	.

Site Code	Site Name	Maximum (oC)	Mean (oC)	Minimum (oC)	Elev (m)	View (%)	Distance from Divide (km)	Discharge (m^3/s)	Depth (m)	Bankfull Width (m)	Azimuth (degrees)
PH	Hungry Creek (Lower)	11.2	9.2	7.1	.	26-50[a]	1.2	.	.16-.25[a]	.	.
PJ	Johnson Creek (Baseline)	13.9	12.5	11.1	316	25-50[a]	18.2	.	.26-.40[a]	.	.
PI	Catt Creek (above Big Cr)	11.0	10.1	9.2	.	0-25[a]	.	.	.	.	.
PL	S. Fork Willame Cr. (Baseline)	10.0	9.7	9.3	536	0-25[a]	4.2	.	.16-.25[a]	.	.
PM	Clear Fork Cowlitz Cr (Baseline)	10.3	9.5	8.7	335	0-25[a]	27.8	.	.26-.40[a]	.	.
PN	N. Fork Willame Cr. (below unit 6)	12.8	11.5	10.2	.	0-25[a]	.	.	.16-.25[a]	.	.
PO	N. Fork Willame Cr. (at 4700 rd)	13.6	12.2	10.8	.	26-50[a]	.	.	.16-.25[a]	.	.
PP	Quartz Creek (Baseline)	18.6	15.3	12.0	524	51-75[a]	13.8	.	.26-.40[a]	.	.
PQ	Lewis River (Baseline)	14.0	12.7	11.3	347	51-75[a]	50.4	.	.41-.60[a]	.	.
PR	Canyon Creek (Baseline)	14.2	12.8	11.3	366	26-50[a]	12.5	.	.26-.40[a]	.	.
PS	Siouxon Creek (Baseline)	16.1	15.2	14.2	244	51-75[a]	27.8	.	.26-.40[a]	.	.
PT	East Fork Lewis River (Baseline)	15.4	14.2	13.0	293	26-50[a]	17.5	.	.26-.40[a]	.	.

Summer Temperature Regimes

Temporal Patterns

Annual Temperature Patterns. Stream temperature tends to reach annual maximums during July and August and minimums in December and January, illustrated for a small, partially shaded stream in the headwaters of the Deschutes River basin shown in Figure 6.1. Mean water temperature tends to stay relatively close to mean air temperature throughout the year. Water temperature reaches its maximum in August close in time to when maximum air temperature occurs in late July-early August. Solar radiation peaks earlier in June. This timing of annual maximums was similar for all sites regardless of stream size or condition of shading.

The general influence of riparian vegetation shading and stream size (indexed by average depth) are illustrated with temperature profiles from six selected sites chosen to represent very shallow (0-0.15 m), shallow (0.16-0.24), and moderately deep (0.26-0.40 m) streams with vegetative conditions ranging from fully shaded to fully open (or nearly so) (Figure 6.2). Average monthly maximum temperature of the selected sites (chosen from their respective groups based on their length of record) are shown.

It was hypothesized that streams of each size category could be affected by removal of vegetative shading along their banks and in nearby upstream reaches. Differences in stream temperature in relation to riparian vegetation conditions persist during all summer months, although they tend to be greatest when the warmest temperatures of the year are observed in July and August. Maximum temperature tended to be approximately 4 to 5°C higher for the open sites compared to the shaded sites in all stream size categories. The sites in each stream size group are not paired with regard to all important characteristics known to influence stream temperature, such as groundwater inflow and elevation, so these graphs should be interpreted as indicative of relative rather than absolute relationships between open and shaded reaches. For the examples shown in Figure 6.2, the sites in the shallow category were actually somewhat warmer than the deeper streams. This simply reflects differences in other local environmental factors of these sites. Although many sites fell within a similar temperature range as those depicted in Figure 6.2, some sites were higher or lower than those illustrated.

Figure 6.1 Average monthly air temperature (squares), water temperature (circles), and direct solar radiation (diamonds) of a small, partially shaded stream.

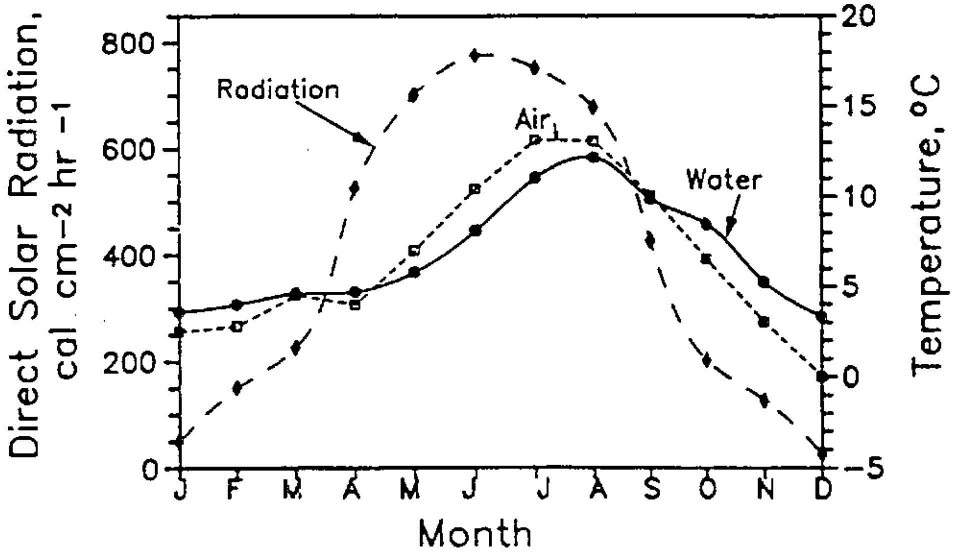
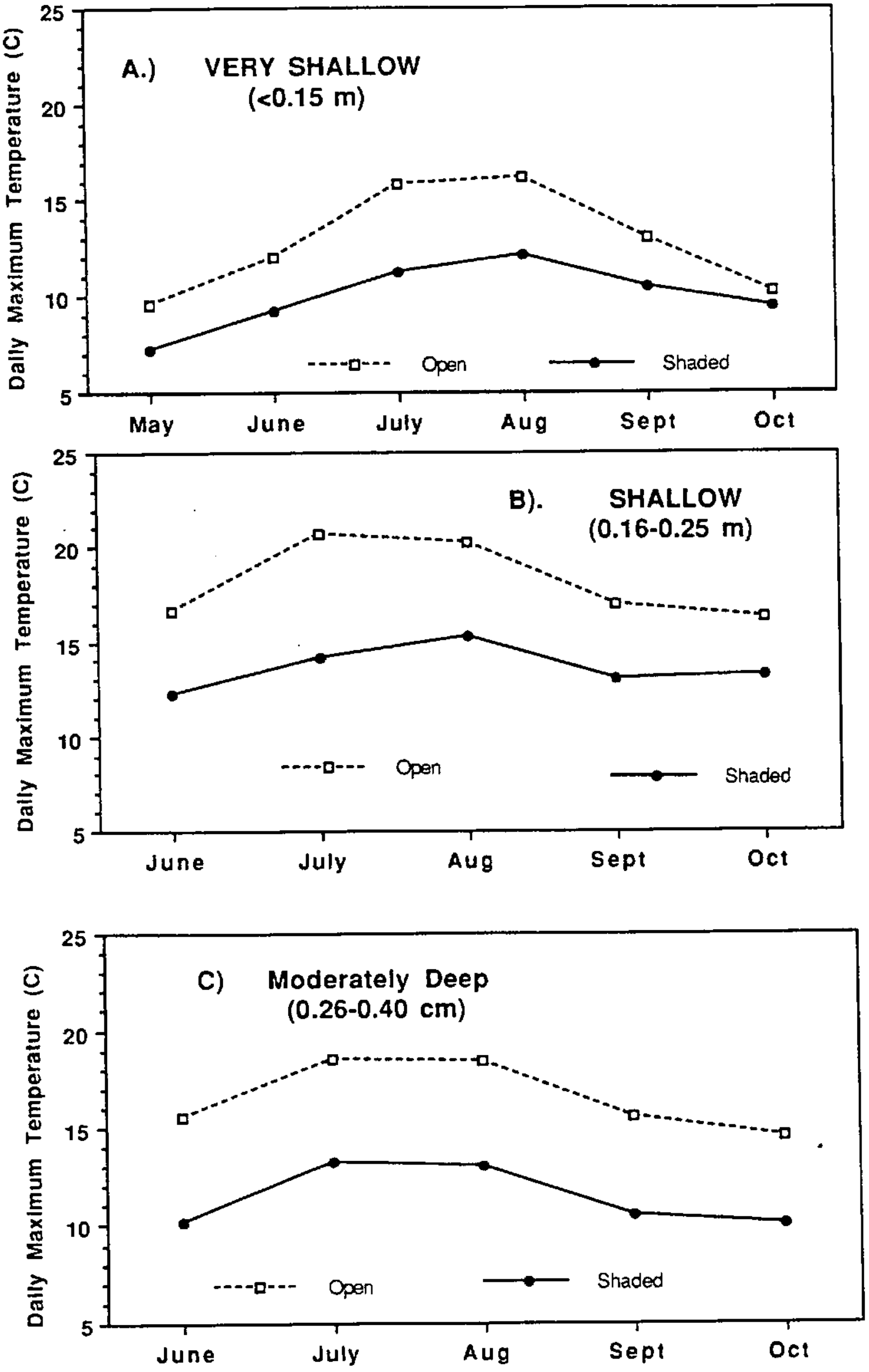


Figure 6.2 Daily maximum average by month for open and shaded sites of three depths: (A) very shallow, (B) shallow, and (c) moderately deep.



Daily Temperature Patterns. Daily water temperature follows the same general trends as the monthly temperature, although daily temperature is more variable in response to changing weather conditions. Examples of daily temperature regimes of three streams and rivers in Washington are provided in Figure 6.3. Similar daily temperature graphs for all 92 sites are provided in Appendix A. Huckleberry Creek (AC) is a fairly small stream in the Deschutes River basin in the western Cascade Range that was fully shaded with second-growth alder. Temperature in this stream never exceeded the Washington forest practice standard of 15.6°C and showed relatively little daily diurnal fluctuation. Daily maximum temperatures as high as 22.5°C were observed for lengthy periods during the summer in the Coweeman River (AL) and Wenatchee River (KA) representing larger and more open streams. Diurnal fluctuations were between 5 and 7°C in both rivers.

To provide a perspective of short-term fluctuations in water temperature, hourly water temperature during the month of August are shown for three sites where hourly air and water temperature data were available in Figure 6.4 . Several characteristics of temperature behavior common to all streams are evident. Water temperature tracked variability in air temperature rather closely at all sites, although the exact relationship between air and water temperature varies from site to site reflecting local reach conditions.

Cee Cee Ah Creek (site EA) is a very shallow, high elevation (1048 m), and partially-shaded stream (30 % shaded) in northeastern Washington. Although air temperature was high over prolonged periods of time, the riparian canopy provided sufficient shading to protect the stream from solar energy and temperatures stayed low (near the groundwater temperature of approximately 10°C). Diurnal fluctuation was only a few degrees and a small proportion of the daily fluctuation in air temperature. On the other hand, Hoffstadt Creek (site AQ) in the Mt. St. Helens blast zone had a wide diurnal water temperature fluctuation that varied nearly as much as air temperature (Figure 6.4b). Stream AQ is somewhat larger and at lower elevation than EA, and has no shading at all. Site AN on the Coweeman River is a larger river that is only 40% shaded. Like the small stream (EA), the diurnal fluctuation of the river was about 5°C (Figure 6.4c). However, the entire water temperature profile of the river site fluctuated more with air temperature than the small stream, and was not so apparently constrained by the groundwater temperature as evidenced by daily minimum water temperature. Groundwater inflow would have a much larger influence on small stream than on larger ones.

Figure 6.3 Daily maximum and minimum temperature during the summer of 1988 for three sites of differing depth.

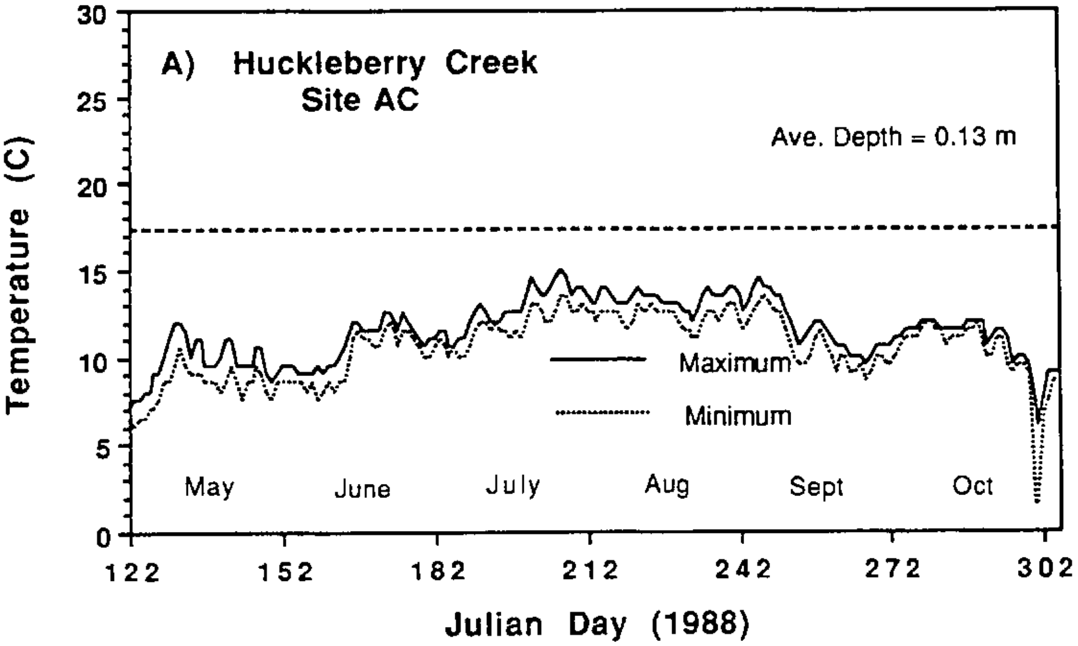
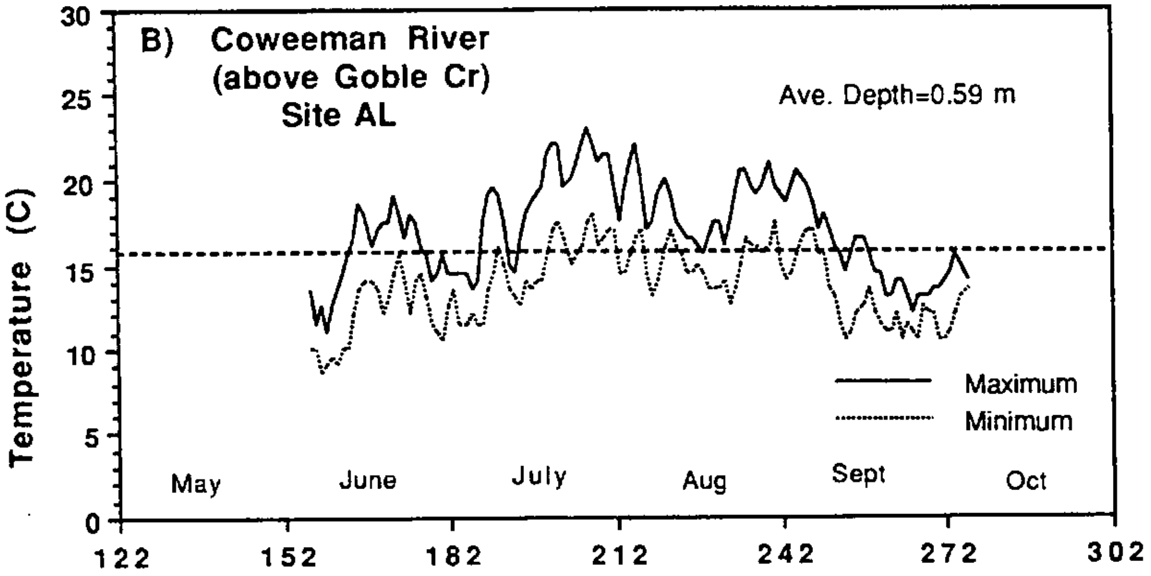


Figure 6.3 Continued



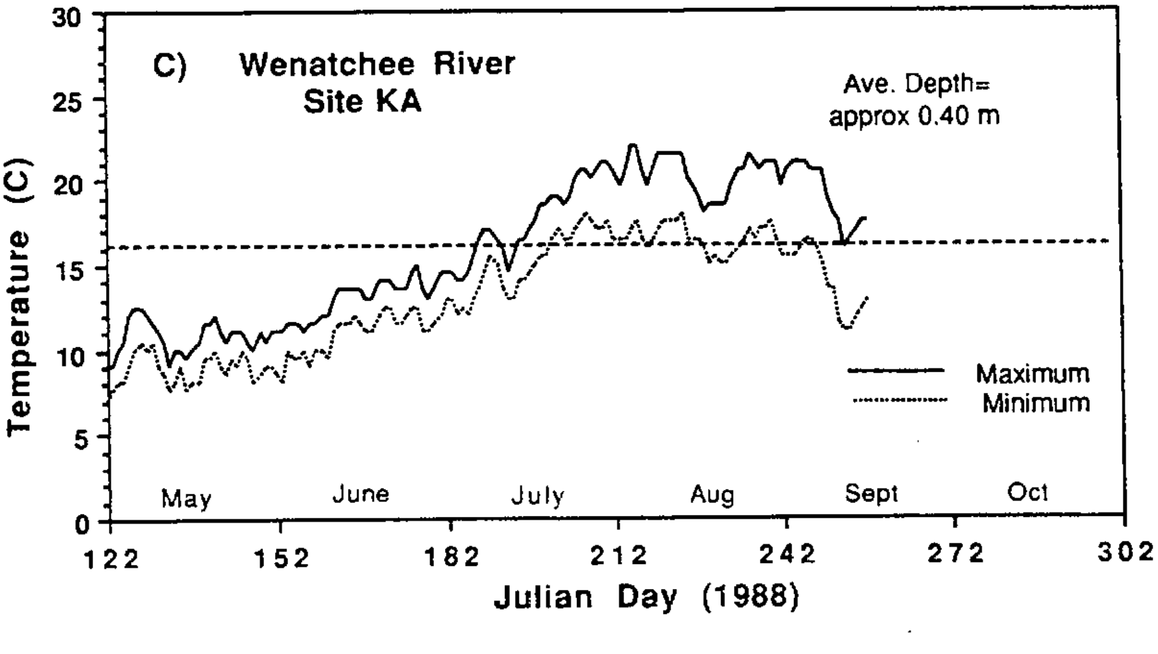
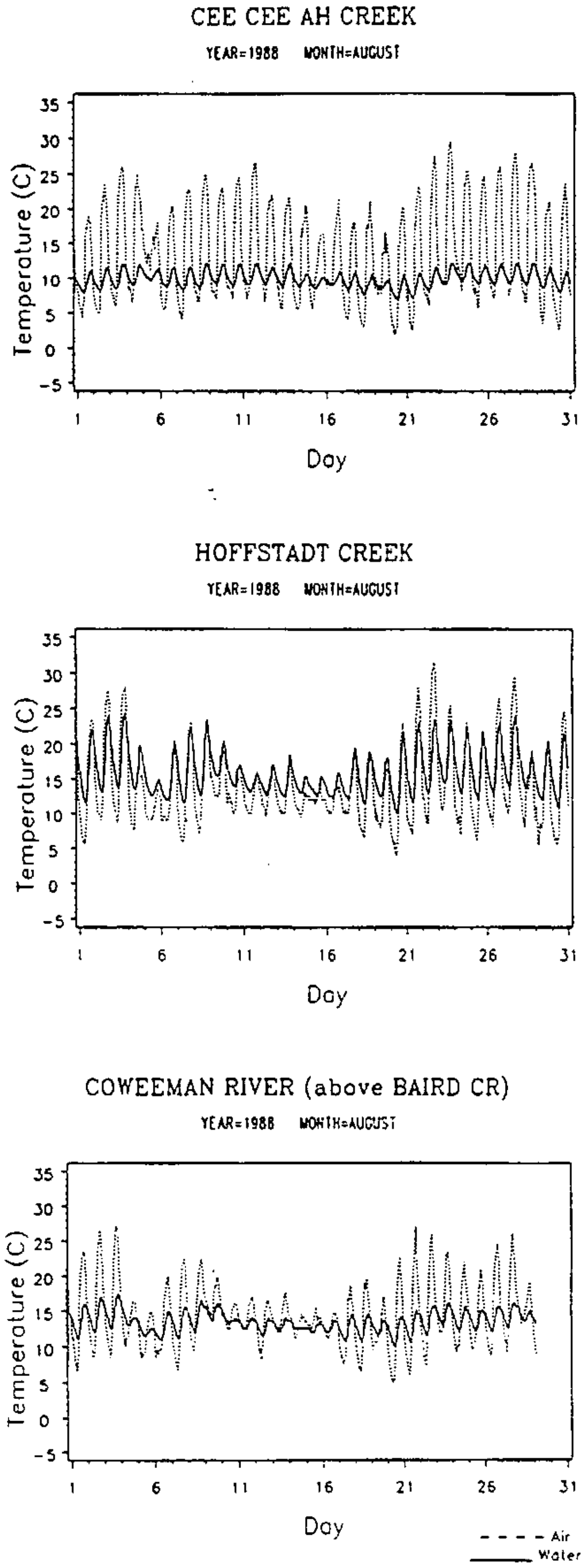


Figure 6.4 Hourly air and water temperature of three sites.



Short-term changes in water temperature occurred with weather patterns marked by varying air temperature. Stream response to weather was within a day for all streams shown (Figure 6.4). Even water temperature in the small stream (EA) with relatively little daily temperature fluctuation was somewhat lower when air temperature was cooler during cloudy periods. The rapid response time of temperature to weather patterns, and the tendency for weather to vary significantly during even the warmest periods of the year over durations of several days is an important consideration in determining whether temperature water quality standards specifying temperature thresholds over sequential periods are likely to be exceeded. For example, site AQ exceeds 15.6°C nearly every day during the period while site AN exceeds this threshold less often and never for 7 sequential days as specified in the Washington forest practice rules.

These results are an important consideration for temperature modeling. Models have often been used to predict the maximum temperature with different shading characteristics. To simplify the required input data, climatic variables are estimated for the warmest possible time (e.g., clear sky conditions in mid-summer). If models are to be used for realistically determining whether temperature standards specifying duration of temperature relative to thresholds are met, it is important to run models using realistic climate data that simulates normally observed variability in weather. More effort should be devoted to developing joint probability distributions of meteorologic variables based on long-term weather records.

Maximum Equilibrium Temperature. Another important characteristic of temperature behavior is the tendency for all streams to reach an upper limit on the maximum water temperature. Note that each stream shown in Figure 6.4 achieves a daily maximum water temperature that it does not pass even when air temperature goes higher. For example, the highest daily maximum water temperature observed frequently in stream AQ is approximately 24°C. This temperature coincides with air temperature on days 8 and 9. However, air temperature is greater than 24°C on at least 7 other days, but water temperature never exceeded 24°C. However, when air temperature was lower than 24°C, water temperature was commensurately lower. The same behavior in maximum water temperature can be seen at sites EA and AN, although the actual equilibrium temperature differs between sites (approximately 12°C at EA and 17°C at AN.)

The equilibrium temperature is such an important concept in stream heating (Edinger and others 1968) that further discussion of its background and meaning is useful. The water temperature observed at any location within a stream system reflects a balance between heat input and heat loss. The rates of both input and loss of heat are influenced by local environmental factors. Heat input is determined by the amount of direct solar radiation reaching the stream environment (Brown 1969) which varies daily and seasonally with position of the sun, and with shading by riparian vegetation or topography. The exchange of heat across the air-water interface is one of the more important factors that govern the temperature of the a water body for a given solar input. Heat loss is largely regulated by the difference between air and water temperature. Conduction to the streambed and groundwater inflow also accounts for heat loss but this is generally a relatively small percent of the total energy budget during the summer.

As a stream is heated by solar radiation and convection over a daily solar cycle, heat loss from evaporation and radiation back to the sky also increases rapidly. Some stream temperature will always be reached where heat loss balances heat gain and no further change in water temperature occurs with increased energy input. Edinger and others (1968) referred to the water temperature at which heat input just balances heat loss as "equilibrium temperature".

Since most of the energy exchange terms involve air temperature, this factor will be very influential in determining the equilibrium stream temperature (Adams and Sullivan 1990). Air temperature continually changes in response to varying meteorological conditions on a daily and seasonal basis and there is an equilibrium water temperature for each air temperature (Edinger and others 1968). The water temperature is continually driven towards the air temperature with the rate determined by the difference between the two. As a result, water temperature tracks air temperature during solar cycles.

Importantly, rapid heat loss at high temperatures sets an upper limit to stream temperature relative to air temperature that is independent of stream size. During hot summer days when the temperature differential is greater than this amount, the heat loss from evaporation and radiation losses is also great and additional incoming heat to the water is quickly lost back to the air. Thus each stream has a maximum temperature observed at a threshold level of air temperature. Assuming maximum energy loading, for air temperatures above this level there will be no increase in the observed water temperature. We refer to this temperature as the "maximum equilibrium temperature." A maximum equilibrium temperature such as those apparent in Figure 6.4 exists for each stream reach reflecting its site conditions.

This principle of maximum equilibrium temperature reveals why most investigators have observed a lack of correlation between maximum air and water temperature in forest streams (e.g. Beschta and Taylor 1988). Although air temperature is important in determining water temperature, there is an inconsistent (non-linear) relationship between daily maximum air and water temperature due to the threshold described above. Daily mean water temperature is less affected by the upper equilibrium temperature and is generally better correlated with daily mean air temperature.

The actual maximum equilibrium water temperature at a location largely reflects the balance of other stream characteristics that regulate heat transfer. For example, shading reduces solar input limiting heating in a reach or large amounts of groundwater inflow cool the stream. In either case, the maximum equilibrium temperature is lower than it would be if shading or groundwater inflow was less. These and other characteristics combine to determine the equilibrium temperature observed at any location at any time. Changes in the local environmental conditions are likely to cause a change in the equilibrium temperature to a new value. The maximum equilibrium temperature is generally what is predicted by models such as Brown's or TEMP-86 (Beschta and Weatherred 1984) when maximum energy-loading climatic conditions are used as input values.

The existence of a maximum equilibrium temperature is very useful for comparing the effects of stream characteristics on temperature of different streams. If the equilibrium temperature can be identified, it should relate to site characteristics in identifiable, albeit complicated, ways. Each site's equilibrium temperature is determined by its unique combination of physical characteristics. Numerous site characteristics contribute to determining stream temperature, and these may vary inter-dependently, independently, or inversely. Thus, quantifying relationships between sites in generalized form is somewhat difficult. Nevertheless, common relationships between maximum equilibrium water temperature and site conditions are explored empirically and using model simulation in following sections.

It should be noted that the major advantage to using a model to estimate temperature is that the site characteristics determining the maximum equilibrium temperature (the deterministic element) and the climatic variability (the transient element) can be treated simultaneously. Thus physical models are likely to be more accurate when modeling over time than generalized empirical models. However, empirical relationships between temperature and stream characteristics may be very useful for identifying streams where temperature is likely to be affected by management activities.

Regional Averages

Maximum, mean, and minimum temperature averaged for July for 92 stream sites located throughout Washington are shown in Figure 6.5 grouped by major geographic regions. Average daily maximum temperature ranged from approximately 9°C in smaller, densely canopied streams to about 21°C in completely open streams. Means ranged from 8 to 18°C, and minimums ranged from 6 to 17°C. Interestingly, the observed range of temperature characteristics was similar between eastern Washington, western Cascades and Puget Lowlands sites. The warmest daily maximum temperatures of 21°C was observed in Chamokane Creek (EB), an open stream located in the Pend Oreille region of eastern Washington that flows through long lengths of pastureland; in Hoffstadt Creek (AQ) in the Mt. St. Helens blast zone; and in Smith Creek (BD) along the Washington coast.

Coastal streams were generally deep slow-moving streams found in low-gradient coastal zones and tended to show warmer than expected temperatures. This may be due to the low elevation which indicates warmer air temperatures. (No sites were located in the fog belt along the coast, which could have had cooler air temperatures.) Minimum temperatures tended to be somewhat high in the coastal streams (Figure 6.5c). For example, Smith Creek (BD), a site with

Figure 6.5 Average July maximum, mean, and minimum temperature grouped by regions (A) western Cascades and Puget Sound lowlands, (B) eastern Washington and (C) coastal Washington

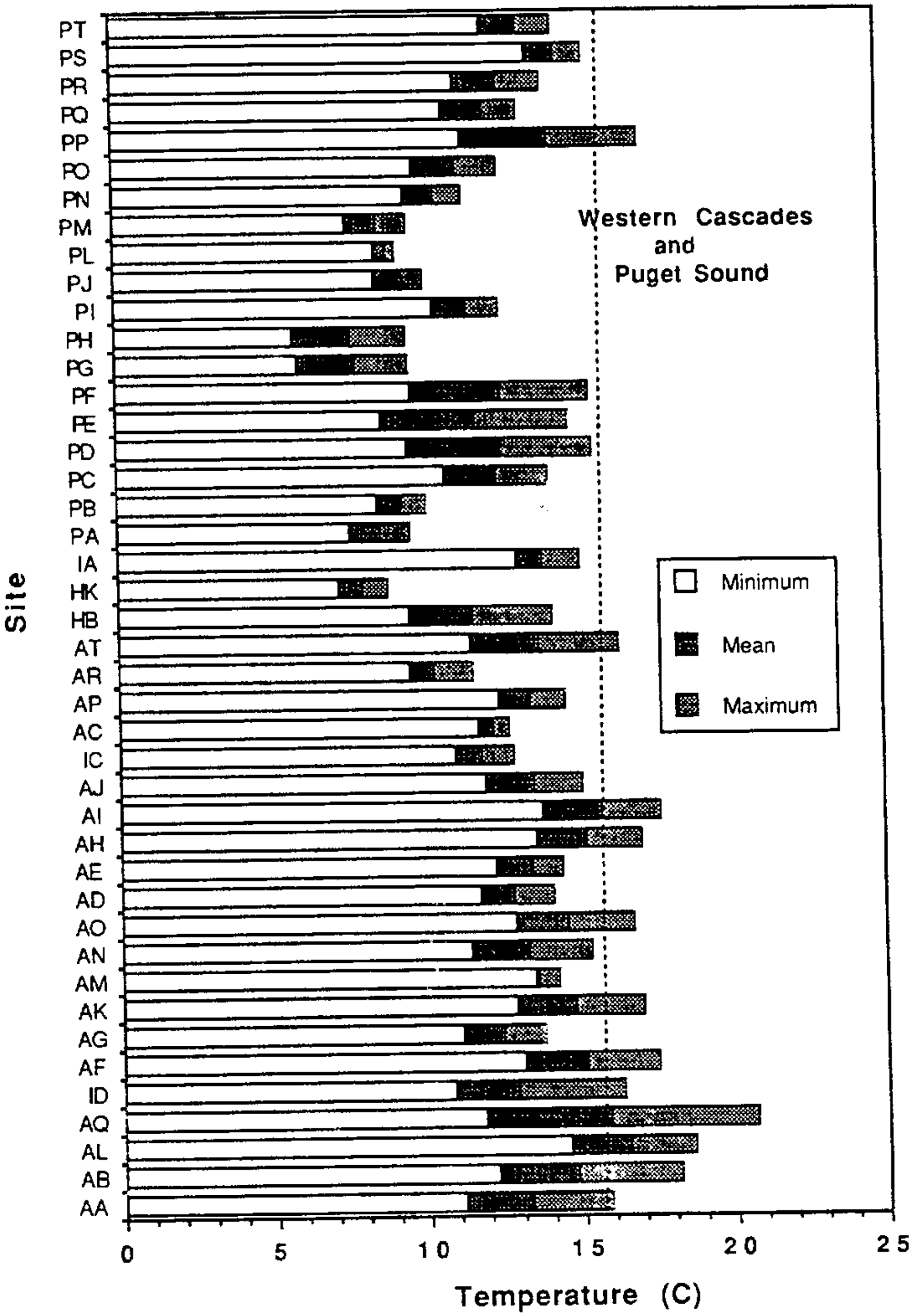
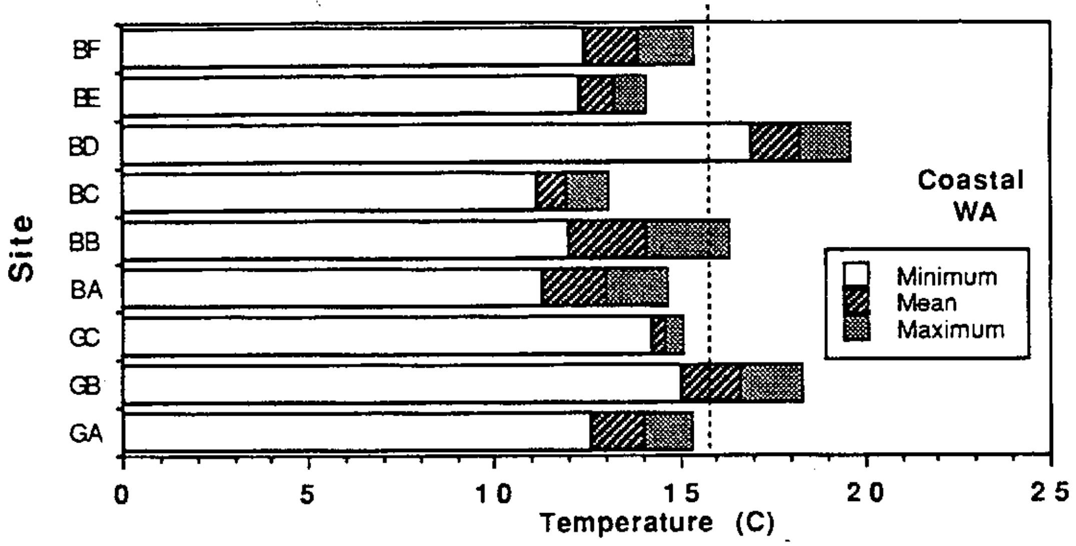
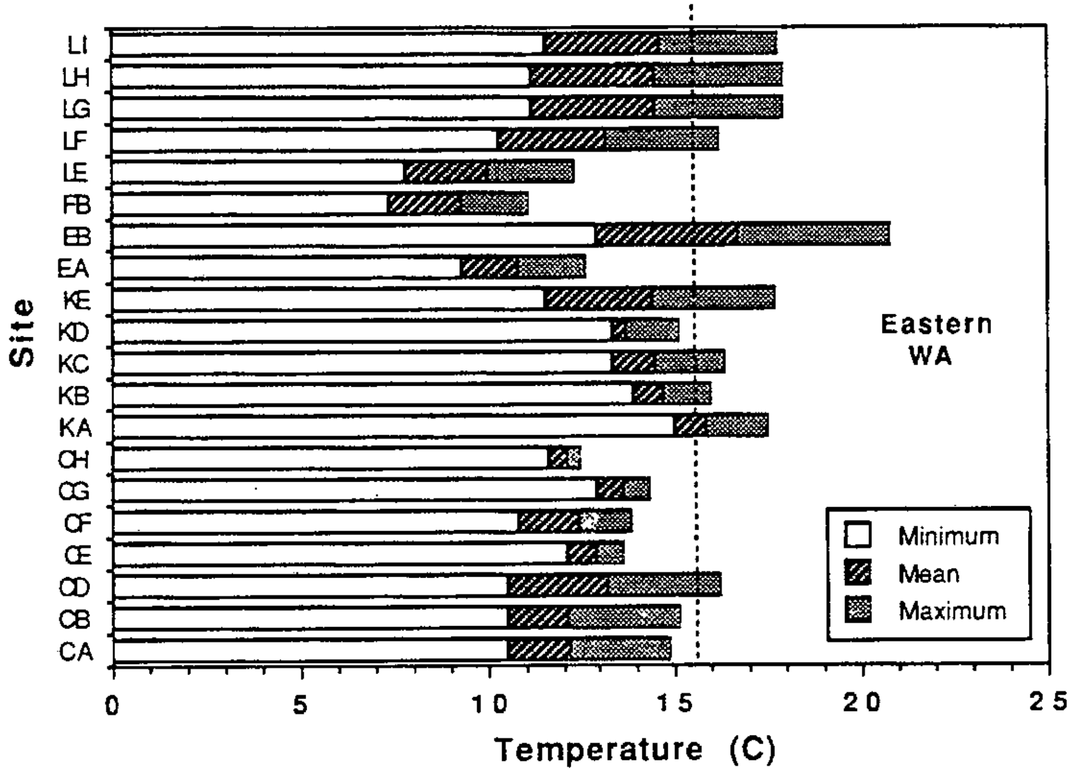


Figure 6.5 Continued





Relationship to Environmental Factors

While each stream location had unique site and basin characteristics, stream temperature characteristics should relate to the dominant environmental variables controlling temperature. Environmental conditions thought to be directly important in determining stream temperature are shading provided by vegetation or topography, air temperature and related meteorologic variables, stream depth and width (because it influences shading), and groundwater inflow rate and temperature. Other important variables identified as important in the scientific literature are channel orientation and streamflow.

General relationships between these stream characteristics and water temperature observed at the observed at the 92 study sites were analyzed with regression analysis. Some of the sites had very detailed site data available, while most of the secondary sites had only very general estimates of important features such as riparian shading and depth.

General trends were determined by grouping data into broader categories of shading and depth using data from all sites wherever possible. The relative importance of the dominant variables was considered and patterns common to many streams were determined to the extent possible. It is evident from the statistics for simple regressions of temperature characteristics as a function of single site variables (Table 6.2) that many factors significantly influence temperature (probability of the T-statistic less than 0.05 or 0.10), although no one characteristic by itself is a good predictor of temperature (low values of R^2). Simple predictive relationships were difficult to identify because many of these variables change systematically in stream systems and relative to one another. As such, observations are not entirely independent.

General Patterns

Riparian Vegetation (Shade). As expected, shade had a major influence on water temperature, particularly the daily maximum. Each site's highest value of daily maximum water and air temperature (an indicator of its equilibrium temperature) averaged by shade category are shown in Figure 6.6. (Incidentally, air temperature did not appreciably differ under more open canopies characterized by shade ranging from 0-75% of the stream surface area, although air temperature was several degrees lower, on average, under dense shading.) The highest water temperatures were observed under open canopies (shading less than 25%), with the hottest observed temperature averaging as high as 21°C during the warmest 1-month period of the year (July 15-August 15). Where shading was 26-50% of the stream surface area, the warmest observed temperature was 17°C, four degrees lower than fully open streams. There was

Table 6.2. Simple linear regression equations for the relationship of various stream characteristics to water temperature (n=36).

Dependent Variable	Independent Variable	Regression Slope	Intercept	Prob>T Statistic	R^2
Daily Maximum	View-to-the-sky (%)	0.043	14.0	0.02	0.16
	Mean Air (°C)	1.120	-0.29	0.00	0.27
	Discharge (m^3/s)	1.989	15.8	0.02	0.17
	Elevation (m)	-0.003	17.8	0.02	0.15
	GW Proportion (%)	-9.10	17.7	0.10	0.06
	Bankfull Width (m)	0.218	14.0	<0.01	0.30
	Depth (m)	10.23	13.7	<0.01	0.23
Daily Mean	View-to-the-sky (%)	0.018	13.4	0.24	0.05
	Mean Air (°C)	0.926	.47	<0.01	0.30
	Discharge (m^3/s)	1.799	13.7	<0.01	0.23
	Elevation (m)	-0.004	16.0	<0.01	0.49
	GW Proportion (%)	-6.52	15.2	0.14	0.05
	Bankfull Width (m)	0.195	12.1	<0.01	0.39
	Depth (m)	9.913	11.6	<0.01	0.30

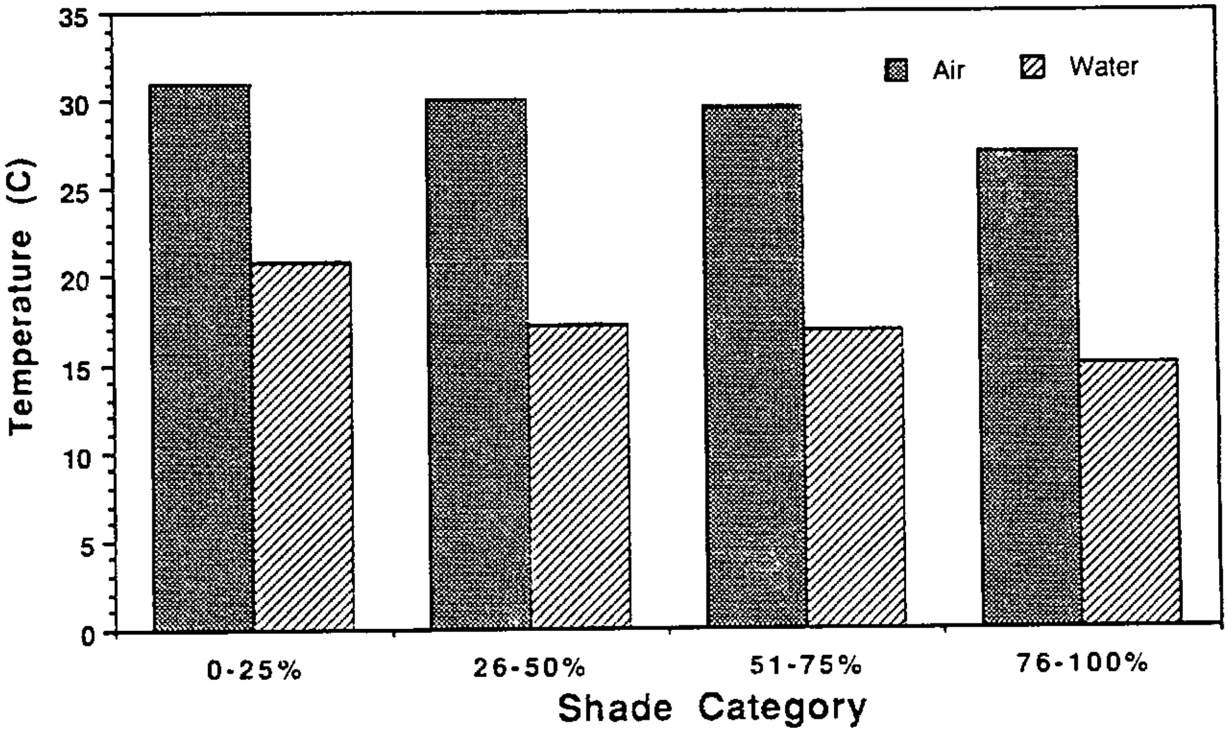
virtually no difference in the warmest temperatures for shading categories of 26-50% and 51-75%. Where shading was as much as 76-100% of the stream surface, the average warmest temperature was 15oC. This value was somewhat high for a completely shaded stream, although a number of small, moderate, and even some larger streams were included in this category where membership was based on shading alone. Since larger streams are generally warmer, stream temperatures shown in Figure 6.6 are undoubtedly higher than if only small streams had been included. If only small streams were included, the maximum temperature should average closer to 11-12oC, or near groundwater temperature.

Holtby and Newcombe (1982) also showed a similar pattern of changes in temperature indices in relation to proportion of stream bank vegetated. They observed a large increase in centigrade thermal units when 25% or less of the bank was vegetated, with significantly lower but intermediate values at slightly greater amounts of shading. They observed little difference in thermal units with shading ranging from 30 to 75% vegetated bank, but lower values were observed when banks were 100% vegetated. (Presumably proportion of bank vegetated corresponds to proportion of stream surface area shaded as described in this study.)

Similar relationships between riparian shading and water temperature characteristics were observed considering average daily values for the entire period of record (not just the one or two warmest days). Average daily maximum, mean, and minimum temperature for July varied with shade category (Figure 6.7). The general trends were consistent among all sites, although individual sites were often higher or lower than the average values. The influence of shade on the daily maximum was most significant, although even the minimum temperatures tended to be higher in open reaches than shaded ones. Only streams in the 0-25% shade category averaged daily maximum temperatures in excess of 15.6oC. Sites in other shade categories were significantly lower, with those in the densest shade averaging only about 12oC. The daily mean temperature averaged by shade category varied from 14.5oC in the open streams to about 12.0oC in the fully shaded streams. Daily minimum temperature averaged 12.0oC in open streams and approximately 10.0oC in shaded streams.

As observed by Brown (1969), the daily maximum temperature of fully shaded streams tended to equal

Figure 6.6 Average warmest air and water temperature (99th percentile) by shade category.



the daily minimum of unshaded streams. It is possible that increased minimum temperatures indicate changes in temperature of shallow groundwater draining to streams from the soil mantle due to warming of soils with timber harvest. No groundwater temperature was measured in this study. However, comparing the minimum temperature of a two nearby paired watersheds where one was clearcut (AA) and one was mostly forested (AR) shows a 2°C difference in minimum temperature (Table 6.1). Hewlett and Fortson (1982) concluded that groundwater temperature could be increased with timber harvest affecting water temperature.

Riparian shading was important in determining water temperature and of primary interest in TFW considerations. However, when site characteristics were considered singly, many other stream characteristics were better predictors of stream temperature than shading (Table 6.2). The relationship between mean and maximum water temperature and stream shade is illustrated in Figure 6.8. There was a relatively low correspondence between sky view and mean water temperature, and a significant, though highly variable relationship with maximum temperature. Clearly, other factors besides riparian vegetation were influential to water temperature and must be considered when estimating the effect of riparian shading on stream temperature.

Figure 6.7 Average July daily temperature characteristics by shade category.

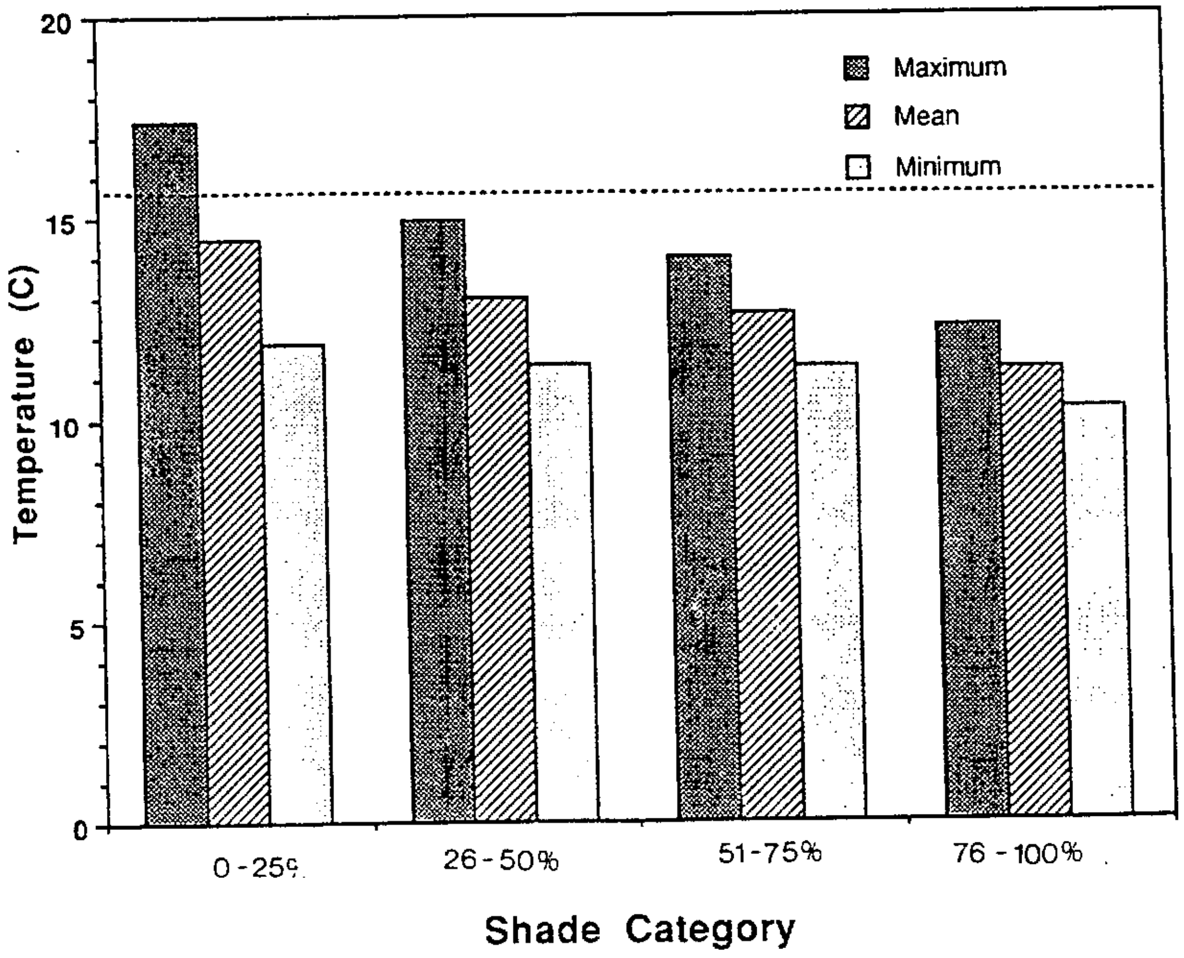
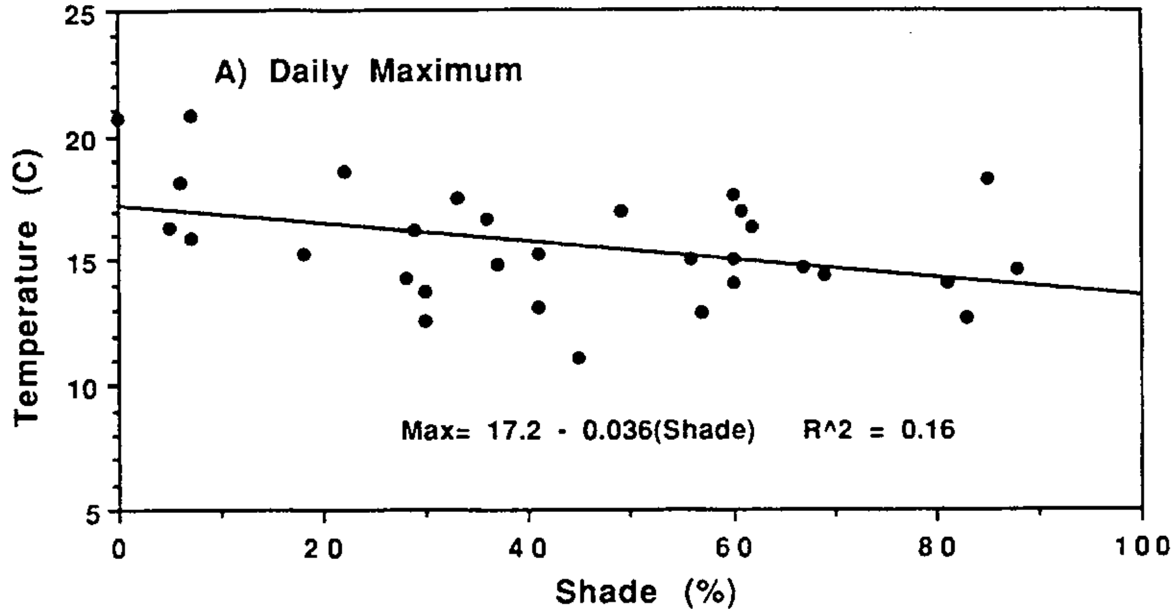


Figure 6.8 Average daily maximum (A) and mean (B) temperature for July in relation to proportion of stream surface shaded.



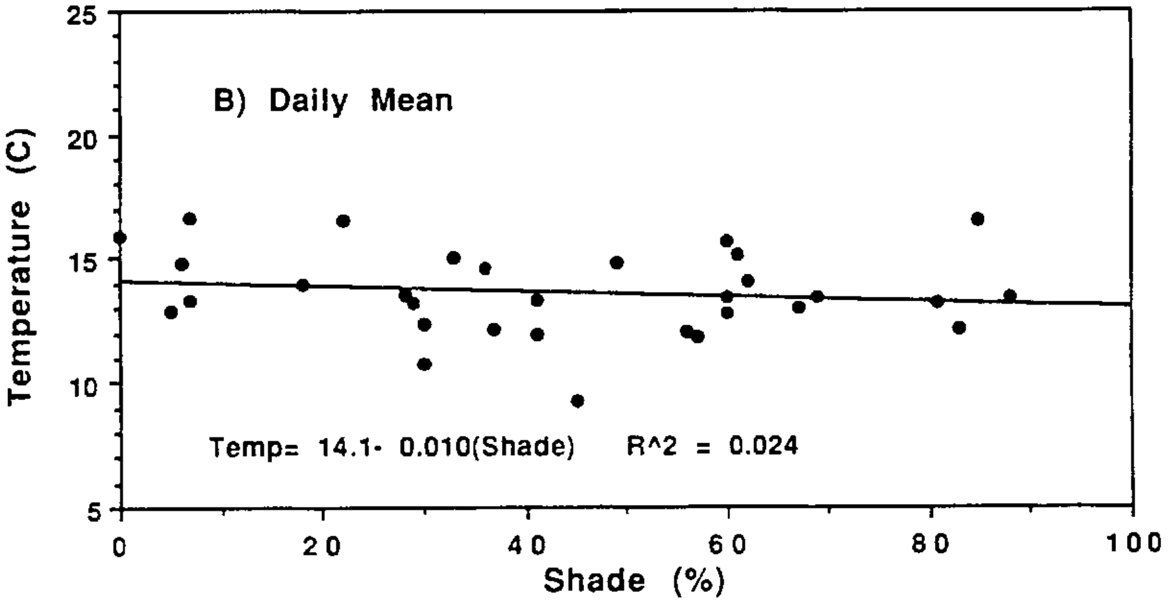
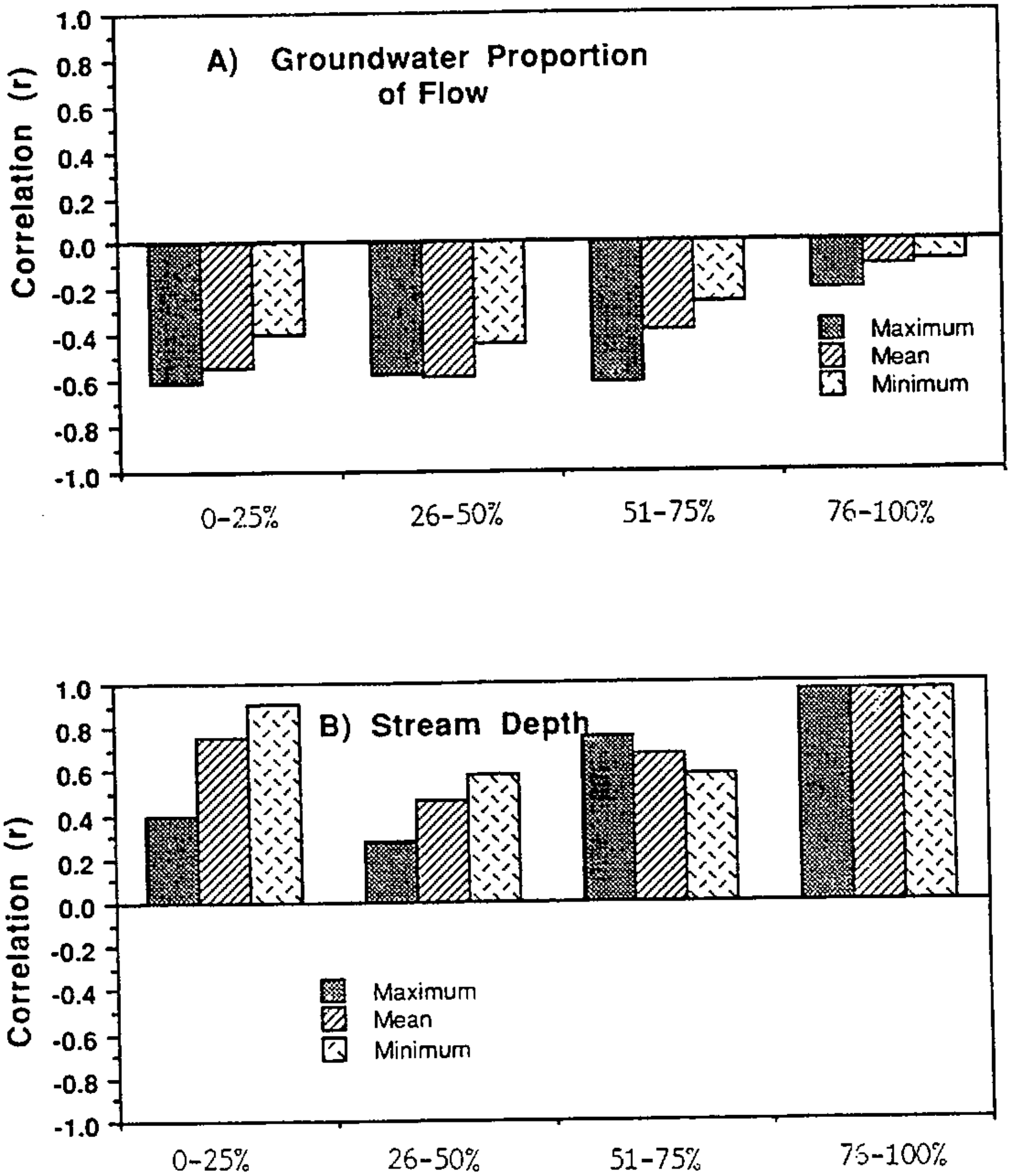


Figure 6.9 Correlation (r) between the environmental factors and the maximum, mean and minimum water temperature for July averaged for sites in general shade categories.



Other environmental variables likely to influence water temperature that are directly suggested by heat transfer processes are air temperature, stream depth, and groundwater inflow. Correlations between temperature characteristics and these site variables are shown in Figure 6.9 and the relative relationship of parameters to maximum temperature within open and shaded streams is provided in Figure 6.10. (Note that correlations shown in these figures computed by shade category may not agree with those listed in Table 6.2 computed for all data.) The discussion of environmental factors below reference Figures 6.9 and 6.10 and Table 6.2.

Groundwater Inflow Proportion. Groundwater inflow proportion to total flow was expected to have a depressing effect on stream temperature. Temperatures were negatively correlated with groundwater inflow proportion. Groundwater inflow proportion tended to have a much lower correlation with temperatures when background temperature was low, such as under fully-shaded conditions and for daily minimum temperatures. Groundwater inflow proportion tended to have less influence than other channel characteristics, as was also suggested in the model sensitivity analysis (Chapter 4).

Stream Depth. Stream depth was also better correlated with temperature when background temperatures were lower. The influence of depth on the maximum temperature was greater under shaded conditions than open conditions. However, depth and air temperature combined were highly correlated with maximum temperature under fully-shaded conditions. This good correlation between temperature characteristics and stream depth and air temperature under fully shaded conditions probably reflects a strong interdependence between these site characteristics as streams get larger. However, it could also be an artifact of low sample size in this shade category.

Figure 6.9 Continued

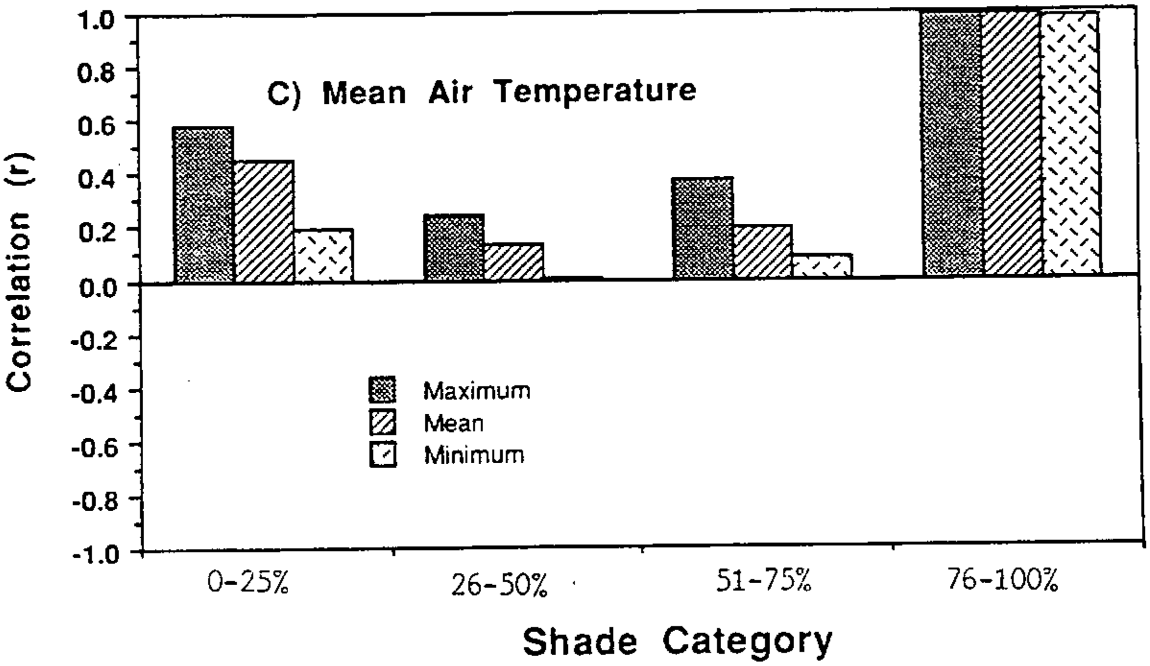
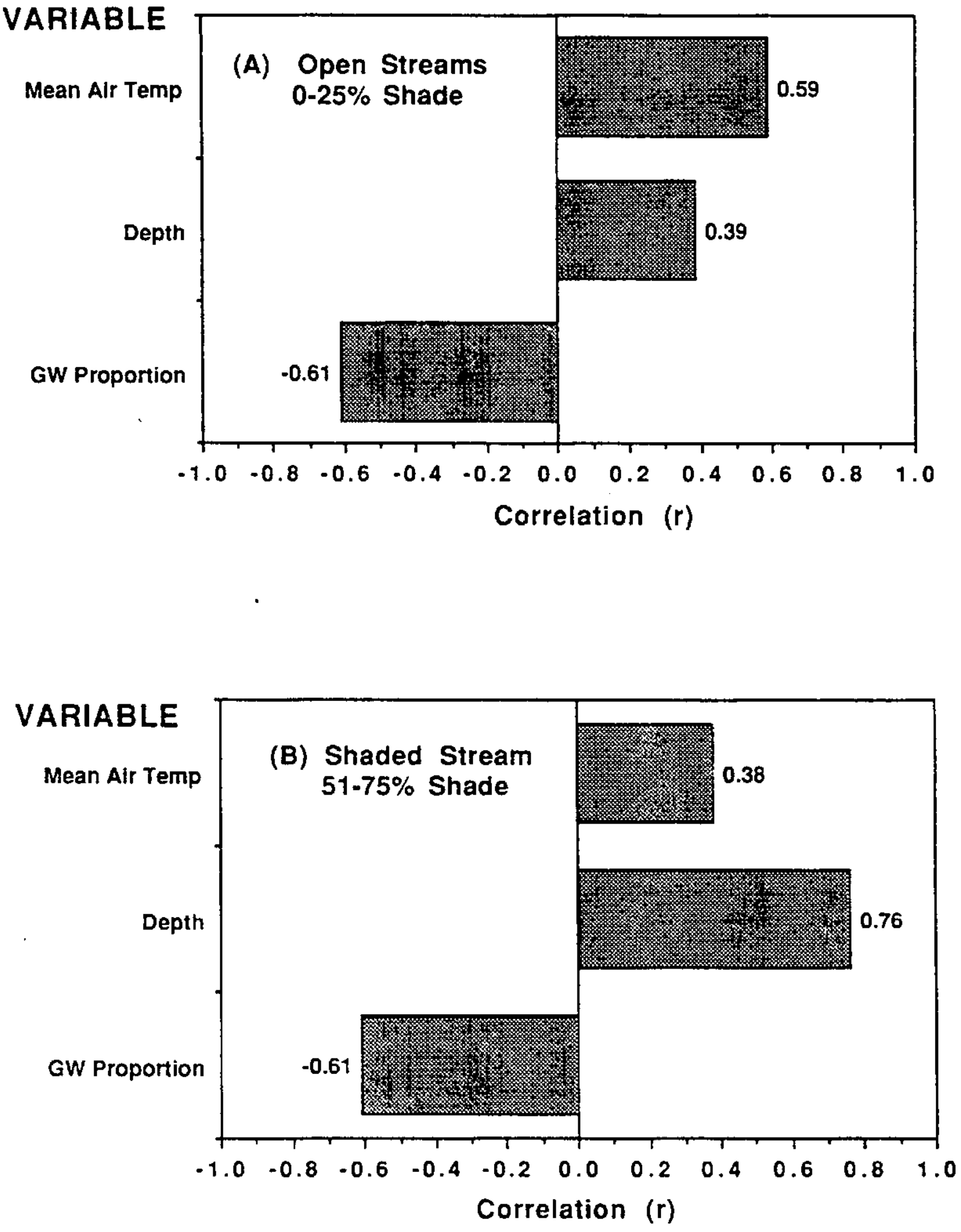
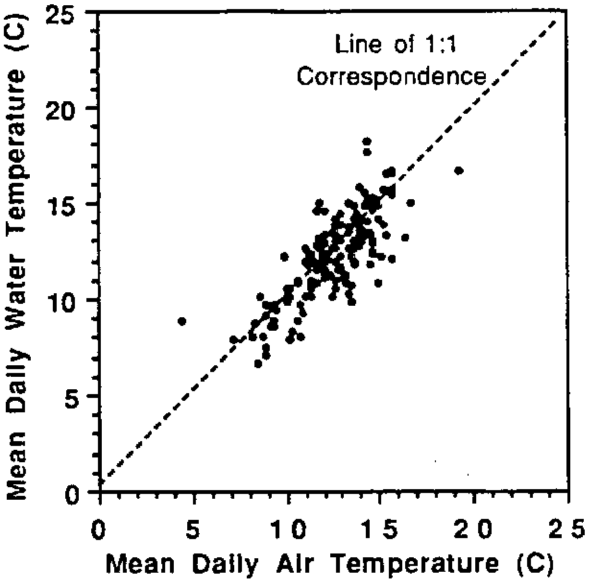


Figure 6.10 Correlation between maximum daily water temperature and environmental variables for open (A) and shaded streams (B)



Air Temperature. As opposed to stream depth and groundwater inflow, water temperature tended to be better correlated with air temperature when water temperature was higher, such as in open streams and for daily maximum temperature.

Figure 6.11. Average monthly temperatures from May through October for all sites where air and water temperature was measured.

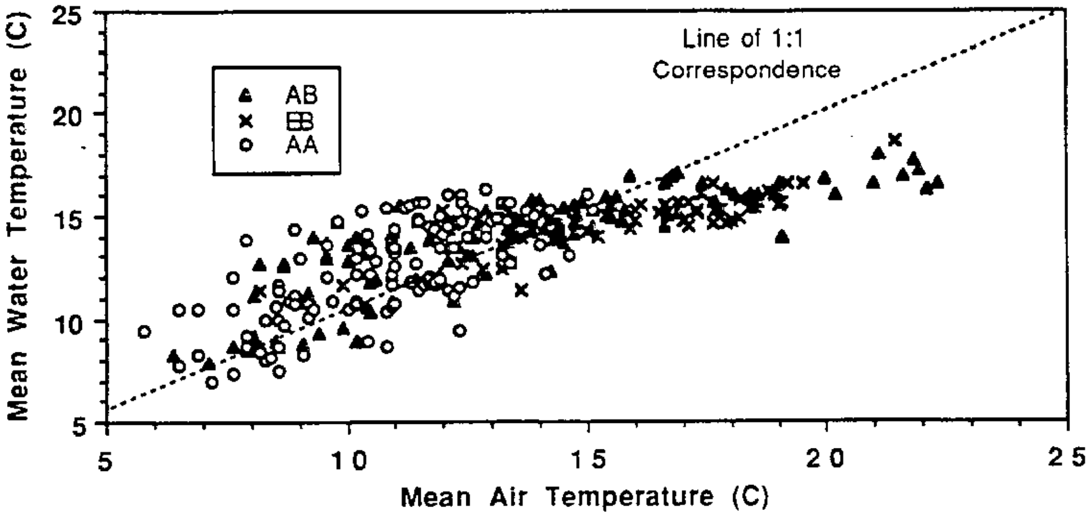


The very high correlation between air temperature and water temperature under dense forest canopies may actually represent a controlling effect on air temperature by the water temperature. The dense canopy acts as a greenhouse preventing evaporation losses.

The daily mean water temperature averaged monthly relative to mean air temperature is shown for all sites in Figure 6.11. Considering the vast difference in sites, there is clearly a general relationship between daily mean air and water temperature. However, for any given air temperature, the monthly mean water temperature varied between sites over a range of 5-8 °C. Other site factors such as riparian shading, groundwater inflow, depth, width and so on determined the exact relationship between mean water and air temperature at each site.

The daily mean air and water temperature for three unshaded sites are shown plotted day by day in Figure 6.12. For higher daily air temperatures, there was much less scatter in the relationship, and streams experiencing the same air temperature tended to have similar water temperature. For example, it would appear that the most significant difference between site AA and the two other sites was that air temperatures at the site were consistently lower. For lower air temperatures, there was greater scatter in the air/water temperature relationship at all three sites, but the range of values was similar despite site differences.

Figure 6.12. Mean daily water temperature in relation to mean daily air temperature at three open sites (AA--Deschutes, AB-Mt. St. Helens blast zone, EB-northeast WA).



Stream azimuth. Forest practice guidelines have in the past conditioned buffer strip shade requirements based on channel orientation. Streams flowing north-south have relatively short periods of direct overhead solar radiation, and therefore riparian shade might be less important than along east-west flowing streams, where more stream is directly exposed during maximum solar angles. Under this hypothesis, contribution of riparian vegetation to shading would vary depending on channel orientation and which bank was protected.

No effect of channel aspect on stream temperature was observed in this study. Rose diagrams of maximum, mean and diurnal fluctuation of temperature in relation to channel azimuth are shown in Figure 6.13. There are no strong trends in higher or lower values with compass direction in any of the three temperature characteristics. (Similar diagrams depicting only open sites show the same patterns as these diagrams with all sites included.)

For streams flowing due easterly or westerly, there appears to be slightly lower maximum and mean temperature and diurnal fluctuation. Unfortunately, there were relatively few streams with this direction of flow, and those that do are partially shaded, making comparisons tenuous.

Lack of a strong effect of channel orientation on temperature appears to be consistent with other studies where this influence was considered. Swift and Messer (1971) observed no influence of channel orientation during the summer months in southern Appalachian streams (although south-flowing streams tended to be slightly warmer during the winter.) Few other studies have directly analyzed this effect. Given the importance of other factors influencing stream temperature besides direct solar insolation, it may not be surprising that channel orientation has less influence on stream temperature than previously thought.

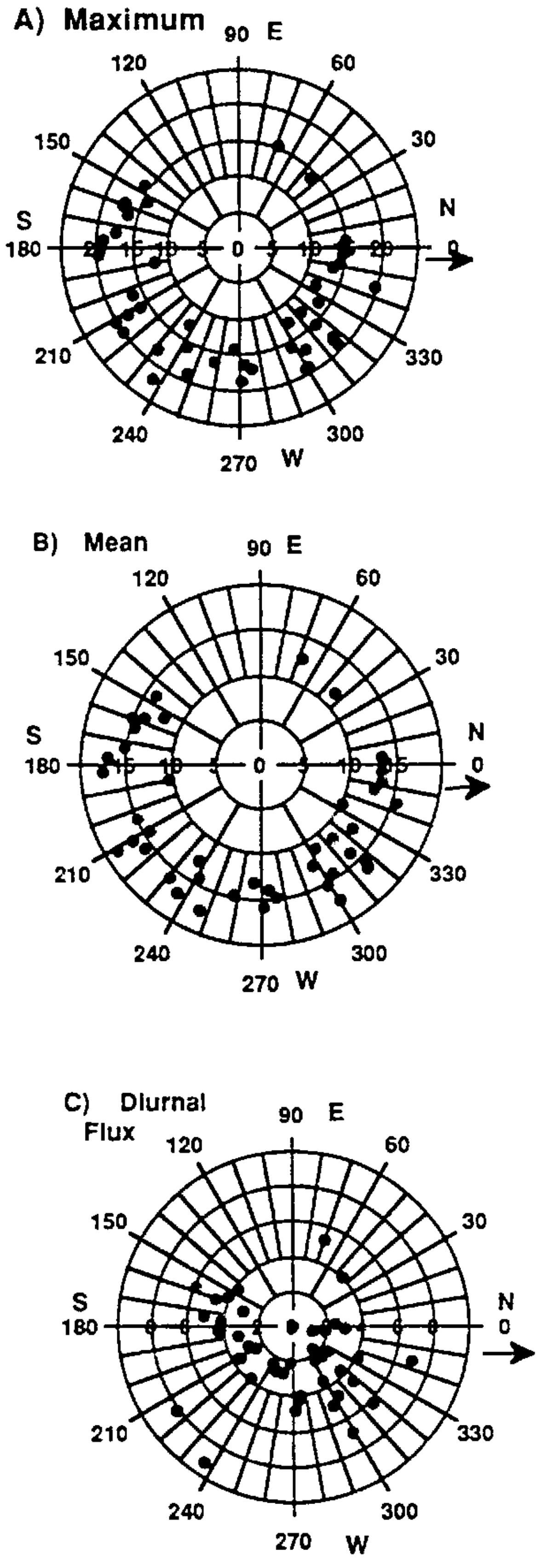


Figure 6.13 Average temperature for the period from July 15 to August 15 in relation to channel azimuth (A is daily maximum, B is mean, and C is diurnal flucuation.

Other Channel and Basin Characteristics. The simple regressions provided in Table 6.2 indicate that several other stream or basin characteristics are significantly related to stream temperature, although these variables are not directly related to processes of heat exchange. These include streamflow volume, channel width, and site elevation. (Brown, 1969, suggested that streamflow volume was directly related to temperature in his heat transfer equation, although dimensional analysis of the equation verifies that the primary variable of importance is stream depth.)

Many stream characteristics such as stream width and shading, streamflow volume and depth, air temperature and elevation are typically strongly correlated with one another (for example, see Chapter 3). Such stream characteristics may integrate many important temperature-determining factors, and therefore may serve as good indicators of stream temperature relationships. Many of these correlating variables are simpler to estimate than those directly involved in heat transfer equations, and therefore the task of predicting stream temperature may be simplified with their use. For example, stream width is strongly related to water temperature (Table 6.2) and is one of the easier site variables to measure or estimate.

Regional Water Temperature Model

Derivation of Relationships. While the simple linear regressions between site characteristics and stream temperature indicated the variables related to stream temperature, no one variable was an adequate predictor of temperature. Multiple linear regressions were performed using data from the primary sites to establish empirical relationships that could be used as

Table 6.3. Multiple linear regression equations for the relationship of a number of stream characteristics to average daily maximum, mean and minimum water temperature (n=36).

Dependent Variable	Independent Variable	Parameter Slope	Prob>T Statistic	R^2	F Value
Maximum	Intercept=4.3			0.63	7.987
	Sky view (%)	0.053	<0.01		
	Mean Air (°C)	0.740	0.02		
	Discharge (Q) (m^3/s)	-1.498	0.02		
	Elevation (m)	-0.004	0.02		
	Azimuth (degrees from north)	-0.005	0.10		
	Bankfull Width (m)	0.202	<0.01		
	Depth (m)	-4.850	<0.01		
Max Water Temp=4.3+((0.740 x Mean Air)-(4.850 x Depth)-(0.004 x Elev)+ (0.053 x Sky view)+(0.203 x BF Width)-(1.50 x Q))					
Mean	Intercept=7.5			0.81	18.948
	Sky view (%)	0.029	<0.01		
	Mean Daily Air Temperature (°C)	0.444	0.02		
	Discharge (Q) (m^3/s)	-1.052	0.13		
	Elevation (m)	-0.004	<0.01		
	Azimuth (degrees from north)	-0.003	0.23		
	Bankfull Width (m)	0.141	0.05		
	Depth (m)	-1.798	0.64		
Mean Water=7.5+((0.029 x sky view)+(0.444 x mean air)-(1.052 x Q)-(0.004 x Elev)- (0.003 x azimuth)+0.141 x BF Width)-(1.798 x Depth))					

general predictors of water temperature (as opposed to using physical prediction models). The objective was to identify site variables providing satisfactory indicators of temperature sensitive streams that could be readily obtained.

Initially, all of the variables in Table 6.2 were used as independent variables predicting the daily maximum, mean, and minimum water temperature and diurnal fluctuation averaged for the period from July 15 through August 15. These included the view factor, mean air temperature, streamflow (Q), elevation, depth, bankfull width and stream azimuth. The regression statistics are provided in Table 6.3, including each parameter's regression coefficient, intercept, and probability that it contributed significantly to the prediction. Maximum temperature had an R^2 of 0.63 (all parameters contributed significantly to the equation). Mean temperature had an R^2 of 0.81(view factor, mean air temperature, elevation, and bankfull width most significant.) Minimum temperature was also predicted very well with an R^2 of 0.88 (elevation, and bankfull width most significant). Diurnal fluctuation was relatively poorly predicted with an R^2 of 0.40 (view factor and mean air temperature most significant). Many of the variables that individually were significantly related to temperature (Table 6.2), albeit with relatively low precision, did not strengthen the predictions when combined with other variables.

In the next step, variables that did not contribute significantly to the prediction equations were removed from the model. An attempt was also made to simplify use of the predictive model in TFW applications by removing difficult to estimate variables such as mean air temperature. The best multiple linear regressions were developed by minimizing the number of variables while maintaining a reasonably high R^2. Prediction models based on easily obtained data were preferred. Removing variables resulted in similar, or occasionally better prediction equations as those using the larger variable list. The recommended

Table 6.3 continued

Dependent Variable	**Independent Variable**	**Parameter Slope**	**Prob>T Statistic**	**R^2**	**F Value**
Minimum	Intercept=10.4			0.88	30.372
	View -to-the sky (%)	0.010	0.12		
	Mean Daily Air Temperature (°C)	0.144	0.28		
	Discharge (Q) (m^3/s)	-0.844	0.11		
	Elevation (m)	-0.004	<0.01		
	Azimuth (degrees from north)	-0.001	0.56		
	Bankfull Width (m)	0.102	0.06		
	Depth (m)	1.409	0.64		
Min Water Temp=10.4+((0.144 x Mean Air)+(1.409x Depth)-(0.004 x Elev)+(0.010x Sky view)+(0.102 x BF Width)-(0.844 x Q))					
Diurnal Fluctuation	Intercept=-6.3			0.40	3.448
	View-to-the-sky (%)	0.040	<0.01		
	Mean Daily Air Temperature (°C)	0.558	0.04		
	Discharge (Q) (m^3/s)	-1.135	0.31		
	Elevation (m)	0.0005	0.64		
	Azimuth (degrees from north)	-0.003	0.48		
	Bankfull Width (m)	0.106	0.31		
	Depth (m)	-5.559	0.35		
Diurnal Fluctuation=-6.3+((0.040 x sky view)+(0.558 x mean air)-(1.135 x Q)-(0.0005 x Elev)-(0.003 x azimuth)+0.106 x BF Width)-(5.559 x Depth))					

prediction equations are provided in Table 6.4.

Although maximum temperature required five variables for adequate estimates, the mean, minimum and diurnal fluctuation were well predicted using two to three variables. The view factor, elevation, and bankfull width was strongly influential on most, but not all, temperature characteristics. Unfortunately, mean air temperature could not be removed from the models without significant loss of model reliability. A method is provided in Chapter 3 for estimatingmean air temperature from basin characteristics.

Model Reliability. The empirical model was evaluated for prediction performance in a manner similar to the analytical temperature models (Chapter 4). Measured site data were used for independent variables in the equation. W-statistics were calculated as predicted temperature minus observed temperature.

As with the analytical models, there was significant variability in model performance from site to site (Table 6.5), but overall the prediction capability was good (Table 6.6). When site-measured data were used, the overall performance score using the scoring criteria for maximum, mean, minimum and diurnal fluctuation temperature described in Chapter 4 was 1040 points, or nearly 88% of the total possible.

Table 6.4. Multiple linear regression equations for the best relationship using selected stream characteristics to maximum, mean and minimum water temperature.

Dependent Variable	Independent Variable	Parameter Slope	Prob>T Statistic	R^2	F Value
Maximum	Intercept=.3			0.69	12.815
	Sky view	0.055	0.001		
	Mean Air	0.794	0.008		
	Q	-2.76	0.03		
	Elevation	-0.003	0.01		
	Bankfull Width	0.262	0.02		
	Max Water Temp=0.3+((0.794 x Mean Air)-(0.003 x Elev)+ (0.055 x Sky view)+(0.262 x BF Width)-(2.76 x Q))				
Mean	Intercept=6.8			0.78	32.325
	Sky view	0.034	0.000		
	Mean Air	0.480	0.01		
	Elevation	-0.005	0.000		
	Mean Water=6.8+((0.034 x sky view)+(0.480 x mean air)-(0.005 x Elev))				
Minimum	Intercept=12.8			0.86	54.507
	Sky view	0.008	0.23		
	Elevation	-0.004	0.000		
	Bankfull Width	0.078	0.01		
	Min Water =12.8+((0.010x Sky view)+(0.102 x BF Width)-(0.004 x Elev))				
Diurnal Flux	Intercept=-5.1			0.51	12.393
	Sky view	0.049	0.000		
	Mean Air	0.409	0.07		
	Flux=-5.1+((0.049 x sky view)+(0.409 x mean air))				

Table 6.5 Performance results of the regionalized empirical temperature prediction models based on study sites. Predicted-observed temperature is same as the w-statistic of model-testing in chapter 4. Summary statistics for regional model performance are provided in Table 6.6.

	Model Using Measured Independent Variables						Model Using Estimated Independent Variables						Observed Temperature oC	
	(Predicted-Observed)				Predicted (C)		(Predicted-Observed)				Predicted			
Site	Max	Mean	Min	Range	Max	Mean	Max	Mean	Min	Range	Max	Mean	Max	Mean
AA	-0.2	-0.8	0.9	-0.2	16.7	13.7	-0.6	-0.2	0.5	0.3	16.3	14.3	16.9	14.5
AB	-1.5	-0.7	-0.6	-0.9	18.4	15.0	-3.6	-1.8	-0.4	-1.9	16.3	13.9	19.9	15.7
AE	1.0	0.2	0.2	0.6	16.2	14.2	-1.7	-1.1	0.3	-0.5	13.5	12.9	15.2	14.0
AF	-1.5	-0.3	0.7	-0.2	17.1	15.7	-2.6	-1.4	0.9	-1.2	16.0	14.6	18.6	16.0
AG	3.3	1.6	1.7	1.8	18.3	15.1	0.4	0.4	1.2	0.8	15.4	13.9	15.0	13.5
AH	-1.0	-1.3	-0.3	-0.8	17.2	14.8	-3.9	-2.2	-0.4	-1.6	14.3	13.9	18.2	16.1
AI	-0.4	-0.7	-0.5	-0.1	18.1	15.8	-4.0	-2.3	-0.6	-1.5	14.5	14.2	18.5	16.5
AJ	-0.4	-0.1	0.6	-0.4	15.9	14.4	-2.3	-1.0	0.5	-1.2	14.0	13.5	16.3	14.5
AK	-1.0	-0.5	1.4	-1.0	17.2	15.2	-2.9	-1.4	1.3	-1.8	15.3	14.3	18.2	15.7
AL	-0.7	-0.4	0.1	1.3	19.1	17.2	-2.6	-2.1	0.5	-0.1	17.2	15.5	19.8	17.6
AM	1.8	-0.5	0.1	2.5	20.9	17.0	-2.1	-2.1	-0.1	1.0	17.0	15.4	19.1	17.5
AN	-0.1	1.0	1.8	-0.2	16.1	15.1	-0.9	0.0	2.0	-1.0	15.3	14.1	16.2	14.1
AO	-0.9	-0.5	-0.8	0.5	16.2	14.5	-2.1	-1.4	-0.5	-0.3	15.0	13.6	17.1	15.0
AP	-1.3	-0.5	0.0	-0.8	14.3	13.9	-2.8	-1.4	0.4	-1.5	12.8	13.0	15.6	14.4
AQ	-2.4	-2.5	0.3	-3.4	19.6	14.4	-5.5	-3.1	-0.3	-3.9	16.5	13.8	22.0	16.9
BC	1.7	1.2	0.7	1.6	16.1	14.3	0.4	0.7	0.7	1.2	14.8	13.8	14.4	13.1
BE	-0.6	0.2	0.7	-0.3	13.9	13.7	-1.5	-0.2	0.7	-0.7	13.0	13.3	14.5	13.5
CA	-0.7	-1.1	0.2	-0.4	13.5	10.7	-0.5	-0.9	0.3	-0.3	13.7	10.9	14.2	11.8
CB	-0.8	-1.1	0.5	-1.1	13.1	10.4	-1.1	-1.2	0.9	-1.2	12.8	10.3	13.9	11.5
CD	-0.7	-0.4	1.1	-0.7	14.7	12.3	-0.6	-1.0	2.1	-1.2	14.8	11.7	15.4	12.7
DA	0.2	0.6	1.0	2.0	19.3	17.5	-1.4	-0.8	0.1	0.8	17.7	16.1	19.1	16.9
DB	-1.6	-0.1	0.3	-0.5	14.6	14.5	-1.8	-0.5	1.1	-0.8	14.4	14.1	16.2	14.6
EA	1.7	0.8	0.9	1.3	13.6	11.0	1.9	0.5	1.4	1.0	13.8	10.7	11.9	10.2
EB	-0.2	0.5	1.3	-1.4	19.9	16.3	-2.8	-1.6	2.8	-3.2	17.3	14.2	20.1	15.8
GA	1.3	1.5	0.7	2.0	17.5	16.3	0.4	0.9	0.9	1.5	16.6	15.7	16.2	14.8
HG	3.6	0.6	0.7	2.1	20.0	15.5	-0.5	-0.6	0.4	1.1	15.9	14.3	16.4	14.9
IC	1.4	0.7	1.3	0.9	13.8	12.2	1.1	0.7	1.3	0.9	13.5	12.2	12.4	11.5
ID	0.5	0.5	1.9	0.1	16.2	13.1	0.6	0.5	2.0	0.1	16.3	13.1	15.7	12.6

This performance was not as good as TEMP-86, only slightly below the TEMPEST model, and better than SSTEMP and Brown's model. The consistency of the empirical model in predicting average temperature within 2°C was usually better than 90% of the sites.

When all independent variables were estimated from generalized relationships developed in Chapter 3 rather than from field measurements, the total score dropped to 840 points. The largest difference was in reduced consistency in predicting the maximum and mean temperature (Table 6.6).

Table 6.6. Performance of the empirical temperature prediction model based on site and watershed characteristics (Table 6.3). The equation was used with measured site values for independent variables, and estimated values from relationships provided in Chapter 3. (Thirty-three sites were used in the analysis.)

Temperature Characteristic	W-Statistic (predicted-observed)	Equation Used With Measured Values	Equation Used With Estimated Values
Maximum	Average	0.0	-1.3
	Standard Deviation	1.46	1.81
	Consistency	90%	61%
Mean	Average	0.1	-0.7
	Standard Deviation	1.11	1.24
	Consistency	94%	78%
Minimum	Average	0.6	0.8
	Standard Deviation	0.72	0.94
	Consistency	100%	91%
Diurnal Fluctuation	Average	0.2	-0.5
	Standard Deviation	1.31	1.34
	Consistency	87%	91%

Winter Temperature Regimes

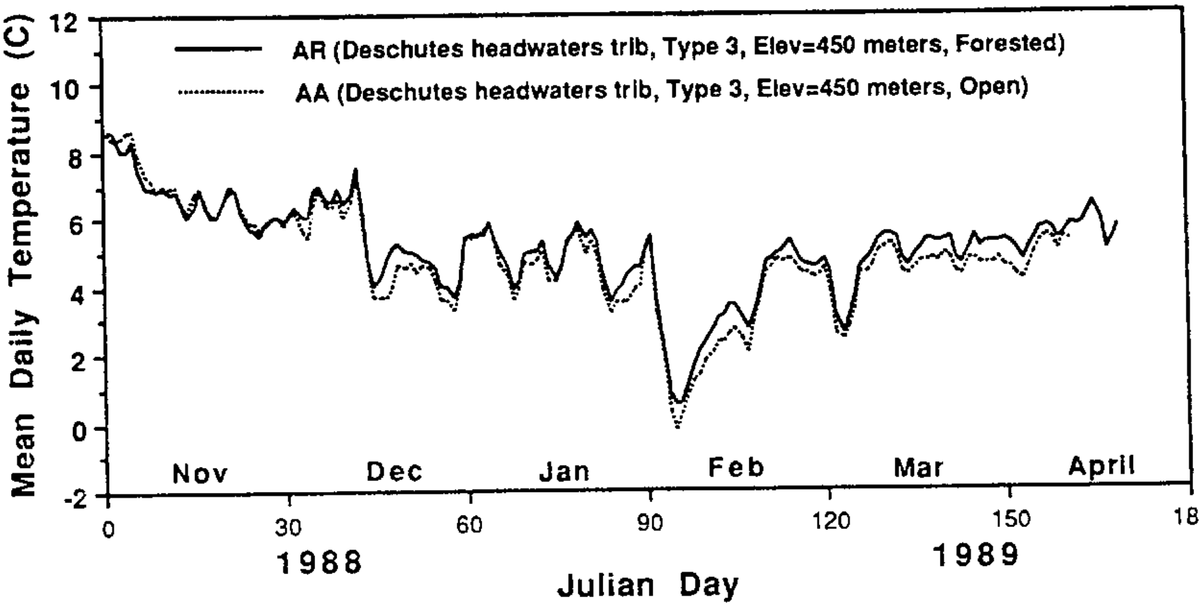
Water temperature was recorded through the winter at eight sites; seven in the western Cascades and one in eastern Washington (Four sites are shown in Figure 6.14). Average monthly water temperature for these sites are provided in Table 6.7. Water temperature reached annual minimums at all sites in February. The lowest temperatures were observed at the highest elevation site (ID) on the Greenwater River located in the western Cascades. The eastern Washington site (EB: Chamokane Cr) was usually the next coldest site, although a distinct warming trend occurred in February at this site that was not observed at other locations in the state. The other six sites located in the Deschutes River basin in the western Cascades ranged between these two sites.

As with summer temperatures, monthly daily mean water temperature shows a strong relationship to mean monthly daily mean air temperature (Figure 6.15). At lower air temperatures characteristic of winter months, however, the water temperature is relatively higher than during the summer months (Figure 6.11 and 6.15) Even though monthly air temperature averaged below zero in some months, water temperature generally reached minimums of approximately 3-4°C. Water's unique density properties at near zero temperatures help to withstand changes in air temperature below the freezing point. Thus, water temperature also seems to have a minimum threshold value relative to air temperature. Prolonged periods of sub-freezing air temperatures can cause streams to freeze, but this was not observed during the measurement period.

Because of the relationship between air temperature and elevation, much of the variability in the average monthly mean water temperatures among sites can be accounted for by elevation (Figure 6.16). Mean daily air temperature for the month of January plotted as a function of elevation shows a distinct trend in lower water temperature with elevation. The influence of forest canopy cover could not be distinguished among the sites, although the coldest site had only 7% riparian cover. This was also the highest elevation site.

The best opportunity for examining the effect of riparian canopy on winter temperatures is by comparing sites AA (Ware Creek) and AR (Hard Creek). These two neighboring streams are paired watersheds within the Deschutes basin where AA is nearly completely open its entire length and AR is covered by mature conifer vegetation for the majority of its length. Except for differences in riparian vegetation, the aspect, elevation and climate of the two sites are identical.

Figure 6.14 Mean daily water temperature at 4 sites during the winter months.



The stream with riparian canopy tends to be slightly warmer than the open stream throughout the winter, although differences are very slight and within measurement error (approximately 0.4°C) (Table 6.7). The cumulative thermal units for the period during the winter when salmon eggs incubate (approximately December through April for coho salmon) are shown in Figure 6.17. Thermal units were calculated as the sum of the daily maximum temperature for each month. Differences in thermal units between the two streams are small. However, differences between the forested and open sites were consistent, and by the end of the period the the cumulative thermal units of the forested stream was approximately 10% greater than the open stream. Virtually all of the difference in cumulative temperature units was observed in April.

Warmer streams under forest canopies were expected, since the canopy acts as insulation to limit heat loss from the stream. During the winter, the incoming groundwater is often warmer than the air temperature, and therefore serves as a source of heat to the stream.

Figure 6.15 Daily mean water temperature in relation to mean air temperature averaged monthly for all sites.

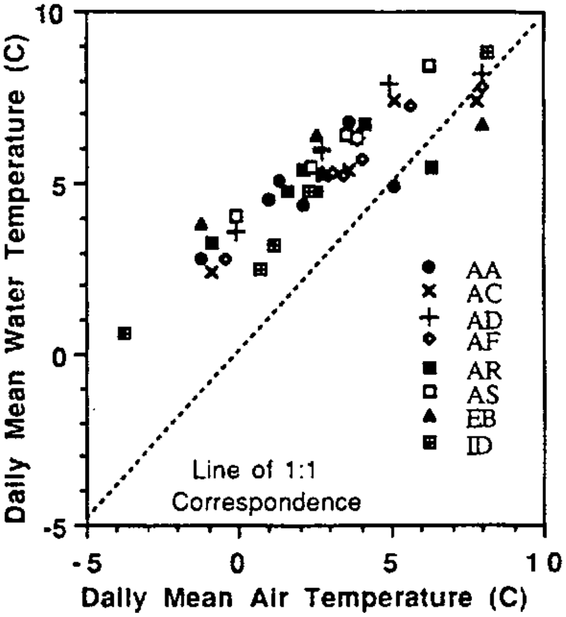
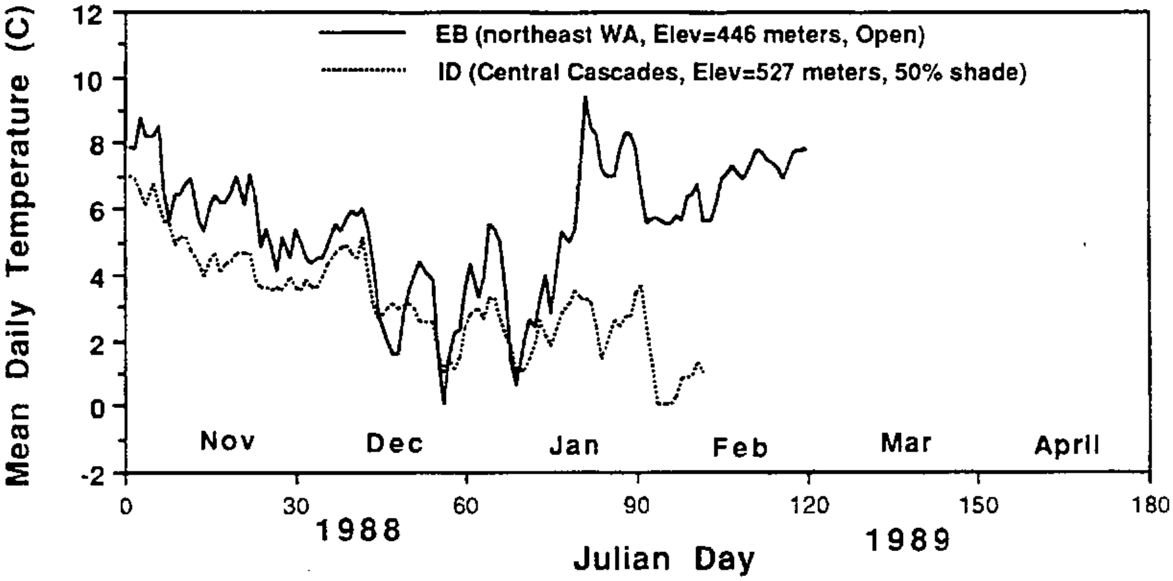


Figure 6.14 Continued



(Incoming solar insolation is minimal during the winter months and does not offer a significant source of heat.) As hypothesized, temperatures in open streams tended to be somewhat lower than in streams covered by dense conifer canopies, but differences were slight. These results do not agree with Holtby's finding in Carnation Creek, British Columbia (1988) where cutover areas were observed to have higher winter water temperature than forested sites. Differences in observed temperature patterns between these two studies are not explained. Interpretations of potential negative impacts of earlier fry emergence offered by Holtby as a consequence of stream warming due to forest removal would not appear to be applicable here.

The results of winter temperature sampling at this limited number of sites did not offer strong evidence that winter temperatures are significantly affected by canopy removal. In general, elevation appears to exert a stronger control on winter temperatures than does vegetation along the stream.

Figure 6.16 Average daily mean water temperature during January in relation to elevation.

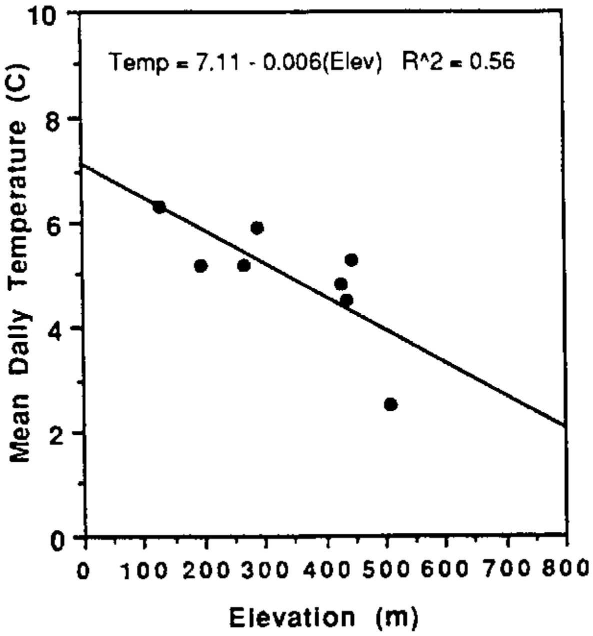
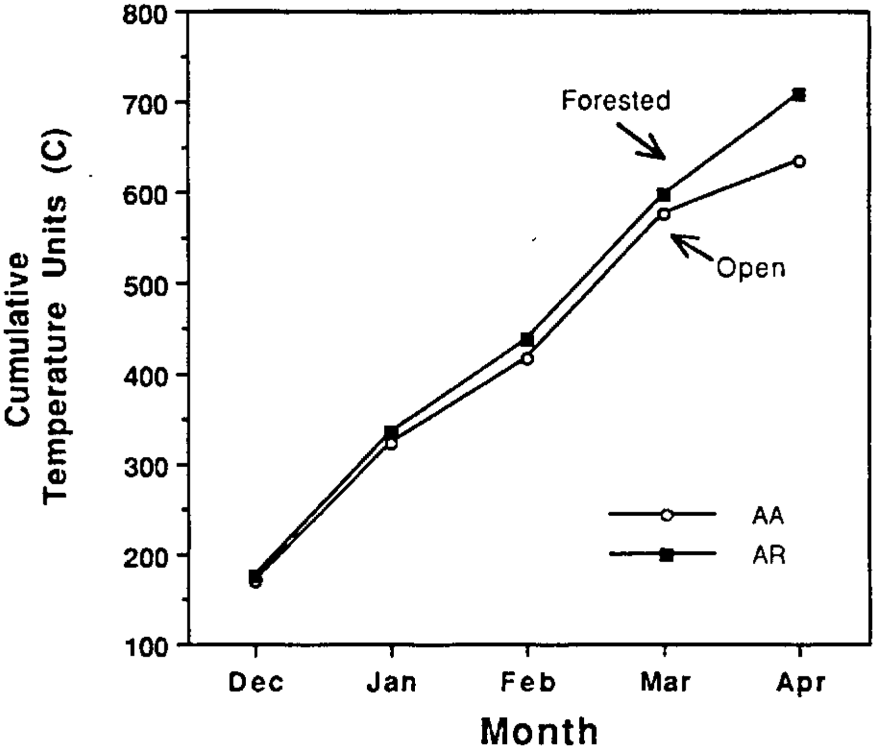


Table 6.7 Average monthly mean daily water temperatures.

Site	View[a] (%)	Elev (m)	Month Nov	Dec	Jan	Feb	Mar	Apr
AA	93	436	6.8	5.1	4.5	2.8	4.4	4.9
AR	20	430	6.7	5.4	4.8	3.3	4.8	5.5
AC	17	197	7.4	5.2	5.2	2.4	5.4	7.4
AD	40	292	7.9	6.0	5.9	3.6	6.3	8.2
AF	67	269	7.3	5.3	5.2	2.8	5.7	7.8
AS	50	130	8.4	6.4	6.3	4.1	5.5	-
ID	95	510	4.8	3.2	2.5	-	-	-
EB	93	446	6.4	3.8	5.3	6.7	-	-

[a] View factor was estimated during the summer months. Sites AC, AD, AF, and AS have substantial amounts of hardwood forests in the riparian zone.

Figure 6.17 Cumulative thermal units for an open and a forested site in the Deschutes basin for the winter incubation period.



BASIN TEMPERATURE PATTERNS

Individual Basins. To study the basin scale effects of forest management on stream temperature, a number of reach study sites were clustered with each of three watersheds. Data for these basins were used to evaluate basin temperature models (Chapter 5), and are further analyzed here to demonstrate general basin temperature patterns. The Deschutes basin in the central Cascade Range of western Washington had the most extensive sampling network (9 sites; Figure 5.4). The Coweeman basin in the Cascade Range in southwest Washington (Figure 5.3) and the Little Natches River in the southeast Cascades of eastern Washington (Figure 5.2) had six and four sites respectively. Schematics of each of the basins identifying major tributaries, sampling locations, their distance downstream from the watershed divide, and the average maximum water temperature for a 7-day period during August are provided in Figure 6.18 (a,b,c). Averaging periods varied for the three watersheds so results should not be compared between rivers.

Timber harvest had occurred in all of the basins; most of the area has been managed with riparian prescriptions applied under forest practice regulations that predate the 1987 revisions. Riparian shading levels were not directly assessed for the entire basin, and discussion of temperature patterns is based on general qualitative knowledge of the watersheds and the site-specific information collected at the reach study sites.

In all of the basins, water temperature tends to increase in the downstream direction as rivers increase in size from their headwaters. Water temperature in headwaters streams in the Deschutes basin were 12.1°C, increasing to 16.4°C near the mouth of the river at Offut Lake in Olympia. The Coweeman River increased from 15.6°C at 17.4 km from the watershed divide to 19.3°C near the mouth. The Little Natches River increased from 14.9°C in tributaries 7.9 km from watershed divide, to 17.9°C at 28.0 km. Increasing temperature in the downstream direction has been identified in rivers throughout the world by Hynes (1970), and discussed conceptually by Theurer and others (1984). Sullivan and Adams (1990) attributed the general tendency for incremental change in temperature to increasing channel width tending to reduce the effectiveness of shading from riparian vegetation, increasing air temperature, increasing stream depth, and decreasing proportion of cooling groundwater inflow. (Local increase or decrease in temperature can also occur reflecting incoming tributaries, or major changes in stream or climatic conditions.)

The possible effects of reduction in shading with timber harvest along the main river and tributary streams are a major concern for TFW managers. The extent to which these effects can be demonstrated to have changed water temperature on a basin scale in the three watersheds studied is not clearly evident. Furthermore, the role of tributary timber harvest versus shading reduction along the mainstem itself is not distinct.

The effect of tributary temperature on the mainstem of the river seems to be more pronounced in the headwaters of the watershed (generally in streams less than approximately 30 km downstream from the watershed divide.). In the Deschutes basin, water temperature in a headwater tributary with mature conifer forests providing dense shading to the stream (Hard Creek) is 12.1°C. A neighboring stream that has virtually no shading along the channel (Ware Creek) is several degrees higher at 15.8°C. Several of the other tributaries in this part of the basin also have little shading (Buck and Lewis Creek). These tributaries may be contributing to higher temperature (14.1°C) in the mainstem of the river at 13.5 km from the watershed divide (site AG). A similar pattern appears to occur in the headwaters of the Coweeman River (Figure 6.18b). Baird Creek enters the Coweeman at a warmer temperature than the river, and probably contributes to the increase in temperature between site AN at 17.4 km and AK at 29.1 km from the watershed divide. (Insufficient sites were available in the mainstem of the Little Natches River to draw inferences of the effect of tributary streams on the river.)

The effects of tributaries appear to be much less pronounced on the lower reaches of the rivers. For example, in the Deschutes basin, virtually all of the tributaries draining to the river between site AG at 13.5 km downstream distance and site AF at 38.8 km from divide have similar or lower temperature than the upper river site, yet temperature increased from 14.1°C to 16.9°C in the 25-km length of river between AG and AF. (Timber harvest in these basins occurred 20-30 years ago and all of the tributary streams are now shaded with mature alder canopies.)

Figure 6.18 Schematics of study basin configurations. Average 7-day maximum temperature for warmest period of record is also shown.

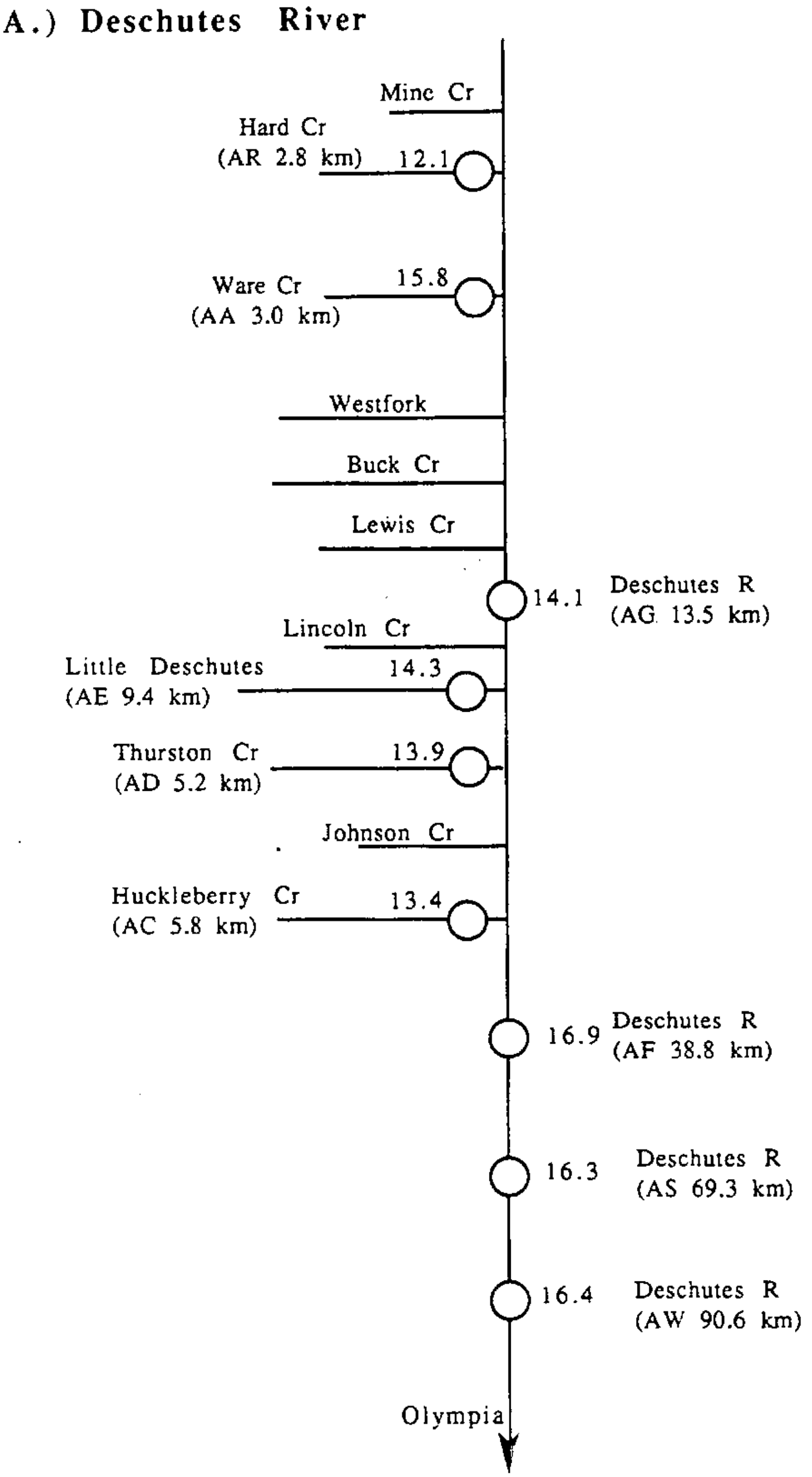
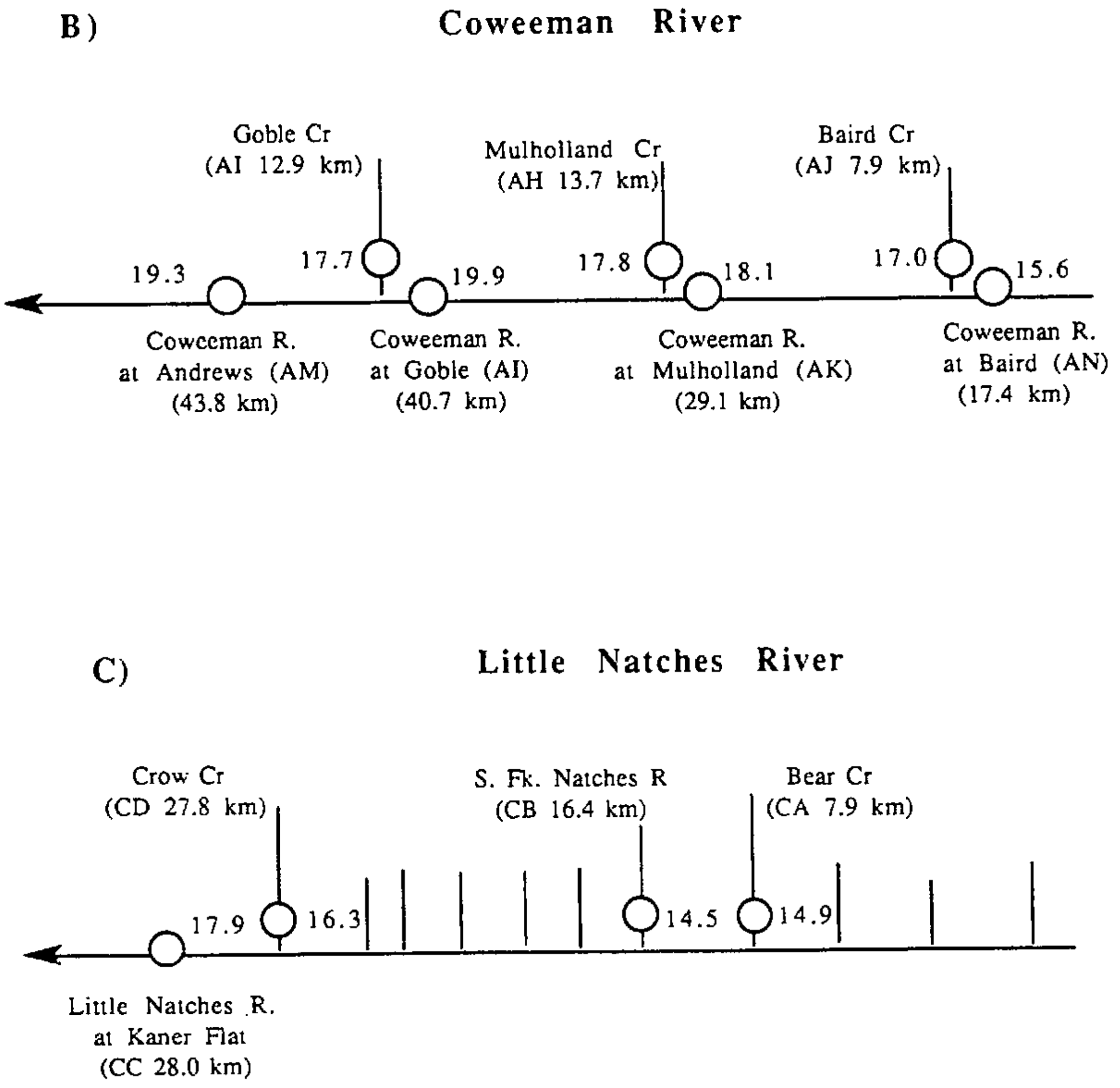


Figure 6.18 Continued



From AF on downstream, the temperature remains relatively constant for the remainder of its length, suggesting that the system's maximum equilibrium temperature has been reached at AF, at a distance of 39 km from the watershed divide. The increase in temperature in this length appears to more related to changes in shading and channel width along the mainstem itself. After passing through a narrow, steep canyon area downstream of site AG, the river widens out in an alluvial valley. Aerial photographs indicate that the channel is clearly visible and therefore less shaded in the wider alluvial zone than in the river upstream of this location.

A similar pattern occurs in the Coweeman River. River temperature increases between site AK at 29.1 km from divide and site AI (40.7 km), even though Mulholland Creek (a major tributary) enters the river at a slightly lower temperature than the mainstem. The increase in temperature is not accounted for by tributary streams, and may be related to changes in shading along the mainstem. Although we do not have the temperature of the mainstem of the Little Natches River above where Crow Creek joins it (site CD), it appears that the temperature of the tributary is also not the cause of the river temperature, since the tributary is cooler than than the river at site CC.

Although higher temperatures in the more downstream reaches of these rivers appear to more related to local river conditions than tributary temperatures, there clearly can be local cooling where cooler tributaries enter. For example, the temperature in the Coweeman River appears to drop about 0.6°C where Goble Creek enters the mainstem at nearly 2°C cooler. A simple calculation on expected cooling influence can be made by assuming that Goble Creek is approximately 30% of the water volume and the mainstem is about 70% (based on watershed area). Using a mixing equation (Brown and others, 1972) where,

$$\text{Temperature}=p_1 \times T_1 + p_2 \times T_2 + \dots p_n \times T_n$$

p_n = proportion of combined flow contributed by each of n streams

T_n = temperature of stream n

In the example described above,

$$\text{Temperature}=(0.3 \times 17.7^{\circ}\text{C}) + (0.7 \times 19.9^{\circ}\text{C}) = 19.24^{\circ}\text{C}$$

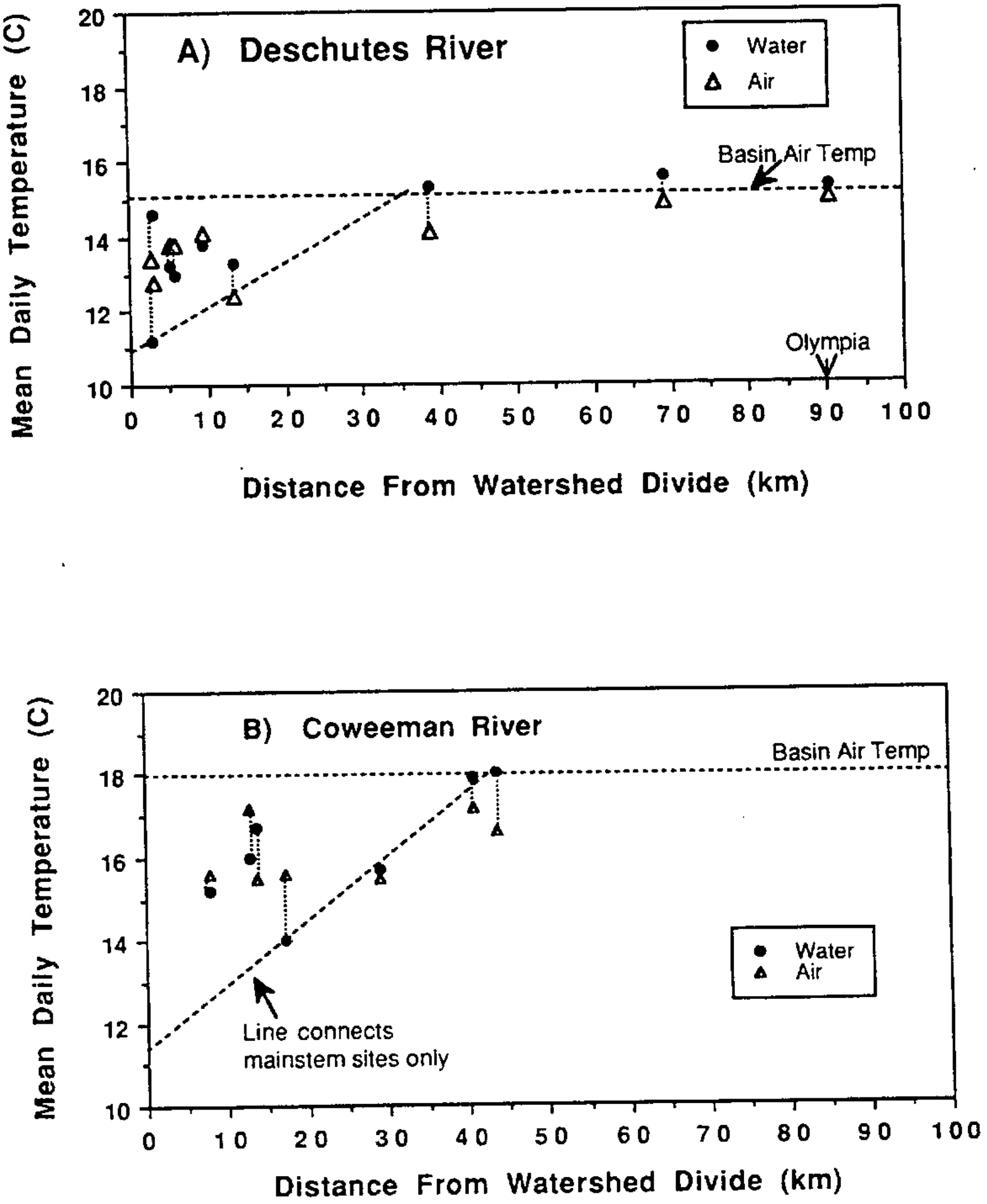
This hypothesized temperature is very near to the temperature of 19.3°C recorded 3.1 km downstream at site AM. Thus, the cooling effect lasted at least 3 km.

Based on the three study basins, several preliminary conclusions can be drawn regarding the effect of timber harvest on a basin scale. Effects of heating (or cooling) from tributaries seemed more pronounced in the headwaters of the basins. The riparian vegetation and stream characteristics of each local river segment strongly influenced river temperature. Clear distinctions between the effects of the general spatial distribution of timber harvest history in the basin and direct local effects where riparian vegetation was disturbed along river banks could not be made. Nevertheless, it is probably safe to assume that river temperatures in managed basins were probably greater because of both of these effects than if the watersheds were forested by mature conifer forests.

All three of the watersheds shared some common characteristics of basin-scale stream heating irrespective of the unique conditions found within each. To illustrate the general patterns of heating in each of the basins, the mean daily air and water temperature are shown as a function of each site's distance from its own source in Figure 6.19 (a,b,c). Most of the sites in the Deschutes basin are located on fully or partially shaded reaches of the mainstem or tributary streams, with the exception of the site at Ware Creek which is completely unshaded (3 km from divide; 14.8 mean temperature). (The effect of timber harvest in Ware Creek is clearly evident, as this site is far higher in temperature than expected based on the line drawn through the more fully shaded sites.) The water temperature tends to be low near the headwaters, and generally increases with distance from the divide (Figure 6.19a). (A very similar basin profile for the Chehalis River was provided in Sullivan and Adams (1989). The same pattern holds true for the Coweeman and Little Natches River, although there are less sites and the rivers are much shorter.

In all three watersheds, the water temperature tends to be less than the air temperature at distances less than 40 km from divide. (An estimate of the average basin air temperature is represented by the dotted line). At distances greater than 40 km, the water temperature tends to be slightly greater than the air temperature, with little change in either for long distances. These results suggest that the maximum equilibrium temperature of the stream systems appears to occur at approximately 40 km from the watershed divide for these rivers. Sullivan and Adams (1989) termed the distance at which rivers reach this system equilibrium the "threshold distance", concluding that water

Figure 6.19 Mean daily temperature profile of three river basins in relation to distance downstream from watershed divide.



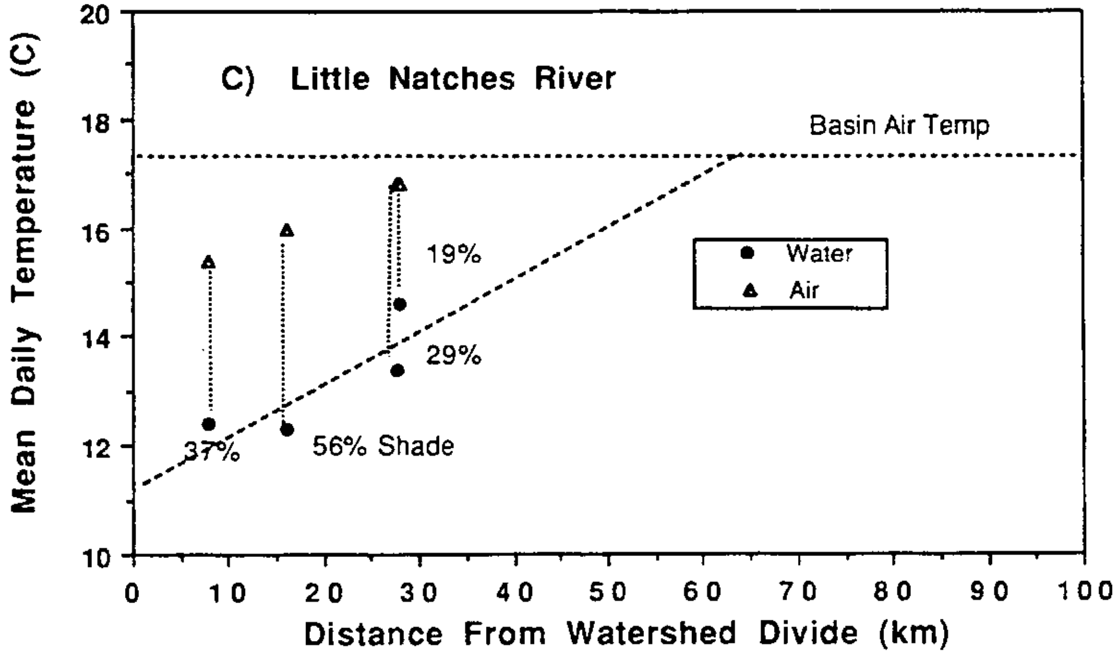
temperature was primarily related to air temperature downstream from this location. Upstream of this location, shading from riparian canopy was thought to have significant effect on stream temperature, where changes in riparian vegetation could increase water temperature up to but not exceeding the mean air temperature by more than ±2-3°C. They observed that the Chehalis River also appeared to reach this system equilibrium at approximately 35-40 km downstream from the watershed divide.

General Statewide Basin Trends. Without detailed accounting of riparian conditions of the sites, it is clear in Figure 6.19 that there was a lower limit of stream temperature (groundwater temperature) that increased with distance in all three of the basins. In smaller basins, the minimum temperature occurred under mature forests, and the warmest temperature was approximately equal to the mean air temperature. Larger rivers were always at or slightly above air temperature. Within each basin, increases from one site to another sometimes seemed to be related to differences in the shading in adjacent reaches, but often there was not a clear change in riparian conditions that accounted for the apparent underlying trend to increase in temperature. In very small, canopied streams the mean temperature was near groundwater temperature.

These same general relationships appear to occur within the three watersheds, as well as when all sites in Washington are considered as a group. The mean daily water temperature occurring at a "reference" air temperature of 20°C for each of the sites is shown in Figure 6.20, and the diurnal fluctuation in relation to stream depth is shown in Figure 6.21 based on measured stream temperature at each site. Considering stream temperature at a reference air temperature such as 20°C, allows the importance of the other environmental factors to be determined and provides an indication of each site's "equilibrium temperature". The selection of 20°C for air temperature was arbitrary, although it coincides with the average daily mean air temperature on the warmest days of the year at many sites. In this case, riparian vegetation is indexed by shading categories and other environmental factors besides air temperature are assumed accounted for by distance from the stream source. Included are secondary sites where relatively little is known about exact stream shading and other characteristics.

Mean water temperature observed at the reference air temperature of virtually all of the sites falls between the expected lower and upper limits, although the relationship to stream shading categories remains highly variable (Figure 6.20). The open sites tended

Figure 6.19 Continued



to have the highest temperatures and the fully shaded sites tended to be the coolest, although there was considerable variability in where sites in the each of the stream shading categories fell within the expected range. Some shaded streams were relatively warm and some open streams were relatively cool. (Considering the wide array of sites included in this analysis these results may actually be rather good.) Because of the variability, however, no simple relationship between mean water temperature and distance for each shade category is drawn.

There was general agreement with the hypothesized relationship between diurnal temperature fluctuation and stream depth, although there was also scatter in values in each shade category (Figure 6.21). The largest diurnal fluctuations were observed in small open streams, while flux tended to be low in small fully-shaded streams. Intermediate shading levels were also intermediate in temperature fluctuation. Deeper streams, had lower temperature fluctuation, and appeared to be independent of shading.

Although there was scatter, there were clear patterns in diurnal fluctuation with depth by shade category. Lines are calculated for each shade category according to a theoretical derivation following equations of heat transfer provided by Adams and Sullivan (1990).

$\Delta T = K/\text{Depth}$ (shown in Figure 6.21)

$K = (\text{heat load}) \times (\text{sky view factor}) \times c_1$

Heat load is assumed to be 280 W/m^2 (maximum solar loading during mid-summer for average Pacific Northwest locations) and the coefficient $c_1 = 0.00571$. This coefficient was empirically derived from the data, but matches reasonably well with estimates based on solving the fluctuating component of Adams and Sullivan's linearized stream temperature model with average values of heat transfer variables. Calculating K for the shade categories yields the values provided in Table 6.8.

Table 6.8 Values of K (heat loading constant) for calculating diurnal temperature fluctuation by sky view factor category.

Sky View Factor	K
1.0 (open)	1.6
0.75	1.2
0.50	0.8
0.25 (mostly shaded)	0.6

This relationship appears reasonably reliable in predicting diurnal temperature fluctuation based on stream depth and shading.

An estimate of baseline temperature under mature forest conditions was estimated by plotting the maximum (equilibrium) temperature of sites with mature forest canopies that were available from the dataset. The maximum temperature of baseline sites (mature conifer canopies) are plotted in relation to distance from watershed divide in Figure 6.22. Stream temperature tends to increase in the downstream direction, although temperature at locations 20 and 50 km downstream were somewhat cooler than the line projected through most of the data. Riparian conditions may still have influenced stream temperature as far as 50-60 km from the watershed divide, rather than the 40-km distance suggested in the individual basins managed intensively for timber shown in Figure 6.19. Unfortunately, there was only one baseline site located this far downstream from divide, and so it was difficult to determine the representativeness of this site. If the site is an outlier (perhaps due to a local source of incoming cooler water such as a tributary or groundwater), then the projected relationship based on the 10 data points would show the effects of shading diminishing at about 40 km from the headwater source, but if the site is included than the cooling effect would appear to extend up to 50 km or farther.

The "threshold distance" where streams are sufficiently wide that shading by even mature forest vegetation provides no significant temperature protection can probably not be resolved with existing data. However, if it can be assumed that a river reaches the maximum system equilibrium point when shading is less than 25% open, (as suggested by the relationship between average site temperature and shading levels), then a distance of approximately 50 km from divide appears to be a reasonable estimate based on the empirical relationship between the view factor and distance from watershed divide for baseline sites (mature conifer vegetation) developed in Chapter 3 (Figure 3.12). One of the most glaring data deficiencies discovered in this project was the lack of quantification of the riparian shading characteristics of mature conifer forests along larger rivers. Improving this knowledge would enhance understanding of the effects of timber harvesting on larger rivers.

Figure 6.20. Mean daily temperature (A) and diurnal fluctuation (B) during the warmest 30-day period as a function of distance from watershed divide by shade category.

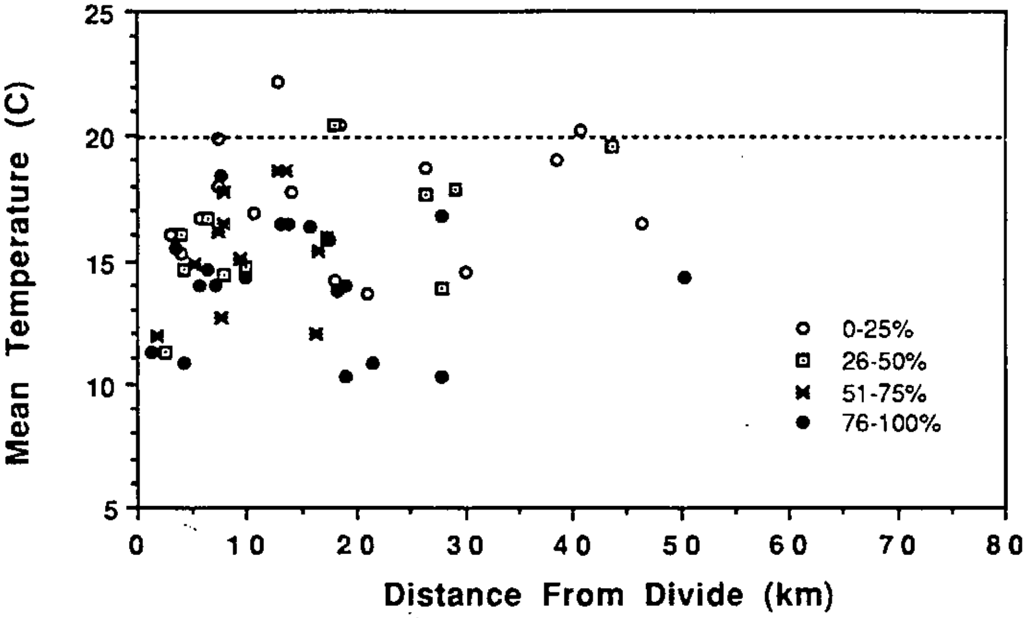


Figure 6.21 Average daily diurnal fluctuation of water temperature during the warmest 30-day period in relation to average stream depth. Plotted points are site averages. Lines for each shade category are calusing using the equation provided.

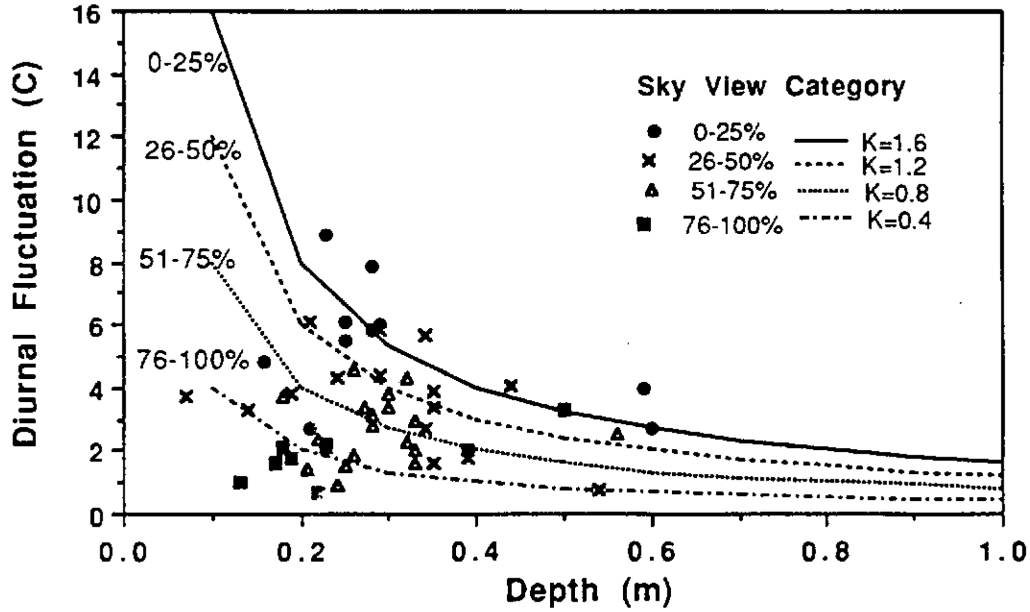
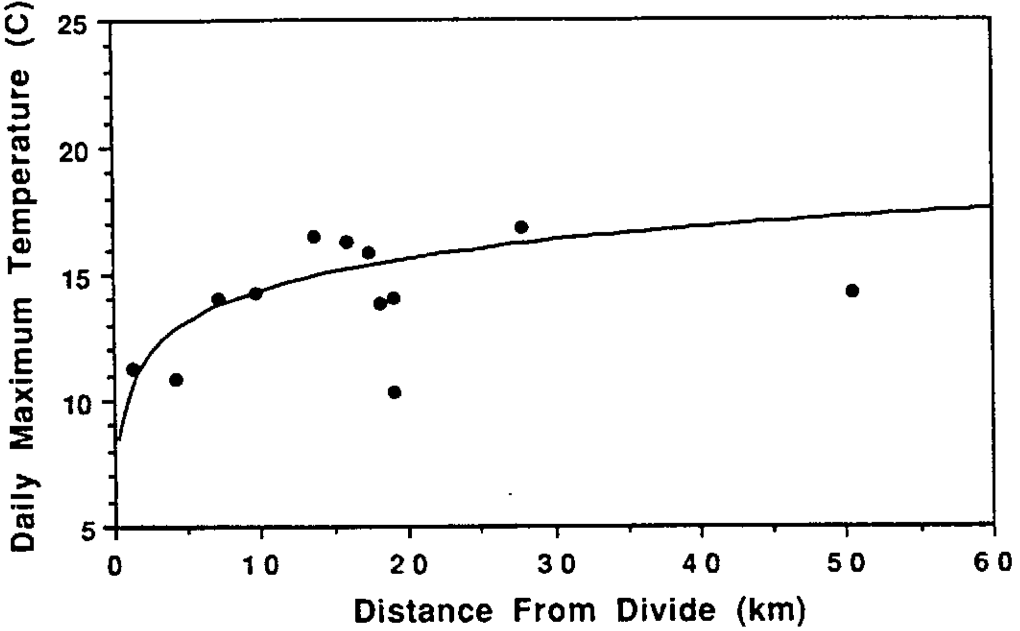


Figure 6.22 Average daily maximum temperature of streams under mature conifer forest canopies (baseline) in relation to distance from watershed divide.



A generalized schematic of the relative change in mean daily temperature and the diurnal fluctuation from baseline temperature under mature forests to completely unshaded streams is provided in Figure 6.23. Important concepts suggested by the illustration are that: (1) there are upper and lower limits of changes in water temperature with riparian vegetation with the envelope determined on the lower temperature scale by groundwater temperature and the upper scale by air temperature; (2) the magnitude of response varies with stream characteristics of width and depth (indexed by distance from watershed divide), and, (3) there is probably a watershed location where shading from riparian; vegetation has little effect on local or downstream temperature.

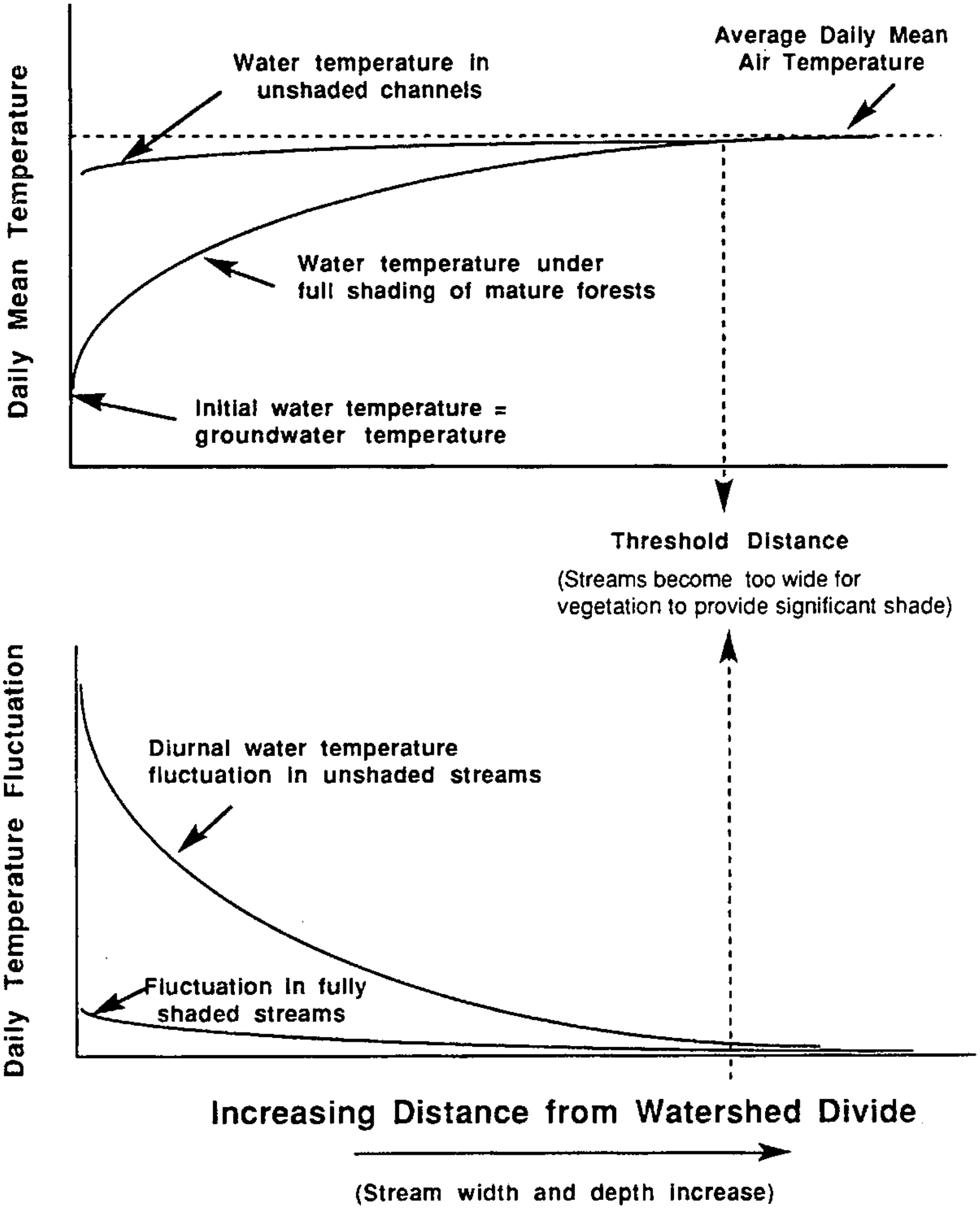
Generalized Basin Temperature Profiles. It was initially hoped that this analysis would lead to basin relationships that could provide a general indicator of probable temperature with changes in riparian vegetation. Although, the general hypothesized relationships suggested are verified, there is too much scatter in the relationships in Figure 6.20 and 6.21 to develop reliable nomagraphs of generalized temperature profiles based on riparian shading conditions alone. Scatter is probably due to unaccounted for local environmental factors that also influence water temperature. Nevertheless, the weight of the data support the general conclusions regarding temperature characteristics on a basin scale depicted schematically in Figure 6.23.

SUMMARY

Shading from riparian vegetation was found to have an important influence on stream temperature but the extent of its cooling effect varied with site elevation. However, it is not possible to predict temperature effects based solely on riparian vegetation. Other environmental factors were also important in determining water temperature, including air temperature, stream width, and so on. (Channel orientation was not a significant influence.) Typically, a combination of local environmental factors were important, and no one factor alone was ever a good predictor of stream temperature.

An empirical "regional" temperature model was developed where average temperature recorded at sites was predicted based on stream and watershed variables. The nomagraphs generated from this exercise represented temperature as a function of distance downstream from watershed divide and could be used as quick index of probable changes in temperature at different watershed locations with riparian vegetation management. However, the

Figure 6.23 Hypothesized temperature patterns for daily mean and diurnal fluctuation in watersheds. (After Sullivan and Adams 1990).



method was not accurate enough on a site-by-site basis to correctly identify temperature with sufficient precision for regulatory purposes. Thus, the temperature prediction model was found to be a useful tool if more accurate estimates of site-specific temperature are required for decision-making.

Basin temperature patterns were analyzed on the limited number of watersheds having a number of sites that were available for this study. All basins showed general warming in the downstream direction consistent with theoretical relationships. Although some local influence of tributary heating (primarily nearer the headwaters) and cooling (primarily in lower reaches) were observed, there were no clear trends in the relationship of basin temperature to harvest patterns in tributaries as opposed to effects of timber removal along the mainstem of the rivers themselves. Mainstem temperature of all the rivers studied appeared to be somewhat warmer within distances of 50 km from the watershed divide than would probably be expected in old growth conifer forests. Effects appeared to be between 3 and 5°C, depending on stream size.

CHAPTER 7

TEMPERATURE SENSITIVITY AND FOREST PRACTICE REGULATIONS

Temperature considerations in forest management are directed towards maintaining low stream temperatures with management of shade in riparian zones. The TFW Agreement strives for temperature protection through riparian vegetation leave requirements for fish-bearing streams. Alternative temperature protection measures are encouraged for temperature "sensitive" waters with sensitivity and strategies to be determined by a TFW temperature method. Alternatives may include increased shading requirements or possible use of a basin-scale temperature model for developing riparian area prescriptions and planning distribution of harvest units along non-fishbearing streams to protect downstream temperature.

Results of the temperature study presented in earlier chapters of this report are drawn together in this chapter to suggest a TFW method to satisfy temperature protection objectives. The results of temperature regime analysis and model-testing provided sufficient information to develop sound recommendations for considering stream temperature in forest management as called for in the TFW Agreement, although all aspects of TFW temperature concerns could not be resolved in this study. Suggestions for addressing remaining questions as recommendations for future research and evaluation needs are provided in Chapter 8.

Water temperature at sites was evaluated relative to Washington state water quality standards criteria to determine whether water quality criteria were exceeded and what kind of site or basin conditions were likely to cause this situation (*Temperature Sensitivity and Regulatory Criteria*). Average temperature characteristics of sites meeting and exceeding water quality criteria are provided and a simple method to identify sites likely to exceed criteria was developed (*Observed Temperature and Regulatory Criteria*). The temperature models were then used in a gaming mode to analyze whether the current riparian regulations are likely to provide adequate temperature protection (*Preliminary Evaluation of Regulation Effectiveness*).

Based on this analysis, model-testing results (Chapters 4 and 5), and temperature regime analysis (Chapter 6), a TFW temperature method that provides a means for identifying temperature of present and future riparian conditions and guidelines for the appropriate application of temperature prediction models is suggested (*Recommended TFW Temperature Method*). The recommended method is outlined in this report. The reliability of method components are established to guide decision-makers in their use.

FOREST PRACTICE REGULATIONS AND WATER QUALITY TEMPERATURE STANDARDS

Forest Practice Regulations

Washington forest practice regulations specify shading requirements to protect stream temperature from adverse increases during the summer months. Within riparian zones along type 1-3 streams, the operator must leave all non-merchantable material providing shade to the stream, and whatever merchantable material is required to maintain 50% of the existing shade. If the maximum daily water temperature exceeds the forest practice temperature criteria described below (termed "temperature sensitive"), then the operator must leave 75% of the existing shade. (See Washington Forest Practices Rules and Regulations 1988; WAC 222-30-040). Washington forest practice regulations specify that the temperature sensitivity of stream types 1,2 and 3 shall be based on field data or records, or from a verified temperature model or method that demonstrate significant adverse water temperature impacts following the proposed timber harvest and shade removal. A stream must be designated temperature sensitive prior to or at the time of the forest practice application.

The smallest streams (type 4) do not require leave strips of riparian vegetation, and it is unclear whether these less shaded streams *significantly* affect the temperature of the fish-bearing streams they flow into. Because timber harvest patterns create a mosaic of vegetation conditions within watersheds, and because heated water can move downstream with flow, concerns remain that inadequate temperature protection measures in upstream waters may have adverse downstream impacts. The cumulative length of small but abundant type 4 waters relative to larger streams makes this question especially important. Temperature concerns along type 4 waters can be addressed through the priority issues process if significant downstream temperature impacts can be expected.

The forest practice regulations pose a series of challenges in developing reliable methods for screening temperature sensitive streams and developing appropriate management solutions to minimize stream temperature effects. Which streams are likely to exceed the temperature threshold, either before or after a proposed activity? Can they be identified without on-site temperature measurement? Will the 50 or 75% of existing shading provide sufficient temperature protection?

Water Quality Standards

Riparian zone management regulations (jointly promulgated by the Forest Practice Board and the Dept. of Ecology and administered by the Departments of Natural Resources and Ecology) are designed to meet water quality criteria in state water quality standards (administered by the Department of Ecology). To protect fish habitat and other beneficial uses, the forest practice regulations stipulate that the average of maximum daily water temperature for seven or more sequential days should not exceed 15.6°C (60°F). Although the exact biological importance of this threshold in natural streams has not been established, the value was presumably selected based on laboratory research associating this temperature with stress levels in salmonids.

The water quality standards for surface waters of the state of Washington (Chapter 173-201-045 WAC), administered by the Department of Ecology, are linked to the Forest Practice Rules and Regulations through a provision for joint promulgation (Chapter 173-202 WAC). These standards and the water-related forest practice rules and regulations are designed to meet state requirements for non-point source pollution control under the federal Clean Water Act (Public Law 100-4) administered by the U.S. Environmental Protection Agency. The water quality standards establish criteria based on three threshold temperatures for streams of different classes. For class AA streams (generally applicable to forest streams), the maximum water temperature shall not exceed 16.3°C (61°F) or the temperature increase from activities shall not exceed 2.8°C. For class A streams (generally applicable to larger rivers in forest zones and elsewhere), the maximum water temperature shall not exceed 18.3°C (65°F) or increase more than 2.8°C. For class B streams (generally larger rivers affected by industrial or agricultural activities and not typically found in forest land use zones), the maximum water temperature shall not exceed 21.3°C or increase by 2.8°C.

A difference between state water quality temperature criteria and forest practice temperature criteria was not recognized during the drafting of the TFW Agreement or the 1987 revision of the Forest Practice regulations. The Department of Ecology will need to resolve these discrepancies. Unfortunately, the existence of dual temperature standards was not identified until very late in the course of the temperature study and well after most analyses were completed relative to the the forest practice criteria. In an effort to address the nonpoint water quality criteria, the TWG performed additional analyses evaluating water temperature relative to criteria in the water quality standard and compared results to those based on the forest practice criteria. It is hoped that these comparisons may assist regulators and managers in evaluating practices based on their effectiveness in protecting beneficial uses.

The criteria in both the forest practice rules and water quality standards assess temperature over short time intervals (respectively 7-day and 1-day). Since the 60°F threshold represents a sublethal temperature, it is unlikely that exceedence for short periods would cause observable changes in aquatic populations. However, increased thermal loading over longer period may be significant.

It may be useful for fisheries managers to recognize the longer duration temperature characteristics of streams as measured by the short interval criteria. Since temperature models can predict temperature over longer intervals and temperature characteristics from Washington streams are known, longer duration performance criteria may be informative for fisheries managers, even though they may not be specified by state law. For informational purposes, the TWG developed a metric based on temperatures observed over 30 days. The 30-day criteria coincides closely with criteria in the water quality standards as it uses the same threshold temperature values but it somewhat masks the peak temperature by virtue of the averaging process.

The TFW temperature study results are expressed relative to both criteria to the extent possible and the TFW temperature method has been designed to address both thresholds as they exist in 1990. Results of the 30-day evaluations are provided for informational purposes.

Criteria for Temperature Categories

The temperature thresholds for the three approaches described above are sufficiently similar that general categories of temperature designated as low, moderate and high can be identified based on criteria specifying temperature thresholds and duration (Table 7.1). Because the thresholds are similar for the low temperature category (15.6 and 16.3°C or a difference of about 0.7°C or 1.3°F), the category designations are reasonably compatible for all three approaches. The primary difference between them is the duration of time over which the temperature occurs. Applying category terminology facilitates discussion of general temperature levels and comparisons between approaches. All subsequent analyses refer to temperature categories of low, moderate, and high as determined by criteria listed in Table 7.1.

Table 7.1. Temperature categories and criteria.

	TEMPERATURE CATEGORY		
STANDARD	**LOW**	**MODERATE**	**HIGH**
Water Quality Standard (instantaneous)	Maximum Less than 16.3°C	Maximum greater than 16.3 °C and less than 18.3°C	Maximum observed greater than 18.3°C
Forest Practice Rules and Regs (7-day sequential)	Daily maximum less than 15.6°C	Daily maximum greater than 15.6 °C (no distinction between moderate and high; all sites exceeded identified as high)	
30-Day Criteria (July 15-Aug15)	Average daily maximum less than 16.3°C	Average daily maximum greater than 16.3°C and and less than 18.3°C	Average daily maximum greater than 18.3°C

Water Quality Standard (WQ) Criteria (Daily Maximum). The water quality standards specify three threshold temperatures for daily maximum temperatures (1-day) and one for allowable change .The upper thresholds are: Class AA streams = 16.3°C (61°F) Class A streams = 18.3°C (65°F) and for Class B streams = 21.3°C (70°F). (The threshold for Class B would apply to few streams likely to be influenced by forest practices and is not included in this analysis.) Corresponding to the WQ thresholds are the temperature categories assigned in this report: Low=less than 16.3°C, Moderate=16.4 to 18.3°C, and High=greater than 18.3. Which threshold determines exceedence of standards for any stream depends on the its class (Class AA, A, or B). Water quality classification of Washington rivers is listed in WAC 173-201-080. Generally, most forest streams are classed AA and some reaches of larger rivers occurring in the forest zone may be classed A. The allowable change threshold of 2.8°C that applies to all three classes is considered in another section and not linked to the temperature categories.

Forest Practice Rule (FP) Criteria (7-day Maximum Average). The forest practice rules identify one threshold temperature (15.6°C or 60°F). Streams exceeding the threshold are termed "sensitive". For consistency of discussion in this report, streams below the forest practice threshold will be referred to as low temperature and those exceeding it will be termed high temperature. No moderate temperature is identified. The FP criteria is applied to the average of the daily maximum temperature for the warmest 7-day consecutive period during the summer.

30-Day Maximum Average. The 30-day measure compares with the WQ standard in that it uses temperature thresholds of 16.3°C (61°F) for moderate and 18.3°C (65°F) for high temperature. It differs in that the 30-day criteria is applied to average daily maximum temperatures observed during the warmest 30-day period of the year (July 15 to August 15).

OBSERVED TEMPERATURE RELATIVE TO TEMPERATURE CATEGORIES

Daily temperature records at all 92 sites were scanned for days where maximum water temperature exceeded the threshold between low and high temperature categories according to the forest practice threshold temperature of 15.6°C (60°F) (Figure 7.1). The temperature category of each site based on measured water temperature assessed relative to each of the three standards is listed in Table 7.2 and based on the criteria provided in Table 7.1. Most streams sampled exceeded 15.6°C at least one day during the summer (78%), and a majority exceeded 15.6°C for seven days or longer (62%).

The temperature threshold was exceeded in streams located in all regions of the state. (The relatively low proportion of sites exceeding the threshold in the southern Cascades shown in Figure 7.1 is because many of these sites were U.S. Forest Service baseline temperature monitoring sites.) The DNR Temperature standard was exceeded in both small and large streams where timber harvest had occurred, and in some of the "baseline" sites located on larger river systems where forest management effects were considered minimal. (See Table 6.1 for site characteristics.)

Where timber harvest had occurred, activities at all sites except one had been conducted prior to the TFW Agreement and do not reflect riparian conditions left under the regulations enacted in 1988. These high observed temperatures at so many locations confirmed that stream temperature was poorly protected with forest practices used in the past. If the water quality thresholds are correct indicators of appropriate performance, then greater stream temperature protection measures in the TFW Agreement were justified.

Observed Temperature Category of Study Sites. Although the criteria for each approach are unique, they identified the temperature category of sites remarkably similarly. (Classification according to a temperature screen discussed in subsequent sections is also shown.) The WQ criteria is slightly more conservative than the FP criteria. A total of 72% of study sites exceeded WQ moderate category threshold (23% moderate and 49% high) while 62% exceeded the FP criteria. Of the additional 9 sites that exceeded the WQ but not the FP criteria, six exceeded the temperature threshold on only 1 day, 2 sites exceeded the threshold for 3 days, and 1 exceeded the threshold for 6 days. Thus, there was relatively little difference in the temperatures interpreted by the two approaches. (If the class of the stream had been considered, the proportion *exceeding* the WQ criteria would have been slightly less in that moderate temperature is allowed in larger rivers.)

Figure 7.1 Days when maximum temperature exceeded 15.6 degrees C. (60 degrees F). If temperature was exceeded a + appears. Dotted vertical lines mark the period from July 15-August 15. (Note that not all sites have equal period of record. See Table 2.1 for record length for each site.)

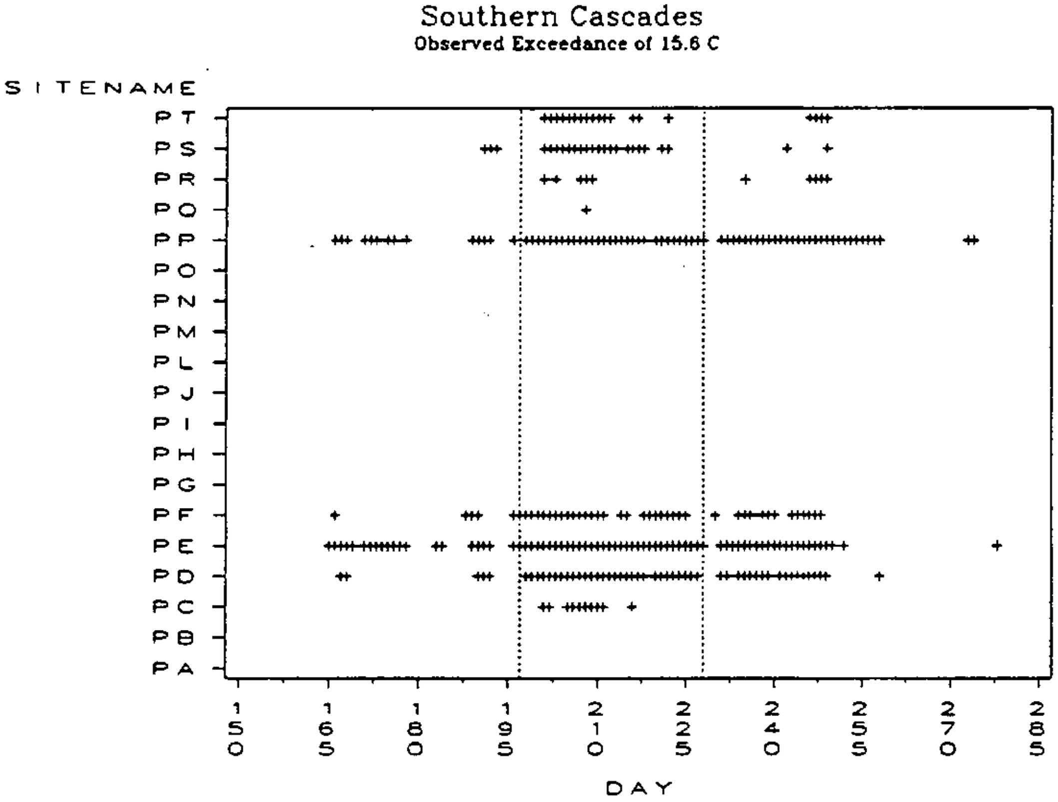


Figure 7.1 Continued.

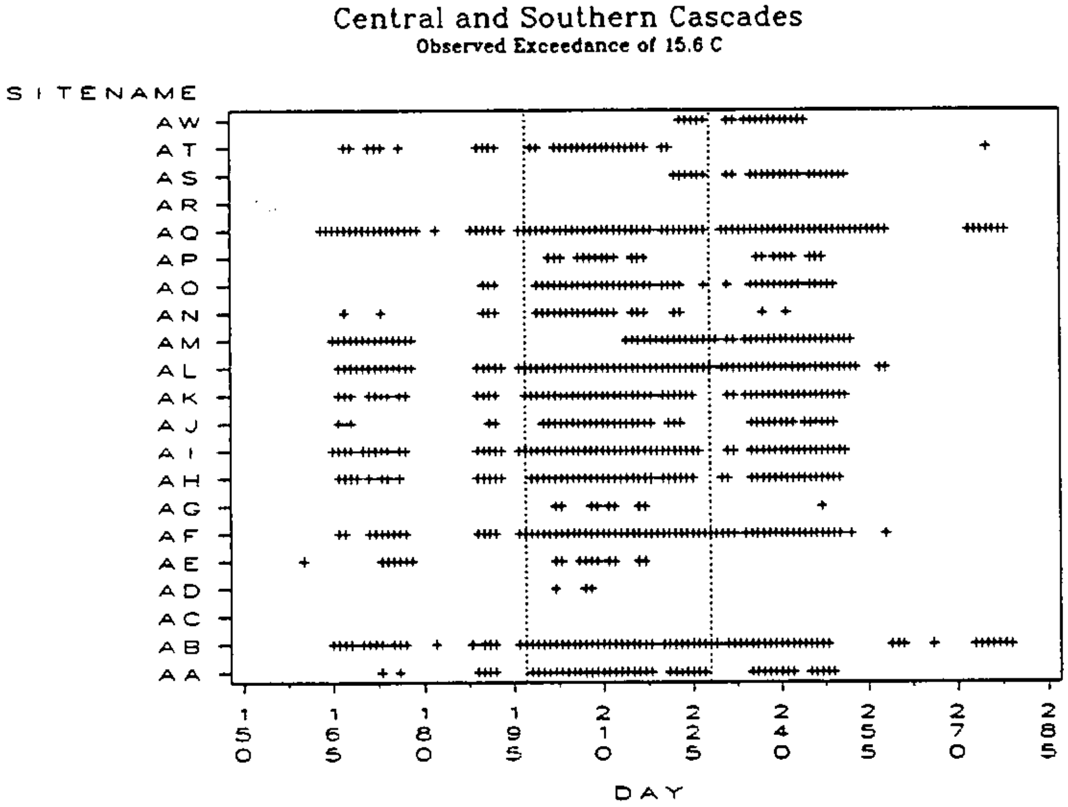


Figure 7.1 Continued.

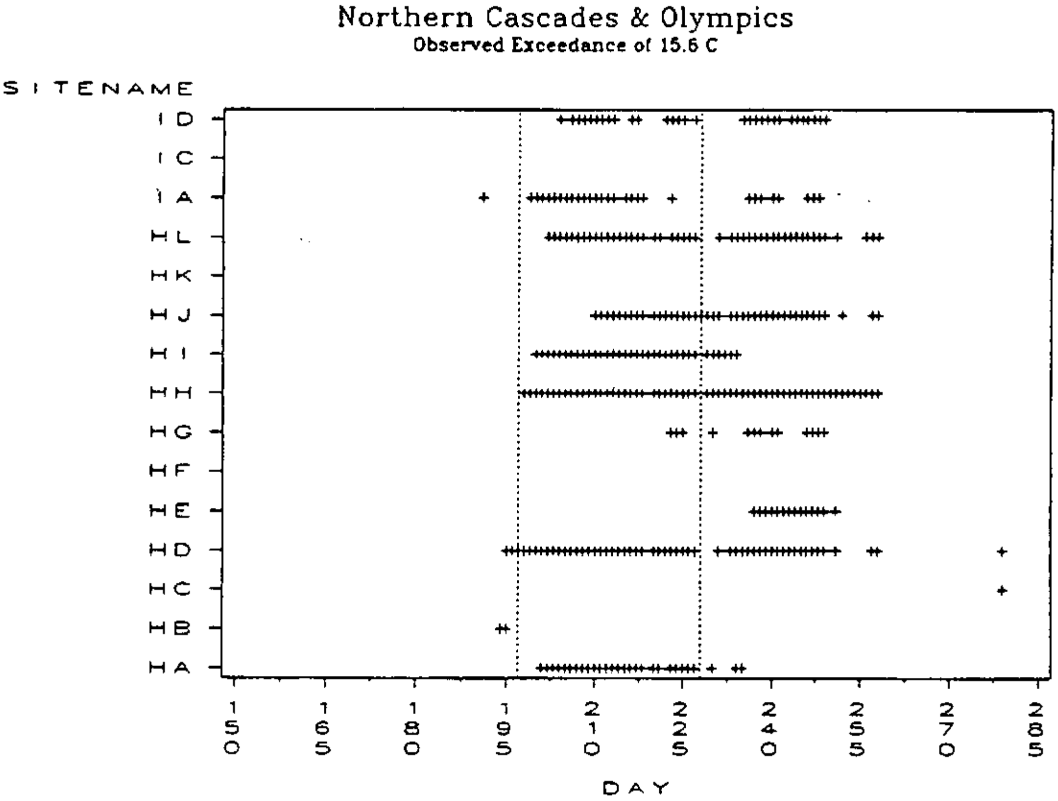
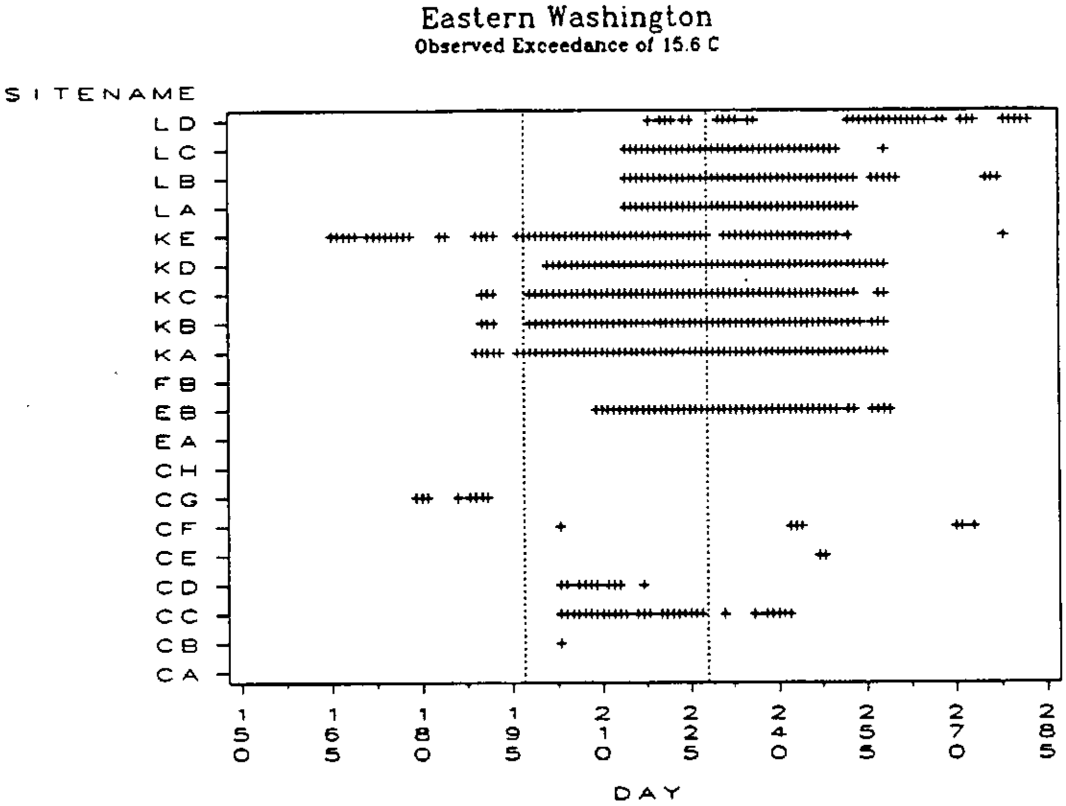


Figure 7.1 Continued.



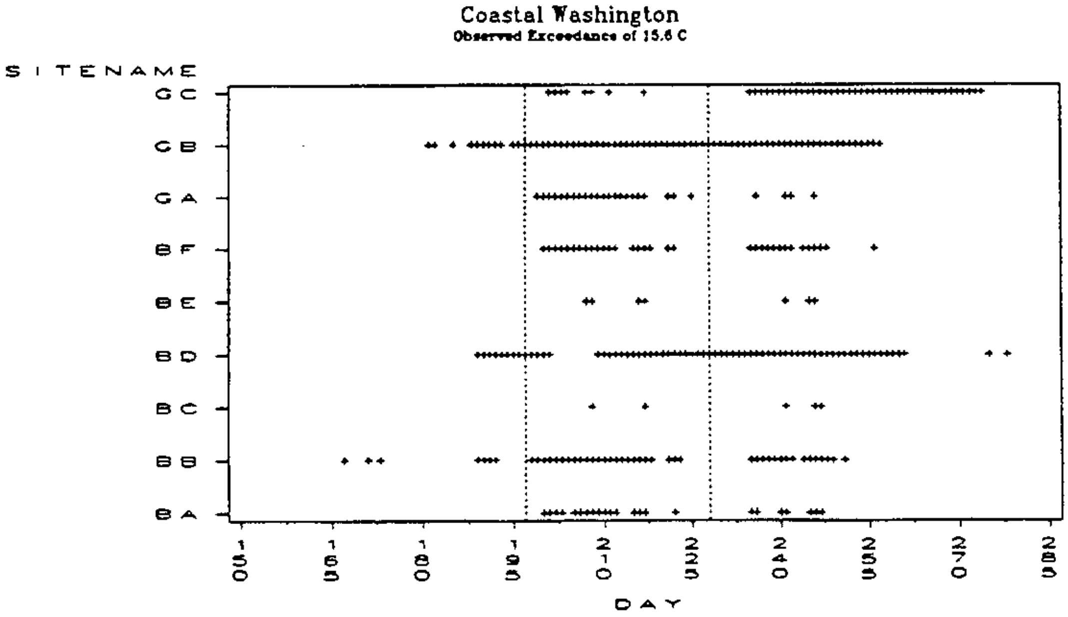


Table 7.2. Estimated temperature category of each site based on criteria for water quality standards described in Table 7.1. Instantaneous maximum temperature for each site is listed .

Site Code	Site	Max Temp(C)	Water Quality	Forest Practice	30-Day	Screen
AA	Ware Creek	18.5	High	High	Mod	High
AB	Schultz Creek	23.0	High	High	High	High
AC	Huckleberry Creek	15.0	Low	Low	Low	Low
AD	Thurston Creek	16.0	Low	Low	Low	Mod
AE	Little Deschutes Creek	16.7	Mod	Low	Low	Mod
AF	Deschutes River (RK60.2)	21.0	High	High	High	High
AG	Deschutes River (RK75.5)	17.0	Mod	Low	Low	High
AH	Mulholland Creek	20.9	High	High	High	High
AI	Goble Creek	20.9	High	High	High	High
AJ	Baird Creek	18.9	High	High	Mod	High
AK	Coweeman River (above Mulholland)	21.0	High	High	High	High
AL	Coweeman River (above Goble)	23.0	High	High	High	High
AM	Coweeman River (above Andrews)	21.9	High	High	High	High
AN	Coweeman River (above Baird)	18.5	High	High	Mod	High
AO	Herrington Creek	19.5	High	High	Mod	High
AP	Porter Creek	18.0	Mod	High	Mod	Mod
AQ	Hoffstadt Creek	26.0	High	High	High	High
AR	Hard Creek	13.5	Low	Low	Low	Low
AS	Deschutes River (RK 41.7)	18.0	Mod	High	No Data	Mod
AT	Gobar Creek	20.5	High	High	Mod	High
AW	Deschutes River (near Offut Lake)	18.0	Mod	High	No Data	High
BA	Abernathy Creek (Lower)	18.9	High	High	Mod	High
BB	Germany Creek (Upper)	21.1	High	High	Mod	High
BC	Naselle River	16.5	Mod	Low	Low	High
BD	Smith Creek	25.0	High	High	High	High
BE	Bear River	16.0	Low	Low	Low	Mod
BF	Abernathy Creek (Upper)	20.0	High	High	Mod	High
CA	Bear Creek	15.5	Low	Low	Low	Low
CB	S.Fork Little Natches River	15.0	Low	Low	Low	Low
CC	Little Natches River at Kaner	18.5	High	High	Mod	Mod
CD	Crow Creek	17.0	Mod	Low	Low	Mod
CE	Bear Creek Watershed (Baseline)	16.0	Low	Low	Low	Low
CF	Wind River (Baseline)	16.0	Low	Low	Low	Low
CG	Trout Creek (Baseline)	17.0	Mod	Low	Low	Low
CH	Trapper Creek (Baseline)	14.5	Low	Low	Low	Low
DA	Pilchuck River (RK 15.4)	21.0	High	High	No Data	High
DB	Pilchuck River (RK 2.7)	16.8	Mod	High	No Data	High
EA	Cee Cee Ah Creek	12.5	Low	Low	Low	Low
EB	Chamokane Creek	21.5	High	High	High	High
FB	Norwegian Creek	13.5	Low	Low	Low	Low
GA	Red Creek (Tributary)	17.4	Mod	High	Mod	Mod
GB	Red Creek	20.8	High	High	High	High
GC	Red Creek (Site 2)	16.2	Low	Low	Low	No Data
HA	Little Deer Creek	20.1	High	High	Mod	High
HB	N. Fork Stillaguamish (up. Deer Cr)	15.2	Low	Low	Low	No Data
HC	Squire Creek	15.3	Low	Low	No Data	Low
HD	Higgins Creek	18.9	High	High	High	High

Table 7.2 Continued

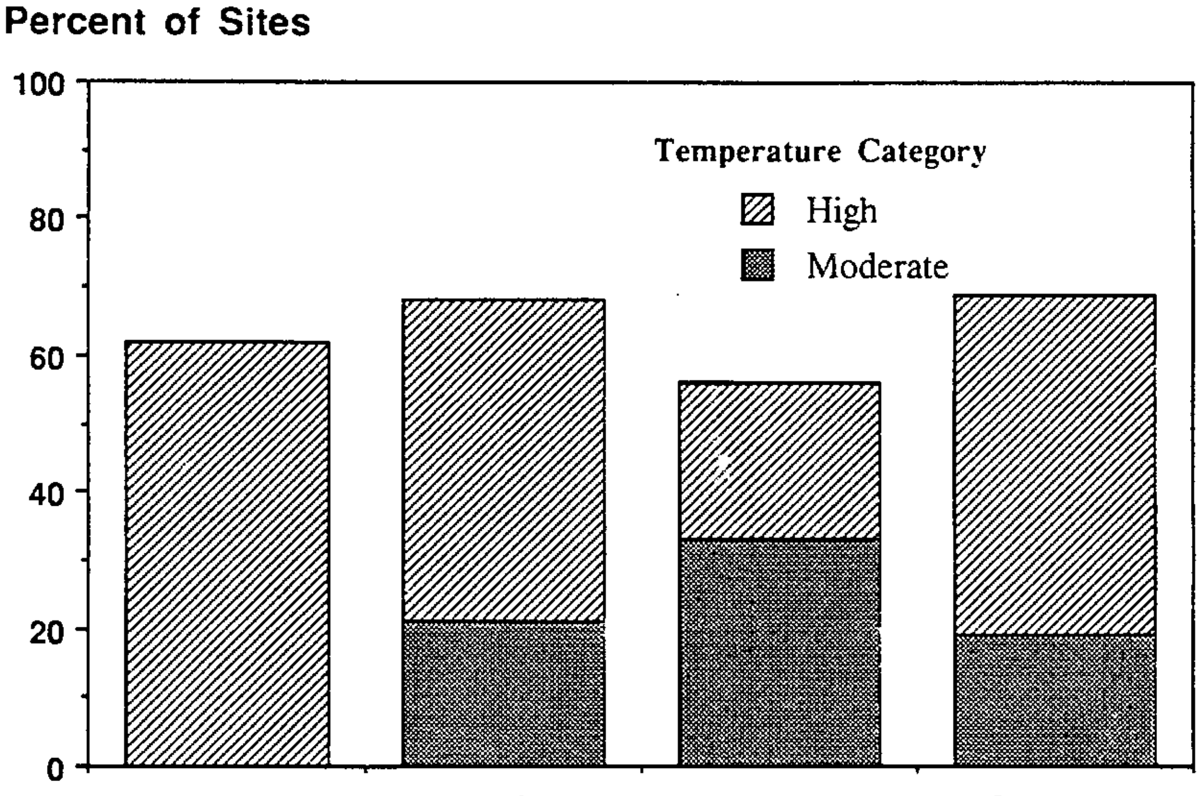
Site Code	Site	Maximum Temp	Water Quality	Forest Practice	30-Day	Screen
HE	S. Fork Nooksack River	19.1	High	High	No Data	High
HF	Tributary to S. Fork Nooksack	14.0	Low	Low	No Data	Mod
HG	N. Fork Stillaguamish (RM 38.8)	16.8	Mod	Low	No Data	High
HH	Deer Creek (above Deforest)	21.8	High	High	Mod	High
HI	Deer Creek (at mouth)	20.9	High	High	High	High
HJ	S. Fork Nooksack (Upper river)	20.6	High	High	High	No Data
HK	Segelson Creek	14.6	Low	Low	Low	Low
HL	N. Fork Stillaguamish (do. Deer Cr)	19.1	High	High	Mod	No Data
IA	Ten Creek	17.5	Mod	High	Mod	No Data
IC	S. Prairie Creek (upper)	14.0	Low	Low	Low	Low
ID	Greenwater River	17.0	Mod	High	Mod	Mod
JA	Snow Creek	-	No Data	High	No Data	No Data
KA	Wenatchee River (Site 1)	22.0	High	High	High	High
KB	Wenatchee River (Site 2)	21.0	High	High	High	High
KC	Wenatchee River (Site 3)	19.5	High	High	High	High
KD	Wenatchee River (Site 4)	21.5	High	High	High	High
KE	Icicle Creek Bypass	23.5	High	High	No Data	No Data
LA	Tucannon River (bel. M.Russels Sp.)	19.5	High	High	No Data	No Data
LB	Tucannon River (at bridge 14)	21.4	High	High	No Data	No Data
LC	M. Russels Spring--Tucannon	17.1	Mod	High	High	No Data
LD	Hartstock Cr--Tucannon	18.8	High	High	No Data	No Data
LE	Tucannon River (Below Panjab Cr)	12.2	Low	Low	Low	No Data
LF	Tucannon River (Below Big 4 Lake)	18.3	Mod	High	Mod	No Data
LG	Tucannon River (Below Deer Lake)	21.1	High	High	Mod	No Data
LH	Tucannon River (Below Cummings Cr)	21.1	High	High	Mod	No Data
LI	Tucannon River (Below Beaver Lake)	20.0	High	High	Mod	No Data
PA	Muddy River (Baseline)	11.0	Low	Low	Low	Low
PB	Clearwater Cr. (Baseline)	11.5	Low	Low	Low	Low
PC	Clearwater Creek (at rd. 9300)	17.0	Mod	-	Low	No Data
PD	Clearwater Creek (upper)	18.5	High	High	Mod	High
PE	Clearwater Creek (Bel. M. Bri.)	23.5	High	High	Mod	High
PF	Clearwater Creek (at Paradise Falls)	18.0	Mod	High	Mod	High
PG	Hungry Creek (Upper)	14.0	Low	Low	Low	Low
PH	Hungry Creek (Lower)	12.5	Low	Low	Low	Low
PI	Johnson Creek (Baseline)	15.0	Low	Low	Low	Low
PJ	Catt Creek (above Big Cr)	12.0	Low	Low	Low	No Data
PL	S. Fork Willame Cr. (Baseline)	11.0	Low	Low	Low	Low
PM	Clear Fork Cowlitz Cr (Baseline)	11.0	Low	Low	Low	Low
PN	N. Fork Willame Cr. (below unit 6)	14.5	Low	Low	Low	No Data
PO	N. Fork Willame Cr. (at 4700 rd)	15.5	Low	Low	Low	No Data
PP	Quartz Creek (Baseline)	20.5	High	High	Mod	Mod
PQ	Lewis River (Baseline)	16.0	Low	Low	Low	Low
PR	Canyon Creek (Baseline)	16.0	Mod	Low	Low	Mod
PS	Siouxon Creek (Baseline)	18.0	Mod	High	Mod	Mod
PT	East Fork Lewis River (Baseline)	17.5	Low	High	Low	Mod

Particularly unexpected was the relatively close agreement between the 30-day criteria and the WQ and FP criteria based on 1 and 7-day values (Figure 7.2). A total of 56% of sites exceeded criteria for moderate temperature, similar to the FP criteria. The 30-day criteria tended to classify more streams into the moderate (32%) than the high (24%) category compared to the WQ criteria. However, the results are surprisingly similar and indicate that when streams are warm, they tend to be warm for relatively long periods of time. This also suggests that the shorter duration temperature criteria are indicative of longer duration temperature conditions.

Modeling Interval. Data were examined to determine when exceedence of the FP temperature threshold tended to occur. The warmest period of the summer of 1988 occurred between July 15 and August 15 on average throughout the state (indicated by vertical dashed lineson Figure 7.1). All streams where temperature data was available at this time and that exceeded the temperature threshold did so during this period. Many also exceeded the threshold temperature at times earlier and later in the summer. Some of the sites were sampled later during the year, and therefore lack of an indication of exceedence in Figure 7.1 during earlier periods does not necessarily mean that temperatures were lower. (Check Table 2.1 for beginning and end of sampling dates.) For sites with shorter sampling periods, the relative occurrence of exceedence temperature between the sites was noted. In all cases, exceedence temperatures during later periods overlapped between stations, indicating that all sites with exceedence occurring during later periods could be assumed to exceed 15.6°C during the selected period. Many streams that barely exceeded 15.6°C did so only during this period.

The TWG selected the interval of time between July 15 and August 15 as the appropriate time to model annual

Figure 7.2 Percent of study sites in temperature classes determined according to temperature criteria in the forest practice rules (FP) and the water quality standards (WQ) (described in Table 7.1.)



maximum stream temperatures. Although the occurrence of the warmest 30-days could vary from year to year, there is a high probability that it will occur during this time.

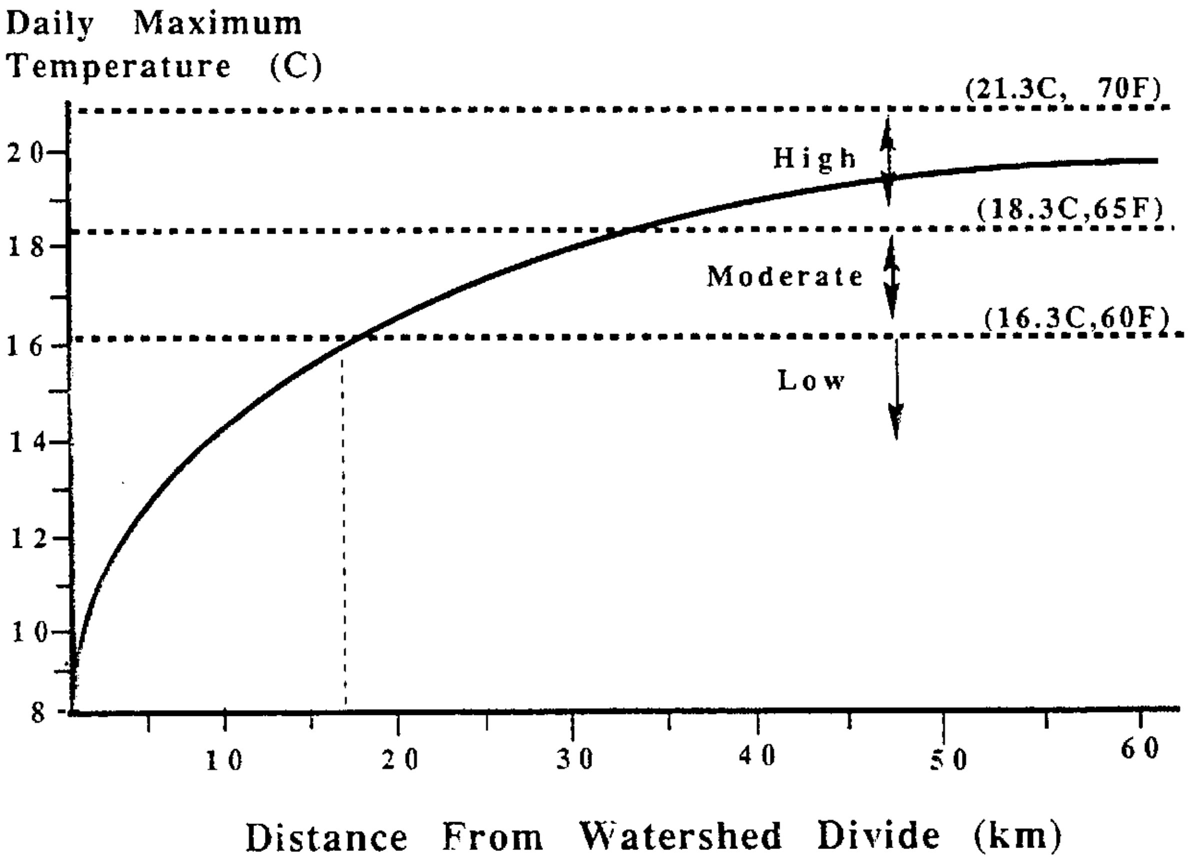
Model Predictions of Temperature Criteria. Temperature predictions from the test of the TEMPEST model (Chapter 4) were examined to determine whether the model correctly predicted the temperature category according to the FP criteria. TEMPEST accurately predicted the observed forest practices temperature category of 28 of 33 test sites for a reliability of 85%. All of the misses occurred at sites where the maximum temperature was close to 16°C, just barely exceeding the threshold. In two of the five misses TEMPEST over predicted the category, while at three sites it underpredicted the category. TEMPEST also correctly identified the temperature category of 90% of the sites according to the WQ criteria, missing only 2. Thus model results were consistent with observed temperature categories.

Temperature Characteristics in Relation to Temperature Categories

The major temperature characteristic addressed by water quality standards is daily maximum temperature. Other characteristics including daily mean, minimum, diurnal fluctuation and cumulative degree-hours may also be important biologically. Average temperature characteristics of streams relative to temperature categories are developed in this section for informational purposes.

Baseline Maximum Temperature. Temperature within reaches flowing through mature forests were evaluated to estimate the expected baseline temperatures within fully forested watersheds. Measured values of maximum daily temperature during the warmest summer period of

Figure 7.3 Estimated baseline daily maximum temperature during the warmest summer days under a mature forest canopy as a function of distance downstream from watershed divide.

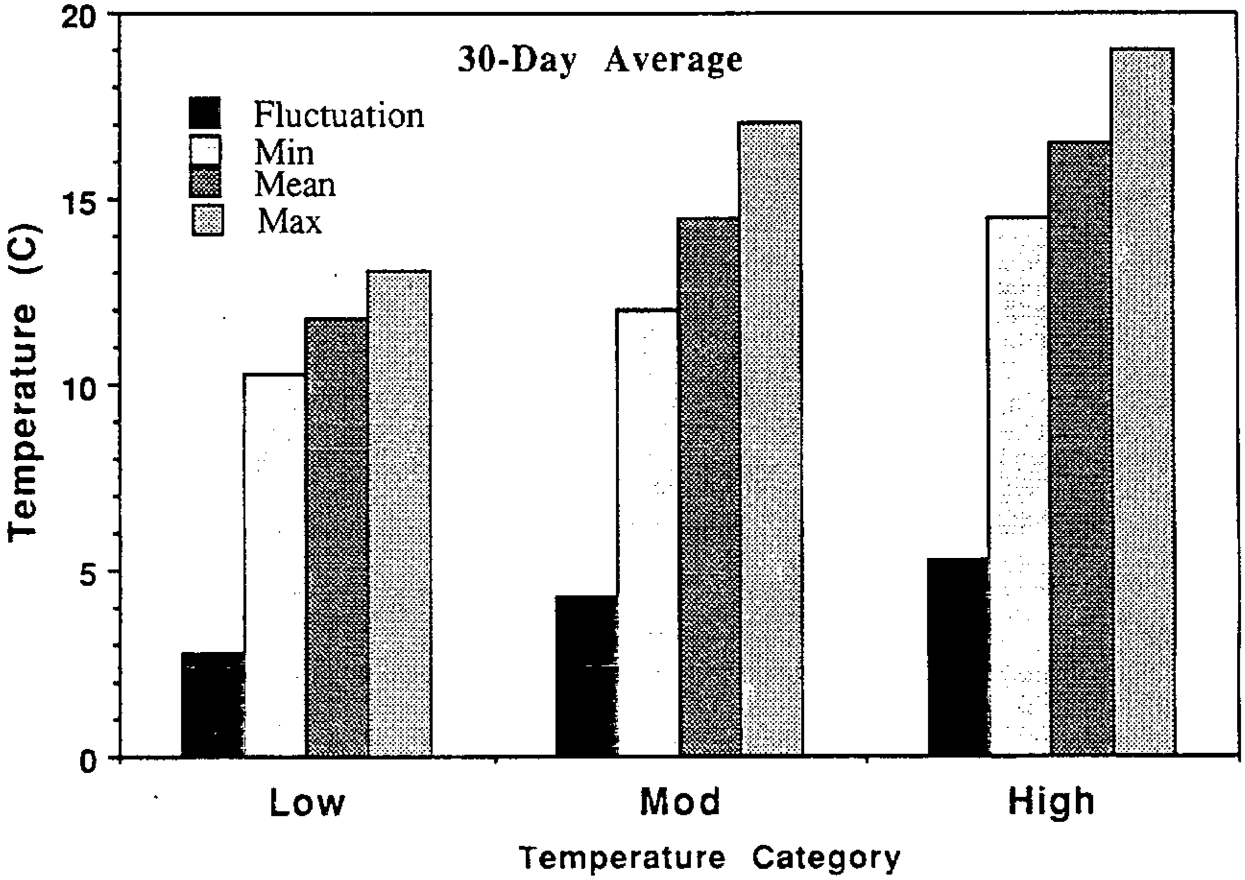


approximately 20 forested reaches of all sizes were composited to draw the relationship between maximum water temperature and increasing stream size (indexed as distance downstream from the watershed divide) shown in Figure 7.3. This graph depicts the best estimate of baseline maximum daily temperature within fully forested watersheds available at present.

As expected from previous research, average stream temperature tends to increase in the downstream direction, even within forested watersheds. Downstream warming occurs because of: (1) increasing stream width reducing the effectiveness of riparian vegetation to shade the stream surface; (2) decreasing proportion of cooler groundwater inflow relative to the flow in the channel; (3) increasing stream depth; and (4) increasing air temperature at lower elevations. Generally stream temperature increases logarithmically with distance (Hynes 1971, Theurer and others 1984). Local deviations in this general trend can occur such as where cooler or warmer tributaries join the system, or at the interface between rivers and oceans where air temperatures may be cooler than similar elevations located inland. Therefore, the baseline maximum temperature in Figure 7.3 should be considered a rule-of-thumb and can vary with local conditions.

Small streams relatively close to the watershed divide are very cool (between 10 and 14°C or 50-56°F). Temperature in the smallest streams is near groundwater temperature. (This represents the minimum possible summertime temperature). Somewhat larger type 2 and 3 streams are also slightly warmer, but temperature is well within the WQ criteria's low temperature category (applicable for Class AA streams). Stream reaches within forested riparian zones located approximately 20 or more kilometers (12 miles) downstream from the watershed divide are likely to be within the WQ criteria moderate category (applicable to Class A streams). Those sites greater than 50-60 km (30-40 miles) from divide are likely to be within the WQ criteria high temperature category

Figure 7.4 Average of daily temperature characteristics for 30-day warmest period by temperature sensitivity class.



(applicable to Class B streams) during the warmest periods of the year, regardless of forest management activities upstream. This condition is reflected in the classification assigned to streams and the designated beneficial uses.

Characteristics of Temperature Categories. Average temperature characteristics of the thirty-day criteria categories are shown in Figure 7.4. For sites in the high temperature category, both daily maximum and mean temperature averaged above 15.6°C for the entire period. The average maximum temperature was nearly 19°C and the minimum averaged nearly 15°C. Although not shown, similar values were observed for the 7-day period.

The duration and magnitude of high temperatures were more modest for those sites in the moderate category. The daily maximum of the moderate category averaged 17.0°C and the daily mean averaged 15.0°C for the 30-day period (Figure 7.4). For the low temperature class, the daily maximum averaged 13.0°C and minimum temperatures were near groundwater temperature (10°C).

Cumulative degree-hours were calculated as the summation of hourly temperature exceeding 15.6°C.

$$\text{Cumulative Degree-hours} = \Sigma\,(\text{Hourly Temp} - 15.6^{\circ}\text{C})$$

For example, an hourly maximum temperature of 20.6°C would equal 5 degree-hours. (If temperature was less than 15.6°C than degree-hours was 0.) Streams in low temperaure categories should have had significantly lower (if any) cumulative degree-hours over time than those in the moderate or high temperature category. Average degree-hours was the cumulative degree-hours for the period divided by the number of hours in the period. The average degree-hours indicate the exposure of organisms to high temperature as an average number of degrees above the threshold for each and every hour during the interval.

Sites where hourly temperature data was available (32 sites) were selected to analyze the cumulative degree hours characteristics by temperature category. The daily temperature records for each were examined for the hottest 7-day period and temperature categories assigned according to the FP criteria. The cumulative degree hours were summed. Site degree-hours by temperature class are shown in Figure 7.5. Average number of degrees exceeding the 15.6°C threshold per hour for the 7-day and 30-day periods are compared in Figure 7.6.

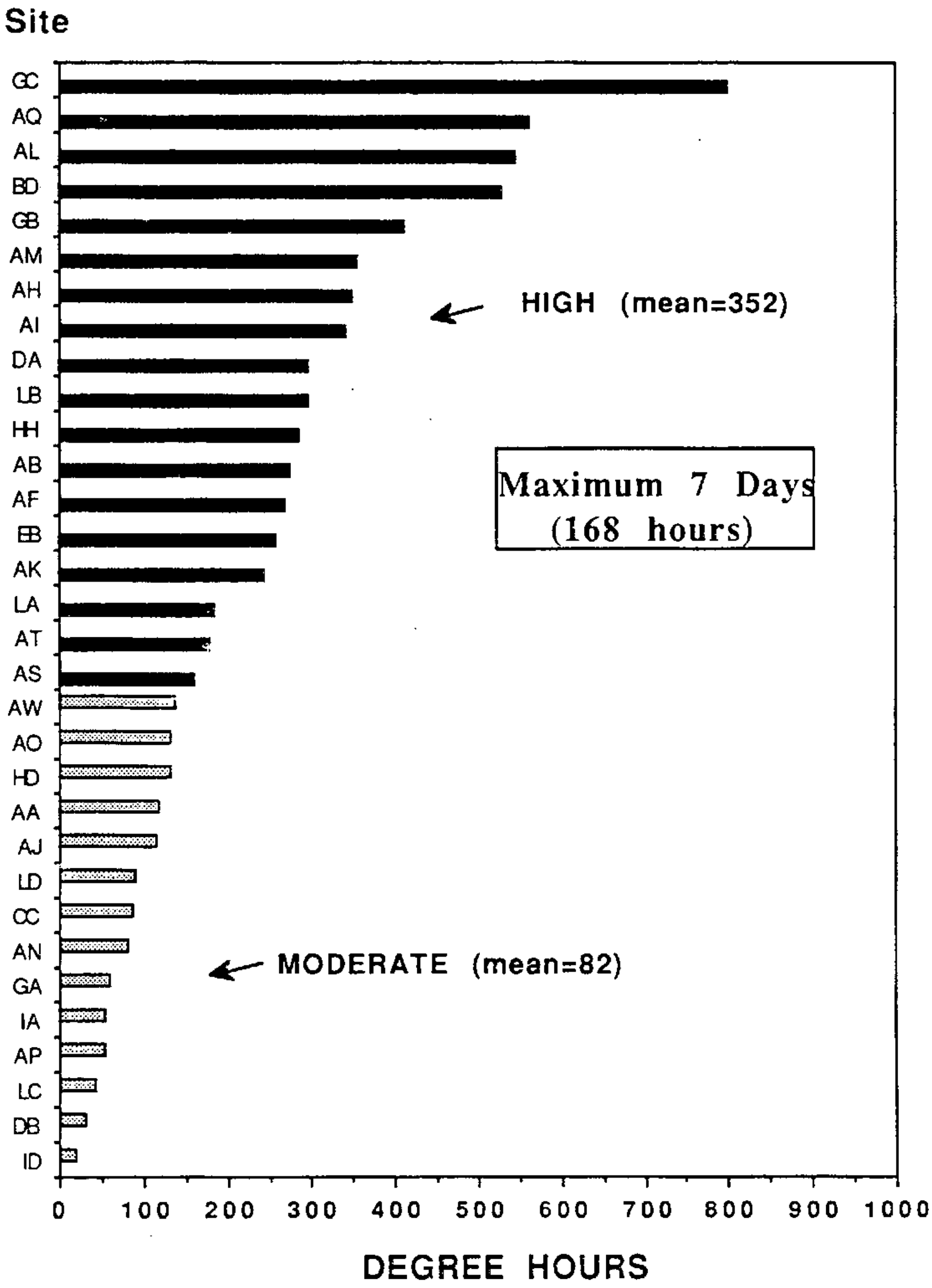
Cumulative degree-hours were large in high temperature streams. Degree-hours for the 7-day period of sites within the high temperature category varied, but cumulative degree-hours averaged four times greater in the high category than in moderate temperature streams (Figure 7.5). The same relationship was observed during the 30-day interval. The number of degrees above the threshold averaged over 2.0 for every hour for the 7-day period and 1.3 for every hour for the 30-day period. The biological importance of either the magnitude or duration of high temperature is not known but the degree-hours indicate that sites in the high temperature category are significantly warmer than those in the moderate category for long periods of time.

The degree-hours of sites in the moderate temperature category were relatively low (average 82 for the 7-day period; Figure 7.5).This translated to 0.6°C per hour for the 7-day period and 0.3°C for the 30-day interval. Cumulative degree-hours were very low in the low temperature category (not shown), but generally were less than 10 for the entire period.

Several temperature characteristics of the temperature categories were interesting. High and moderate temperature categories over 30 days seemed to be equally well differentiated using either criteria of (1) maximum temperatures of 18.3 and 16.3°C respectively, or (2) average daily mean relative to 16.3°C. With this method, the site was classified as high when both the daily maximum and daily mean exceeded the threshold (Figure 7.7). Temperature was moderate when the daily maximum exceeded the 16.3°C threshold but not the daily mean. Also of note was the similarity in the assigned temperature category based on the 7-day and 30-day intervals. Each site classified by temperature during the 7-day period fell into the same temperature category as those based on the 30-day average temperature characteristics (Figure 7.7).

This strong relationship between sensitivity examined at the 7-day and 30-day timeframes was an unexpected but fortuitous outcome of the analysis. These results suggest that longer-term averages can be effectively interpreted for short-term temperature characteristics and vice versa. Since most available records are presented as monthly averages, these may be more informative than previously thought.

Figure 7.5 Sum of the degree hours greater than 15.6C for sites during the warmest seven days of the year. (High temperature category are black lines and moderate category are hashed lines.)



Finally, the single threshold criteria used in the Washington forest practice rules to distinguish low temperature streams and high temperature streams (termed "sensitive" in the TFW Agreement) were not very discriminating in identifying streams of very different temperature characteristics. Indicative of this differences are the cumulative degree-hours of sites in the moderate and high temperature categories shown in Figure 7.5. All of the sites screen similarly relative to the categories, yet there are marked differences in temperature of reaches exceeding the 60°F threshold.The FP criteria identified most streams as high, including several larger rivers considered relatively close to baseline shading conditions under mature conifer forests.

The recognition of moderate and high temperature categories in the WQ criteria is a more realistic reflection of what occurs in natural forest streams as suggested by higher baseline temperatures in larger rivers (Figure 7.3). However, the location of the boundary between river water quality classes should be examined to ensure it realistically reflects expected baseline temperatures for each class.

Temperature Sensitivity Screen

What were the site characteristics that determined the streams most likely to have low, moderate or high temperature? At this point in the analysis, the most consistent observations are that unshaded streams tended to have moderate to high temperature, while fully shaded small to medium-size streams tended to have low temperature. These patterns are more fully explored in developing a temperature sensitivity screening method.

The analysis of temperature relationships to stream characteristics in Chapter 6 showed that a number of environmental factors were well correlated with stream temperature. Several good empirical relationships between stream characteristics and water temperature were developed based on 5 of the most important environmental variables including stream shading, mean air temperature, elevation, discharge, and bankfull

Figure 7.6 Average degrees exceeding 15.6 deg C by temperature class for 7-day and 30-day intervals

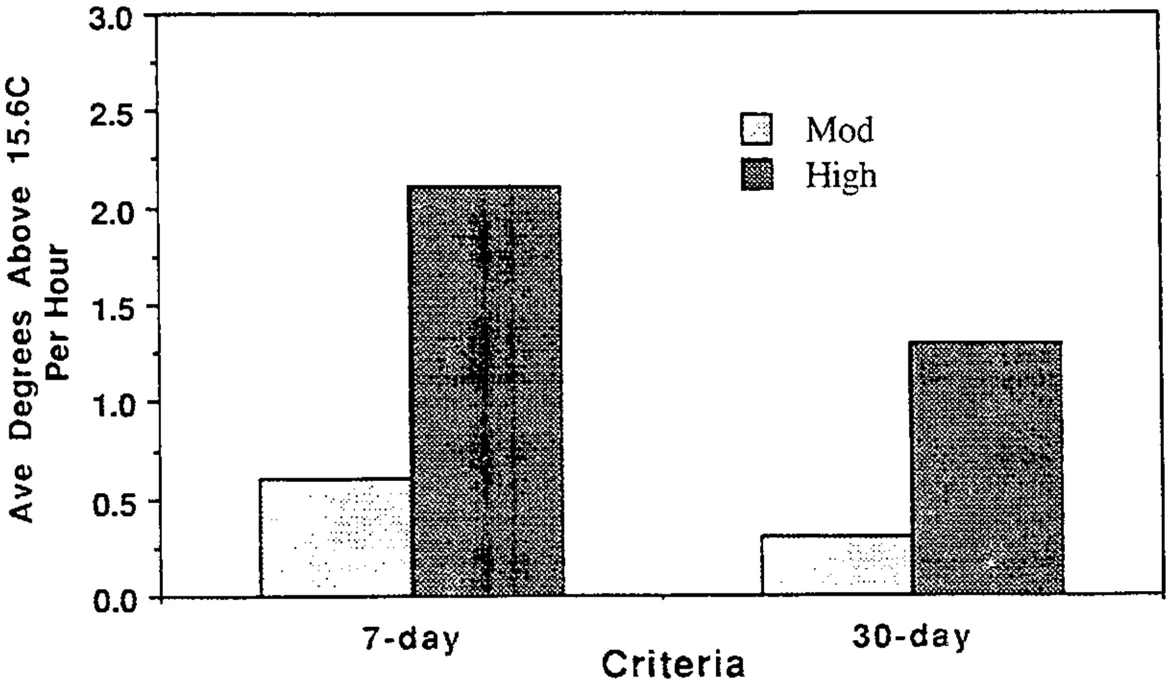
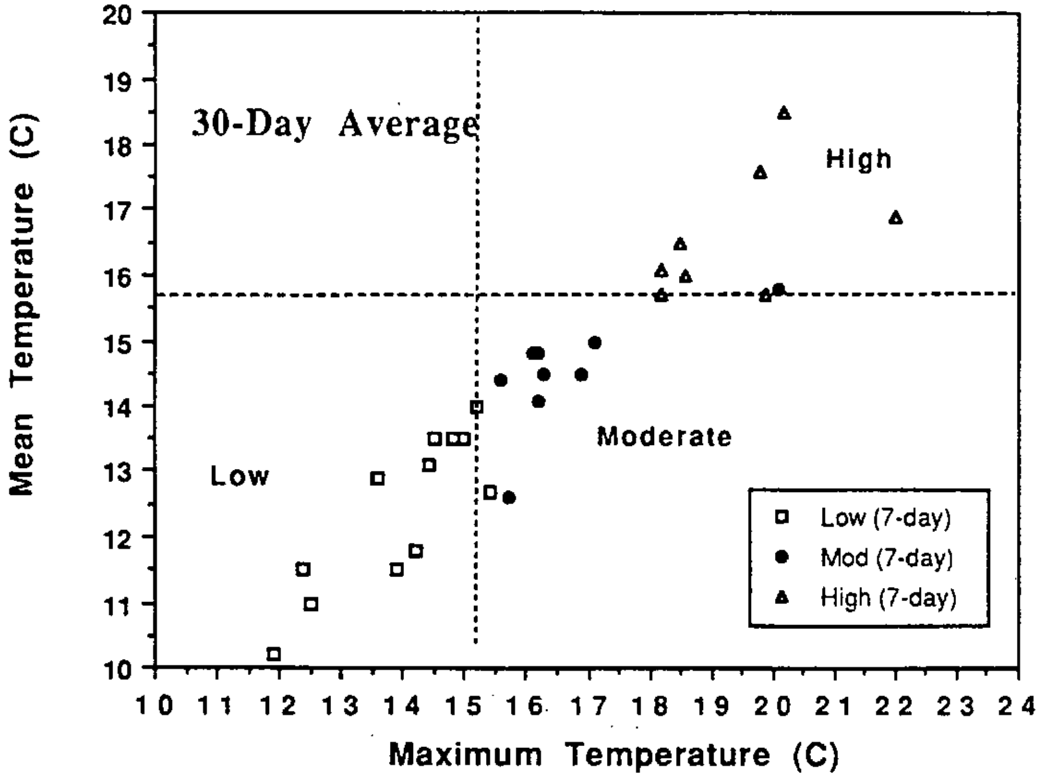


Figure 7.7 Plot of site 30-day maximum and minimum temperature. Temperature category zones are delineated by relationship to 15.6 degrees C. Plot symbols indicate category determined by 7-day maximum temperature.



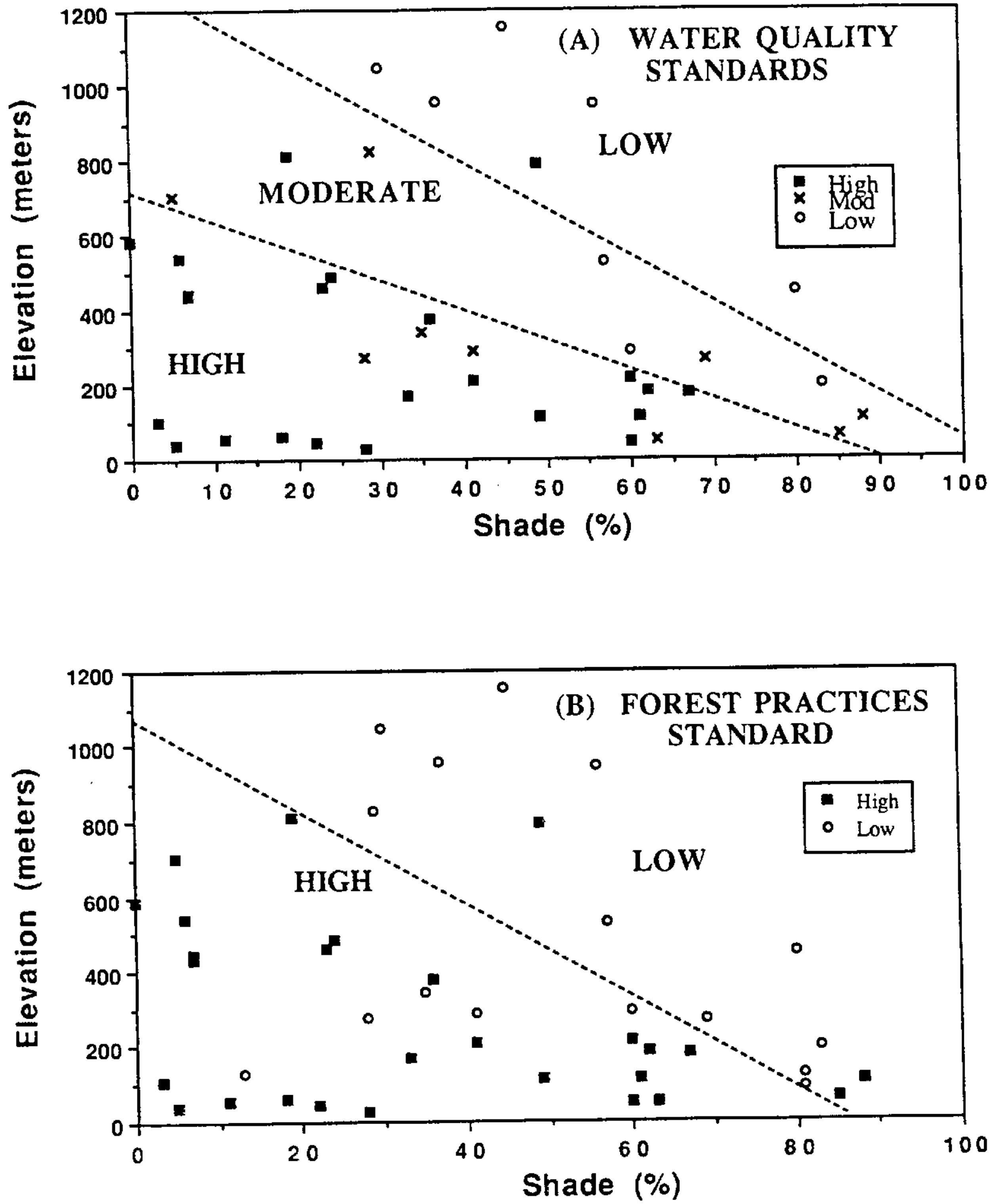
width (Chapter 6; Table 6.4). These same variables are also used in the temperature prediction models.

In an attempt to develop a temperature sensitivity screen, this regionalized relationship was used to estimate maximum temperature which was then assessed according water quality criteria. It was hoped that this empirical equation could serve as a satisfactory temperature prediction model. However, the regional prediction equation was not very effective at correctly identifying the temperature category for regulatory purposes. The estimates agreed with the observed temperature category for only 45% of the sites. The equations tended to predict lower temperature categories then were observed.

As a next step, discriminant analysis was used to identify what site characteristics related to the observed temperature categories. As expected, sites within each of the temperature categories were related by the same stream and climate characteristics suggested by regional models. Elevation, shading and stream width were again statistically significant.

Ignoring stream width, sites identified by temperature class in relation to *elevation* and *shading* is shown for each of the three temperature standards in Figure 7.8 (a,b,c). Two lines dividing the low, moderate and high category regions are hand-fitted through the points. Although there are some clear misses, there is a remarkably good sorting of temperature categories for all three approaches based on these two site characteristics alone. In addition, the placement of lines delineating temperature categories relative to shade and elevation were similar despite the differences in the criteria.

Figure 7.8. Site temperature categories based on the three temperature criteria (listed in Table 7.1) in relation to site elevation and stream shade. Criteria are (A) water quality standards, (B) forest practice standards and, (C) 30-day averages.

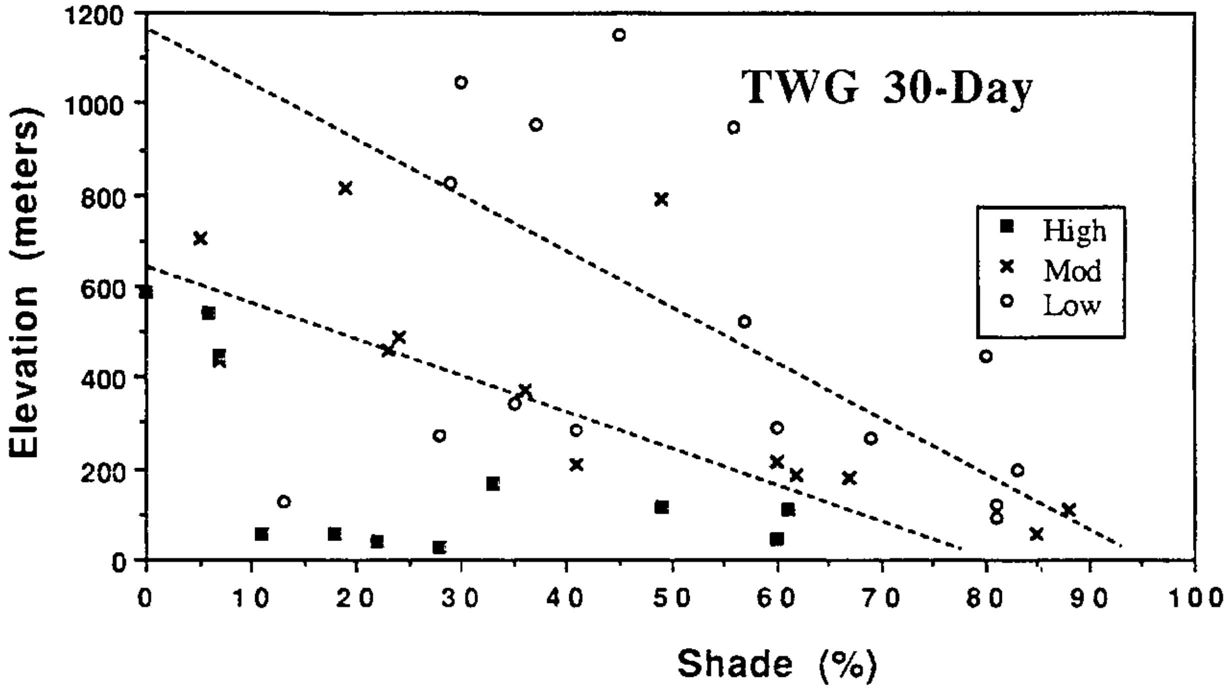


Excluding several points that fall near the lines separating the categories, 89% of the sites classified by the screen based on site characteristics were correctly placed in the appropriate WQ temperature category based on measured temperature (Table 7.2). The screen tends to <u>overestimate</u> the temperature category compared to observed temperature, and is therefore conservative. Of the 11% of the sites that were not classified the same as observed temperature, the screen classed six sites too high and 2 sites too low.

The screen can be used as an estimate of expected temperature category of a reach to a proposed riparian harvest plan. The estimated temperature category of a site can be determined from site elevation and general level of shading based on Figure 7.8, both before and after a proposed harvest activity. The recommended level of shading can be determined by finding the appropriate elevation on the vertical axis and by then moving across the screen until the appropriate temperature category is reached before and after harvest.

An alternative formulation of the data depicts estimated maximum temperature in relation to stream shade by elevation category in 200 meter increments (Figure 7.9). The results are similar to those in Figure 7.8 since they are based on the same data. A site's estimated temperature and shade sufficient to achieve appropriate temperature to meet water quality standards can be determined by tracing the site's elevation line until the threshold temperature is found at the appropriate shading. Either graphic can be used to estimate maximum temperature or temperature class, although Figure 7.9 is less accurate in predicting the temperature category of the site. The temperature at only 69% of sites are correctly categorized by Figure 7.9. Futhermore, the maximum temperature predicted from the graph was within 1°C of observed at only 44% of the sites and within 2°C at 63% of the sites. Therefore, the figure is useful for obtaining an idea of relative changes and for estimating the maximum temperature value, but results must be applied carefully for regulatory purposes. Figure 7.8 is more accurate because fewer lines must be estimated and elevation is

Figure 7.8 Continued

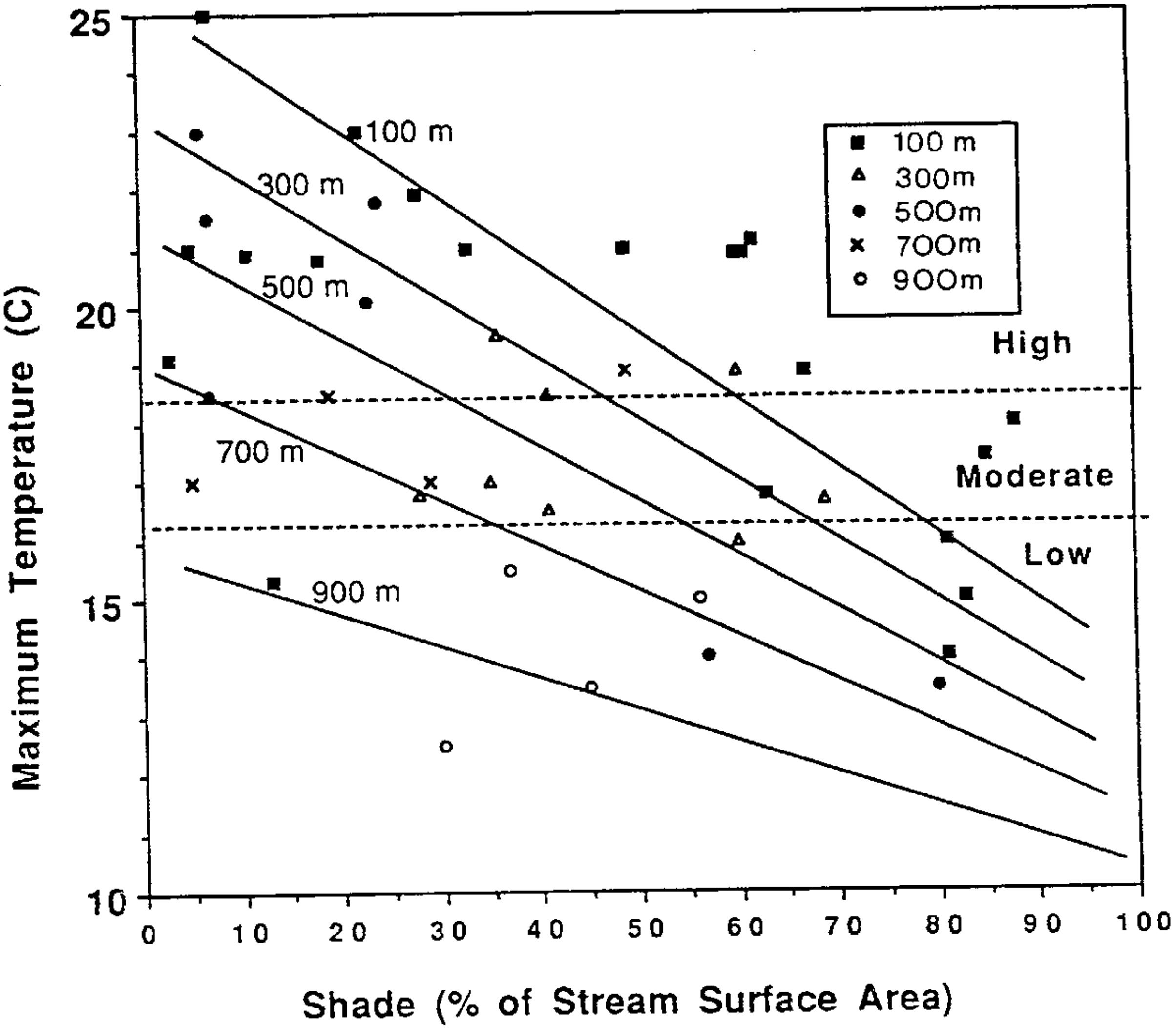


not broadly estimated and is recommended for determining temperature category.

The results depicted in Figures 7.8 and 7.9 have important implications for understanding the effects of timber harvest on stream temperature. Shading from riparian vegetation has a different influence on stream temperature depending on the elevation of the site. Higher elevation streams are cooler, even under fairly open conditions. No high temperature streams were observed at elevations greater than approximately 800 meters (2400 ft). Conversely, low elevation streams were extremely susceptible to higher temperatures, even under fairly dense shading conditions. For example, shading of 60% at 100 m (300 ft) would produce high temperature, while the same shade at just 200 to 400 m (600-1200 ft) would have moderate temperature. A majority of the sites with high temperature were found at less then 200 m (600 ft) elevation. At higher elevations, only sites with virtually no shading at all had high temperature.

The principles evident in Figure 7.8 are consistent with understanding of the physics of stream heating. Water temperature is highly dependent on air temperature which varies systematically with elevation (Chapter 6). The relationship is applicable throughout Washington, and probably also valid in other states of reasonably

Figure 7.9 Estimated maximum annual temperature of sites by elevation group in relation to shade.



similar latitude. This relationship is probably valid in much of Oregon and parts of British Columbia and Idaho, but should be verified before use in the more northern and southern extremes of the Pacific Northwest (California or Alaska).

PRELIMINARY EVALUATION OF REGULATION EFFECTIVENESS

Understanding the effectiveness of riparian management regulations is an important consideration in developing a TFW temperature method. Determining how to identify locations not adequately protected by forest practice rules requires knowing where the rules are effective.

When this study was initiated in the summer of 1988, there were limited numbers of sites with riparian zones designed according to the then recently revised regulations. As a result, the study did not attempt to directly field test the effectiveness of the regulations in protecting water temperature. Instead, because the selected model proved to be so reliable at predicting temperature under all riparian conditions, the TWG felt it constructive to use the model to simulate the probable effect of the riparian management regulations developed in the TFW Agreement. In addition, the empirical relationships based on measured stream temperature shown in Figures 7.8 and 7.9 were also used to assess the effects of current regulations, much the same as the prediction model. Both methods were used to evaluate riparian management zone rules for temperature protection.

Although not a substitute for direct field-testing, this modeling exercise also provides an early indication of whether the riparian rules provide adequate temperature protection.

Water Types 1-3

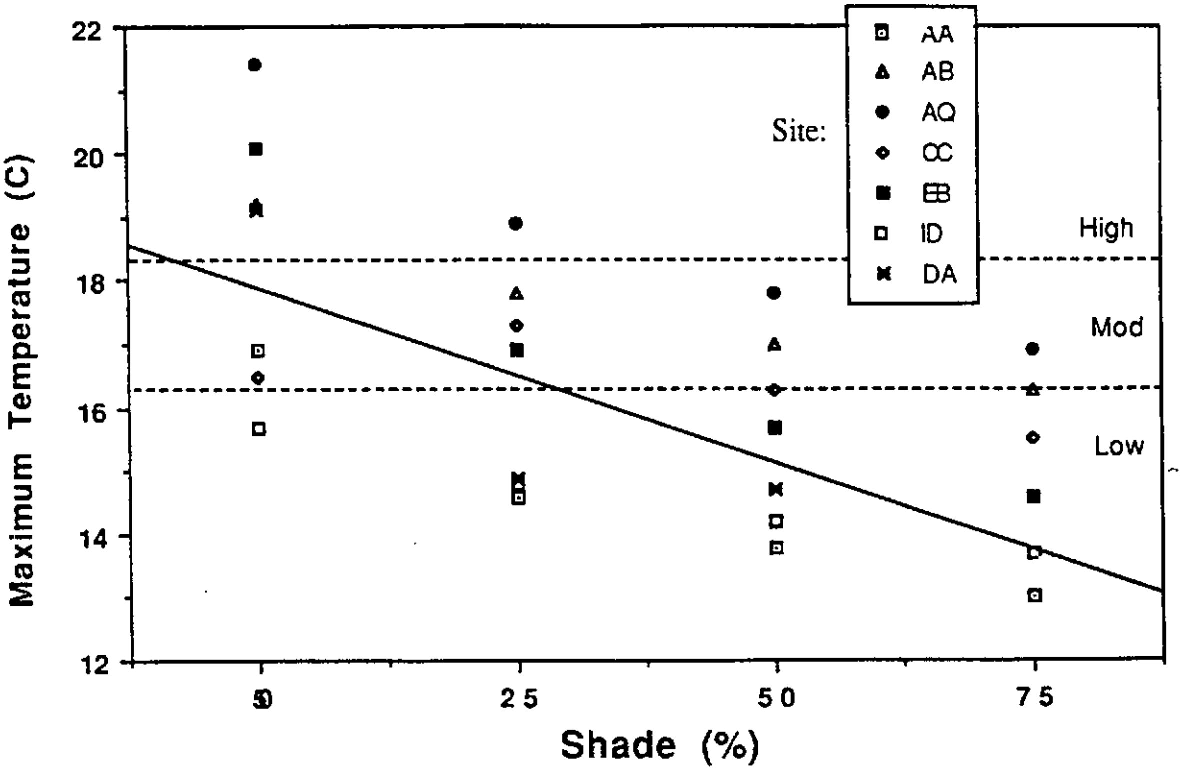
Evaluation of the riparian zone regulations was performed with the model on thirteen of the thirty-three model-testing study sites. It was considered essential that the analysis be conducted only on sites where air temperature was directly measured, since significant errors in model predictions can result from errors in air temperature estimates. The sites selected represented a range of elevations and stream sizes, but all had little existing shade (all of the sites were less than 35% shaded, and many were less than 10% shaded). To minimize the possibility of drawing erroneous conclusions based on model errors, only sites where temperature predictions in the original model-test averaged within 1°C were included. The simulations consisted of running the models using measured and estimated input data as in the model-test (Chapter 4), but varying the shade factor at 25% increments. Shading levels of 25, 50 and 75% were tested.

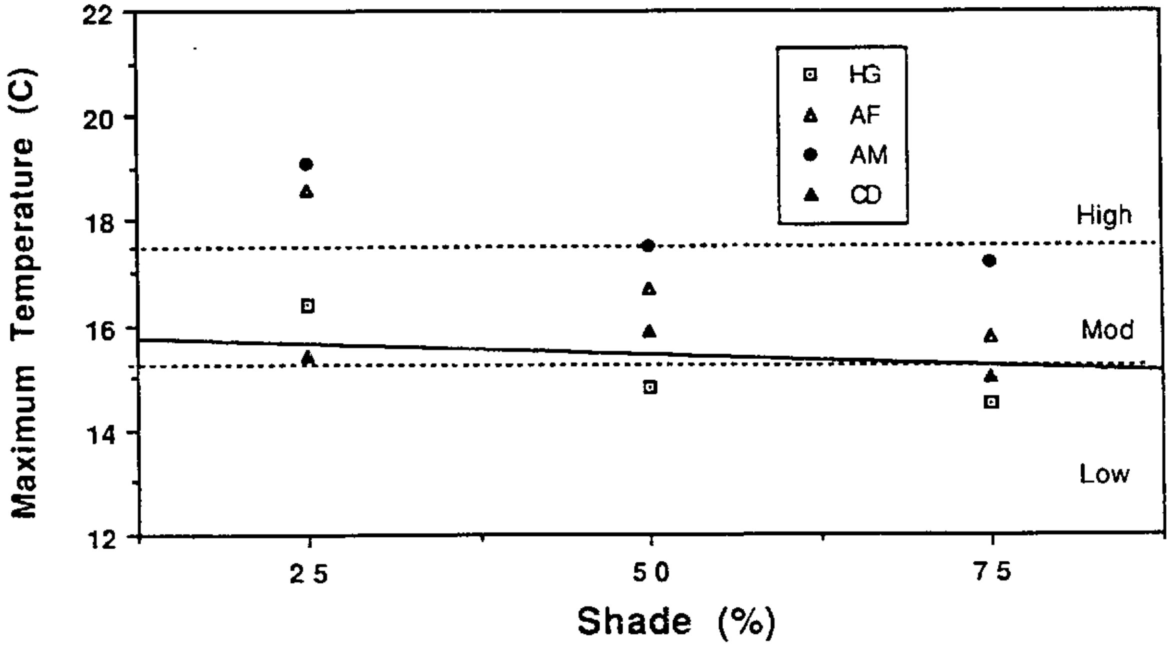
As hypothesized, 30-day maximum temperatures tended to decline from unacceptably high levels with increasing levels of shading. Average maximum temperatures for the simulations are plotted by shade in Figure 7.10. According to the model, temperatures falling in the moderate category should tend to occur when streams are approximately 50% shaded. Temperature tends to fall into the low temperature category around 60-80% shading on average. This level of shading would not be found along larger rivers because they are too wide but would be common for water types 2 and 3, depending on the naturally occurring vegetation.

Although temperature declined at most of the sites to moderate or low with levels of shading required by the regulations, some did not. Notably, temperatures in the high temperature category were estimated for most of the sites at lower elevations along larger rivers (AM and AL on the Coweeman River and AF on the Deschutes River), even when a shading level as high as 75% was simulated. However, shading of 75% (assumed to be approximately the upper maximum amount of shade for rivers this large) decreased temperatures into the moderate category for these larger rivers. These rivers are classed A and therefore moderate temperature would meet the WQ temperature standard.

Similar inferences can be drawn by examining the daily model predictions relative to the forest practice standard threshold of 15.6°C. Examples illustrating the general observed results are provided for four sites in Figure 7.11. During simulations, Site AA had virtually no days exceeding 15.6°C at 50% or greater shading. Site EB in eastern Washington was initially much warmer and did not achieve low temperature until 75% shading, although the standard was barely exceeded at 50% shading.

Figure 7.10 Estimate of effectiveness of shade levels on maximum stream stream temperature based on model simulations.





These results are consistent with the temperature sensitivity relationship based on shade factor and elevation shown in Figure 7.8. At low elevation, riparian shading is less effective. Consequently, moving across the horizontal axis from these sites' existing shade (approximately 30% shaded) to 50% would still place these sites in either the high temperature category or at the boundary between the high and moderate categories (Table 7.3). It would appear based on the empirical relationship that shading levels greater than 80% would be required to bring these rivers to low temperature and 70 to 80% shade would be needed to achieve moderate temperature.

Table 7.3. Average shade characteristics of T/F/W riparian zones based on Dept. of Wildlife surveys (A. Carlson, Washington Department of Wildlife.) Data is from 1988 and 1989 riparian field surveys. Values for each stream are averages of 2-10 observations.

Region	Water Type	Average Shade (%)	Range of Values (%)	Number in Sample
East	1	15	--	1
	2	41	--	1
	3	72	15-91	9
West	1	61	8-96	22
	2	70	23-98	11
	3	78	32-99	57

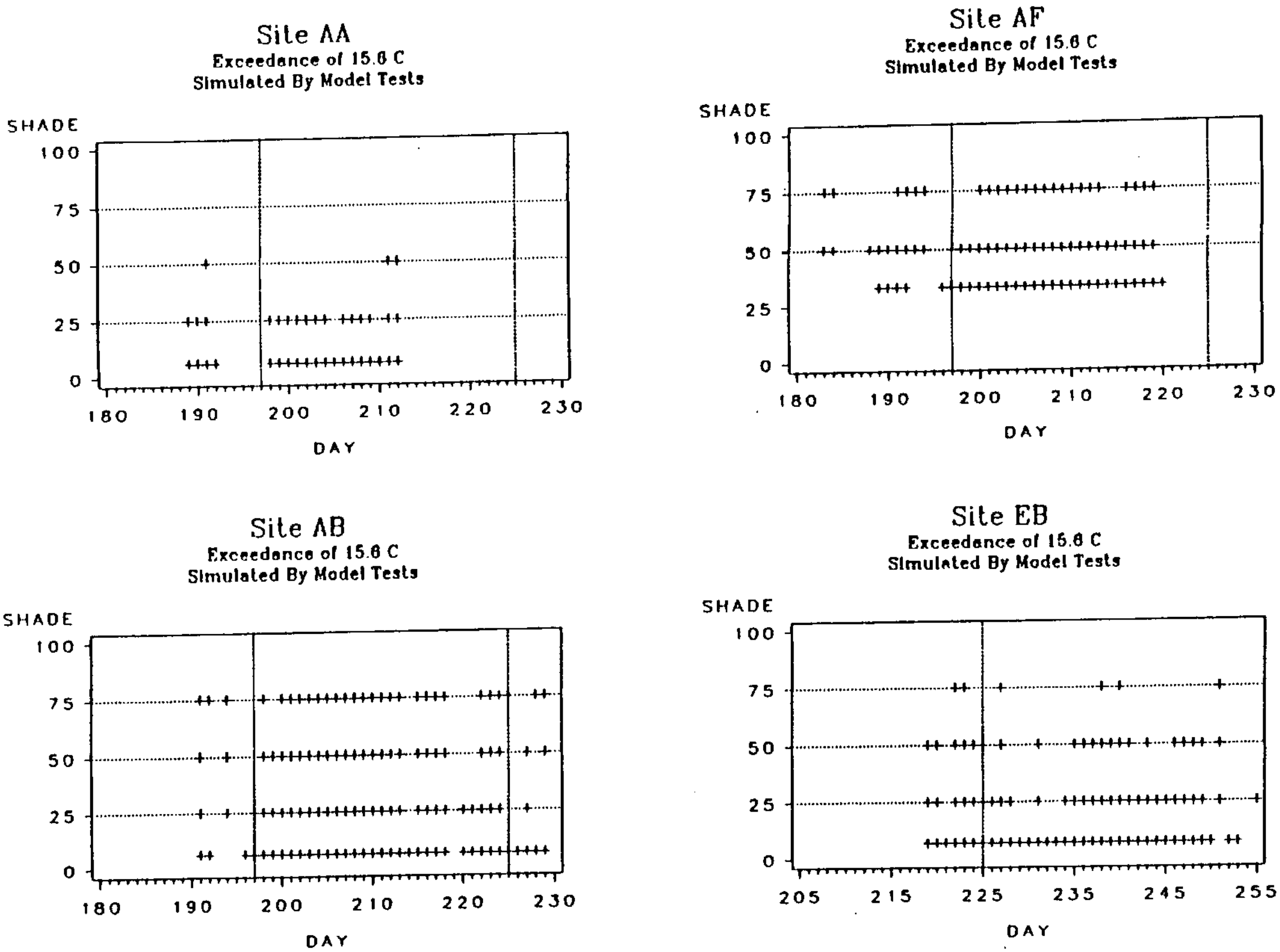


Figure 7.11 30-day simulation of water temperature relative to forest practice standard for various shading levels on 4 sites.

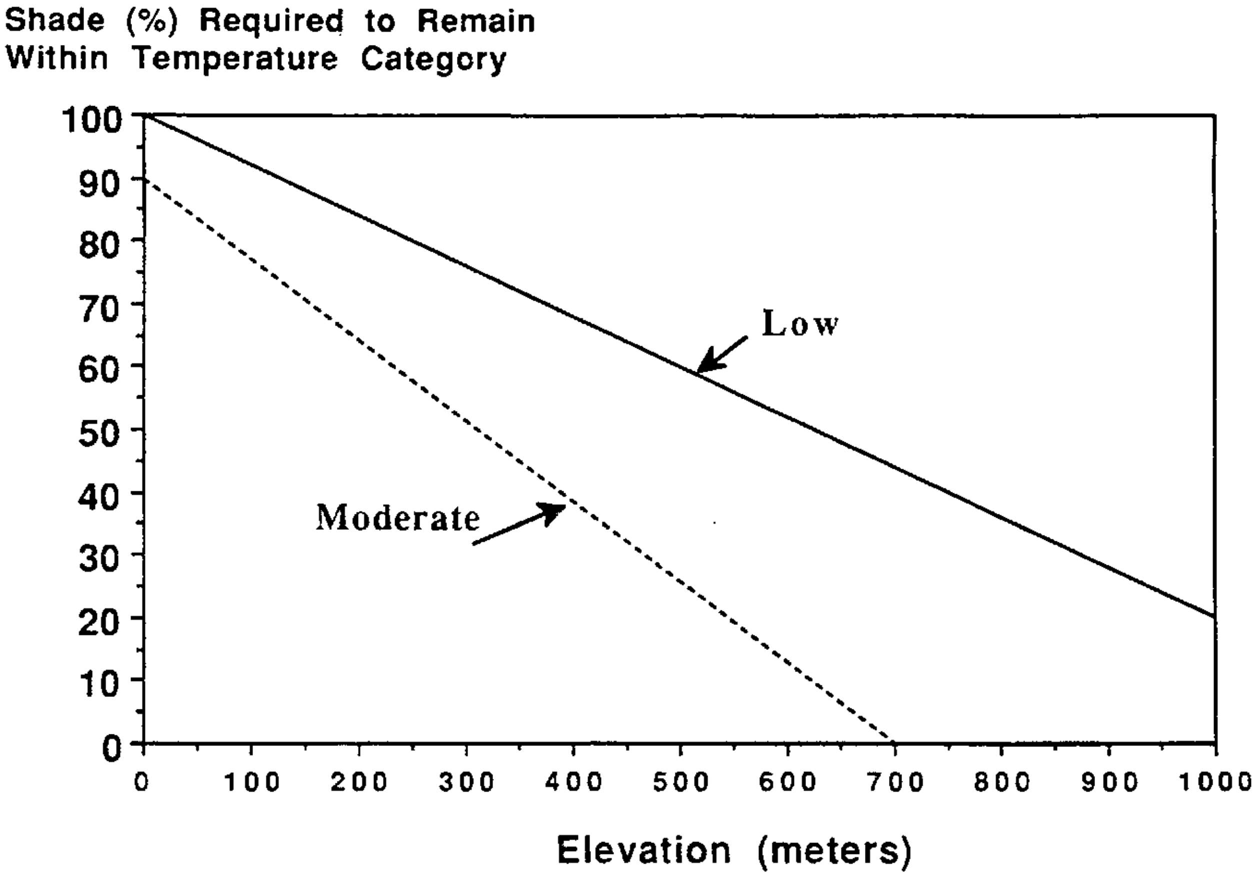
Recommended shading to meet water quality standards. Current regulations stipulate maintenance of 50 or 75% of the *existing* shade along stream types 1,2 and 3, depending on the temperature category of the reach. Based on evaluations with temperature models and the temperature screen (Figure 7.8), it appears that the specified shade requirement in the regulation is insufficient to maintain stream temperature within water quality standards in many situations.

Since the effectiveness of shade is dependent on elevation, the shading requirement should also vary by elevation. Recommended shade to maintain temperature standards is shown in Figure 7.12.The relationship was derived from the temperature screen shown in Figure 7.8a. On average, managing riparian vegetation to the recommended shading specified by elevation should maintain maximum water temperature of Type 1-3 waters within water quality standards.

The water quality standards also limit the incremental change in maximum water temperature to 2.8ºC from nonpoint sources. Is this specification of the water quality standards met by following the above shading recommendations that limit the maximum temperature to 16.3ºC in most type 2 and 3 streams?

When considering that riparian zones are designed for both water quality, and fish and wildlife habitat considerations, the answer would appear to be yes. The baseline maximum temperature relationship (Figure 7.3) is redrawn for the zone less than 40 kilometers from watershed divide to include an estimate of a 2.8ºC increment in Figure 7.13. An increase to 16.3ºC would be less than 2.8ºC incremental increase from expected baseline in most forest streams. For the streams less than 20 kilometers (12 miles) from divide, riparian rules maintain temperature less than the 16.3ºC threshold. Theoretically, the most significant changes in maximum temperature will be in the small streams

Figure 7.12 Estimated shading required in relation to site elevation to maintain maximum temperature within desired water temperature category according to Washington water quality standards.



within this zone. For type 3 streams located between 3 and 10 km from divide (1.8 to 6 miles), the increase in maximum temperature to 16.3°C is greater than a 2.8°C change from baseline. For all other type 1-3 streams, the incremental increase to 16.3°C is less than 2.8°C. (Temperature effects in type 4 waters will be discussed in later sections.)

The incremental change in temperature in type 3 streams would also vary by elevation. Referring to Figure 7.9, type 3 streams at high elevation will increase from 11.0 to 13.0°C if shade declines from 90 to 50% of the stream surface area. (Estimated baseline shading in type 3 waters is approximately 70 to 90%). This change is within the allowed 2.8°C increment. Lower elevation sites can increase to a greater extent with shade removal, but baseline temperature also tends to be higher. If sufficient shade is maintained to keep maximum temperature in the low category, then the incremental change should be about 2-3°C. Therefore, the incremental increase is likely to be close to, if not below, the standard, and may exceed it only in low elevation streams.

Figure 7.13 Schematic of baseline temperature (from Figure 7.3) and potential incremental increase in relation to distance from watershed divide. Only in small streams close to watershed divide is the allowable change to 16.3 deg C greater than 2.8 deg C. (shown as hatched area).

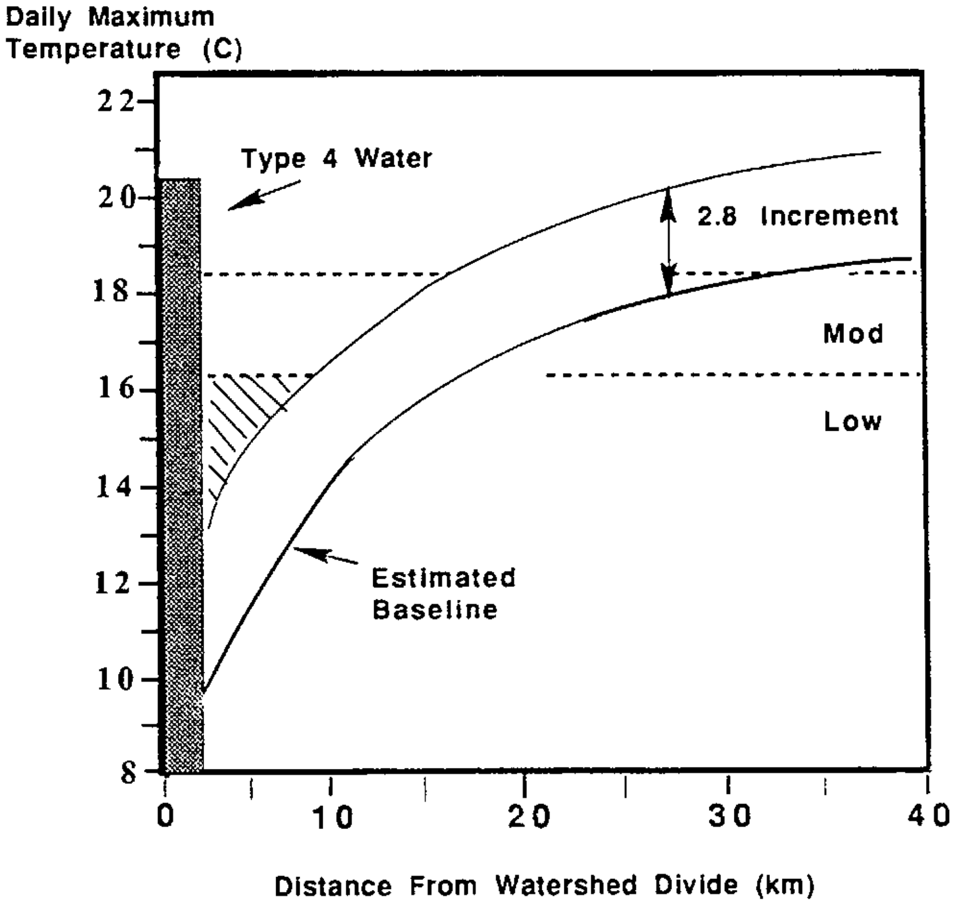


Table 7.4 Maxmimum shade removal by elevation zone to meet incremental increase portion of water quality temperature criteria.

Elevation Zone (meters)	Possible Shade Removal
0-200	22%
201-400	25%
401-600	30%
601-800	32%
>800	45%

A general amount of shade removal allowed within the 2.8°C incremental increase can be estimated from Figure 7.9. Moving 2.8°C on each of the elevation lines shows that from 22 to 45% of the shade can be removed, depending on elevation, and still remain within the 2.8°. (Table 7.4) In general, the maximum temperature criteria would restrict shade removal before the incremental increase criteria would.

Since the riparian vegetation is managed to meet a variety of resource objectives, it is likely that some shade will always remain regardless of shade requirements. Assuming that (1) minimum shading levels of 50% are maintained in all streams to meet other riparian zone management objectives, and that (2) the shade requirements maintain maximum temperatures within the 16.3°C threshold, it is likely that the incremental increase specifications of the water quality standard will also be met in most, if not all, type 3 streams. By the warmer nature of larger streams, forest management following the above recommendation should not cause an incremental increase exceeding water quality criteria in water types 1 or 2. In general, however, meeting the maximum temperature criteria will also meet the incremental criteria.

Riparian Shading Under Current Regulations. Surveys of riparian buffer zones left under the TFW rules indicate that shade requirements specified in the regulations are generally met or exceeded during timber harvest activities. In fact, shading levels tend to be close to the suggested shading recommended above. Table 7.3 lists the average shade of east and westside riparian zones along different stream types measured in the Department of Wildlife riparian study (pers. comm., A. Carlson, Washington Department of Wildlife). Riparian zones along large streams (type 1) tend to have less shading, especially on the eastside of the state, although sample sizes are small. On average, however, landowners are leaving shading that meets suggested levels, including the higher shading requirements applied to temperature "sensitive" streams, although these sites had not been so designated at the time of harvest.

Water Types 4 and 5

No shading is required for type 4 streams, although typically some shade remains after logging from brush and slash. No overstory canopy can be expected for periods of approximately 5 years or more after timber harvest. Removal of shade along type 4 waters is likely to result in large increases in maximum temperature since small shallow streams respond rapidly to changes in energy (Brown 1969). No type 4 streams were included in this study. However, shallow unshaded type 3 streams showed the highest daily maximum temperatures and it is probable that type 4 water temperature could also increase to similar high levels without shade. Observed daily maximum temperature in open, small streams during the warmest periods ranged from 18-22°C (shown as the maximum temperature of type 4 waters in Figure 7.3). It is also likely that the temperature sensitivity of type 4 waters is probably similar to that of type 1-3, where high elevation streams should be cooler than lower elevation sites.

The downstream effect of type 4 waters could not be determined with the sites available in this study. While many unshaded type 4 streams are expected to be in the high and moderate temperature categories for some period after harvest, the extent that these waters may warm downstream fish-bearing reaches remains unclear. Some factors tend to diminish temperature concerns associated with type 4 waters. The type 4 streams within a basin tend to be the highest in elevation, and therefore somewhat cooler.These streams are generally very shallow and make up a relatively small volume of total flow of downstream reaches, where riparian buffers maintain low temperature. Other factors increase concerns. Type 4 streams make up a large proportion of the length of streams in the headwaters region of a basin. The overall importance of type 4 streams in determining downstream temperature is not clear because of these offsetting factors.

Estimating the effect of changes of type 4 temperatures on larger downstream sites is important, but it is not as simple as assuming that downstream reaches will have the same temperature as upstream reaches. A general hypothesis of the effects are as follows.

Where a type 4 water immediately joins a larger stream, the effect on temperature can be calculated as a simple mixing ratio based on temperature and volume of the two water bodies (Brown and others 1971). For example, an unshaded type 4 waters at approximately 20°C (68°F) may enter a shaded downstream waters ranging from 13°C (55°F) if they are small or 20°C (68°F) if they are large (Figure 7.3). The type 4 stream would probably have no measurable effect on the large stream, but could increase the temperature of the small stream. If they were of nearly equal volume, the resulting temperature would be approximately 16°C (61°F) and near the temperature threshold. Generally, the type 4 stream is of lower proportion and the actual temperature would be somewhat less than this. The situation described is probably quite common in the current riparian management rules.

However, once the water enters the downstream reach, initially warming or cooling it, the water will adjust to the equilibrium temperature of the reach as it flows through depending on the site conditions of that downstream reach. If water enters the larger stream at a warmer temperature than the larger stream's equilibrium, determined from its shade and other stream characteristics, the water will cool as it moves downstream until the equilibrium temperature for the reach is re-established. Thus, in the above example where the type 4 enters a small type 3 stream whose baseline temperature is expected to be 14°C, the stream would tend to cool from 16°C where it enters to 14°C (61°F).

How fast the temperature adjusts, and therefore the downstream extent of warming or cooling (referred to as response distance) is dependent on stream velocity and on stream depth as it dictates a flow volume's response time to changes in energy. Since small streams respond quickly to changes in energy, the downstream zone of influence of many type 4 streams may be relatively short. This could not be determined in this study. However, temperatures of all stream reaches, including type 3's, were predicted accurately without knowing *anything* about the shading in upstream reaches (Chapter 4), suggesting that the hypothesis may have some merit.

Understanding and predicting the effects of type 4 stream temperatures on downstream fish-bearing waters will require improved understanding of these heat transport principles as well as direct measurement of temperature in the specific situation described above. A suggested approach to this research is further outlined in Chapter 8.

Basin Temperature Considerations

Prior to the study, it was perceived that dispersing harvest units throughout a watershed guided by a basin temperature prediction model might be a feasible approach to addressing the downstream temperature concerns. However, after performing the study, the TWG felt that a basin approach introduced unnecessary complexity and difficulty into the management process without improving temperature protection. Basin temperature models were very cumbersome to use and were not considered feasible for use on a widespread basis. They were also not very reliable temperature predictors when used in a manner the TWG felt could be expected in routine TFW use (Chapter 5). Primarily, study results also showed that a large number of stream should be adequately treated under riparian zone management guidelines.

Instead of trying to use basin temperature model in harvest planning, the TWG recommends that temperature sensitivity of water types 1-3 be addressed by the TFW temperature method described below and that the need for alternative methods for determining temperature protection needs for type 4 waters be established after a carefully designed field study.

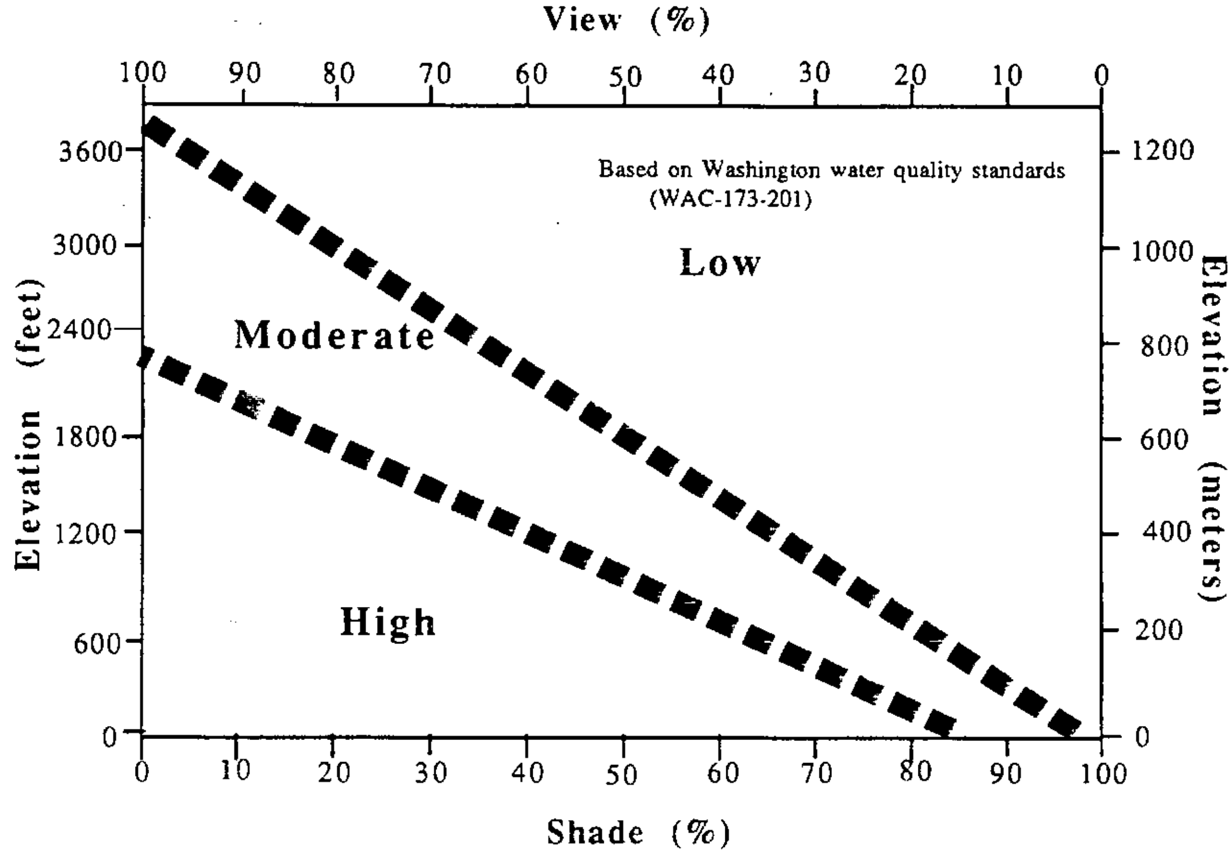
RECOMMENDED TFW TEMPERATURE METHOD

General recommendations for the TFW temperature method based on the temperature screen and the prediction model are offered here. The method is intended to provide necessary protection to the stream without being overly time consuming or difficult to apply. A user's manual providing detailed instructions on the use of the method will be prepared with the assistance of the DNR and TFW participants who are likely to use it in the field.

It should be noted that components of the TFW method are recommended by the Temperature Work Group only if they were found likely to improve stream temperature protection in forest management. Conclusions of what to include in the method are based on observed temperature, the ability to identify temperature sensitive streams based on their site characteristics, an appreciation of the effectiveness of riparian zone management techniques established in the temperature study, and model-testing discussed in earlier chapters of this report. The TWG efforts focused on providing the simplest but reasonably reliable methods possible. Several techniques for temperature prediction other than models were attempted with the assumption that graphs are simpler to produce and easier for TFW managers to use. The demand to satisfy identified management needs for sound resource decision-making determined what components are recommended in the TFW temperature management strategy. Practicality considerations were very important in helping to select among available methods, including models, to use for each component.

No basin model is recommended at this time. The Temperature Work Group feels that better information can be obtained using a stream reach approach. If stream temperature is properly managed within an upstream reach, then the downstream water temperature will not increase from management activities. (Normal downstream heating as rivers increase in size can be expected.) Two streams with moderate temperature can combine to cause another moderate temperature stream but not a high temperature stream. Temperature can be no warmer than the warmer of the two combining reaches.

Figure 7.14. Temperature categories for type 1-3 streams based on Washington water quality standards. Temperature categories are divided by broad dashed line.



Temperature impacts may be present now from forest practices prior to TFW. However, as the shading within basins recovers, more of the streams will be managed for low or moderate temperature. Stream temperature protection in type 4 and 5 streams is not addressed in the recommended method but suggestions for further work are described in research recommendations (section 7.4). Recommendations will, however, be provided in the user's manual as they are developed based on subsequent research projects.

Temperature Screen

The recommended method is based upon the temperature screen for exceedence of water quality standard shown schematically in Figure 7.14. The temperature screen is redrawn from data presented in Figure 7.8a and addresses water quality standards. The temperature screen is first applied for existing conditions for the site specified in a forest practice application. The shaded areas on the screen indicate situations when models may be applied versus when the shading prescription can be safely made without it. These reflect situations where small changes in shade may cause high temperature. Elevation and the percent of the channel shaded are the only site-specific information needed at this point in the process. (A description of how to estimate shade will be provided in the users manual.)

The existing temperature category of the site is determined based on existing shade conditions. The expected temperature category after harvest is then determined by estimating the amount of shade that will remain after harvest. Depending on existing and predicted temperature category, the method indicates several potential outcomes.

If stream temperature category is predicted to be low or moderate before and after the forest practice, then there are no temperature concerns related to timber harvest (depending on stream class) and the normal procedures for determining riparian zone leave trees should be followed. Shade estimates for RMZ's left under TFW riparian regulations indicate that 50-75% shade generally remains suggesting that normal operating procedures for riparian zone planning should be sufficient in many locations.

Special consideration may be required for sites with elevations less than 200 meters (600 ft) that have existing shade levels between 80% and 40%. Use of a temperature prediction model may be suggested in these circumstances to confirm the screen's estimates of stream temperature category and suggested shade level.

If the estimated falls near the line dividing categories, the riparian leave area should be *carefully* designed with shading being a primary design consideration during riparian zone layout. This design would need to be done on site when the riparian trees are marked considering the contribution of streamside vegetation to shading the water surface with the objective of achieving the specified level shading of the water surface.

If the temperature category changes from either low or moderate to high then modeling may be warranted to confirm predictions made with the screen and to assist in designing alternative riparian prescriptions (percent shade) that will maintain the predicted post-harvest temperature category within the desired level (low to moderate).

Added care must be taken when the site is on the margin between categories. It is important to remember that the definition of the boundaries is imprecise and the proposed alternate riparian prescription preventing high temperature should place the site estimate well within the target category. The thick lines separating temperature categories in Figure 7.12 reflect the ambiguity in defining categories.

Temperature category boundaries on Figure 7.14 are tight at low elevations, and relatively small changes in vegetation may result in relatively large changes in the temperature of the site. Altering the percent shade from 80% to 50% on a site at 100 meters (300 ft) elevation changes the sensitivity from low to high. The same alteration of percent shade for a site at an elevation of 600 meters (1800 ft) does not change the sensitivity rating from low.

The temperature category screen was developed using data from only 42 streams although they represent a large variety of sites from all regions of the state, all sizes of streams, and all levels of shading. While other sites can be expected to conform, this is a still a fairly small dataset on which to base the screen. Further efforts should focus on providing additional data to revise and improve the screen's predictive capacity. Recommendations on how to do so are provided in Chapter 8.

Site Model

The temperature screen is not sensitive to local anomalous conditions but reflect average conditions. The prediction model may be useful to use when unusual circumstances may be present that may influence local temperature. These may include a variety of situations such as the presence of high amounts of groundwater inflow as springs.The prediction model is also useful for providing more accurate estimates of temperature where desired. More specific site data are required than for the temperature screen.

TEMPEST is the temperature model recommended for use in the TFW method. This model was shown to have excellent performance in predicting temperature during model-testing, and was reliable and practical to use. Other models were also tested, and several were shown to be good predictive tools, although none was rated as highly as TEMPEST considering all three qualities of predictive accuracy, model reliability and practicality.

The purpose in using the model is to predict whether a site will exceed the temperature standard with management of shade in a riparian zone. The TWG proposes that the model predict temperature over a 30-day time interval that coincides with the warmest period of the summer (July 15-August 15). The predicted maximum temperatures can be evaluated to determine the amount of riparian zone shading to be left to meet temperature standards. Instructions on using the model will be provided in the TFW users manual.

Reliability of the TEMPEST model reliability was very good (95% of the sites were predicted within 2°C of the measured average) when detailed, carefully measured input data was supplied. Data input requirements include a variety of site and climatic data including geographic location, elevation, shade (%), and stream depth. The TWG realized that many of the variables, particularly climatic information, would be impossible to measure in routine TFW application of the model. Most climatic variables, such as air temperature and relative humidity, fall into this category. Water temperature is especially sensitive to air temperature and finding some way to estimate appropriate air temperature regimes was critical to successful application of the model. Methods for estimating as much input data as possible without reducing model prediction reliability are provided in the user's manual.

To provide reasonable climatic information, the data sets of climate input values used in model-testing were developed into standard data sets that the model draws on. Choice of input values is based on information the user supplies as easy-to-obtain watershed and regional information. The datasets are comprised of climate variables from 6 NOAA weather stations and composites of air temperature profiles developed from those measured at the study sites in forested streams. As a result, the model predicts water temperature based on the climatic conditions that occurred during the summer of 1988 unless measured air temperature is provided. Air temperature during this period was slightly warmer than the long-term average at all of the weather reference sites.

SUMMARY

Temperature at all sites was evaluated relative to water quality criteria to determine whether water quality standards or forest practice rules were exceeded. A large percentage of the sites harvested prior to the TFW Agreement exceeded temperature thresholds of 15.6°C (forest practice rules) or 16.3°C (water quality standard) at some time.

A simple relationship between riparian vegetation (shade factor) and elevation provides a surprisingly reliable means of initially determining the likely temperature regime under different levels of shade. The importance of shading and elevation were identified using both the temperature prediction models, and by examining stream temperature data from around the state. Very high elevation streams (greater than 800 m or 2400 ft) rarely had high temperature under any shading conditions, including open. Conversely, the temperature in very low elevation streams (less than 100 m or 300 ft) were the most dependent on shade, requiring significant amounts to maintain temperatures in the moderate or low temperature categories.

Finally, the temperature models were used in a gaming mode to analyze whether the current riparian regulations are providing adequate temperature protection. Levels of shade specified in the forest practice regulations appear to be inadequate in many situations to provide sufficient temperature protection to meet water quality standards. Varying amounts of shade based on elevation are recommended. Fortuitously, riparian zone surveys suggest that the shade remaining in riparian management zones designed for a variety of objectives in TFW generally exceed shade requirements and are likely to meet shade needs recommended by this study.

A simple and reliable temperature method is recommended for TFW use to identify and address temperature sensitivity concerns. The method incorporates riparian management regulations and identifies specific situations when alternative prescriptions may be required. The method does not rely on basin temperature models which are cumbersome to use and would not improve TFW temperature management strategies.

Recommending a TFW temperature method is the responsibility of the TFW Cooperators. The Departments of Ecology and Natural Resources and the Forest Practices Board are responsible for final approval. The selected method and specific guidelines for applying it along with decision criteria directing management response will be described in a separate "user's manual". The user's manual will be prepared by the Temperature Work Group with the assistance of the Department of Natural Resources, Department of Ecology and TFW participants. A field trial involving TFW cooperators likely to use the method is recommended to further refine it before is is widely used in forest management decision-making throughout the state. Future improvements of the method can be accomplished by revising the user's manual. Implementation of study results in TFW is further discussed in Chapter 8.

CHAPTER 8

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

The TFW Agreement calls for establishment of a temperature method to determine protection strategies for temperature sensitive waters. The TFW Agreement allows for temperature protection by riparian vegetation leave requirements for fish-bearing streams and for possible use of a basin-scale temperature model for planning distribution of harvest units along non-fishbearing streams to protect downstream temperature.

The TFW temperature study was designed to generate information for two primary purposes: data was collected from forest streams extensively throughout the state to develop a temperature sensitivity screening method and intensively at a smaller number of sites and basins to evaluate the predictive capabilities of existing temperature models that could be used in a TFW temperature method. Each of these topics has been developed in far greater detail in earlier chapters. Study conclusions are briefly summarized in this chapter (*Study Conclusions*).

A TFW method was developed and considerations relating to its transfer to TFW field implementors are reviewed (*Technical Transfer*). Study recommendations involve some suggested changes to forest practice regulations and greater clarification of forest practice rule administration relative to temperature standards. Therefore, a number of policy steps beyond the responsibility of the Temperature Work Group are required before formal adoption of any procedures recommended in this report. For the benefit of TFW cooperators, these are outlined to assist their understanding of the incorporation of temperature esearch results into the TFW management process.

Appropriate monitoring projects are suggested (*Recommendations of TFW Temperature Monitoring Needs*) and important remaining information gaps are identified along with approaches to address them by way of research (*Further Evaluation and Research Needs*). Filling information gaps may improve reliability of the recommended TFW method, but should not significantly alter the overall method outlined. Management policies may be affected by additional information depending on the outcome of key research projects, such as the effects of type 4 streams on downstream temperature.

Finally, the implementation of this study has been unique in TFW with its inter-agency study team and statewide group of cooperators who made it possible with field efforts and funding. A brief discussion of some of the participation elements of the project and our TFW interactions that both helped and slowed our progress are provided for adaptive management considerations (*TFW Adaptive Management*).

STUDY CONCLUSIONS

Temperature and stream characteristics were monitored at ninety-two study sites representing a variety of riparian shading conditions ranging from mature conifer forests to sites completely open and devoid of shade. Where timber harvest had occurred, activities at all sites except one had been conducted prior to the TFW Agreement and do not reflect riparian conditions left according to the regulations adopted in 1987. At least 50 individuals representing 33 organizations participated in the study.

Factors influencing temperature at a site. Typically, a combination of local environmental factors including air temperature, stream width, and strea depth were an important influence on stream temperature, but no one factor alone was ever a good predictor of stream temperature (Chapter 6).Shading from riparian vegetation was found to have an important effect on stream temperature but the extent of its cooling effect varied with site elevation. It was not possible to predict temperature effects based solely on riparian vegetation.

An empirical "regional" temperature model was developed where average temperatures at sites was predicted based on stream and watershed variables and compared to recorded temperatures. While this method provided generally valid results in predicting temperature under different levels of shading, it was not able to correctly identify temperature on a site by site basis with sufficient precision. Thus, the temperature prediction model was found to be useful if more accurate estimates of site-specific temperature are required for decision-making.

Basin temperature. Basin temperature patterns were analyzed in three watersheds having a number of sites located within them (Chapter 6). Although some local influence of tributary heating (primarily nearer the headwaters) and cooling (primarily in lower reaches) was observed, there were no clear trends in the relationship of basin temperature to harvest patterns in tributaries as opposed to effects of timber removal along the mainstem of the rivers themselves (a practice common in previous decades). All basins showed general warming of water and air temperature in the downstream direction which is consistent with theoretical relationships. Mainstem temperature of all the rivers studied appeared to be somewhat warmer within distances of 50 km from the watershed divide than would probably be expected in mature conifer forests. This probably reflects the effects of past forest management.

Existing conditions of temperature sensitivity . Many of the 92 study sites were found to exceed water quality temperature criteria including most reaches with less than 50% shade but including some reaches with mature forest canopies along larger rivers. Of all sites, 62% were found to be temperature sensitive according to the Forest Practice rules and 72% exceeded the DOE water quality temperature criteria (Chapter 7). Approximately 30% of all sites had high temperature (most with nearly complete removal of shade) and 30% had moderate temperature. Although larger streams were expected to have warmer temperatures, this large number of sites exceeding biologically-determined criteria confirm that past riparian management practices had significantly affected temperature in forest streams.

The study further showed that temperature sensitivity could be correctly identified for a longer 30-day period, with similar results as using a shorter duration 7-day (Forest Practice Rules) or 1-day (DOE-Water Quality Criteria) period. This provides some assurance that the temperature standards are also meaningful over a longer timeframe. Since the 15.6°C (60°F) temperature is a sublethal standard, the duration of higher temperatures may be of importance in influencing fish health.

Effectiveness of Current Riparian Zone Management Regulations in Stream Types 1-3. Current regulations stipulate maintenance of 50 or 75% of the *existing* shade along stream types 1, 2 and 3, depending on the temperature sensitivity of the reach. One of the primary purposes of this study was to develop a method to identify the temperature sensitivity of a reach prior to a forest practice to guide the level of shading needed to protect stream temperature. The effects of riparian rules on stream temperature were not directly measured in this study, although the adequacy of riparian rules was evaluated by analysis of both stream data collected throughout the state and by the temperature prediction model. An appreciation of the effectiveness of riparian rules for temperature protection was an essential element in developing a method to recognize those sites not protected during normal administration of the regulations.

Study results suggest that maintaining the *total* stream shading at between 50 and 75% minimizes changes in stream temperature associated with timber removal in the riparian zone along most (but not all) forest streams. Study results also suggested that the effectiveness of shade varies with elevation. Temperature protection can best be achieved with a shading requirement that varies with elevation. In general, the recommended goal is to leave 50-75% of the stream shaded after cutting, rather than leaving 50-75% of the *existing* shade as specified in current rules. Following this guideline temperature in type 1-3 streams will comply with water quality standards.

Some sites will not have this level of shading, either because of past forest practices, natural variability of vegetation, or because the stream is too wide for effective shading by streamside vegetation. We estimate that, on average, streams at less than approximately 40 km (25 miles) downstream from watershed divide have the potential for effective amounts of shading and that riparian vegetation is most important for protecting stream temperature within this zone. For streams located at greater than this distance where rivers are relatively wide and the riparian vegetation does not influence stream temperature sufficiently to maintain temperature in the low temperature category. On average, temperatures are expected to be moderate in rivers at distances approximately 20 km (12 miles) downstream from divide and high at about 50 km (30 miles) from divide.

Surveys of riparian buffer zones left under the TFW rules indicate that forest managers are tending to leave more shade than required in the current regulations and that the recommended goal for stream shading is generally met or exceeded during timber harvest activities. Riparian zones along large streams (type 1) tend to have less shading, especially on the east side of the state, although sample sizes were small. On average, however, landowners are leaving shading that meet current requirements, including those applied to temperature sensitive streams, although these sites had not been so designated at the time of harvest.

Temperature Sensitivity Screen (Stream type 1-3). Stream and basin characteristics of sensitive sites were evaluated to identify what features could be used to recognize existing or potentially sensitive streams. Although many characteristics were shown to correlate with stream temperature, two factors were of such overwhelming importance that they could be used as a basis for a simple but reliable method for screening for temperature sensitivity. Riparian shading and site elevation (which probably indicates air temperature regime) were effective at sorting sites for temperature categories (Chapter 7). The screen correctly identified the sensitivity category of 89% of the 42 Washington sites where data was available.

The most significant concepts illustrated by the screen are that (1) riparian vegetation is important in protecting stream temperature, and (2) the importance of the shading varies with elevation because streams at high elevation streams are cooler than those at lower elevations regardless of shade. It would appear that very low elevation sites (less than 100 meters or 300 feet) are more likely to have significant temperature impacts from vegetation removal, even with high amounts of shading of the stream surface. Low elevation streams may require greater attention to temperature protection during harvest planning. Conversely, higher elevation sites (2400 feet) are rarely temperature sensitive under any riparian shading levels.

Type 4&5 Waters. No shading is required for type 4 streams in current forest practice regulations, although typically some shade remains after logging from brush and slash. No overstory canopy can be expected for periods of approximately 5 years or more. The downstream effect of type 4 waters could not be determined with the sites available in this study. While many unshaded type 4 streams are expected to be in the high or moderate temperature categories for some period after harvest, the extent that these waters may warm downstream fish-bearing reaches remains unclear. These streams are generally very shallow and make up a relatively small volume of total flow of downstream reaches, which under current rules, appear to have sufficient buffers to keep temperatures low. However, these streams make up a large proportion of the length of streams in the headwaters region of a basin. Understanding and predicting the effects of type 4 stream temperatures on downstream fish-bearing waters will require improved understanding of these heat transport principles as well as direct measurement of temperature. A suggested approach is outlined in the section recommending future evaluation and research needs.

Temperature Modeling. Four reach temperature prediction models were rigorously evaluated for prediction accuracy and reliability and practicality of use (Chapter 4). Several of the models were found to predict water temperature with reasonable reliability, even when input data was estimated. Models varied in predictive capability and practicality. One reach model was selected that satisfied both prediction accuracy and practicality criteria selected with TFW field managers in mind. The computer model is extremely simple to use by anyone.

The basin models were far more difficult to use than the reach models. Data and model requirements were intense and it is unlikely that general forest managers could routinely commit the time or resources required to run a basin model. Furthermore, none of the basin models performed well enough, were sufficiently practical and reliable, or had appropriate gaming capabilities to justify their use (Chapter 5).

TFW Temperature Method. Modified riparian rules for stream types 1-3 would provide temperature protection, there remains a need to identify situations where rules would not provide sufficient protection or where alternate plans may be suitable. In fact, two distinct watershed situations of temperature sensitivity that are not yet fully quantified can be recognized: (1) sites along stream types 1-3 that may require greater (or possibly less) shading to maintain adequate stream temperature then specified by regulation, and (2) the downstream effect of temperature changes in type 4 and 5 waters where no shade is required. Temperatures in large rivers are not as greatly influenced by riparian vegetation because they are too wide.

A TFW temperature method is recommended in Chapter 7 that combines the use of a simple temperature screen requiring a minimal amount of site-specific data, riparian zone management design, and a reach temperature prediction model to be used on a limited basis. The screen can be applied to forest practice applications to make a quick assessment as to whether temperature standards are likely to be exceeded. The screen may suggest to the applicant to manage the riparian management zone (RMZ) as usual or to more carefully design the leave trees for shading. The reach model may be used to assist in the design by specifying shading level requirements if high temperatures are expected. As currently envisioned, appropriate decisions can usually be made without using the model.

Basin Temperature Concerns. Prior to the study, it was perceived that dispersing harvest units throughout a watershed guided by a basin temperature prediction model might be a feasible approach to addressing the downstream temperature concerns. However, after performing the study, the TWG felt that a basin-wide planning approach to temperature protection introduced unnecessary complexity and difficulty into the management process without improving temperature protection. Basin temperature models were very cumbersome to use and were not very reliable temperature predictors when used in a manner the TWG felt could be expected in routine TFW use. Primarily, study results also showed that a large number of stream should be adequately treated under current regulations.

Instead of trying to use basin temperature model in harvest planning, the TWG recommends that temperature sensitivity of water types 1-3 be addressed by the TFW temperature method and that the need for alternative methods for determining temperature protection needs for type 4 waters be established after a carefully designed field study.

TECHNICAL TRANSFER

The 1988 temperature study was successful in generating a practical and reliable prediction methodology that appears to be useful to TFW managers. The recommended method and the supporting technical documentation justifying the TWG conclusions are the primary products of this project report.

TFW Implementation. Adoption of a TFW method requires further steps by many TFW participants. These include:

- TFW Policy and Administration Committee (using the Field Implementation (FIC); the Training, Information and Education (TIE); and Cooperative Monitoring, Evaluation and Research (CMER) standing committees),
- Department of Natural Resources (DNR) (Forest Practice Regulation and Assistance Division),
- Department of Ecology (DOE)
- Washington Forest Practices Board

These groups must establish a process to reach consensus on the recommended temperature method to be adopted by TFW, forge regulatory response if necessary, and provide training to appropriate personnel in the use of the agreed upon TFW method. As representatives of CMER and project cooperators, the Temperature Work Group of the Water Quality Steering Committee will assist in this effort as requested (and to the extent possible).

The recommendations offered in this report are very consistent with the language in the TFW Agreement and Forest Practice Regulations for temperature sensitivity and use of a temperature method. Some recommendations, however, may deviate sufficiently from what is currently in the regulations that changes may be required if these recommendations are followed. The DNR and DOE will need to determine where changes may be needed and assist the TFW process in implementing them.

In addition, the difference between the temperature criteria specified in the water quality standards and the forest practice regulations must be resolved by the DOE. It is recommended that these agencies consult with biologists and TFW participants concerning biologic temperature concerns and recommendations. Determining the *best* biological temperature performance standards may require further biological research. Until such information is available, the recommended TFW method addresses the current water quality standards. However, the method can easily accommodate more complex biological criteria if that is found to be useful in the future.

Manager's Field Trial. The Cooperative Monitoring, Evaluation, and Research workplan identifies a series of research and evaluation steps that may be necessary to bring management tools, such as a temperature method, on line for TFW managers. This plan calls for steps to first identify the most promising and practical technical methods and to develop them with objective technical evaluations to demonstrate that they work (Technical Trials). Once methods are shown to work technically, it is important to prove their effectiveness when used on a wider scale within TFW with management field trials (Management Trials). It is quite feasible that some tools that may work when used by specialists or on a limited basis will not work as well when used more widely by field managers.

Perhaps through sponsorship of FIC and CMER, supportive regional managers should be asked to perform a management trials by using the temperature method with followup evaluations to determine user satisfaction and effectiveness. These same cooperators should participate in the refinement of the mechanics of the method and assist the Temperature Work Group in producing the user's manual. The management trial could be conducted for a period of several months with useful results. The Temperature Work Group would assist in this management trial as part of the technical transfer of the method. Results of the management trial should be useful for TFW decision-makers in reaching consensus on the recommended method.

Reaching consensus on a temperature method and implementing regulation changes (if necessary) could be a lengthy process. It is recommended that management field trials be conducted concurrent to discussions using a pilot temperature method described in a draft user's manual. The pilot temperature method could be used as an interim TFW method on a trial basis until any changes in regulations are implemented. Revisions of the method can be accomplished by revising the user's manual.

Regional Workshops. Although a final TFW temperature method has not yet been adopted, and may not be for some time, the Temperature Work Group recommends that project results be communicated to interested TFW participants in regional workshops jointly sponsored by CMER and FIC. The purpose of the workshops would be (1) to share study results on model-testing, and the effects of forest management on temperature regimes of Washington, and the technical background for the recommended methods, (2) to update participants on the TFW process and its progress to date in addressing temperature concerns, (3) to expose participants to the prototype method and to obtain initial feedback from field managers, and (4) to solicit participation by managers in the field trial.

Specific training in the official TFW temperature method must await its formal adoption. Presumably, the Department of Natural Resources with the assistance of the Training, Information and Education Committee will be responsible for technical transfer of the finalized TFW method.

RECOMMENDATIONS ON TFW TEMPERATURE MONITORING NEEDS

Monitoring is needed for both model improvement and evaluation of the effectiveness of the recommended methods in protecting temperature.

Effectiveness Monitoring. Determining the effectiveness of the recommended methods requires establishment of a temperature monitoring program. Monitoring efforts should be well coordinated so that improved statewide databases can be established and that concerns are addressed according to priority.

The overall effectiveness of the the temperature management strategies identified in the Agreement can be determined by establishing monitoring networks within watersheds. If TFW temperature management strategies are working effectively, the temperature at monitoring sites should show either no change over time if uncut previously, or should show improvement in temperature as shade recovers in riparian zones harvested prior to current regulations. Basin monitoring should include temperature in tributary and mainstem sites measured over time. Several basins with 4 or more sites that are currently monitored on a routine basis by TFW participants include Deer Creek (Tulalip Tribe), the Deschutes River (Weyerhaeuser Company) and the Tucannon River (USFS and WDF). It is advisable that sufficient data on site characteristics be collected so that the baseline (fully-shaded) temperature can also be estimated with the temperature model.

Temperature Screen Effectiveness. Monitoring should also be done to determine if the screening method correctly identifies the temperature categories of rivers in response to forest management. The number of streams rating low, moderate and high temperature should be recorded according to water type. For streams with special management prescriptions, the actual riparian shading achieved should be compared to the target shading level sought.

Maximum/minimum thermometers deployed briefly during July or August would be sufficient to determine the temperature category according to the screen.

The screen itself can be easily verified and modified with data collected by field studies or monitoring by TFW temperatures. Maximum water temperature can be collected with maximum/minimum thermometers or other devices during the warmest times of the year (preferably sometime from July 15 to August 15). Deployment of instruments for one or two weeks should be sufficient. The shading and elevation of the site can be determined using methods described in this report or the user's manual. These data can be used to further validate and improve the temperature screen.

TFW Implementation. Monitoring plans should evaluate how well the temperature screen and models are used by managers. It is important to know how often the model is used, geographic distribution of use, and problems with methods. Statistics on the use of the temperature sensitivity screening criteria when processing forest practice applications should be collected. The method could be reviewed at annual general TFW training workshops to provide an index on how well the method is understood and if it is being properly used. This information will help in making any revisions to the method to better fit the managers needs.

Improvement of Regional Relationships Used in Method. A number of empirical relationships are used to supply data to the model and to construct the sensitivity screen (stream characteristics such as depth and climate data such as air temperature and relative humidity). Collecting additional data for several of the regional databases used for selecting input parameter values could improve modeling reliability. Monitoring should emphasize the more important parameters, particularly shading. Especially lacking are shading measurements from streams with streamside vegetation of mature conifer forests along all sizes of streams. Having this information would provide a basis for estimating baseline shading conditions and would provide an indication of the stream size beyond which riparian zone shading is no longer effective for temperature control. Proper sensitivity screening would also be greatly aided by an increased knowledge of shade as a function of water type, and of the site's distance from watershed divide under natural and TFW managed reaches.

Stream reaches from a limited number of randomly selected forest practice applications, stratified by geographic distribution and the temperature category predicted after harvest, should be monitored for water and air temperature. Additional data on stream depth as a function of distance from divide with data stratified by geomorphic stream type would be helpful for temperature modeling as well as many other TFW purposes. Collecting additional data on summer stream flow related to distance from divide for eastern Washington and coastal areas is needed but is of somewhat lesser significance for improving model performance.

Improving functional relationships between local air temperature at stream sites with both basin air temperatures and regional air temperature profiles is needed. Air temperature should be correlated with a site's distance from watershed divide, bankfull stream width, riparian condition and any unique climatic characteristics of the site. Most newer thermographs can monitor both air and water temperatures. Temperature monitoring should address regional variability and allow the development of better regional climatic data. More data on wetted and bankfull stream width as a function of distance from divide is needed to improve regressions used to select air temperature profiles and groundwater inflow rates within the model.

Most of these monitoring needs could be incorporated into work coordinated by the CMER Ambient Monitoring Steering Committee. Those items which do not lend themselves to ongoing monitoring should be completed either under a special short-term study or by making a request to TFW temperature study cooperators.

FURTHER EVALUATION AND RESEARCH NEEDS

Downstream Effect of Stream Heating in Type 4 Waters. Since no basin models can be recommended at this time, further exploration of reach linkage, or heat transfer from one reach to the next, should be a high priority research need. Presumably, removal of riparian vegetation would have the greatest effect on stream temperature within the headwaters streams less than the 11-mile distance. Thus, most type 2,3, and 4 streams would be likely to increase temperature from relatively low baseline values, while many type 1 waters may already be in the moderate or high temperature categories. This is partly addressed by the water quality standards by designating appropriate categories by assigned stream class.

Research should focus on the downstream temperature effects from riparian management on type 4 waters. Temperature protection for larger streams are addressed by forest practice regulations. Specific questions that need to be addressed include the following. What are the temperature regimes for type 4 streams in Washington? What are the downstream temperature effects of type 4 streams (either cooling or heating)? How far downstream is temperature effected by management of upstream riparian shade? How can situations of potential downstream temperature sensitivity related to a type 4 stream be identified?

The TWG recommends a study be initiated in the summer 1990 with the objective of developing a method to address temperature concerns related to type 4 streams and downstream temperature effects. August stream temperatures should be monitored during July or August in selected sites chosen to represent an array of management conditions found in Washington forested type 4 streams. Monitoring would include locations within the type 4 streams and several successive downstream locations to determine whether cooling occurs. This would allow the characterization of temperature regimes for these streams and a determination of their downstream zone of influence. Additionally, the response distance within type 3 waters can be better understood. A scaled down version of the basin model (MODEL-Y) may be used to compare predicted to actual temperatures. Study site selection should consider the effects of elevation and various riparian conditions on temperature. Study conclusions should include a determination of the minimum size of type 4 streams which have a potential to impact larger downstream waters.

Effectiveness of Regulations in Protecting Temperature in Type 1-3 Waters. The evaluation of regulation effectiveness in this report should be considered preliminary. No direct field evaluations of temperature in riparian zones left under the current regulations were performed. Instead, the prediction models were used to simulate the probable temperature regimes at sites with shading levels comparable to those in current streamside buffers. The temperature prediction model was very accurate in predicting temperature in a number of shaded and unshaded reaches, and may therefore be assumed to be reasonably reliable in estimating the effects of shading levels. Nevertheless, these model results should be verified with specific field evaluations of the effectiveness of the regulations.

The field evaluations should measure temperature at the up and downstream ends of riparian zones along a number of different stream sizes and locations in the state. Stream reaches from a limited number of randomly selected forest practice applications, stratified by geographic distribution and the sensitivity rating predicted after harvest, should be monitored for water and air temperature. For a rigorous evaluation of the regulation, temperature should be measured hourly for a period of 2-4 weeks during the warmest period of the summer. The prediction model should also be run at each of the study sites to confirm the model prediction capabilities. All data required to run the models with the greatest reliability, including air temperature, should be collected. (For routine checks on regulation effectiveness, a maximum/minimum thermometer could be used instead of hourly data.) Depending on shading level remaining in the riparian buffer relative to the shading before harvest, the expected temperature regime can be estimated with the model or screen, and data collected at the site will verify whether the expected temperature change (if any) in the reach.

Riparian Conditions and Local Climate. In order to improve the reach model predictive ability, a better understanding of the relationship between local climate and riparian conditions is needed. Developing average daily humidity profiles and evaporation rates as a function of riparian shading would improve the model.Though no specific study is proposed at this time the need for improving regional climate relationships should be kept in mind in case data collection could be incorporated into other studies. This should have relatively low priority compared to other information needs.

Biological Effects of Temperature. As more information on the biological effects of stream temperature becomes available it will be possible to more precisely define TFW issues relative to temperature. A TFW study of biological effects of temperature is in progress. Current criteria for estimating temperature sensitivity emphasize maximum water temperature. The model and methods developed in this study can be easily adapted to more complex temperature criteria if they are shown to be of importance to fish. Daily mean, minimum, diurnal temperature and cumulative degree days are possible parameters of future interest. The temperature model recommended by the TWG can evaluate a number of temperature parameters over whatever timeframe is of interest. As a result,temperature performance criteria may not need

Table 8.1 Summary of recommended temperature monitoring, evaluation and research needs to address remaining questions with suggested priority levels.

Type of Project	Topic	Priority
Evaluation	a. Manager's field trial of method prototype	High
	b. Temperature Screen Validation	High
	c. Downstream temperature effect of type 4 (small) streams	High
	d. Effectiveness of regulations in protecting temperature in type 1-3 streams	High
Monitoring	a. Overall effectiveness of T/F/W Agreement in providing temperature protection	Moderate
	b. Method implementation	Moderate
	c. Regional relationships--riparian shading in mature forests	High
	d. Regional relationships--stream characteristics	Moderate
Research	a. Biological Effects of Temperature	Mod
	b. Riparian conditions and streamside climate	Low
	c. Management effects on winter stream temperature	Low

to be as simplistic with regard to input parameters or time intervals as the one currently used.

Winter Stream Temperature. Most of this study is based on summer temperatures. Future research on riparian effects on winter stream temperature may also be of interest. Reduction in overhead canopy can lead to greater back radiation of heat energy to the sky which may reduce the stream temperature during the winter.This could have a significant effect on fish since the timing of fry emergence is dependent on the cumulative heat during incubation. A subtle temperature change with a long duration could alter emergence timing. The limited amount of winter temperature data available in this study indicated a small decrease in cumulative degree hours in a completely open channel at higher elevations. Specific recommendations on the objectives of winter temperature studies should be developed by the TFW committee responsible for reviewing biological effects of stream temperature.

A summary of the Temperature Work Group's consensus on the priority of the recommended monitoring, evaluation and research needs listed in the last two sections is provided in Table 8.1.

TFW ADAPTIVE MANAGEMENT CONSIDERATIONS

Several situations unique to TFW aided the TWG during implementation of this project. The high interest shown in the project among cooperators and their subsequent monitoring efforts enabled many more study sites to be located across the state than would have been possible by the TWG alone. (In fact, there was more interest among Eastern Washington cooperators than is shown by the small number of east side study sites. A strike and fire conditions during the summer of 1988 prevented many volunteers from actually participating). The TWG encourages other cooperative studies of this type within TFW. The additional information gathered was well worth the high level of coordination essential for this cooperative effort.

One of the major factors that contributed to what the TWG viewed as a successful team effort was a commitment by the study organizers to communicate with TFW participants frequently and at all phases of project development. Another ingredient that contributed to the successful performance of this study was that the project goal was clearly stated in the TFW Agreement. This allowed the TWG to be flexible as the scope of our investigation evolved, with confidence in the overall project direction and requirements for the final product.

A negative aspect of the project organization was that commitments of time and requirements for resources were not carefully planned. This oversight in planning was due both to the cooperative nature of the project and the continually expanding scope of work. The TWG did not anticipate how much time it would take to build a product that would be responsive to evolving TFW needs. The TWG continually encountered unexpected difficulties from project beginning right through to the final report as problems and conflicts surfaced. This resulted in repeated delays in the presentation of study results, in continuing requests for further funding, and in volunteer efforts by members of the TWG. The TWG is grateful for the patience and continued assistance shown by the cooperators during this process, and feels quite strongly that the final temperature model and methods are a much better product than what would have been produced otherwise.

DATA ARCHIVE

Temperature and site data collected during the study as well as all model analyses will be archived with the Department of Natural Resources Forest Regulation and Assistance Office.

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