Chapter VII

TEMPERATURE

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INTRODUCTION

The temperature of small headwater streams of forested areas is an important determinant of overall water quality. Temperature acts not only to control the metabolic rates and functions of aquatic biota but also serves to maintain community structure. Change in temperature affects species composition. Microorganisms at the base of the food chain may be directly affected which eventually will affect all higher organisms in the food pyramid.

Water temperature changes may be either beneficial or detrimental. A moderate temperature increase in streams that are cooler than optimum could increase productivity and have a beneficial effect on the aquatic environment. However streams having temperatures that approach critical threshold limits during the summer months may exceed these limits and have a detrimental effect on aquatic organisms. In addition, winter stream temperatures may be decreased by canopy removal. Exposure of the water surfaces could result in greater convectional heat loss from the water to the atmosphere.

Increased stream temperature affects fish populations in several ways, many of which are detrimental. High temperature kills fish directly, decreases the dissolved oxygen (DO) concentration, increases the susceptibility of fish to disease by increasing bacteriological activity, affects availability of food, and alters feeding activities of fish. Increased stream temperatures indirectly alter community composition by providing a habitat favorable to warm water species.

There are numerous publications that relate the impacts of timber harvesting to stream temperature and subsequent effects on fish populations (Eschner and Larmoyeux 1963, Brown and others 1971). Their studies show that removal of shading vegetation as a result of harvesting can increase stream temperatures because of increased exposure to solar radiation. The magnitude of the impact is a function of the amount of critical canopy removed, duration of exposure, streambed material, area exposed, stream discharge, initial water temperature, and groundwater influx (Stone 1973). Cloud cover is not considered since maximum potential daily temperature increase is being evaluated.

THE PROCEDURE

SOURCES OF ENERGY INFLUX CONTRIBUTING TO INCREASED WATER TEMPERATURE

Removal of streamside vegetation that provides shade to the water surface can cause significant stream temperature increases. Several sources of energy influx interact and contribute to the net change in temperature of a stream. This relationship may be expressed in the following energy budget equation (Brown 1969 and Lee 1977):

$$\Delta H = NR \pm A_d \pm C_d \pm E \pm C_v \qquad \text{(VII.1)}$$

where:

- ΔH = energy manifested by a change in water temperature,
- NR = net radiation (incoming-outgoing all wave radiation),
- A_d = advective energy exchange due to precipitation, ground water, or tributary flows,
- C_d = conductive energy exchange between streambed material and water,
- E = evaporation and condensation, and
- C_v = convective energy exchange at water surface, atmosphere interface.

Net Radiation, NR

Brown (1969, 1972) has shown that 95 percent of the energy influx of small, completely exposed streams can be accounted for by net radiation. Net solar radiation is defined as the algebraic sum of incident and reflected sun and sky shortwave radiation, incident and reflected atmospheric longwave radiation, and longwave radiation emitted by the water body. It is the principal energy influx controlling the maximum temperature increase in exposed streams. Solar radiation itself is not controllable, but the amount of water surface exposed can be controlled. Shading by vegetation limits the amount of solar radiation received by the water course (Reifsnyder and Lull 1965).

Advective Energy Flux, A_d

Advective energy flux is the transmission of heat by horizontal currents through a fluid such as the atmosphere or water. In specific situations these significantly modify temperature increases; for example, advective inputs by groundwater normally decrease maximum summer temperatures. Groundwater temperatures generally approach the average annual air temperature, and so are generally cooler than surface water during the summer months. The magnitude of this reduction will depend upon the temperature difference between the surface and the groundwater, and upon the volume of groundwater entering the stream as compared to the volume of streamflow in the surface water.

Advective inputs by tributaries may either increase or decrease maximum receiving stream temperature depending upon whether the tributary stream contains warmer or cooler water. Like groundwater, the magnitude of the change in water temperature of a receiving stream will be determined by the temperature and volume of the tributary flow compared to the temperature and volume of the receiving stream. Temperature changes associated with ground water or tributary flows can be expressed mathematically by a simple proportion:

$$\Delta T_a = \frac{D_1 T_1 + D_2 T_2}{D_1 + D_2} \qquad \text{(VII.2)}$$

where:

- ΔT_a = change in water temperature, receiving stream,
- D_1 = discharge, receiving stream,
- T_1 = temperature, receiving stream,
- D_2 = discharge, tributary stream, and
- T_2 = temperature, tributary stream.

Conductive Energy Exchange Between Streambed Material And Water, C_d

In a conductive energy exchange heat is transferred through matter by kinetic energy (energy of motion) from particle to particle. Stream temperatures will vary with streambed composition. Generally, bedrock streambeds will act as heat sinks with resulting conductive losses of energy from the water body to the rock (Brown 1972). Gravel, sand, and fine materials comprising streambeds have interparticulate voids that minimize conductive heat losses. The color of the rock also influences the magnitude of the conductive heat loss. Darker rock will absorb more energy than lighter rock.

Evaporation And Condensation, E

Evaporation is the principal process by which heat is lost from the water surface. It occurs whenever the saturation vapor pressure of the water is greater than the ambient vapor pressure. This happens during the summer when the water is cooler than the air and, in particular, during the midday period. Heat loss from the water via evaporation is only a fraction of the radiant energy influx and does not significantly alter the maximum temperature increases in most small streams where silvicultural activities are conducted. However, as the water temperature increases to equilibrium, evaporation increases and heat loss from the water due to evaporation may exceed the heat influx from net radiation.

Convective Energy Exchange, C_v

Convective energy exchange occurs whenever there is a temperature gradient between the water mass and air mass. The energy exchange may be positive or negative depending upon whether the air is warmer or cooler than the water. During critical periods of maximum water temperature, the air mass will usually be warmer than the water and will reinforce the radiant energy influx to increase water temperature.

BROWN'S MODEL: ESTIMATING MAXIMUM POTENTIAL TEMPERATURE INCREASE

Brown (1970, 1972) developed a model for predicting the maximum potential daily change in temperature resulting from the complete exposure of a section of stream channel to direct solar radiation using the energy budget approach. Field measurements showed that net thermal radiation accounted for over 95 percent of the energy influx to exposed water courses (Brown 1969). (Validation of Brown's model is discussed in appendix VII.A.) The energy term in the initial model was simplified based upon the assumption that net solar radiation is the only source of energy to an exposed stream. The simplified model is:

$$\Delta T = \frac{AH}{Q} 0.000267 \qquad \text{(VII.3)}$$

where:

- ΔT = maximum potential daily temperature increases expected from exposing a section of stream to direct solar radiation, in degrees Fahrenheit.
- A = surface area in square feet of stream exposed to direct solar radiation,
- Q = discharge of the stream, in ft^3/sec
- H = incident heat load (net solar radiation) received by the exposed water surface in BTU/ft^2-min, and
- 0.000267 = constant required for unit conversion converts flow from ft^3/sec to lb/min.

PROCEDURAL DESCRIPTION

Brown's procedure for determining the maximum potential daily temperature increase in terms of incident heat load (H), discharge (Q), and exposed surface area of flowing water (A) follows. These descriptive paragraphs correspond with the procedural flow chart organization in figure VII.1.

Determination Of Incident Heat Load, H

The incident heat load (net solar radiation), H, received by a water surface is determined by (1) the maximum solar angle of the sun; (2) the length of time a given volume of water will be exposed to solar radiation; (3) the amount of bedrock in the stream; and (4) the amount of vegetative and topographic shading of the water surface. The following steps are involved in computing the incident heat load.

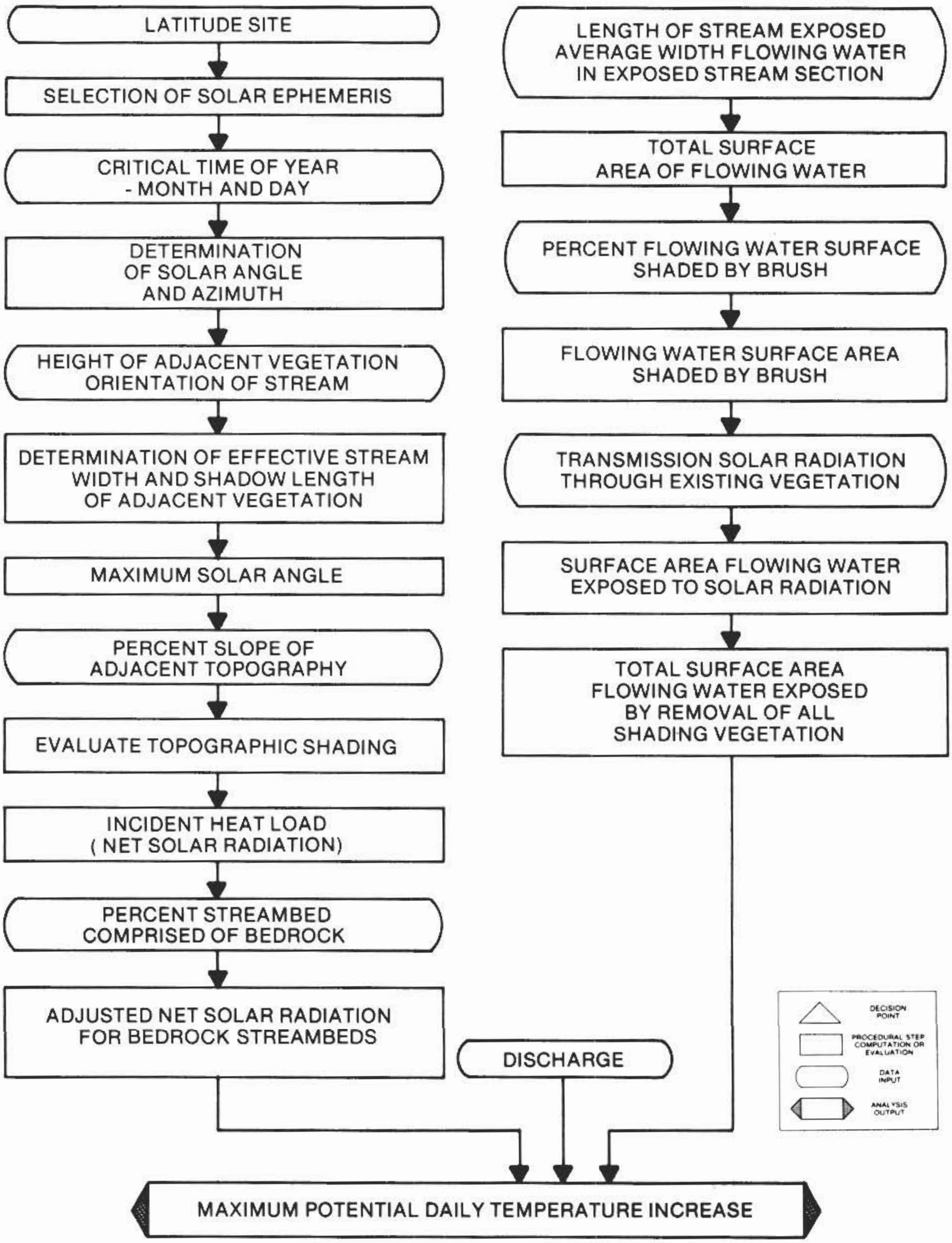


Figure VII.1. Flow diagram showing the sequence of steps and data required for evaluating the maximum potential daily temperature increase in degrees Fahrenheit.

LATITUDE SITE

The latitude of the site must be known. Exact latitudinal location to the nearest minute or second is not required, as the difference in net radiation over two to three degrees of latitude is not significant for this analysis procedure.

SELECTION OF SOLAR EPHEMERIS

A solar ephemeris is defined as a table or figure that gives the sun's location, angle and azimuth, for each day. Four solar emphemerides are provided (figs. VII.2 - VII.5), representing four latitudes — 35° N, 40° N, 45° N, and 50° N. Select one solar ephemeris most appropriate for the latitude of the site of the silvicultural activity. For example, if the latitude of the site is 40-½° N, the solar ephemeris for 40° N would be utilized.

CRITICAL TIME OF YEAR — MONTH AND DAY

Select the time of year when stream temperature increases are critical. This normally occurs during the summer months when the stream is lowest and heat influx is greatest.

Using the previous example, locate the declination in the solar ephemeris for 40° N latitude (fig. VII.3) that corresponds to the date when maximum water temperature increase is anticipated. If the critical period is the second week in July, the declination would be +21-½°. Interpolate between given declination lines for dates other than those given. For the declination of the second week in July, interpolate between declinations +23°27′ and +20° (June 22 and July 24, respectively).

DETERMINATION OF SOLAR ANGLE AND AZIMUTH

Maximum radiation will occur during the midday hours on clear days. The heat load received by the stream depends on the solar angle and azimuth. As the solar angle increases, more radiant energy reaches the water surface and there is a reduction of reflected radiation. Brown (1970) developed curves for net incoming (shortwave and diffuse) solar radiation (BTU/ft^2−min) based upon solar angle and reflectivity. He determined that heat might be added to a stream by incoming longwave radiation; however, back radiation from the water was about the same magnitude. Therefore, the net change in stream heat from longwave radiation is assumed to be zero. Solar angle and azimuth, of course, depend upon season, time of day, and latitude.

Continuing with the same example, with a declination +21-½°, determine the azimuth and solar angle for various times during the day from the solar ephemeris (fig. VII.6) and record the values as shown in table VII.1. Azimuth readings are found along the outside of the circle (fig. VII.6) and are given for every 10 degrees. Solar angle (i.e., degrees above the horizon) is indicated by the concentric circles. The time is indicated above the +23°27′ declination line and is given in hours, solar time.

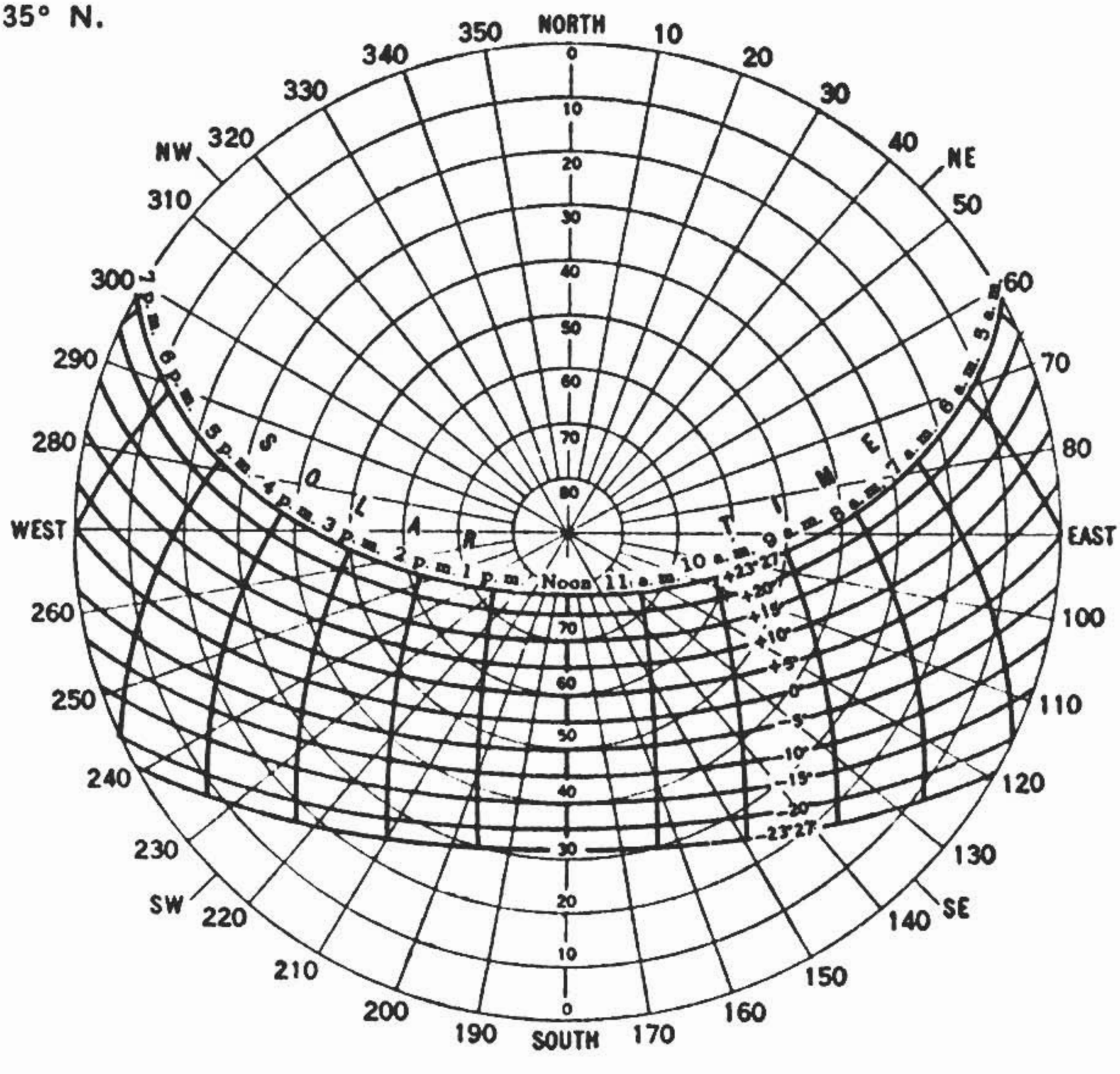
Table VII.1.—Variation of solar angle and azimuth with time of day[1]

Daylight savings time	Solar angle	Solar azimuth
12:30	70	155
1:00 (solar noon)	72	180
1:30	70	205
2:10 (oriented with stream)	68	225
2:30	65	235
2:45	60	240
3:10	55	245

[1]See "Chapter VIII: Procedural Examples" for worksheets corresponding to data appearing in this chapter's tables and figures.

To determine the solar angle and azimuth that would occur at 12:30 p.m. daylight savings time: follow along the +21-½° declination line that is interpolated between the +20° and +23°27′ line. Locate the point that is equal distance between the 11:00 a.m. (12:00 a.m. daylight savings time) and noon (1:00 p.m. daylight savings time) time interval. This point represents 12:30 daylight savings time.

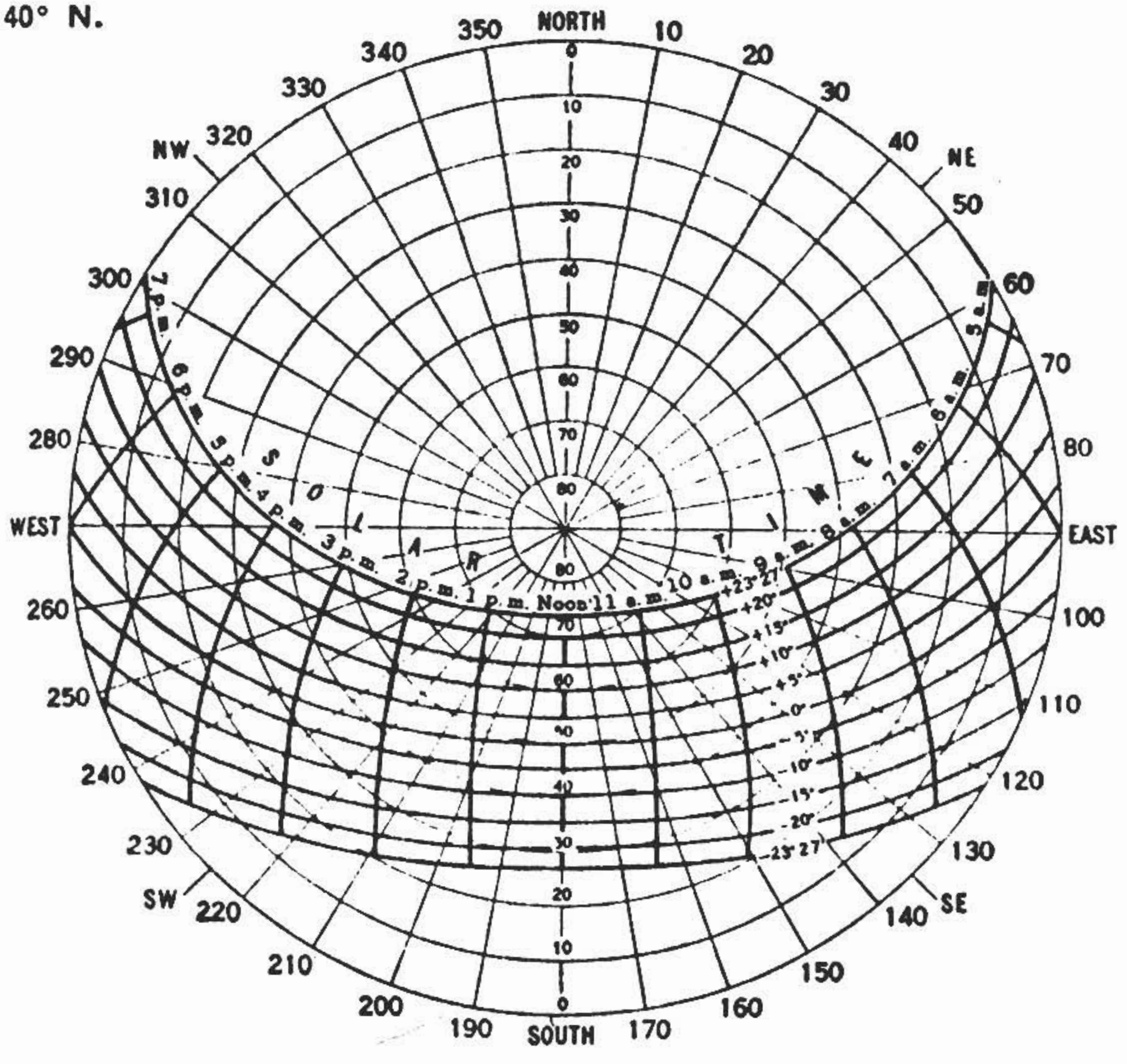
35° N.



Declination	Approx. dates
+23° 27′	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 12
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
− 5°	Mar. 8, Oct. 6
−10°	Feb. 23, Oct. 20
−15°	Feb. 9, Nov. 3
−20°	Jan. 21, Nov. 22
−23° 27′	Dec. 22

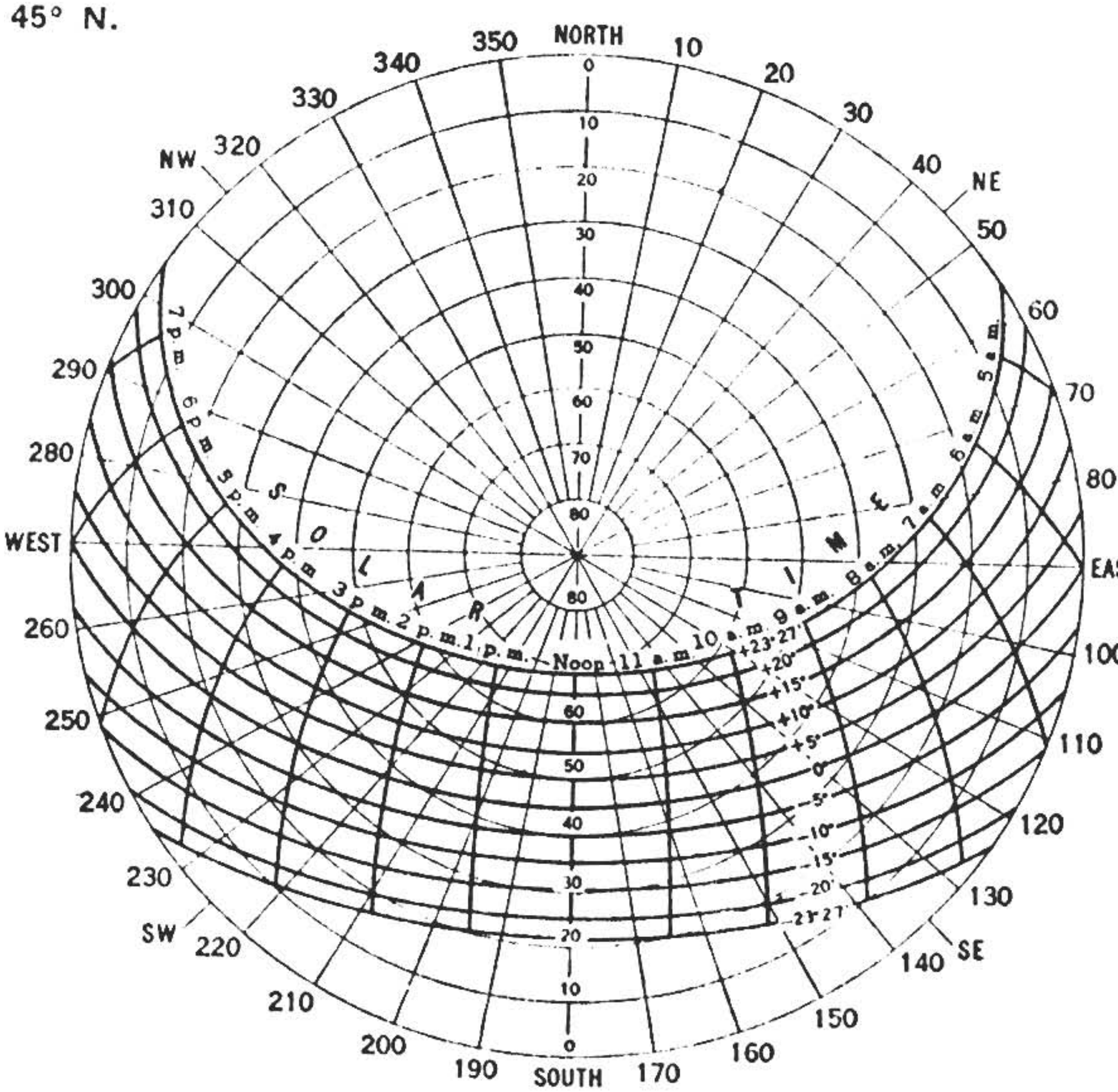
Figure VII.2.—Solar ephemeris for 35° N latitude.

40° N.



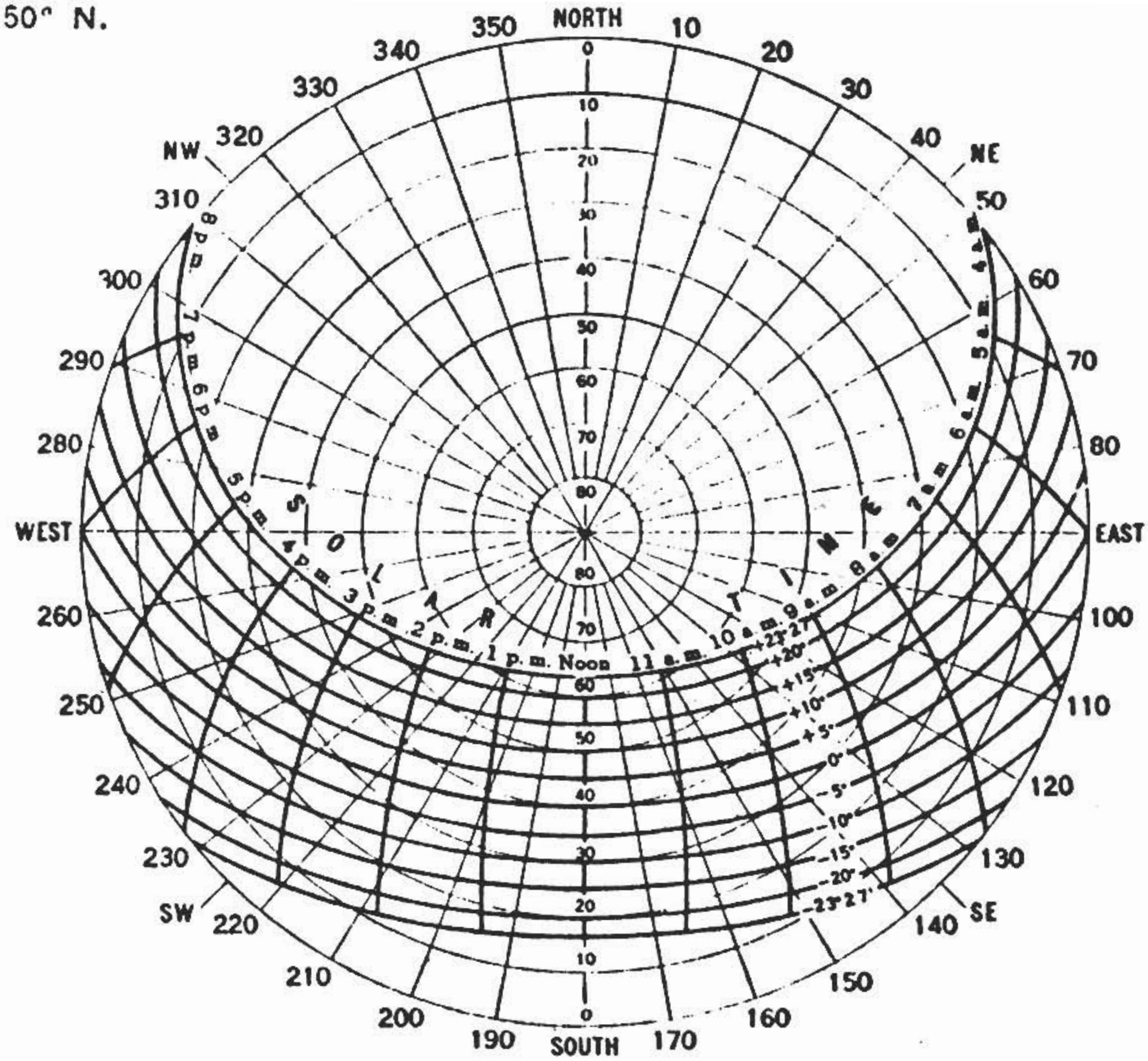
Declination	Approx. dates
+23° 27′	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 12
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
− 5°	Mar. 8, Oct. 6
−10°	Feb. 23, Oct. 20
−15°	Feb. 9, Nov. 3
−20°	Jan. 21, Nov. 22
−23° 27′	Dec. 22

Figure VII.3.—Solar ephemeris for 40° N latitude.



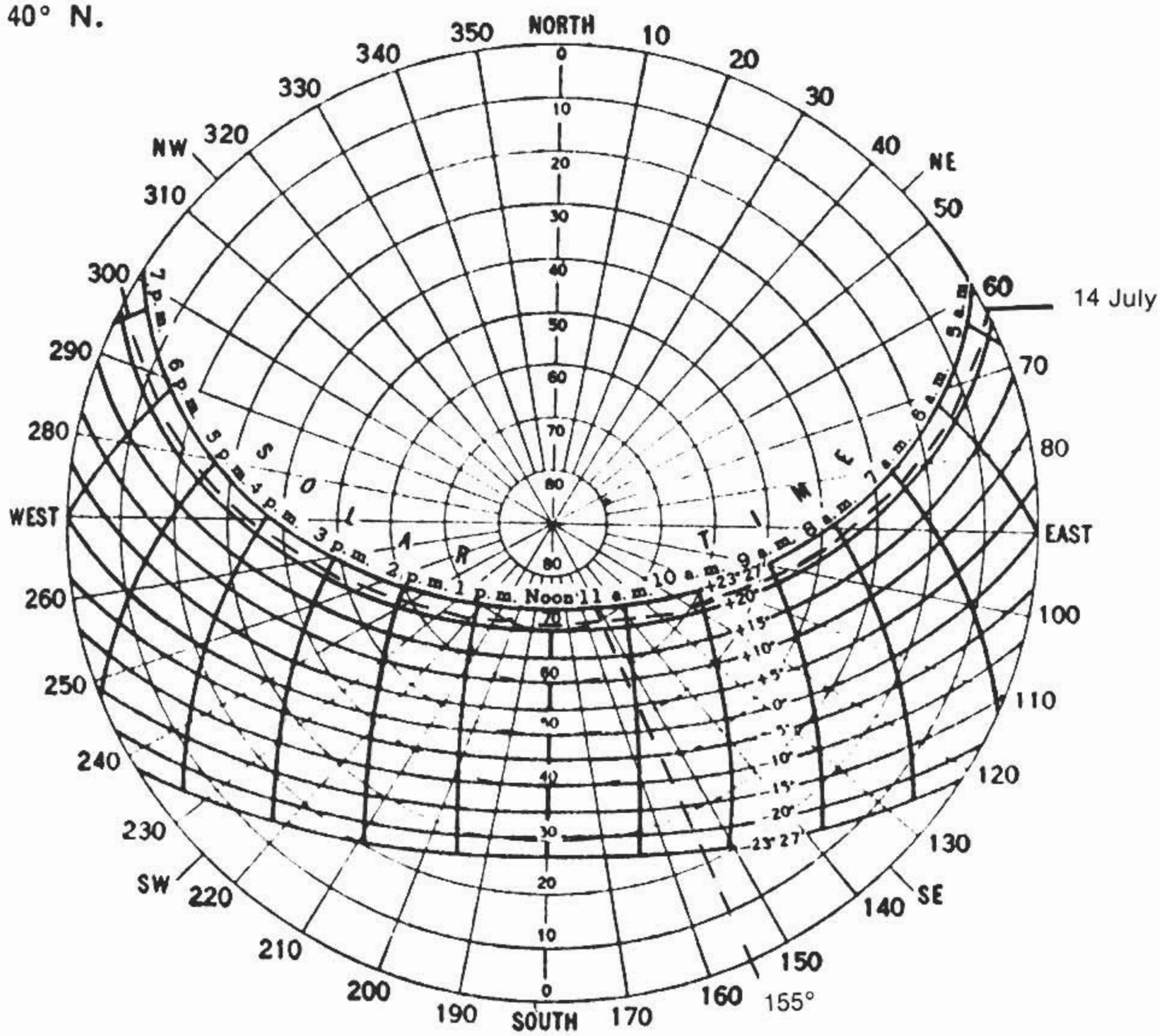
Declination	Approx. dates
+23° 27′	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 12
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
— 5°	Mar. 8, Oct. 6
—10°	Feb. 23, Oct. 20
—15°	Feb. 9, Nov. 3
—20°	Jan. 21, Nov. 22
—23° 27′	Dec. 22

Figure VII.4.—Solar ephemeris for 45° N latitude.



Declination	Approx. dates
+23° 27′	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 12
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
— 5°	Mar. 8, Oct. 6
—10°	Feb. 23, Oct. 20
—15°	Feb. 9, Nov. 3
—20°	Jan. 21, Nov. 22
—23° 27′	Dec. 22

Figure VII.5.—Solar ephemeris for 50° N latitude.



	Declination	Approx. dates
	+23° 27′	June 22
14 July ⟶	+20°	May 21, July 24
	+15°	May 1, Aug. 12
	+10°	Apr. 16, Aug. 28
	+ 5°	Apr. 3, Sept. 10
	0°	Mar. 21, Sept. 23
	− 5°	Mar. 8, Oct. 6
	−10°	Feb. 23, Oct. 20
	−15°	Feb. 9, Nov. 3
	−20°	Jan. 21, Nov. 22
	−23° 27′	Dec. 22

Figure VII.6.—Use of the solar ephemeris given the following illustrative data: latitude of 40-½° N, second week in July, and 12:30 p.m. daylight savings time.

The solar angle is determined by noting where the point established above (12:30 p.m. with a declination of +21-½°) occurs in respect to the solar angle lines present on figure VII.6. The solar angle lines are represented as concentric circles and range from 90° at the center to 0° at the periphery. The point established above falls on the 70° line; therefore, the solar angle is equal to 70°.

The solar azimuth is determined by noting where the point established above occurs in respect to the solar azimuth lines that radiate out from the center of the circle. The point falls midway between the 150° and 160° lines; therefore, the solar azimuth equals 155°.

More points should be selected about the midday period when solar radiation is at the greatest intensity as opposed to the early morning and/or late afternoon when solar radiation is less.

HEIGHT OF ADJACENT VEGETATION ORIENTATION OF STREAM

The height of vegetation adjacent to the stream effects the shading of the stream. Taller vegetation casts longer shadows and so can be further from the stream and still provide shade. The orientation of the stream azimuth in respect to the sun also determines the length of shadow. For a more detailed discussion of these relationships, refer to appendix VII.B.

DETERMINATION OF STREAM EFFECTIVE WIDTH AND SHADOW LENGTH OF ADJACENT VEGETATION

Evaluate the orientation of the sun (i.e., solar angle and azimuth determined previously, table VII.1), with the stream and determine what vegetation exists that shades the stream. To do this, compare stream effective width with shadow length. Determine the maximum solar angle (i.e., maximum radiation influx to stream) that will occur when the stream is exposed due to the silvicultural activity.

Assuming a stream azimuth of 225° and a height of 70 feet for vegetation adjacent to the stream, the following numerical computations illustrate how stream effective width and shadow length can be evaluated.

The direction the shadows fall across the stream will determine effective width of the stream (for a discussion of effective width, see appendix VII.B, "Streamside Shading").

Effective width is computed using the following formula:

$$\text{EW} = \frac{\text{measured average stream width}}{\text{sine}\,|\,\text{azimuth stream - azimuth sun}\,|} \qquad \text{(VII.4)}$$

The azimuth of the particular stream used for this illustration is 225°. This value (EW) varies depending on the time of day. For example, at 12:30 p.m. (table VII.1), EW would be equal to:

$$\text{EW} = \frac{1.5 \text{ ft}}{\text{sine}\,|\,225° - 155°\,|} = 1.6 \text{ ft}$$

The absolute value of azimuth of the stream less azimuth of the sun must be less than a 90° angle. Should the difference exceed 90°, subtract this absolute value from 180° to obtain the correct acute angle. The sine is then taken of this computed acute angle.

Shadow length (S) is computed using the formula:

$$\text{S} = \frac{\text{height vegetation}}{\text{tangent solar angle}} \qquad \text{(VII.5)}$$

For example, at 12:30 p.m., S would be equal to:

$$\text{S} = \frac{70 \text{ ft}}{\text{tangent }(70°)} = 25.5 \text{ ft}$$

Note, the only periods of the day that should be considered are those times when existing vegetation that will be eliminated by the silvicultural operation effectively shades the stream; i.e., when the shadow length extends onto some portion of the stream.

MAXIMUM SOLAR ANGLE

In the illustration used previously, the existing trees scheduled to be cut do provide shade to the stream. The only time of the day when the existing trees do not shade the stream occurs about 2:10 p.m. when the stream's effective width is infinity

Table VII.2.—Computation of stream's effective width (EW) and vegetative shadow length (S) based upon stream azimuth, solar azimuth, and solar angle

Daylight savings time	Solar angle	Solar azimuth	Effective width (EW = 1.5/sine 225-Solar azimuth)	Shadow length (S=70/tangent Solar angle)
	(°)		(ft)	(ft)
12:30	70	155	1.6	25.4
1:00	72	180	2.1	22.7
1:30	70	205	4.4	25.5
2:10	68	225	(infinity)	28.2
2:30	65	235	8.6	32.6
2:45	60	240	5.8	40.4
3:10	55	245	4.4	49.0

(sun is oriented with the stream) and the shadow length is only 28.2 feet (table VII.2). Therefore, removal of this vegetation would result in exposure of the water surface to increased solar radiation.

The proposed silvicultural operation would have the maximum impact on water temperature at 1:00 p.m. (solar noon) when the solar angle and radiation are greatest and when existing vegetation presently providing shade is removed. Therefore, the maximum solar angle would be 72°.

PERCENT SLOPE OF ADJACENT TOPOGRAPHY

The percent slope of the adjacent topography must be measured or estimated.

EVALUATE TOPOGRAPHIC SHADING

Topographic shading should be evaluated to determine if the water course would be shaded by topographic features. For topographic shading to be present, the percent slope of the ground must exceed the percent slope of the solar angle (i.e., tangent solar angle).

If the slope of the topography adjacent to the stream is 30 percent and table VII.2 gives the solar angle as 72° or 308 percent, topographic shading is not possible due to the angle of the sun and relatively gentle topographic relief.

INCIDENT HEAT LOAD (NET SOLAR RADIATION)

Given a specific site, the rate of incoming radiation is constantly changing. To determine the approximate heat load for the model, the length of time a given volume of water will be exposed to direct solar radiation also must be determined. Travel time of the stream can be found by measuring any of the following: average stream velocity using a current meter (ft/sec); empirical relationships using channel slope data; and/or dye tracing. The net solar radiation must be averaged for the time that the water will be exposed. This is accomplished by identifying or interpolating the appropriate midday solar angle curve and locating on the time axis the period of day that the stream will be exposed (fig. VII.7).

The radiation value occurring at the midpoint of the proposed period can normally be used as the average net radiation value. However, when the travel time is several hours and the exposed period goes from midmorning to early afternoon (for example, 9 a.m. to 1 p.m.), it may be necessary to consider the change in slope of the curve and to select a net radiation value more representative for the period rather than the midpoint. However, it should be noted that this model is for stream reaches less than 2,000 feet in length; travel time will normally not exceed 2 hours and generally will be less than 1 hour, thereby eliminating the need to determine an average net radiation value.

Estimate the incident heat load for the site (fig. VII.7). Continuing with the previous example:

1. Use the maximum solar angle determined previously (72°).
2. In figure VII.8, interpolate between the 70° and 80° curve to obtain the 72° values.
3. Determine the critical time period (1:00 p.m. in this example).
4. Find the average H value. Travel time through the exposed section of stream channel is only 0.3 hour; therefore, it is not necessary to find an average H value. From figure VII.8, with a 72° midday angle, the H value for 1:00 p.m. is approximately 4.7 BTU/ft^2-min; if we had used the solar ephemeris for 45° N latitude, the H value would have been 4.5 BTU/ft^2-min. Figure VII.8 illustrates the procedure used to obtain H in this example.

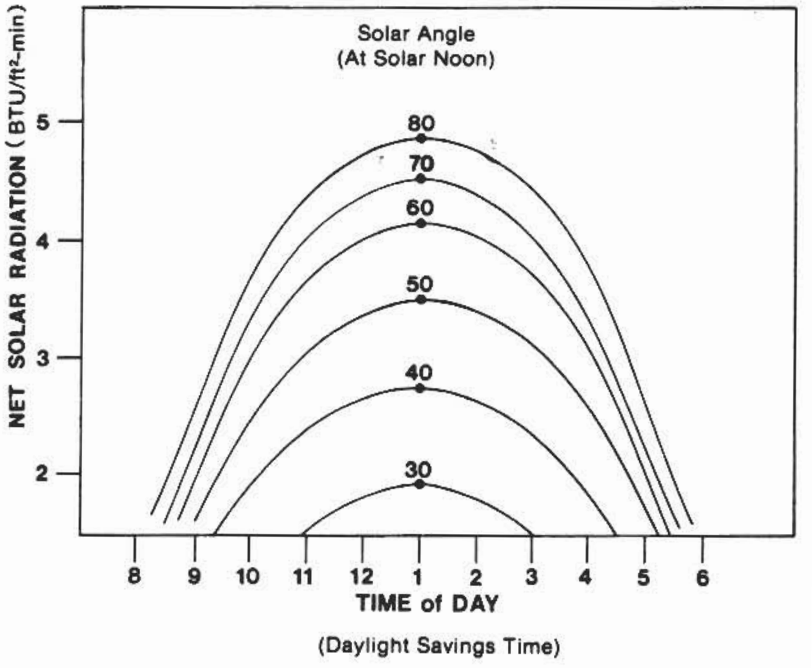


Figure VII.7.—Hourly values (BTU/ft^2-min) for net solar radiation above water surfaces on clear days between latitudes 30° N and 50° N for several solar paths (Brown 1970).

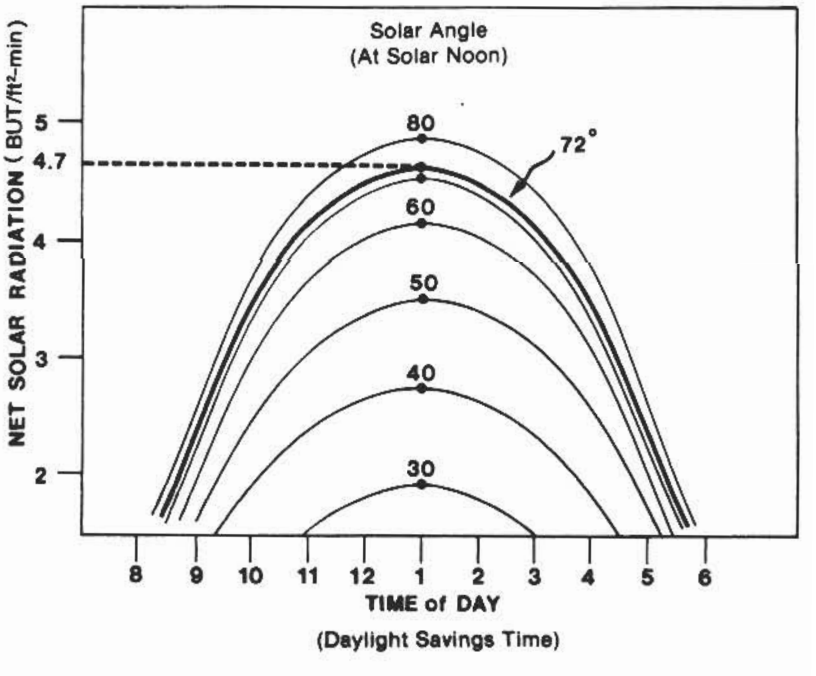


Figure VII.8.—Determination of net hourly solar radiation using noon angle of 72°. H is 4.7 BTU/ft^2-min.

PERCENT STREAMBED COMPRISED OF BEDROCK

The percentage of streambed comprised of bedrock must be measured or estimated.

ADJUSTED NET SOLAR RADIATION FOR BEDROCK STREAMBEDS

Bedrock in the streambed acts as a heat sink, and conductive loss of energy from the water to the rock may occur. Brown (1972) recorded a 20-percent reduction of the incident heat load in a streambed entirely composed of bedrock. Assuming a linear relationship for lesser exposure of bedrock, use figure VII.9 to adjust H when bedrock is exposed in the streambed.

$$H_{adjusted} = [\%WH] + [\%B\,(1.00 - C)\,H] \qquad \text{(VII.6)}$$

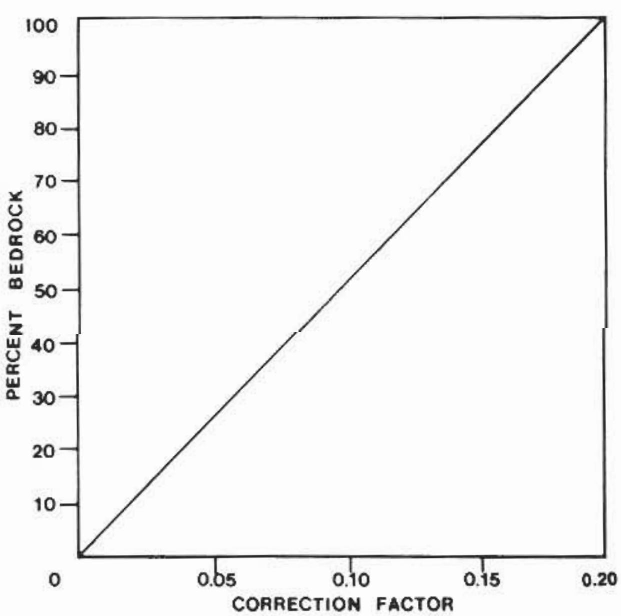


Figure VII.9.—Correction factor for the heat-sink effect of bedrock streambeds.

where:

- W = percent streambed without bedrock[1] (e.g., 0.10),
- H = unadjusted heat load (e.g., 4.7 BTU/ft^2-min with a solar ephemeris for 40° N latitude),
- B = percent streambed with rock[1] (e.g., 0.90), and
- C = correction factor[1] (e.g., 0.18).

C is obtained from figure VII.9. In the example, bedrock comprises 90 percent of the streambed; therefore H should be reduced by 18 percent.

$$H_{adjusted} = 0.10(4.7) + 0.90\,(1.00 - 0.18)\,4.7 = 3.94$$

Determination Of Discharge, Q

DISCHARGE

Discharge, that takes place during the critical summer period following silvicultural activities, when maximum water temperature may be anticipated, represents the flowing portion of the stream. This value should reflect any changes in discharge quantity and timing due to the silvicultural operation. "Chapter III: Hydrology" presents a discussion of a procedure and methodology for deriving these values. Discharge should be measured during the critical summer period prior to the proposed silvicultural activity. Any adjustments in discharge due to the silvicultural activity can then be made on this previously measured value.

Determination Of Exposed Surface Area Of Flowing Water, A

The exposed surface area of a stream is that portion of the flowing water affected by the silvicultural operation. Large pools with little or no flow do not significantly influence temperature increase of the flowing water. Brown (1972) found no temperature gradient in small pools in the direction of flow and only a small (0.2° C) gradient in large pools. The lack of complete mixing in the

[1] *All percent values used in equation VII.6 should be in decimal form.*

pools limits the transfer of heat (i.e., absorbed solar radiation) from the stagnant water in the pool to the flowing water. If the total surface area of pools is considered in determining stream surface area exposed, the predicted potential temperature increase will be inaccurate; and if more than one pool is present in the reach, the magnitude of error is increased even more. Dye can be used, if necessary, to determine the surface area of a pool that should be used in predicting temperature change.

Furthermore, the surface area of flowing water exposed by removal of vegetation must be adjusted to account for the surface exposure prior to the removal of the vegetation. Riparian vegetation and timber do not normally shade a stream so completely as to preclude the transmission of all solar radiation to the water surface. For example, a western coniferous stand with 400 square feet of basal area/acre may allow 5 to 15 percent of the solar radiation to penetrate (Reifsnyder and Lull 1965).

The following steps are involved in computing the exposed surface area, A.

LENGTH OF STREAM EXPOSED AVERAGE WIDTH FLOWING WATER IN EXPOSED STREAM SECTION

The length of stream that will be exposed by the silvicultural activity is measured or estimated. The average width of flowing water in this exposed section of stream is measured or estimated during the time of year when stream temperature is critical. Accuracy of these measurements or estimates is critical as the accuracy of the analysis is dependent upon this information (see app. VII.A, "Validation of Brown's Model").

TOTAL SURFACE AREA OF FLOWING WATER

The length of stream exposed, multiplied by the average width of flowing water, gives surface area.

For example, a stream with a length of 530 feet and an average width of flowing water of 1.5 feet has a total surface area of flowing water of 795 square feet.

$$A_{total} = LW = 530 \text{ ft} \times 1.5 \text{ ft} = 795 \text{ ft}^2 \qquad \text{(VII.7a)}$$

PERCENT FLOWING WATER SURFACE SHADED BY BRUSH

The percent shade provided by riparian brush and shrubs is estimated by field observation. Again, this estimate should be made during the time of year when stream temperature is critical. For the example discussed here, it was estimated that 15 percent of the flowing water surface was shaded.

FLOWING WATER SURFACE AREA SHADED BY BRUSH

The combination of shade provided by brush and tree canopy will generally prevent most of the net solar radiation from reaching the water surface. The surface area shaded by brush is therefore determined.

In this example, with 15 percent of the flowing water shaded during the critical period, surface area shaded by brush would be estimated at 120 square feet.

$$A_{shade\ brush} = LW\ (\%\ \text{stream shaded by brush only}) = 530 \text{ ft} \times 1.5 \text{ ft} \times 15\% = 120 \text{ ft}^2 \qquad \text{(VII.7b)}$$

TRANSMISSION SOLAR RADIATION THROUGH EXISTING VEGETATION

The solar radiation passing through the existing crown canopy must be measured or estimated. Refer to appendix VII.B for a discussion of how this might be measured and appendix VII.D for tabular displays of the relationship between stand density and transmission of solar radiation.

SURFACE AREA FLOWING WATER EXPOSED TO SOLAR RADIATION

Using surface area exposed under current vegetative canopy cover, correct for transmission of light through the existing stand that has a percent crown closure. Whenever possible, use only angular canopy density values (see "Angular Canopy Density" in app. VII.C). If only vertical crown closure values are available, estimate percent transmission of solar radiation. Values for these estimates may be obtained from Technical Bulletin 1334, pages 72-76 (Reifsnyder and Lull 1965). Assuming a crown closure of 65 percent, figure VII.10 shows that approximately 8 percent of the solar radiation will be transmitted through the canopy and reach the stream.

$$A_{\text{presently exposed}} = (A_{\text{total}} - A_{\text{shade brush}})(\%\text{ transmission through existing vegetation}) \quad \text{(VII.7c)}$$

$$= (795\ ft^2 - 120\ ft^2) \times 8\%$$

$$= 54\ ft^2$$

The flowing water, therefore, has approximately 54 square feet exposed to solar radiation.

TOTAL SURFACE AREA FLOWING WATER EXPOSED BY REMOVAL OF ALL SHADING VEGETATION

The surface area required is the additional surface area of flowing water that would be exposed due to the silvicultural activity. The total surface area of flowing water cannot be used because part of the stream (in the example, 54 ft^2) is exposed under the existing pre-silvicultural activity vegetative conditions.

$$A_{\text{adjusted}} = A_{\text{total}} - A_{\text{exposed pre-silvicultural activity}} \quad \text{(VII.7d)}$$

$$= 795\ ft^2 - 54\ ft^2$$

$$= 741\ ft^2$$

Assuming that all vegetation is removed, the exposed surface area of flowing water would be 741 square feet in the example. If some of the current vegetative cover were to remain, the surface area shaded by the remaining vegetative cover would also be subtracted from A_{total}.

Determination of Maximum Potential Daily Temperature Increase, ΔT

Determine the maximum potential daily temperature increase in degrees Fahrenheit using H, Q, and A values as derived through the previous steps. Compute the maximum potential change in daily temperature assuming all riparian vegetation is removed using Brown's model:

$$\Delta T = \frac{AH}{Q}\, 0.000267 \quad \text{(VII.3)}$$

where:

ΔT = maximum potential daily temperature increase in degrees Fahrenheit

A = adjusted surface area

Q = mean discharge that will occur within the exposed reach during critical period following silvicultural operation

H = adjusted heat load BTU/ft^2-min

Equation VII.3 becomes:

$$\Delta T = \frac{A_{\text{adjusted}} H_{\text{adjusted}}}{Q}\, 0.000267 \quad \text{(VII.3a)}$$

(The use of subscripts indicates that the variables in Brown's original model, equation VII.3, have been refined in this handbook.)

In the example:

$$A_{\text{adjusted}} = 741\ ft^2$$
$$H_{\text{adjusted}} = 3.94\ BTU/ft^2\text{-min}$$
$$Q = 0.4\ cfs$$

so that:

$$\Delta T = \frac{741\ ft^2 \times 3.94\ BTU/ft^2 - min}{0.4\ cfs}$$

$$0.000267 = 1.9°\ F$$

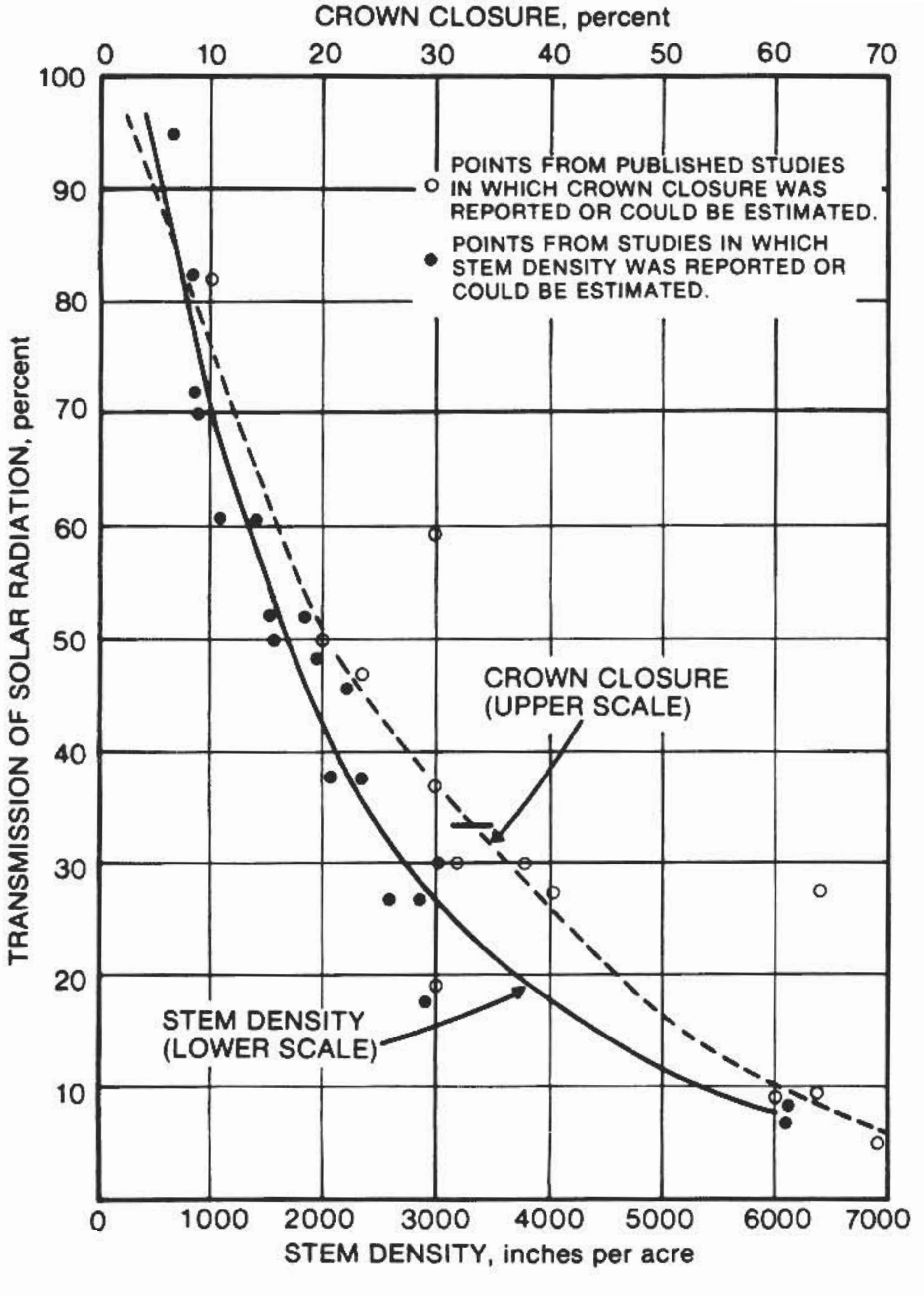


Figure VII.10.—Transmission of solar radiation as a function of stem density and crown closure (Reifsnyder and Lull 1965).

Evaluation Of Downstream Temperature Increases

To evaluate downstream impacts of increased water temperatures caused by silvicultural activity, a mixing formula is used (fig. VII.11):

$$T_D = \frac{D_M T_M + D_T T_T}{D_M + D_T} \qquad \text{(VII.8)}$$

where:

- T_D = temperature downstream after the treated stream enters the main stream,
- D_M = discharge main stream,
- T_M = temperature main stream above the treated tributary,
- D_T = discharge stream draining treated area,
- T_T = temperature stream below treated area equals temperature above plus computed temperature increase (i.e., Brown's model) or $(T_A + \Delta T) = T_T$,
- T_A = temperature stream above treated area (measured in field), and
- ΔT = temperature increase computed using Brown's model.

The mixing ratio formula merely weights the resultant temperature (T_D) by discharge. (It should be noted that small streams with large temperature increases will be diluted if the stream flows into a larger water course.)

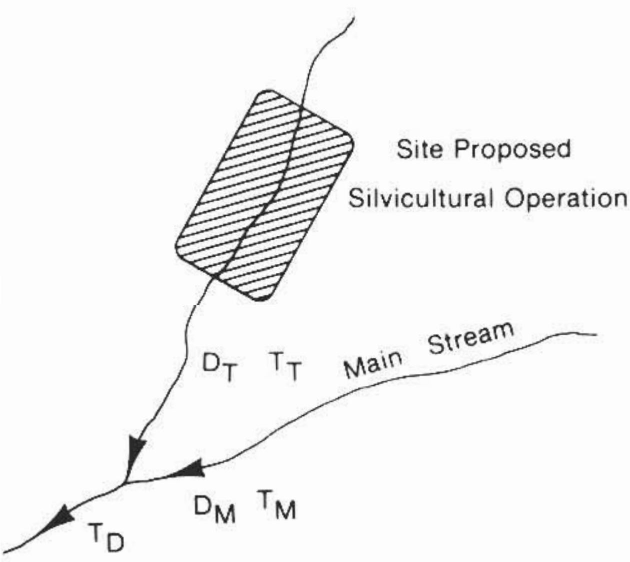


Figure VII.11.—Components of the mixing formula for evaluating the downstream impact of increased water temperature caused by silvicultural activities upstream.

Please note, there are two factors to consider when estimating the total downstream temperature increase due to upstream silvicultural activities. First, the total increase in water temperature caused by the operation itself must be determined (i.e., Brown's model). Second, the reduction of water temperature due to groundwater inflow must be determined. These factors must be estimated, and these estimates are generally subject to considerable error.

Total Increase In Water Temperature

Water temperature increases due to silvicultural activities have already been discussed. These increases will not normally be reduced by subsequent passage through undisturbed stands if the distance is short. The air temperature over a stream during the critical summer period is usually warmer than the water, even in undisturbed areas; furthermore, the net radiation input will continue to be positive. Therefore, it will generally be impossible for the water temperature to be reduced by convective, evaporative, or radiative energy loss to the atmosphere.

It follows that up to some limit, known as the equilibrium temperature, successive silvicultural activities on one stream will have a compounding effect on water temperature increases: water temperature increases due to downstream activities will be added onto increases caused by upstream operations. This compounding effect may be eliminated or minimized, however, if the travel time between activities is of such duration as to preclude arrival of water from an upstream activity to a lower activity before evening when cooler air temperatures and back radiation can lower the water temperatures, or when there are inflows of cooler groundwater of sufficient magnitude to dilute warmer surface water.

Reduction In Water Temperature Due To Groundwater Inflow

Groundwater is cooler than summer surface water, and it can reduce water temperature increases caused by silvicultural operations. Since groundwater temperature is fairly constant for wide areas, well and/or spring water temperatures can be used as a measure of groundwater temperature. A rough rule to be applied, if necessary, is that the groundwater temperature is approximately equal to the average annual air temperature.

Groundwater discharge can be measured in the field. Increasing discharge downstream can be assumed to be groundwater inflow only if there are no inflowing tributary streams and if there has been no recent precipitation event which might still be entering the stream as quick flow rather than base flow.

In trying to estimate groundwater discharges on small streams, the error of measurement is likely to be high and the potential for groundwater cooling the stream is quite large. This combination can lead to significant error in predicting temperature change below an exposed reach.

Once groundwater temperature and inflow have been measured, or estimated, the mixing ratio formula can be used to evaluate its impact on reducing temperature increases caused by silvicultural operations upstream. Groundwater that becomes surface flow is subject to radiation and convection heat influxes resulting in temperature increases.

The formula is the same mixing ratio as the one previously presented in equations V.2. and V.8.

$$T_D = \frac{D_G T_G + D_T T_T}{D_G + D_T} \qquad \text{(VII.9)}$$

These variables are represented on figure VII.12 where:

T_D = temperature downstream at some point of interest, degrees Fahrenheit,

D_G = discharge of the groundwater, cfs; it is equal to the discharge at the point of interest less the discharge immediately below the silvicultural operation,

T_G = temperature groundwater, degrees Fahrenheit,

D_T = discharge immediately below the silvicultural operation, cfs, and

T_T = stream temperature below the silvicultural operation which is equal to the temperature above plus computed temperature increase or $T_A + \Delta T = T_T$, and where:

T_A = temperature stream above the treated area (measured in field), and

ΔT = temperature increase computed using Brown's model.

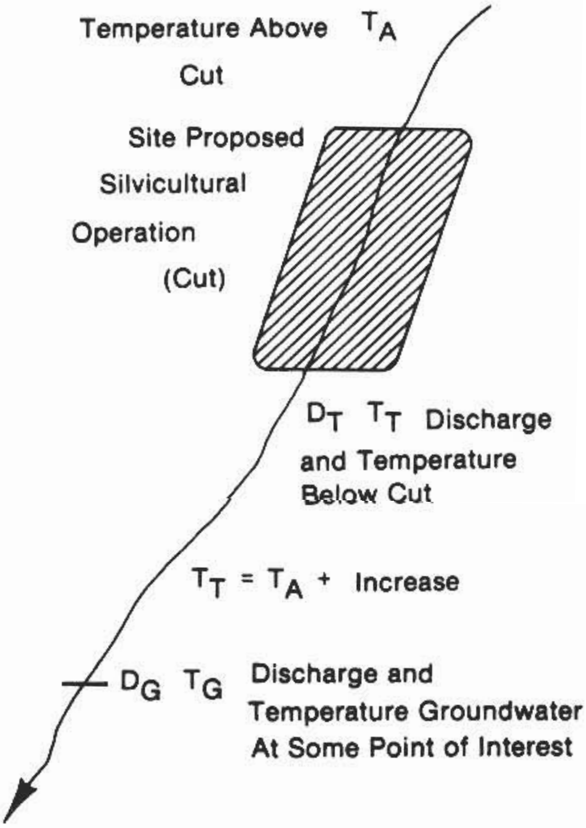


Figure VII.12.—Components of the mixing formula for evaluating the impact of ground water temperature and inflow on reducing temperature increases due to silvicultural activities upstream.

APPLICATIONS, LIMITATIONS, AND PRECAUTIONS

1. Application of the model should be limited to stream sections of less than 2,000 feet in length. Beyond this distance, evaporative and convective energy losses, assumed to be negligible in the simplified model, become important sources of dissipation.
2. Accurate measurement of data is critical.
   a. It is essential to measure the average width of flowing water when stream temperature is critical (i.e., during the summer months). Streambed or water surface width should not be used for computing average width of flowing water if any exposed rocks, gravel bars, or pools are present in the cross section; to do so would result in computed maximum temperatures in excess of actual values.
   b. Discharge should be measured whenever possible and should represent the mean discharge through the exposed reach of stream. If there will be no increase in discharge during the critical summer period following the silvicultural activity, the discharge measured before the activity may be used. However, if the silvicultural activity will result in increased discharges during the summer, all calculations must be based upon the post-silvicultural activity discharge. ("Chapter III: Hydrology" can be used to estimate the discharge during the critical summer period.)
   c. Shading, both vegetative and topographic, must be determined as accurately as possible. Angular canopy density measurements should be taken to estimate vegetative shading. All shading is important. Understory noncommercial trees, brush, and low shrubs may be more significant for shading purposes than commercial timber. Assuming the stream is completely shaded at all times is probably erroneous and will result in estimated temperature increases far above actual increases.
   d. The proportion of the exposed streambed composed of bedrock must be estimated in order to account accurately for the heat sink.
3. Small streams with braided flows require more accurate field measurements of stream width than larger, single channel streams.
4. The capacity of a stream for absorbing heat is limited. As stream temperature approaches air temperature, equilibrium will be reached.
5. The model does not consider inflowing cool ground water. Such a consideration could significantly reduce the maximum temperature increase predicted by the model. If inflowing ground water could alter the temperature increase, its impact can be evaluated by using a mixing formula (eq. VII.9).

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APPENDIX VII.A:

VALIDATION OF BROWN'S MODEL

Brown developed and verified his model in the West, and utilization by western forest hydrologists has had good results.

To determine its national applicability, a very limited validation of the model was conducted in the East using two treated, clear-cut watersheds (Watersheds 3 and 7) and a control (Watershed 4) on the Fernow Experimental Watershed, Parsons, West Virginia.

The field data collected from Watersheds 3 and 7 consisted of the length and width of the exposed stream reach following treatment, discharge, and percent bedrock in streambed. In addition, the actual water temperature was recorded so that the estimated water temperature increase, computed using Brown's model, could be compared with the actual increase. Water temperature of the control watershed was also measured and was used to approximate the water temperature of the treated watersheds before treatment.

Using Brown's model, initial estimations of the water temperature increases following treatment were +6° F to +10° F higher than the actual measured values. It was determined that the average stream width, not the average width of flowing water, was measured. When the average width of flowing water was measured Brown's model estimated within +1° F to +3° F of the actual water temperature increase, table VII.A.1. No data were available to estimate the amount of streamside vegetative shading and, therefore, the estimated values would tend to be high.

Table VII.A.1.—Summation of validation test using data (°F) from Fernow Experimental Watershed, Parsons, West Virginia

Watershed/ treatment	Estimated temperature using procedure presented	Measured temperature	Difference
	°F	*°F*	
3/clearcut	64	63	+1
7/clearcut	63	60	+3
4/control	---	58	---

This validation not only indicates that Brown's model is applicable for use in the East, but also reaffirms the importance of obtaining accurate field measurements. The model is only as accurate as the data that are used.

Actual computations for the two treated watersheds follow:

Watershed 3, Clearcut

L = 2,336 ft

W = 1.35 ft (average width flowing water)

[Initial width used was 3.30 ft but this was the average width of the stream.]

A = LW = 2,336 ft × 1.35 ft = 3,154 ft^2

Latitude = 39°

Maximum water temperature occurs on August 28

Maximum Solar Angle = 60° on August 28

Bedrock = 20% Correction Factor = 0.95

H = 4 BTU/ft^2–min

$H_{adjusted}$ = H × Bedrock Correction Factor
= 4 BTU/ft^2 × 0.95
= 3.8 BTU/ft^2–min

Q = 0.53 ft^3/s

$$\Delta T = \frac{A\,H_{adjusted}}{Q}\,0.000267$$

$$= \frac{3{,}154ft^2\ (3.8\ BTU/ft^2 - min)}{0.53\ ft^3/s}\,0.000267$$

$$= 6°\ F$$

Water temperature = 58° F for Control Watershed 4 (not cut)

Control temperature + ΔT = Estimated water temperature of clearcut

58° F + 6° F = 64° F

Estimated temperature = 64° F[1]

Measured temperature = 63° F for Watershed 3

[1] *No information on shading brush; therefore estimated increase may be high.*

Watershed 7, Clearcut

L = 2,380 ft

W = 1.80 ft (average width flowing water)
[Initial width used was 2.60 ft, but this was the average width of the stream.]

A = LW = 2,380 ft = 2,380 ft (1.80 ft)
= 4,284 ft^2

Latitude = 39°
Maximum water temperature occurs on August 28.

Maximum Solar Angle = 60° on August 28

Bedrock = 25% Correction Factor = 0.95

H = 4 BTU/ft^2-min

$H_{adjusted}$ = H(Bedrock Correction Factor)
= 4 (0.95) = 3.8 BTU/ft^2-min

Q = 0.83 ft^3/s

$$\Delta T = \frac{A\,H_{adjusted}}{Q}\,0.000267$$

$$= \frac{4{,}284ft^2\ (3.8\ BTU/ft^2 - min)}{0.83\ ft^3/s}\,0.000267$$

$$= 5°\ F$$

Water temperature = 58° F for Control Watershed 4 (not cut)

Control temperature + ΔT = Estimated water temperature of clearcut

58° F + 5° F = 63° F

Estimated temperature = 63° F[2]

Measured temperature = 60° F for Watershed 7

[2]*No information of shading brush; therefore, estimated increase may be high.*

APPENDIX VII.B:

STREAMSIDE SHADING

Research conducted throughout the country has demonstrated that removal of commercial and noncommercial streamside vegetation will result in increased water temperatures due to increased exposure of the water surface to direct radiation. Using Brown's model, the magnitude of the temperature increase varies with the proportion of stream exposed.

Maximum increases are associated with clearcutting in the streamside area. The increases reported range from a few degrees to 28° F, depending upon the area and discharge of the streams affected (Eschner and Larmoyeux 1963, Meehan and others 1969, Brown and Krygier 1970, Brown 1971, and Swift and Messer 1971). Water temperature can be maintained, however, if there is adequate shading of the water surface during periods of maximum solar radiation. Shading may be topographic, vegetative, or a combination of both.

TOPOGRAPHIC SHADING

Shading by topographic features includes not only the major land forms, but also the minor changes in relief associated with streambanks. The potential for topographic shading is determined partly by orientation of the stream with the sun, and partly by latitudinal location.

Orientation of topographic features in relation to stream and sun is crucial. Streams oriented east-west may be shaded in the morning by topographic features to the south. North-south oriented streams may be shaded in the morning by topographic features situated to the east, and to the west in the afternoon.

Latitudinal position of the stream influences the extent to which topography or surrounding vegetation may be effective because latitude determines solar angle. The path of the sun varies during the year from 23-½° N latitude (June 21) to 23-½° S latitude (December 22). When the solar angle is vertical, directly overhead, there is no possibility for topographic shading; as the angle decreases from the vertical, the probability and effectiveness of topographic shading are increased.

VEGETATIVE SHADING

Vegetative shading normally will be the dominant onsite factor controlling the amount of solar radiation directly striking the water surface. Shading is not limited to dominant and codominant tree species, but encompasses all vegetation to include brush, shrubs, and other low-growing species.

1. The effectiveness of the shade created will vary with vegetation type. The effect of type includes not only species differences but also age class. The proportion of tree bole in a live crown influences the extent of shade provided. Mature coniferous stands, with much of the lower bole free of limbs, may offer only partial shade; whereas younger stands, with most of the bole in live crown, will provide adequate shade for small headwater streams.
2. The density or spacing of vegetation also determines the amount of radiation the water receives. In poorly stocked stands with low density and crown closure, the trees may be so widely spaced as to preclude effective shading of the water course.
3. For a stream of a given width, the height of vegetation necessary to effectively shade a water course will vary with the distance from the stream and the solar angle and orientation. There is a direct relationship between distance from the stream and height of vegetation necessary to provide adequate shade (fig. VII.B.1).
4. For a stream of a given width, there is also a relationship between solar angle and height of vegetation needed to provide stream shading. When the solar angle is perpendicular to the stream surface (i.e., directly overhead), the only shading is that from vegetation overhanging the water; the height of riparian vegetation becomes irrelevant (fig. VII.B.2).
5. Orientation of the sun with respect to the stream determines the "effective" width of the stream versus the actual stream width. Effective width is the length of shadow required to reach completely across the stream. The actual width would equal the effective width only when the sun was oriented at right angles to the stream

Figure VII.B.1.—Low growing shrubs and brush adjacent to a water course may provide adequate shade, while taller vegetation is necessary further from the stream.

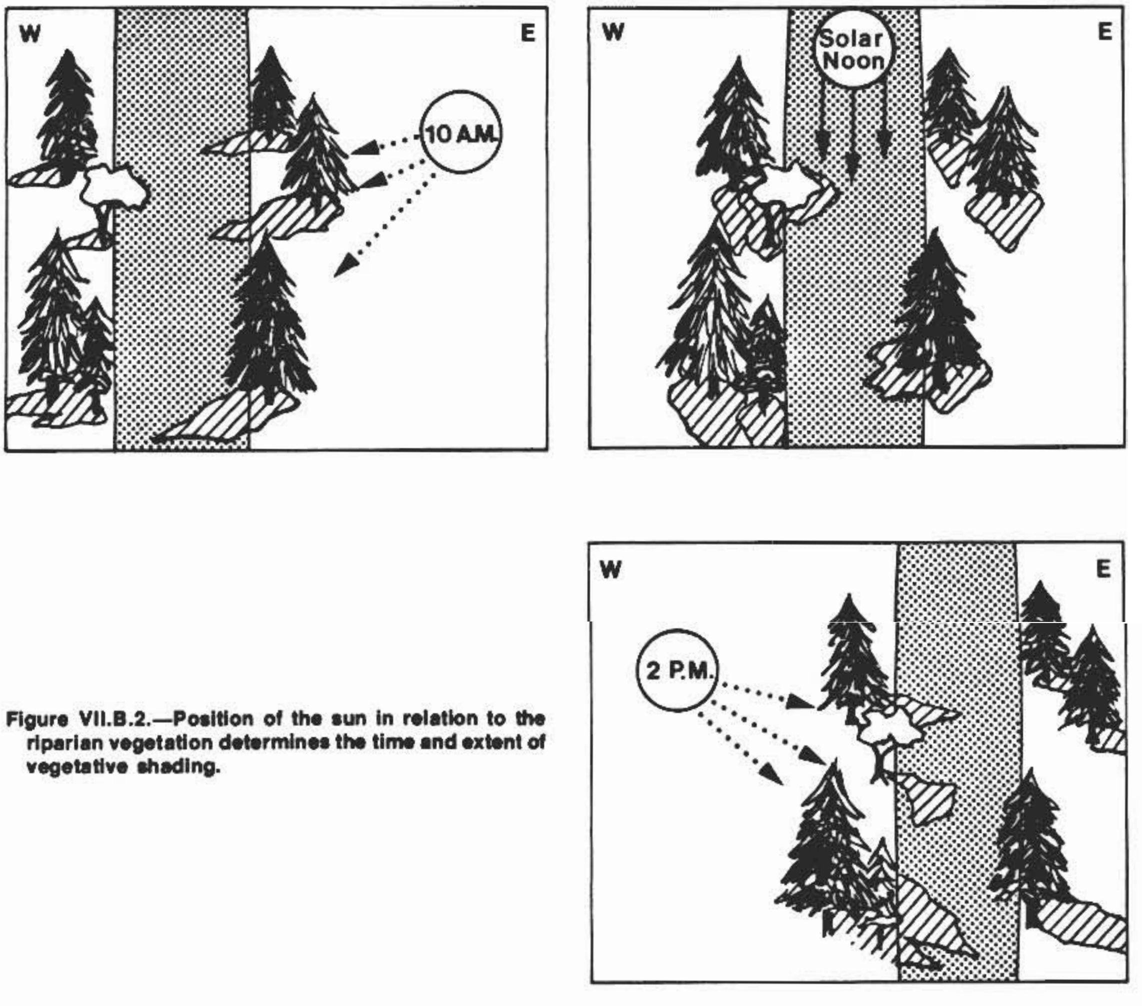

Figure VII.B.2.—Position of the sun in relation to the riparian vegetation determines the time and extent of vegetative shading.

(e.g., due east of a north-south flowing stream, fig. VII.B.3). At all other times the effective width would be greater than the actual stream width and would reach a maximum value (infinity) when the sun was directly above the stream.

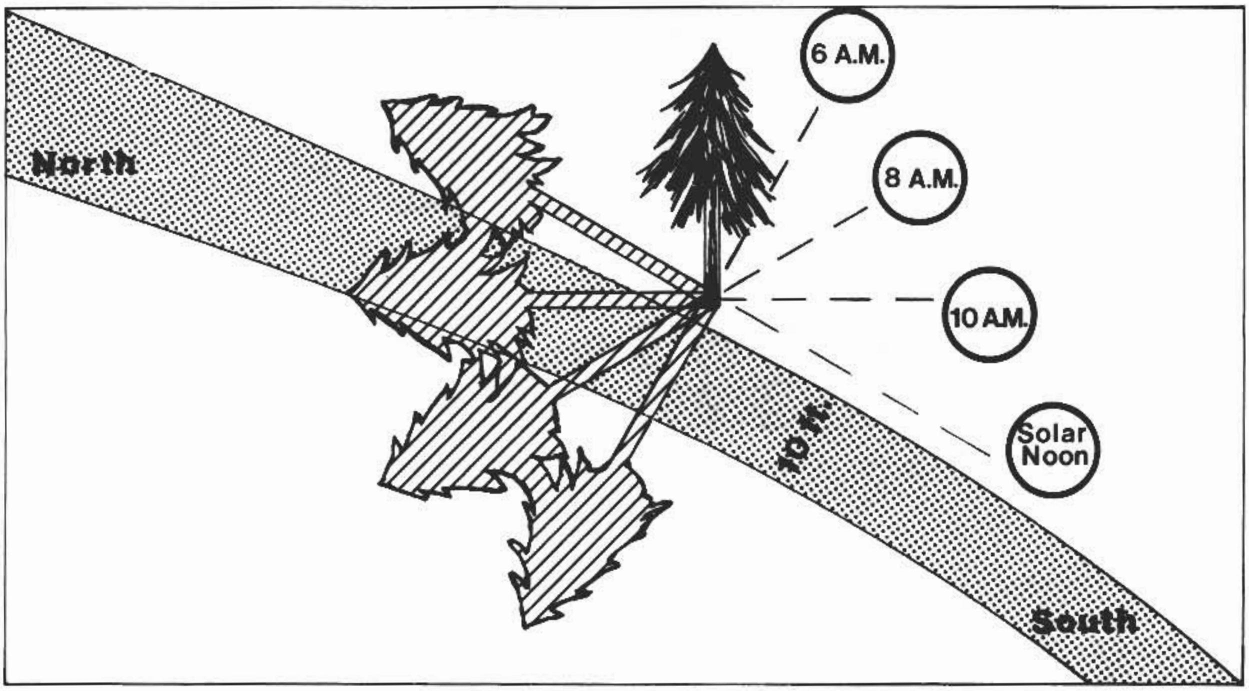

Figure VII.B.3.—Orientation of the sun with the stream determines the length of shadows necessary to completely shade the water surface.

APPENDIX VII.C:

WATERSIDE AREAS

Designation of waterside areas by land managers can be used to prevent or minimize water temperature increases. It is not feasible to establish general standards for waterside areas; however, Brazier and Brown (1973) have evaluated some of the factors that determine the effectiveness of such areas.

COMMERCIAL TIMBER VOLUME

Commercial timber volume is not a significant parameter for determining shading of the stream by the vegetation in the waterside area. Due to the relatively narrow width of the headwater (1st, 2nd, and 3rd order) streams, the effectiveness of the shade produced by noncommercial tree species, shrubs and low growing vegetation can be as great as that produced by commercial species. In addition, there is a great variability between volume (board feet) and crown closure (density) which is manifested in the spacing and number of trees per unit of area. A few large trees with a large commercial volume may have little protective capability because of wide spacing, or because crowns may be too high or sparse to shade the streams. Many pole-sized trees with a smaller commercial volume may effectively shade the stream due to their close spacing and dense canopy.

STRIP WIDTH

In the past, land managers have arbitrarily designated waterside areas according to such factors as width (which has ranged from less than 50 feet to several hundred feet), topography, or percent slope. Strip width alone is not an important factor in determining effectiveness of the vegetation in shading the stream. Strip width is critical for stream protection only as it is related to canopy density, canopy height and stream width (fig. VII.C.1).

Canopy densities of less than about 15 percent angular canopy density (ACD) do not provide sufficient shade for a measurable reduction in heat load. Above this value, however, there should be a

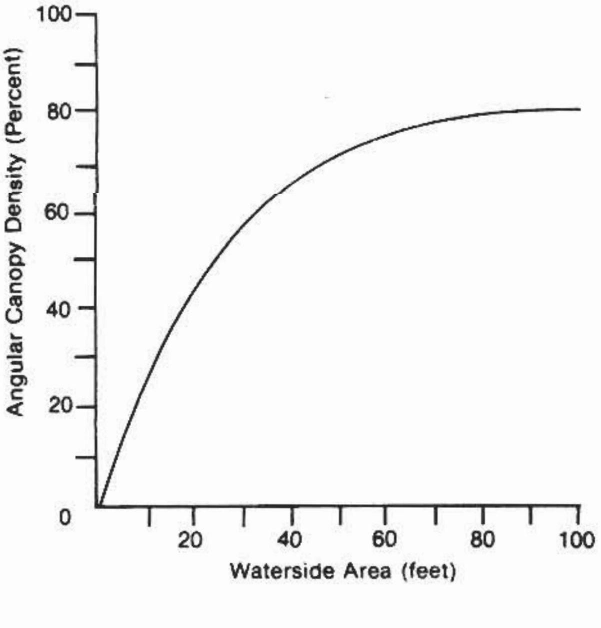

Figure VII.C.1.—The relation between waterside area width and angular canopy density (Brazier and Brown 1973)

direct relationship between heat reduction and angular canopy density until the canopy approaches 100 percent ACD. As the density approaches 100 percent, additional increments in density should block less radiation than the previous increment. Therefore, with greater canopy density, the relationship between the amount of heat blocked and the angular canopy density should approach some maximum value at a level less than complete blockage of all incidental radiation (fig. VII.C.2).

When the angular canopy density is not known or cannot be measured, stream shading may be estimated using a clinometer or abney level to identify those crowns which contribute shade to the stream. Vertical crown closure values can be used to obtain a rough estimate of stream shading, but it should be noted that angular canopy density and vertical crown closure are normally significantly different. The importance of obtaining accurate measurements of stream shading cannot be overemphasized; it is the basis for establishing effective waterside area widths to protect the stream from excessive temperature increases.

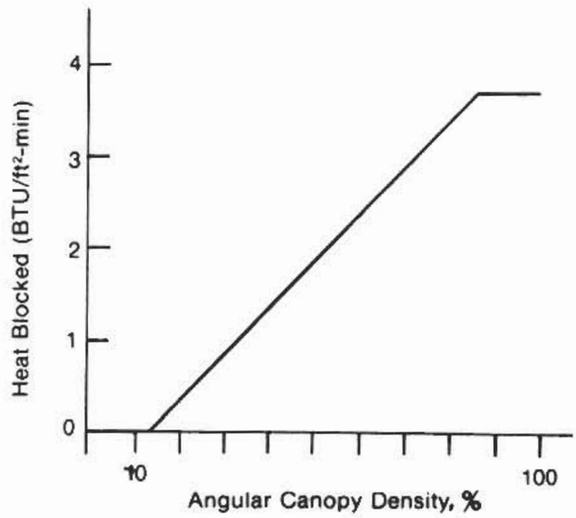

Figure VII.C.2.—The relation between angular canopy density (ACD) and heat blocked (ΔH) (Brazier and Brown 1973).

APPENDIX VII.D:

GENERAL RELATIONSHIPS BETWEEN LIGHT INTENSITY OR TRANSMISSION OF SOLAR RADIATION AND VEGETATIVE COVER

Table VII.D.1.—Effects of stand density removal on light intensity (%) (USDA For. Serv.)

Quantity removed	Percent Fully stocked stand removed	Light intensity
Stem density	0	8
	25	14
	50	26
	[1]75	[1]55
Canopy closure	0	4
	25	6
	50	16
	75	43
Basal area	0	10
	25	15
	50	27
	75	52

[1]Example: Removing 75 percent of the stems would increase the light intensity from 8 percent to 55 percent.

Table VII.D.2.—Effects of tree spacing (ft) on light intensities (%) (USDA, For. Serv.)

Spacing (ft)	Trees (number/ac)	Light intensity
4 × 4	2,721	15
6 × 6	[1]1,210	[1]16
7 × 7	889	36
9 × 9	538	60

[1]Example: By removing slightly less than half the trees (538) from a 6 × 6 foot spacing (1,210) increases the light intensity from 16 percent to 60 percent.

Table VII.D.3.—Percent light intensity through small-[1] and large-[2] crown trees (Reifsnyder and Lull 1965)

Stem density (in/ac)	Basal area (ft/ac)	Percent of small-crowned trees 0-33	34-67	68-100
		Percent light intensity		
200	20	87	90	94
700	60	57	70	78
1,200	100	34	50	63
1,900	180	13	30	43
3,700	400	7	10	12

[1]Small—western white pine, western larch, and Douglas-fir.
[2]Large—grand fir, western hemlock, and western red cedar.

Table VII.D.4.—Percent light intensity through eastern conifers (Reifsnyder and Lull1965)

Species	Basal area (ft^2/ac)	Light intensity
White pine, balsam fir	209	7
White pine, white spruce, balsam fir	171	9
White pine, red pine	103	27
White, red, jack pine, white spruce, balsam fir	103	25

Table VII.D.5.—Percent light intensity through conifer plantations (Reifsnyder and Lull 1965)

Spacing (ft)	Light in open
2 × 2	15.9
4 × 4	36.0
6 × 6	46.6
8 × 8	55.4

Table VII.D.6.—Stand basal area (ft^2/a) and equivalent solar loading (BTU/ft^2−min) beneath the canopy (Hughes 1976, personal communication)

Solar loading % of open	Total stand basal area Dense crown[1]	Moderate crown[2]
10	255	400
15	200	305
20	160	245
25	135	210
30	120	180
35	105	160
40	90	140
45	80	120
50	70	105
55	60	90
60	55	80
65	45	70
70	35	55
75	30	45
80	25	35
85	20	30
90	10	20
95	5	10
100	0	0

[1]Dense crown includes normally stocked stands of western hemlock, western redcedar, Sitka spruce, Pacific silver fir, and uneven aged mixed stands. Also overstocked hardwood stands.
[2]Moderate crown includes even aged Douglas-fir stands, and normally stocked red alder or black cottonwood.

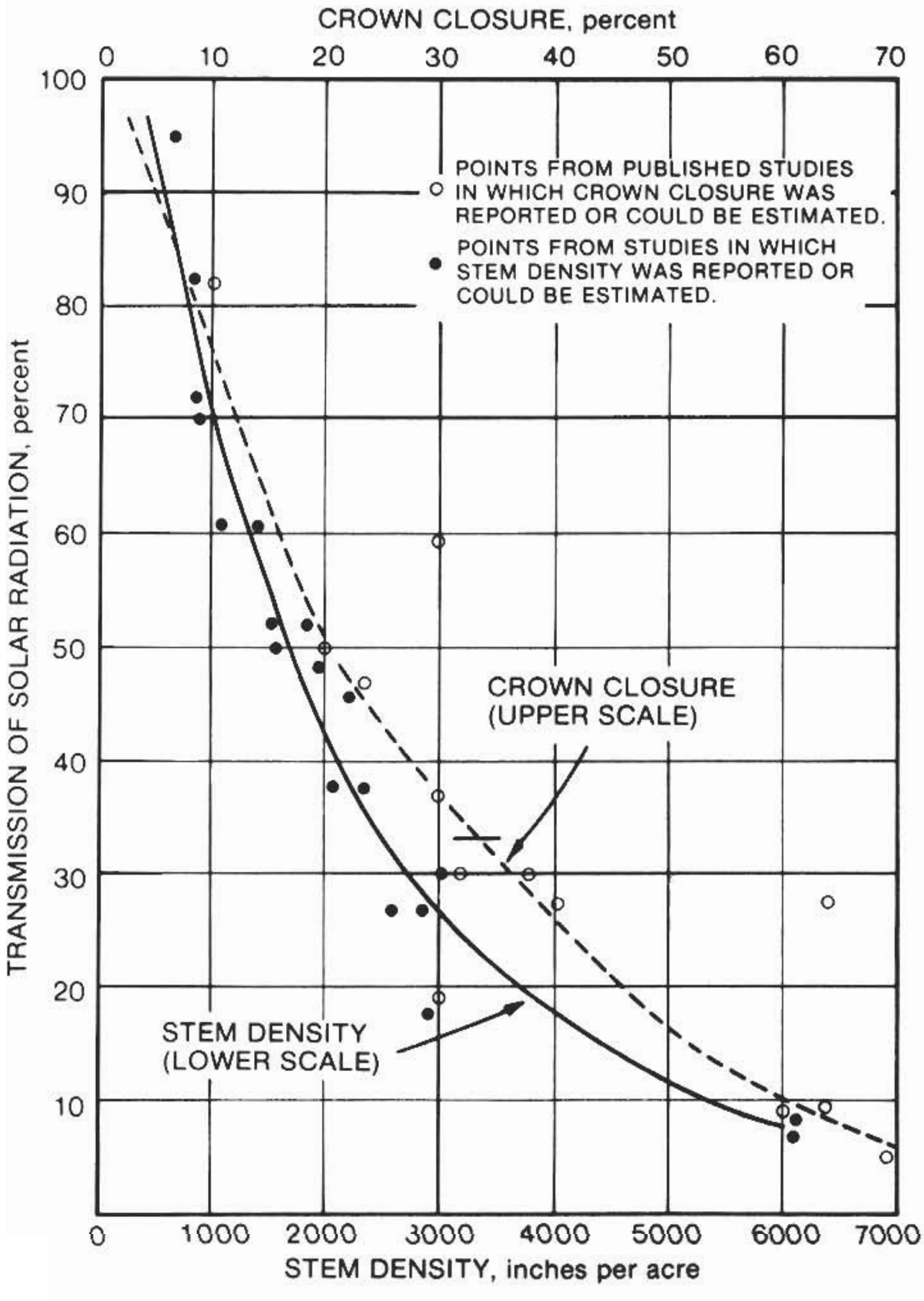

Figure VII.D.1. Transmission of solar radiation as a function of stem density and crown closure (Reifsnyder and Lull 1965).