Appendix C
Summary of Basic Physics Principles—Heat, Heat Transfer, and Thermal Properties of Water

C-1. Temperature

Table C-1 compares the temperature scales for the three conventions used for snow hydrology fundamentals.

Table C-1
Comparison of Temperature Scales

	Celsius °C	Fahrenheit °F	Kelvin K
Melting point of ice	0	32	273
Boiling point of water	100	212	373
Divisions between fixed points	100	180	100

Conversion formulas: $^\circ F = \frac{9}{5} {}^\circ C + 32$

$$^\circ C = \frac{5}{9}(^\circ F - 32)$$

$$K = {}^\circ C + 273$$

C-2. Heat Energy

In older literature, heat quantity was expressed in terms of calories, where

one g-cal = heat required to raise 1 g of water 1 °C, from 15 to 16 °C

In expressing mechanical energy, the convention in the metric system is to use Joules or ergs (1 erg = 10^{7}J). Recognizing that heat is a form of energy, the calorie is now defined in terms of the joule. A joule is a unit of work energy equal to a newton-meter. A watt, a unit of power, is equal to one joule per second. By international agreement

1 g-cal = 4.186 J

In hydrology and meteorological practice, the term kilo-Joule is used

1 kg-cal = 4.186 kJ

Table C-2 summarizes the equivalents of energy/work for several contemporary and older standards of units.

Table C-2
Units of Energy and Work

	J	kcal	kWh	Btu	ft-lb
1 J =	1	239×10^{-6}	277.8×10^{-9}	948.4×10^{-6}	0.7376
1 kcal =	4186	1	1.163×10^{-3}	3.968	3.087×10^{3}
1 kWh =	3.6×10^{6}	860	1	3413	2.655×10^{6}
1 Btu =	1055	0.252	293×10^{-6}	1	778.6
1 ft-lb =	1.356	324×10^{-6}	376.8×10^{-9}	1.286×10^{-3}	1

Note: J = Joule (1 Joule = 1 watt-second); kcal = 1000 calories; kWh = kilowatt-hour; Btu = British Thermal Unit; ft-lb = foot-pound.

C-3. Heat Capacity, Specific Heat

The ratio of heat supplied a material to the corresponding temperature rise is called the heat capacity.

$$\text{Heat Capacity} = \frac{Q}{\Delta t}$$

To obtain a figure that is characteristic of the material of which the body is composed, the specific heat of a material is used. This is defined as heat capacity per unit mass

$$C_p = \frac{\text{heat capacity}}{\text{mass}} = \frac{Q}{m\Delta t}$$

where C_p equals the specific heat, commonly expressed in kJ/(kg K) or cal/(g °C).

Table C-3 lists specific heats for substances common to snow hydrology.

Table C-3
Common Specific Heats

Substance	kJ/(kg K)	cal/(g·°C)
Water, 0 °C	4.217	1.01
Water, 20 °C	4.182	1.00
Ice	2.09	0.55
Air, dry, 20 °C	1.007	0.24
Sat. water vapor, 0 °C	1.864	0.46

Table C-4
Latent Heats for Water

	kJ/kg	cal/g
Melt (fusion)	333.5	79.5
Condensation (vaporization), 0 °C	2500	597.3
Condensation (vaporization), 10 °C	2477	591.7
Condensation (vaporization), 20 °C	2453	586.0
Sublimation, 0 °C	2834	677.0
Sublimation, -30°C	2839	678.2

C-4. Change in Phase, Latent Heat

The amount of heat absorbed (or given off) by a mass of material as it undergoes a change in phase (solid to liquid to gas, or reverse) is called the latent heat. The phase change involved occurs without a change in the temperature of the material itself. To compute the heat requirement for a phase change:

$$Q = mL$$

where

Q = heat energy, kJ (or cal)

m = mass, kg (g)

L = latent heat, kJ/kg (or cal/g)

a. Water and other substances can undergo a direct phase change from solid to gas when conditions are favorable (a function of temperature and pressure). This is called sublimation.

b. The common use in snow hydrology is for phase changes of water as it condenses from vapor to liquid, or as it melts from solid to liquid form. The latent heat quantities for these phase changes are given in Table C-4.

C-5. Heat Transfer

a. Conduction. Transfer of heat within a solid body by molecular activity because of a differential in temperature in the body is called heat conduction. This phenomenon is encountered in snow hydrology when snowmelt caused by heat conducted from the ground is considered. The measure of a material's ability to conduct heat is given by its coefficient of thermal conductivity, k. Thus, heat transferred is given by

$$Q = kA\,\frac{dT}{dx}$$

where

Q = heat flux

k = coefficient of thermal conductivity, commonly expressed as kW/(m K)

A = cross-section area

dT/dx = temperature gradient

Table C-5 gives values of k for some common substances

Table C-5
Coefficients of Thermal Conductivity

Substance	kW/(m·K)
Ice	2.3×10^{-3}
Limestone	2.2×10^{-3}
Peat	0.08×10^{-3}
Silt and clay	$0.4\text{-}2.1 \times 10^{-3}$
Sandy soils	$0.25\text{-}3 \times 10^{-3}$
Wood	$0.15\text{-}0.20 \times 10^{-3}$
Air	2.3×10^{-5}

b. Convection. This term is applied to heat transfer in a fluid through the movement of the fluid, brought about by natural or induced pressure or density differences. An example of natural convection would be the overturning of a lake as cold air cools the surface layer of the water. In snow hydrology, convection heat transfer is one of the processes by which heat is transmitted through the air to the snow surface. In this case, the air movement is induced by the wind, and the mathematical representation of the phenomenon is based upon equations for turbulent exchange.

c. Radiation. Radiation energy exchange refers to the continual emission of energy, which occurs from all bodies, in the form of electromagnetic waves. When they fall on a body that is not transparent to them, they are absorbed and their energy is converted to heat. The radiant energy emitted by the surface depends upon the nature of the surface and on its temperature. At low temperatures, the rate of radiation is small, but as the temperature of the emitter is increased, the radiation intensity increases very rapidly, in proportion to the 4th power of the absolute temperature of the body. The maximum amount of radiation for a given temperature is called the blackbody radiation. A body that radiates at the maximum intensity for every wavelength at the given temperature is called a blackbody. This term applies regardless of the literal color of the body; the sun is a perfect blackbody, and the surface of snow is nearly so.

(1) The radiant energy is emitted in a mixture of different wavelengths, which can be expressed in the form of a continuous spectral distribution. As the temperature of the emitter increases, there is a general decrease in the wavelength of the maximum intensity. A general equation expressing the energy emitted by a blackbody to the wavelength and temperature was derived by Max Planck in 1900. The total blackbody radiation over all wavelengths at a given temperature is measured by the area under a Planck curve for that temperature. This integration, known as the Stefan-Boltzmann law, yields the equation

$$E = \sigma T^4$$

where σ, the Stefan-Boltzmann constant = 5.7×10^{-11} kJ/(m^2 s K^4)

(2) This relationship is used directly in equations for snowmelt, both attributable to solar radiation and from the surface of the snow as a long-wave radiation. Discussion of solar radiation is continued further in Appendix D.