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Techniques of Water-Resources Investigations
of the United States Geological Survey

CHAPTER D1

WATER TEMPERATURE—INFLUENTIAL FACTORS, FIELD MEASUREMENT, AND DATA PRESENTATION

By Herbert H. Stevens, Jr., John F. Ficke,
and George F. Smoot

BOOK 1

COLLECTION OF WATER DATA BY DIRECT MEASUREMENT

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, Secretary

GEOLOGICAL SURVEY

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PREFACE

The Department of the Interior has a basic responsibility for the appraisal, conservation, and efficient utilization of the Nation's natural resources, including water as a resource, as well as water involved in the use and development of other resources. As one of the several Interior agencies, the U.S. Geological Survey's primary function in relation to water is to assess its availability and utility as a national resource for all uses. The U.S. Geological Survey's responsibility for water appraisal includes not only assessments of the location, quantity, and availability of water but also determinations of water quality. Inherent in this responsibility is the need for extensive water-quality studies related to the physical, chemical, and biological adequacy of natural and developed surface- and ground-water supplies. Included, also, is the need for supporting research to increase the effectiveness of these studies.

As part of its mission the Geological Survey is responsible for a large part of water-quality data for rivers, lakes, and ground water that is used by planners, developers, water-quality managers, and pollution-control agencies. A high degree of reliability and standardization of these data is paramount. This manual was prepared to provide accurate and precise procedures for the field measurement of water temperature.

The series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called books and is further subdivided into sections and chapters. Book 1 is on the collection of water data by direct measurement. Section D is on water quality.

The unit of publication, the chapter, is limited to a narrow field of subject matter. This format permits flexibility in revision and publication as the need arises. "Water Temperature—Influential Factors, Field Measurement, and Data Presentation" is the first chapter to be published under Section D of Book 1. The chapter number includes the letter of the section.

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WATER TEMPERATURE—INFLUENTIAL FACTORS, FIELD MEASUREMENT, AND DATA PRESENTATION

By Herbert H. Stevens, Jr., John F. Ficke, and George F. Smoot

Abstract

This manual contains suggested procedures for collecting and reporting of water-temperature data on streams, lakes and reservoirs, estuaries, and ground water. Among the topics discussed are the selection of equipment and measuring sites, objectives and accuracy of measurements, and data processing and presentation. Background information on the influence of temperature on water quality and the factors influencing water temperature are also presented.

Introduction

The growing importance of water temperature in water-quality control has increased the necessity and demand for water-temperature data. A large amount of water-temperature data has been and is currently being collected in the United States (Pauszek, 1972). There is great concern, however, regarding the accuracy of the data collected and how well the data document variations in the temperature regimen. Nonrepresentative water-temperature data can lead to erroneous assumptions about the extent of thermal alterations to the environment caused by the activities of man and by natural phenomena. The purpose of this manual on water temperature is (1) to present the influential factors of temperature on water quality and the factors that influence water temperature, (2) to describe suitable instrumentation for water-temperature measurement and to suggest procedures for the collection of water-temperature data, and (3) to suggest procedures for the processing and reporting of water-temperature data. Part 1 will be of most interest to water managers and those designing a water-temperature data-collection network, whereas parts 2 and 3 are important to those active in data collection so that the data will be truly representative.

Remote thermal-infrared sensing can provide information on heat radiation along lines and over areas from both land and water surfaces. Such information can aid in the understanding of thermal budgets and (or) the hydrodynamic behavior of water bodies. For instance, features that have been observed from thermal-infrared imagery include wind streaks, thermal bars, plungings and upwellings, pulses of discharge into low-velocity water, flow lines, ground-water seeps, and boundaries between water masses. The application of remote sensing to the measurement of water temperature is not covered in this report and will be detailed in a future manual.

The authors extend thanks to A. F. Moench for his contribution of the sections on ground water.

Purposes of water-temperature measurements

Water-temperature measurements are essential to determine the utility of water and the effects that water uses have on temperature, and they have many applications in ground-water hydrology.

Water use and stream standards

Water temperature is an important factor of the utility of water. It has a direct influence on the quality of water for domestic supplies, fish and wildlife culture, assimilation of wastes, and industrial and agricultural uses.

Domestic water below 10°C (Celsius) is considered to be satisfactory for drinking. Chemical and biochemical reactions induced at higher temperatures produce undesirable tastes and odors in water. For water treatment, however, flocculation and sedimentation rates increase, and the effect of chlorine on bacteria are greater at higher water temperatures.

Large increases in water temperature will cause rapid fish death, and moderate increases in water temperature will cause slow fish death by increasing their metabolic rates and oxygen requirements and by decreasing their resistance to disease and toxic substances.

For water purification, temperature affects the concentration of dissolved oxygen and the rate of BOD (biochemical oxygen demand).

Temperature affects the usefulness of water for industrial processing or cooling. In agriculture, excessively high or low irrigation-water temperatures may affect crop growth and yields.

Many uses of water degrade water quality and alter its temperature in the proocess. The release of bottom water from stratified artificial impoundments will decrease the downstream water temperatures, whereas the discharge of industrial wastes and cooling waters, the return of irrigation water, and similar recycling processes usually increase the temperature of receiving waters. The return of warm water to aquifers has been known to increase ground-water temperatures by 20°C (McKee and Wolf, 1963) and to significantly alter the ground-water hydrology. The most significant addition of man-made heat into waterways is from thermal-electric power-generating plants. The Water Resources Council (1968) stated that roughly 10 percent of the total flow of waters in United States' rivers and streams is withdrawn for the production and condensation of steam and that water temperatures of the affected streams are raised an average of 8°C.

State and interstate water-pollution-control agencies have established restrictions on temperature or allowable temperature increases. The standards are related to the reasonable and necessary use of waters in the public interest. The National Committee on Water Quality Criteria (U.S. Environmental Protection Agency, 1973) presented comprehensive water-quality criteria for the various beneficial uses of water. In order to meet these criteria, practical procedures must be developed to adjust and control water temperatures. However, more knowledge of the effect that water uses have on water temperature and knowledge of the natural controls on water temperature is needed.

Applications in ground-water hydrology

Purposes for which ground-water-temperature measurements may be made range from quality considerations for domestic, municipal, and industrial uses to problem solving in geology and hydrology. Ground-water-temperature data may be used to study rates and directions of ground-water movement, identify areas of recharge and discharge and zones of leakage around dams and dikes, evaluate aquifer parameters, locate geologic features, monitor the movement of ground-water pollutants, and prospect for and evaluate geothermal resources. In addition, temperature data can be used in modeling ground-water-flow systems. As this manual is limited in scope, measurements made in the soil, atmosphere, or unsaturated zone of the aquifer are not discussed, even though these may have direct application to problems of ground-water hydrology.

Making quantitative estimates of ground-water flow from temperature data was considered from a theoretical standpoint by Stallman (1960, 1963). He presented a partial differential equation for the simultaneous flow of water and heat through saturated porous materials. Bredehoeft and Papadopulos (1965) solved this equation for the steady-state problem in one dimension and presented type curves that, when matched with the data of temperature versus depth from a well, allow the rate of vertical ground-water flow to be calculated. The basis of this method is the fact that vertically moving ground water will distort the normal geothermal gradient. Using a modification of this theory to increase the sensitivity of the matching technique, Stallman (1967) and Sorey (1971) applied the method in the field to obtain values of the rates of water movement through semiconfining beds which were in good agreement with those determined by independent methods. The same theory was applied by Cartwright (1970) to estimate the quantity and location of water discharged from the Illinois basin each year.

Stallman and Sammel (1972) showed how under special conditions it may be possible to evaluate ground-water velocities, aquifer transmissivity, and vertical hydraulic conductivity from profiles of temperature and gradient of head. Numerical methods for solutions to the general differential equation describing the simultaneous flow of water and heat in porous media and their application to ground-water-flow modeling are given by Supkow (1971).

Birch (1947) studied the vertical circulation of ground water by measuring the temperature profile in a well near Colorado Springs, Colo. Schneider (1964) used the temperature of a number of discharging wells to evaluate flow characteristics of carbonate-rock aquifers in Israel. In a similar manner, Feder (1973) used temperature measurements in wells and springs to determine the extent of vertical circulation of ground water in the carbonate-rock aquifers of Missouri.

Another application of ground-water-temperature measurements is to monitor man-caused changes in the ground-water environment, such as those caused by the injection of radioactive or other heat-producing waste materials. Davis and De Wiest (1966) pointed out that temperature logs of wells could be used to locate gas leaks and cemented zones.

The usefulness of temperature logging in wells for evaluating uphole and downhole water movement has been described by Tait (1972). Trainer (1968) used temperature measurements in wells to locate bedrock fractures, and Lovering and Morris (1965) were able to relate geologic structures to ground-water temperatures.

Ground-water-temperature measurements are presently being made to aid in prospecting for geothermal resources (F. H. Olmstead, written commun., 1973).

Temperature scales and units of measurements

The three temperature scales used in the United States for measuring water temperatures are the Fahrenheit (°F), Celsius or centigrade (°C), and kelvin (K) scales. These scales are all based on one primary reference point, which represents the temperature of melting ice at standard atmospheric pressure. For the various scales, this point is assigned the numerical value of 32°F, 0°C, and 273.15 K, respectively. The value of 273.15 K is set to make the scale an absolute thermodynamic scale. The temperature interval between the primary reference point and a secondary reference point, which is the temperature of boiling water at standard atmospheric pressure, is divided into 180 Fahrenheit degrees, 100 Celsius degrees, and 100 kelvins (Besancon, 1966; Weast and Selby, 1966).

In concurrence with the trend for using metric units, the U.S. Geological Survey has adopted the Celsius scale. Although the name centigrade is commonly used for this scale, which was invented in 1742 by Anders Celsius, the name Celsius is preferred. This editorial policy, which is observed also by the National Bureau of Standards, is in accord with the recommendation of the Eleventh General Conference (1960) on Weights and Measures, represented by 33 nations that subscribed to the Treaty of the Metre. The principal reasons for preference of Celsius are twofold—(1) with reference to the kelvin thermodynamics scale, the term "centigrade" is not truly accurate, and (2) in French technical literature, the term "centigrade" is applied to the divisions of a quadrant of a circle (Stimson, 1962). The kelvin scale, or centigrade absolute, was originated by Lord Kelvin. The zero point of the kelvin scale (-273.15°C) is the temperature at which all the thermal motion of the atom stops. The kelvin scale is specific as the preferred scale in the International Systems of Units (SI) adopted by the Eleventh General Conference on Weights and Measures (Mechtly, 1969).

The following formulas may be used to convert a temperature reading from one scale to another:

$$C = (5/9)(F - 32), \quad (1)$$
$$C = K - 273.15, \quad (2)$$
$$F = (9/5)C + 32, \quad (3)$$
$$F = (9/5)K - 459.67, \quad (4)$$
$$K = C + 273.15, \text{ and} \quad (5)$$
$$K = (5/9)(F + 459.67) \quad (6)$$

where

C is the temperature in °C,
F is the temperature in °F, and
K is the temperature in kelvins.

The conversion between Celsius and Fahrenheit to the nearest 0.5 degree is shown in table 1.

Part 1. Influential Factors

The significance of temperature in the field of water-quality control necessitates an understanding of the various processes and phenomena that control the temperature of water in streams and lakes and in the ground. Probably the most obvious of these is the climatic factor. Lakes and streams in northern latitudes obviously are colder, stay frozen longer, and do not get as warm as do the waters in the subtropical areas. However, there are factors other than the climate affecting temperature of water. These include the physical characteristics of the water itself, which are different from the physical characteristics of soil, rock, or air, the mixing processes, location on the face of the Earth or within the Earth, and other phenomena.

The following paragraphs deal in some detail with the influence of temperature on water quality and the factors influencing water temperature.

Influence on water quality

Temperature is recognized as one of the most important factors in the field of water-quality control. It influences almost every physical property of water and every physical process that takes place in water, most chemical reactions in water, and, most importantly, all biologic organisms in the aquatic community.

Physical

The physical properties of concern in the field of water quality include density, specific heat, latent heats of fusion and of vaporization, viscosity, vapor pressure, surface tension, gas solubility, and gas diffusibility (Parker and Krenkel, 1969; U.S. Federal Water Pollution Control Administration, 1968). The variation in several properties with temperature for freshwater are shown in table 2. These physical properties, in turn, influence stratification, evaporation, velocity of settling particles, and the content and rate of replacement of dissolved oxygen.

In studying the role of temperature of water in nature, density probably is more important than any other temperature-related physical factor. For convenience, the density of water is usually said to be 1.0 g/ml (gram per millilitre). However, as shown in both table 2 and figure 1, it varies a measurable and significant amount. Maximum density is 1.000000 g/ml at 3.94°C. At 0°C (freezing temperature) it is 0.9998679 g/ml. It is significant that the curve shown in figure 1 increases in slope at temperature above maximum density. This means that the difference in density between 20° and 30°C is much greater than the difference in density between 10° and 20°C.

Density of water also is affected by the compressibility factor, which is almost linear at the rate of 4.2×10^{-6} g/ml per metre of depth. As a result of compressibility, water at 11.6°C at 100 metres depth has the same density as water at 4°C at atmospheric pressure. At a depth of 100 metres water has its maximum density at a temperature of 3.82°C.

Thermal stratification, which is stratification induced by density differences between waters of different temperature, inhibits vertical mixing and oxygen transfer to lower areas of lakes and reservoirs.

Chemicals in solution also affect water density. The amount of density increase due to solution varies with the concentration and the chemical constituent. For example, water having sodium chloride (NaCl) in a concen-

Table 1.—Temperature conversion between Celsius and Fahrenheit to nearest 0.5°

[From Porterfield, 1972. The numbers in the center columns refer to temperatures, either in Celsius or Fahrenheit, which are to be converted to the other scale. If converting Fahrenheit to Celsius, the equivalent temperature will be found in the left columns. If converting Celsius to Fahrenheit, the equivalent temperature will be found in the right columns]

	0 to 24.5			25.0 to 49.5			50.0 to 74.5			75.0 to 100.0	
-18.0	0	32.0	-4.0	25.0	77.0	10.0	50.0	122.0	24.0	75.0	167.0
-17.5	.5	33.0	-3.5	25.5	78.0	10.5	50.5	123.0	24.0	75.5	168.0
-17.0	1.0	34.0	-3.5	26.0	79.0	10.5	51.0	124.0	24.5	76.0	169.0
-17.0	1.5	34.5	-3.0	26.5	80.0	11.0	51.5	124.5	25.0	76.5	170.0
-16.5	2.0	35.5	-3.0	27.0	80.5	11.0	52.0	125.5	25.0	77.0	170.5
-16.5	2.5	36.5	-2.5	27.5	81.5	11.5	52.5	126.5	25.0	77.5	171.5
-16.0	3.0	37.5	-2.0	28.0	82.5	11.5	53.0	127.5	25.5	78.0	172.5
-16.0	3.5	38.5	-2.0	28.5	83.5	12.0	53.5	128.5	26.0	78.5	173.0
-15.5	4.0	39.0	-1.5	29.0	84.0	12.0	54.0	129.0	26.0	79.0	174.0
-15.5	4.5	40.0	-1.5	29.5	85.0	12.5	54.5	130.0	26.5	79.5	175.0
-15.0	5.0	41.0	-1.0	30.0	86.0	13.0	55.0	131.0	26.5	80.0	176.0
-14.5	5.5	42.0	-1.0	30.5	87.0	13.0	55.5	132.0	27.0	80.5	177.0
-14.5	6.0	43.0	- .5	31.0	88.0	13.5	56.0	133.0	27.0	81.0	178.0
-14.0	6.5	43.5	- .5	31.5	88.5	13.5	56.5	134.0	27.5	81.5	179.0
-14.0	7.0	44.5	0	32.0	89.5	14.0	57.0	134.5	28.0	82.0	179.5
-13.5	7.5	45.5	.5	32.5	90.5	14.0	57.5	135.5	28.0	82.5	180.5
-13.5	8.0	46.5	.5	33.0	91.5	14.5	58.0	136.5	28.5	83.0	181.5
-13.0	8.5	47.5	1.0	33.5	92.5	14.5	58.5	137.0	28.5	83.5	182.0
-13.0	9.0	48.0	1.0	34.0	93.0	15.0	59.0	138.0	29.0	84.0	183.0
-12.5	9.5	49.0	1.5	34.5	94.0	15.5	59.5	139.0	29.0	84.5	184.0
-12.0	10.0	50.0	1.5	35.0	95.0	15.5	60.0	140.0	29.5	85.0	185.0
-12.0	10.5	51.0	2.0	35.5	96.0	16.0	60.5	141.0	29.5	85.5	186.0
-11.5	11.0	52.0	2.0	36.0	97.0	16.0	61.0	142.0	30.0	86.0	187.0
-11.5	11.5	52.5	2.5	36.5	98.0	16.5	61.5	143.0	30.0	86.5	188.0
-11.0	12.0	53.5	3.0	37.0	98.5	16.5	62.0	143.5	30.5	87.0	188.5
-11.0	12.5	54.5	3.0	37.5	99.5	17.0	62.5	144.5	31.0	87.5	189.5
-10.5	13.0	55.5	3.5	38.0	100.5	17.0	63.0	145.5	31.0	88.0	190.5
-10.5	13.5	56.0	3.5	38.5	101.5	17.5	63.5	146.5	31.5	88.5	191.0
-10.0	14.0	57.0	4.0	39.0	102.0	18.0	64.0	147.0	31.5	89.0	192.0
- 9.5	14.5	58.0	4.0	39.5	103.0	18.0	64.5	148.0	32.0	89.5	193.0
- 9.5	15.0	59.0	4.5	40.0	104.0	18.5	65.0	149.0	32.0	90.0	194.0
- 9.0	15.5	60.0	4.5	40.5	105.0	18.5	65.5	150.0	32.5	90.5	195.0
- 9.0	16.0	61.0	5.0	41.0	106.0	19.0	66.0	151.0	33.0	91.0	196.0
- 8.5	16.5	62.0	5.5	41.5	107.0	19.0	66.5	152.0	33.0	91.5	197.0
- 8.5	17.0	62.5	5.5	42.0	107.5	19.5	67.0	152.5	33.5	92.0	197.5
- 8.0	17.5	63.5	6.0	42.5	108.5	19.5	67.5	153.5	33.5	92.5	198.5
- 8.0	18.0	64.5	6.0	43.0	109.5	20.0	68.0	154.0	34.0	93.0	199.5
- 7.5	18.5	65.5	6.5	43.5	110.5	20.5	68.5	155.0	34.0	93.5	200.5
- 7.0	19.0	66.0	6.5	44.0	111.0	20.5	69.0	156.0	34.5	94.0	201.0
- 7.0	19.5	67.0	7.0	44.5	112.0	21.0	69.5	157.0	34.5	94.5	202.0
- 6.5	20.0	68.0	7.0	45.0	113.0	21.0	70.0	158.0	35.0	95.0	203.0
- 6.5	20.5	69.0	7.5	45.5	114.0	21.5	70.5	159.0	35.0	95.5	204.0
- 6.0	21.0	70.0	8.0	46.0	115.0	21.5	71.0	160.0	35.5	96.0	205.0
- 6.0	21.5	71.0	8.0	46.5	115.5	22.0	71.5	161.0	36.0	96.5	206.0
- 5.5	22.0	71.5	8.5	47.0	116.5	22.0	72.0	162.0	36.0	97.0	206.5
- 5.5	22.5	72.5	8.5	47.5	117.5	22.5	72.5	162.5	36.5	97.5	207.5
- 5.0	23.0	73.5	9.0	48.0	118.5	23.0	73.0	163.5	36.5	98.0	208.5
- 4.5	23.5	74.5	9.0	48.5	119.5	23.0	73.5	164.0	37.0	98.5	209.5
- 4.5	24.0	75.0	9.5	49.0	120.0	23.5	74.0	165.0	37.0	99.0	210.0
- 4.0	24.5	76.0	9.5	49.5	121.0	23.5	74.5	166.0	37.5	99.5	211.0
									38.0	100.0	212.0

tration of 50,000 mg/l (milligrams per litre) has a density of about 1.035 g/ml. It is the density effects of solutions that are of great concern in estuaries, and in some saline lakes, where density effects of the solutions are often more significant than the density effects of temperature.

Another density effect that often must be

Table 2.—Physical properties of concern in the field of water quality as a function of temperature

Temperature °C	Vapor pressure (mm /Hg)	Viscosity (centipoise)	Density (gm/ml)	Surface tension (dynes/cm)	Oxygen solubility (mg/l)	Nitrogen solubility (mg/l)
0	4.579	1.792	0.99987	75.6	14.6	23.1
5	6.543	1.519	.99999	74.9	12.8	20.4
10	9.209	1.307	.99973	74.2	11.3	18.1
15	12.788	1.140	.99913	73.5	10.2	16.3
20	17.535	1.005	99823	72.8	9.2	14.9
25	23.756	.894	99707	72.0	8.4	13.7
30	31.824	.801	.99567	71.2	7.6	12.7
35	42.175	.722	.99406	70.4	7.1	11.6
40	55.324	.656	.99224	69.6	6.6	10.8

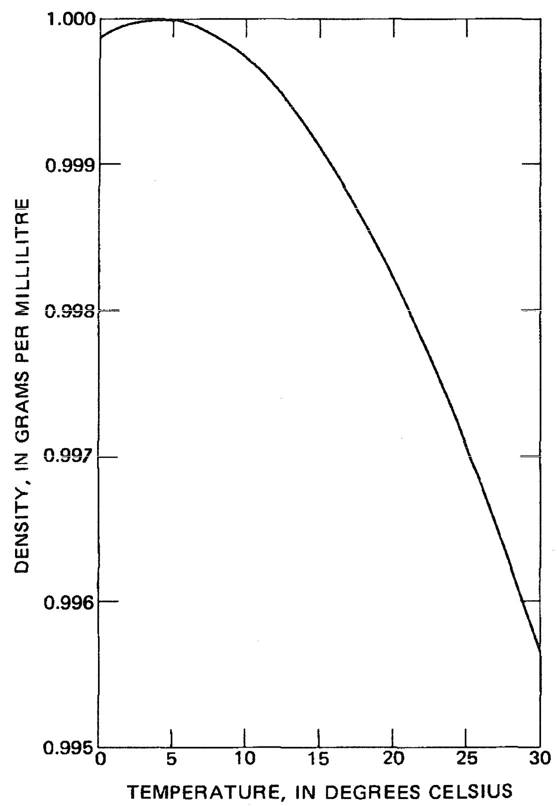


Figure 1.—Temperature-density relationship of water at 1 atmosphere (760 mm Hg (0°C)) pressure

considered is the lower density of ice. Ice at 0°C has a density of 0.9168 g/ml. This, of course, is responsible for the common phenomenon of ice floating on water.

Specific heat probably is the most prominent physical characteristic of water controlling its temperature. The specific heat of water is considerably larger than specific heat of most materials on the face of the Earth; therefore, water heats more slowly and cools more slowly than the atmosphere, rocks, or soil. For most calculations the specific heat of water is assumed to be 1.0 calorie per gram per degree Celsius (cal g^{-1}° C^{-1}). Actually, it ranges from 1.0080 to 0.9989 cal g^{-1}°C^{-1} in the temperature range of 0° to 25°C (Forsythe, 1954, p. 161).

Latent heats of fusion and of vaporization of water also are rather high in comparison with most materials. For example, the latent heat of fusion of ice is 79.7 calories per gram at 0°C, and the latent heat of vaporization is 539.6 calories per gram at 100°C.

Evaporation, a mechanism in cooling water bodies, occurs when the vapor phase is not in equilibrium with the liquid phase of the water. The evaporation rate becomes greater as increases in water temperature elevate the water-vapor pressure.

The velocity of settling particles in a non-turbulent medium is inversely proportional to the water viscosity and density (U.S. Inter-Agency Report, 1957). Since both properties contribute to increased settling rates at higher temperatures, a difference in water temperature can have a significant effect on the location and amount of sediment and sludge deposition in sluggish rivers, reservoirs, and estuaries (Colby and Scott, 1965; Guy, 1970).

Aquatic organisms depend on dissolved oxygen in water to maintain their life and reproductive processes. Lower gas solubility induced at higher temperatures is an essential aspect of thermal pollution. Recent investigations on the Columbia River indicate that fish are seriously affected in water which has become supersaturated with nitrogen and other atmospheric gases (Snyder and Blahm, 1971). This supersaturation has resulted partly from rapid warming and mostly from sudden increase in pressure as air-entrained water plunges over spillways of dams, deep into tailwater pools.

Reaeration—the dissolution of oxygen from the atmosphere—is a process by which a stream replaces consumed oxygen. Temperature variations that alter the surface reaeration coefficient by changing the molecular-diffusion coefficient of oxygen in water can be important in modifying the waste assimilative capacity of streams (Bennett and Rathbun, 1972).

Chemical

Temperature affects chemical reactions. Generally, the rate of a chemical change is approximately doubled for each 10°C rise in temperature (Parker and Krenkel, 1969; U.S. Federal Water Pollution Control Administration, 1968). In an irreversible reaction, higher temperatures will decrease the time required to produce the final products. In a reversible reaction, temperature influences both the length of time required to reach equilibrium and the proportion of the reactants and products at equilibrium conditions. Water temperature affects ionic strength, conductivity, dissociation, solubility, and corrosion.

Biochemical reactions, which result mainly from microbial activity, are influenced by temperature. Catalysts, known as enzymes, bring about chemical reactions at lower temperatures. Taste and odor problems are induced by temperature-accelerated chemical or biochemical action that produces such substances as hydrogen sulfide, methane, and partially oxidized organic matter. These tastes and odors are usually more noticeable when oxygen is depleted.

Biological

Temperature changes are important to purification processes in water and on the higher aquatic organisms. Temperature effects on microorganisms are significant to the biological processes of waste stabilization because of induced changes in growth and death rates. In general, the higher the temperature, the more active a mirco-organism becomes, unless the temperature or secondary effect becomes a limiting factor.

Biodegradable organic material entering water exerts a BOD which must be satisfied before assimilation of the material is completed. The rate of oxidation varies with temperature, type of waste, and type of biological life that assimilates and oxidizes the waste. High water temperatures intensify the action of the microorganisms and cause BOD to be satisfied in a shorter time (or distance from the discharge point) than low temperatures; however, the reduction of dissolved oxygen at higher temperatures may limit the waste-assimilation capacity of the water.

The effects of water temperature on higher aquatic organisms have been the subject of many studies (Brett, 1956; Burrows, 1963; Ordal and Pacha, 1963; Parker and Krenkel, 1969; Cairns, 1971; Snyder and Blahm, 1971). Although these effects are very complex and vary with the species of fish and with other existing conditions, they may be summarized as follows:

1. Death through direct effects of temperature changes:

   Many of the biologists just cited have presented temperature extremes which can be endured by aquatic organisms. The lethal temperature for a given organism is not fixed, but varies between some limits that are dependent upon the sublethal temperature to which the organism has become acclimatized. The extent of the temperature increase that will cause death depends upon how close the initial water temperature is to the lethal temperature.

   Rapid decreases in water temperature cause chill death among fish. The artificial warming of waters and subsequent quick cooling, such as occurs when a thermal-power-generation plant closes down, often triggers chill death. The deaths would not have taken place had the water not been artificially warmed.
2. Death through indirect effects of temperature changes:

Slow death at moderate temperatures is caused by a decrease in the availability of dissolved oxygen, disruption of food supply, and decrease in the resistance to disease and toxic substances. Elevated temperatures increase the metabolism, respiration, and oxygen demand of fish. The respiration approximately doubles for a 10°C rise in temperature; hence, the demand for oxygen is increased under conditions where the supply is lowered. Because fish normally take on the temperature of their environment (poikilothermic animals), water temperature has a significant effect on diseases they host. Increased water temperatures are generally conducive to outbreaks of diseases. A disease of young silver salmon, however, is attributed to bacterium which thrives only in cold water.

3. Interference with critical activities in the life cycle:

   Fish show a preference for water of a definite temperature range. The discharge of heated waters can create a hot-water barrier that effectively blocks the spawning migrations of many species of fish. Much lower temperatures are required for spawning and hatching of eggs than to maintain healthy adult fish. Water temperature is an important factor for fish to complete their life cycles.

4. Competitive replacement by more tolerant species:

   A healthy aquatic community is one in which many species are present. Most forms of stress, such as heat, cause a decrease in the complexity of the aquatic community and a competitive replacement by more tolerant species.

   Changes in temperature can change the character of the fish life in a stream without any direct mortality. Cold-water game fish will generally avoid a heated reach of a stream, and they will be replaced by a coarse warm-water fish.

Ambient relationships

Water on the surface of the Earth is influenced by heating and loss of heat in almost every direction. Figure 2 illustrates a section of a stream that is influenced by heat from radiation, the air, ground water, and the bed of the stream. Other effects, which are not shown by the illustration, include the heat of biological processes, heat of solution of chemicals, radiochemical decay, thermal pollution, and geophysical heat. The energy components of figure 2 are expressed by the energy budget equation:

$$Q_s - Q_r + Q_a - Q_{ar} + Q_f - Q_{fr} - Q_b - Q_e - Q_h + Q_{gw} + Q_{in} - Q_{out} + Q_{hb} - Q_w = Q_x, \quad (7)$$

where

Q_s = incoming shortwave solar radiation (direct and diffuse),

Q_r = reflected solar radiation,

Q_a = atmospheric radiation (long wave),

Q_{ar} = reflected atmospheric radiation,

Q_f = forest radiation (long wave),

Q_{fr} = reflected forest radiation,

Q_b = back radiation from the water surface (long wave),

Q_e = energy used by evaporation,

Q_h = energy lost by convection,

Q_{gw} = heat advected into the reach by ground water

Q_{in} = heat content of streamflow entering the reach,

Q_{out} = heat content of streamflow leaving the reach,

Q_{hb} = heat conducted from the streambed or banks,

Q_w = energy advected by evaporating water, and

Q_x = change of heat content of water in the reach (+ for increase).

Temporal and spatial variations

As water moves through the ground or across the surface of the Earth its temperature changes in response to its environment. Streams may warm or cool, lakes go through

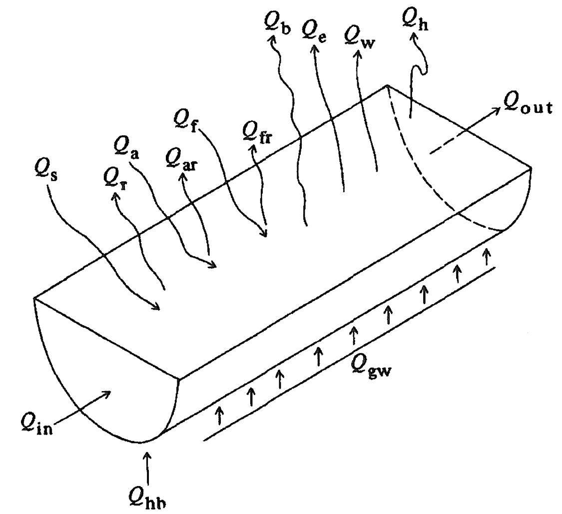


Figure 2.—Principal energy components in the heat balance of small streams. See text for explanation of symbols. (Modified from Pluhowski, 1972.)

their seasonal cycles, and ground water may warm or cool in going from one place to another. The following paragraphs provide more detailed discusssion on the phenomena often seen in streams, lakes, estuaries, and ground water.

Streams

When streams are fed principally by ground water they generally exhibit change in temperature of only a few degrees. This is especially true of streams that are well shaded. In ground-water-fed and shaded streams, the temperature of the water will be about the same as the mean annual air temperature or the temperature of the aquifer, except during cold weather when the streams freeze. Shaded streams supplied by snowmelt also exhibit generally uniform temperatures and usually are very cold, at least in their upper or shaded reaches.

When streamflow consists largely of runoff from rainfall, the temperatures show great seasonal variations. During cold spring or autumn rains, the water temperatures will be relatively low, but during times of summer thundershowers their temperatures will run relatively high.

Unshaded streams show the effect of radiation heating, especially during the warmer seasons of the year. These streams frequently have water temperature higher than the mean air temperatures in the area.

Whereas radiation is the main factor influencing the temperature of unshaded streams, the water also exchanges a great deal of heat with the air and shows the effect of heat exchange with the streambed. Figure 2 shows examples of both these actions in a reach of stream. Data from Pluhowski (1972), given in table 3, show the magnitude of some of the energy terms for a reach of streams in Virginia.

Seasonal temperature variations in a stream represent a damped mean monthly atmospheric-temperature curve. In temperate climates the water temperature never reaches the lower extreme of air temperature, which may be below freezing, and it will be slightly above or below the upper extreme of air temperature depending upon the degree of shading. A similar air-water temperature correlation exists in semitropical climates; however, the difference between the water-temperature extremes will be smaller with the lower extreme approaching the mean daily air temperature on winter days. The effect of shade is shown by stream-temperature data in figures 3 and 4 for two different types of streams in Oregon. Monthly mean water temperatures for the east-west-oriented streams (fig. 3) were higher than the monthly mean air temperatures during the summer months, whereas the air temperatures were higher than the water temperatures on the more shaded, north-south-oriented streams (fig. 4).

Reservoirs in the stream channel also alter the temperature of waters in the stream. The type and extent of the alteration depends upon the size, operating schedule, and construction of the reservoir. For example, a stream discharging from the upper layers of a reservoir generally will be considerably warmer than the waters flowing into the reservoir. On the other hand, waters discharging from the deeper parts of the reservoir will be considerably colder than the inflowing waters. Only during periods of complete mixing of reservoirs in spring or au-

Table 3.—Energy-budget computations for Colvin Run near Reston, Va., for the period 1415–1500 hours (e.s.t.) July 15, 1969

[From Pluhowski, 1972. 1 ly (langley)=1 gram-calorie cm^{-2}]

Stream reach (1):		
Beginning at site 5A	feet above mouth	1,190
Ending at site 5B	feet above mouth	90
Length of reach	feet	1,100
Average width	feet	9.0
Average depth	foot	.25
Discharge (2):		
At site 5A	cfs	1.3
At site 5B	cfs	1.3
Time of travel (3):		
From site 5A to site 5B	minutes	45
Measured stream temperatures (4):		
Initial (site 5A at 1445 hr)	°C	24.4
Final (site 5B at 1500 hr)	°C	27.8
Solar radiation (5):		
Q_{so}, total incoming solar radiation	ly	44.6
Reduced 12.5 percent for bank shading	ly	-5.6
Q_s, solar radiation reaching stream	ly	39.0
Q_r, reflected solar radiation (3 percent)	ly	-1.2
Q_i, absorbed solar radiation (insolation)	ly	37.8
Atmospheric radiation (6):		
ε, emissivity		.87
Q_a, atmospheric radiation (reduced 3 percent to include albedo losses)	ly	23.0
Outgoing long-wave radiation (from stream to atmosphere) (7):		
ε, emissivity		.97
Q_{bw}, back radiation	ly	-29.2
Evaporation (8):		
Q_e, evaporation heat flux	ly	-3.6
Conduction (at streambed) (9):		
T_{gw}, ground-water temperature below stream	°C	16.7
Q_{hb}, conductive heat flux	ly	-1.1
Convection (at air-water interface) (10):		
Q_h, convective heat flux	ly	1.0
Heat-flux summary (11):		
Net heat flux to stream	ly	+27.9
Predicted temperature at site 5B, 1500 hr (12):		
Temperature change caused by heat gain	°C	+3.7
Final temperature	°C	28.1
Remarks (13):		
A positive heat flux indicates incoming energy to the reach, whereas a negative heat flux denotes loss of energy.		

tumn is the reservoir outflow temperature approximately equal to the inflow temperature.

Geologic setting usually plays a minor role in stream temperature. Most often geological setting is important as it influences stream shading, as in the case of a stream flowing along the north side of a hill or within a deeply cut canyon. However, geologic setting can be important when rock fractures allow the escape of warm or hot ground waters into a stream.

Lakes and reservoirs

A lake responds to environmental heating effects in much the same manner as does a stream. Figure 2 and equation 7 describe the heat exchange between a lake and its environment in the same way they describe conditions in a stream.

Radiation and evaporation usually are the largest terms in the energy budget, as shown in table 4, which presents data for the 30-day period during June and July 1965 in a small lake in Indiana. Table 4 does not include the term for heat storage in the lake sediments or for ground-water inflow. The small amount of available data on exchange of heat with the lake bottom show that the rate of heat storage or release by the sediment seldom exceeds 30 calories per square centimetre per day, and throughout most of the season the rate is considerably less. Ground-water inflow to Pretty Lake was very small during this period and is ignored in this energy

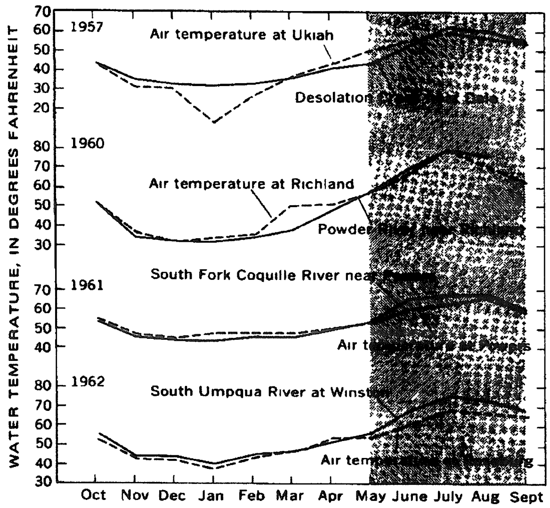


Figure 3.—Comparison of monthly mean air and water temperatures for selected east-west-oriented streams in Oregon. (Summer months patterned. From Moore, 1967, p. K21.)

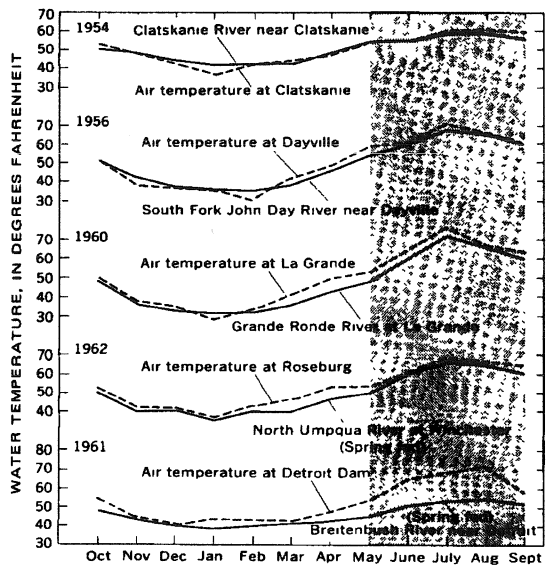


Figure 4.—Comparison of monthly mean air and water temperatures from selected spring-fed or north-south-oriented streams in Oregon. (Summer months patterned. From Moore, 1967, p. K22.)

budget. In equation 7 the term Q_x represents the change in heat storage in the lake.

Whereas the heating and cooling of water in the lake are largely effected by external heat sources and sinks, the temperature distribution within a lake is largely controlled by water density. As a lake is heated at the surface by solar energy and heat exchange with a warm atmosphere, the water at the surface becomes warmer than the water deeper in the lake. At temperatures warmer than 4°C, the warmer surface water is also less dense than the cooler water at greater depth. The result is a temperature stratification within the lake (fig. 5) with a relatively warm zone known as the *epilimnion,* and a relatively cool zone called the *hypolimnion.* At mid-depth the lake will have a zone of rapid temperature change with depth called the *metalimnion.* The horizontal plane where the temperature curve passes a point of inflection is the *thermocline.* In some engineering literature and older limnologic literature the word thermocline also is defined as meaning the whole metalimnetic zone (Hutchinson, 1957, ch. 7).

In temperate climates where lakes cool to freezing or near freezing in the winter, the deep water of a lake will be near the temperature of maximum density. In shallower lakes, the waters are mixed by wind action as the lake heats; the hypolimnetic temperatures are several degrees above maximum-density temperature but always less than surface temperatures. In tropical or subtropical climates, stratification of lakes also exists, but the hypolimnion temperature may be 20°C or warmer than the hypolimnion temperature of temperate climate lakes.

As a temperate lake cools in the autumn, the epilimnion deepens, and the thermocline moves downward. Final circulation is not accomplished until the surface temperature is

Table 4.—Energy-budget computations for Pretty Lake, Lagrange County, Indiana, for the period June 8–July 8, 1965

[From Ficke, 1972, p. A16. Q values given in calories per square centimetre per day]

Q_s	628
Q_r	38
Q_a	726
Q_{ar}	22
Q_b	867
$Q_v = (Q_{in} - Q_{out})$	3
Q_x	48
Q_e	332
Q_h	37
Q_w	13

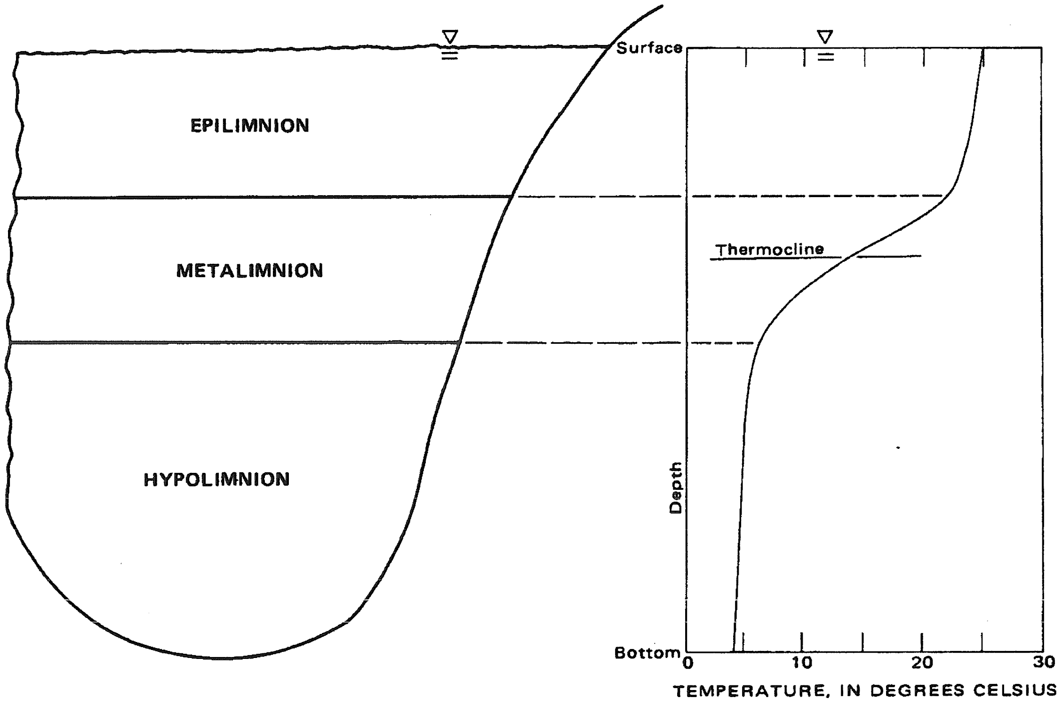


Figure 5 —Zones of a thermally stratified lake

nearly equal to the temperature of hypolimnion. This process of autumnal cooling and circulation is called the *turnover* or *overturn.* Data in figure 6 demonstrate this phenomenon at Pretty Lake, Ind. (Ficke, 1965).

When the water at a lake surface cools to freezing temperature in wintertime, it also becomes less dense than the deeper waters. The result is that lakes also will demonstrate thermal stratification in the winter, with surface temperatures at 0°C and temperatures in the deeper waters somewhere between 0° and 4°C. Thermal radiation penetrating lake ice often will warm the waters under the ice to temperatures of a few degrees above those of maximum density.

Reservoirs on large rivers have their temperature influenced by the flow patterns of inflowing streams. For example, a stratified reservoir having relatively cool inflowing water exhibits an *underflow* pattern. Cold water entering the reservoir is more dense than the epilimnetic water of the reservoir and flows to the lowest point of the reservoir. As the water flows through the lake, it may be released through a bottom outlet and hardly mix at all with the waters on the lake surface. On the other hand, lakes with warm inflowing water may exhibit an overflow pattern where warm waters may flow across the surface not mixing with the colder epilimnetic waters. A lake with a large flow-through-to-volume ratio that has a warm inflow and a bottom outlet may be rather effectively flushed—cool water from the hypolimnion leaves the bottom outlet and is replaced by warmer inflowing and epilimnetic water.

Estuaries

Heating and cooling of estuaries is similar to processes in both lakes and streams. Estuaries resemble lakes in that they, at times, have relatively ponded water with diverse circulation patterns, and they represent a relatively conservative mass of water. Estuaries have both inflow and outflow from the sea; however, and in many these inflow-outflow volumes are many times the volume of the upstream freshwater inflow.

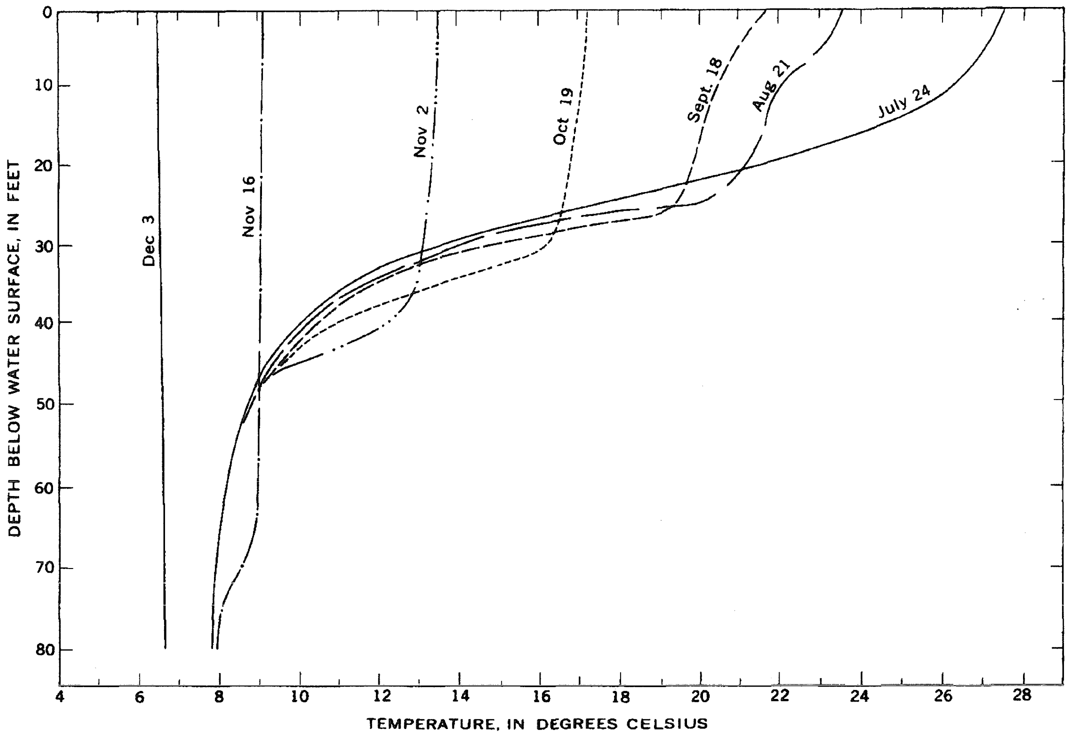


Figure 6.—Water-temperature profiles averaged from measurements at 21 locations on Pretty Lake, Ind., during the summer and autumn of 1963 (From Ficke, 1965, p C200.)

At the mouth of many estuaries the temperature is uniform over the cross section and nearly the same as in the open sea; upstream, however, temperature gradients usually increase rapidly (Kinne, 1967). Tidal flats and other areas where velocities and depths are low exhibit greater diurnal-temperature fluctuations than in the deeper areas. Also, strong winds can produce surface currents in the direction of the wind and produce bottom currents in the opposite direction. The resulting circulation patterns and wave action can greatly influence thermal stratification.

The density and thermal patterns vary from estuary to estuary. Freshwater may very well be flowing downstream while the saltwater wedge on the bottom of the estuary is flowing upstream. These same patterns are complicated by mixing which may or may not occur. Situations may vary from almost total isolation of the freshwater and saltwater to rather complex mixing patterns across the estuary.

Pritchard (1952) classified estuaries according to their geomorphology. The bar-built estuary is found along the Gulf of Mexico coast, and the more common coastal plain estuary is found along the east and west coasts. The bar-built estuary is formed by an offshore bar normally deposited on shoreline having very small slopes; consequently, the enclosed bay is shallow. Between the shallow bay and the open sea, there is a narrow channel that depends upon tidal currents to keep it scoured. The coastal plain estuary refers to river valleys that have been drowned by virtue of the rise in sea levels since the glacial period and is generally an elongated indenture in the coastline with a single river as the source of freshwater at the upper end, whereas the lower end has a free connection to the sea.

Pritchard (1955) also indicated that there is a sequence of coastal plain estuarine types—salt-wedge estuary, vertically stratified or partially mixed estuary, and vertically homogeneous estuary. Each has a distinct stratification and circulation pattern, as shown in figure 7. The position an ėstuary takes in this sequence depends primarily upon the river flow, tidal flow, width and depth. The Mississippi River is an example of a salt-wedge estuary. Because of the low tide range and large river discharge, the freshwater flows out over a wedge of saltwater at the bottom, and the mixing process is relatively slow. In the partially mixed estuary, the tide range is large enough so that the amount of saline water entering the estuary is sufficient to produce salinity gradients that vary gradually over the entire depth. The Chesapeake Bay and the Columbia River estuary are good examples of this type of estuarine system. The mixing in the verticallly homogeneous estuary is such that is has no vertical salinity gradients. There is evidence that the lower, relatively wide parts of the Delaware Bay are of this type.

Ground water

Ground water generally is very uniform in temperature throughout the year. As noted above, streams fed by ground water are remarkably uniform in temperature. Moreover, the temperature uniformity of ground water has long made it sought after for cooling purposes. Nonetheless, temperatures of shallow ground water fluctuate seasonally, owing to conduction of heat from the land surface and to variations in the temperature of water recharging the ground-water body. Ground-water temperatures also vary with depth, owing to the geothermal gradient, and areally because of heat transport by ground-water movement.

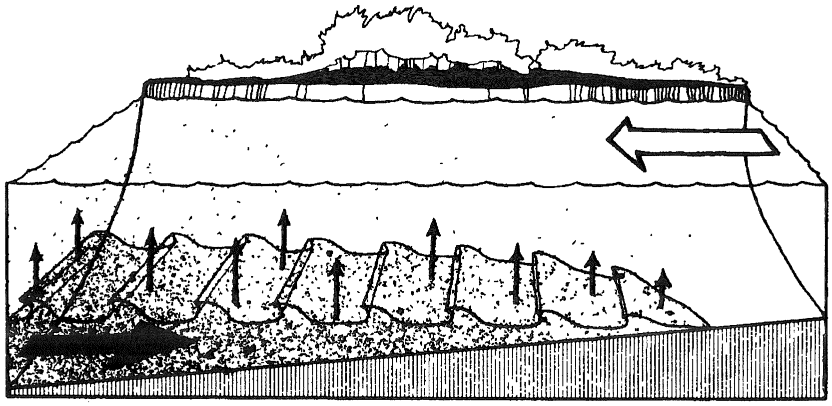
Because of heat conduction from the land surface, very shallow ground water will show diurnal and seasonal temperature variations of about the same magnitude as those observed for surface-water bodies. However, due to the insulating properties of the Earth, these variations are greatly attenuated with depth, and annual fluctuations generally are less than 0.5°C at depths of 10 metres or greater (Collins, 1925).

Ground-water temperatures are influenced by heat conduction upward from deep within the Earth, as well as by heat conduction downward from land surface. Consequently, ground water 10 to 20 metres below land surface generally exceeds the local mean annual air temperature by 1° to 2°C. Moreover, at depths greater than 20 metres, ground-water temperatures generally reflect the geothermal gradient and, hence, usually increase by 2° to 3°C per 100 metres of depth (Collins, 1925).

Ground-water temperatures may be significantly influenced by the temperature of recharge water from losing streams. Supkow (1971, fig. 58) shows a ground-water-temperature anomaly of about 7°C in the vicinity of Rillito Creek, which he attributes to recharge of colder water from the creek. Moreover, effects of induced recharge on the temperature of water pumped by wells near streams has been studied by several investigators. Schneider (1962, p. B5) tabulated the results of six reports that show the temperature of pumped ground water from different well fields to vary seasonally from 8° to 18°C. For these same studies, the river sources of induced recharge showed seasonal temperature fluctuations that varied from 25° to 29°C. Rorabaugh (1956), in one of the reports cited by Schneider, described effects of induced recharge on ground-water temperatures in detail.

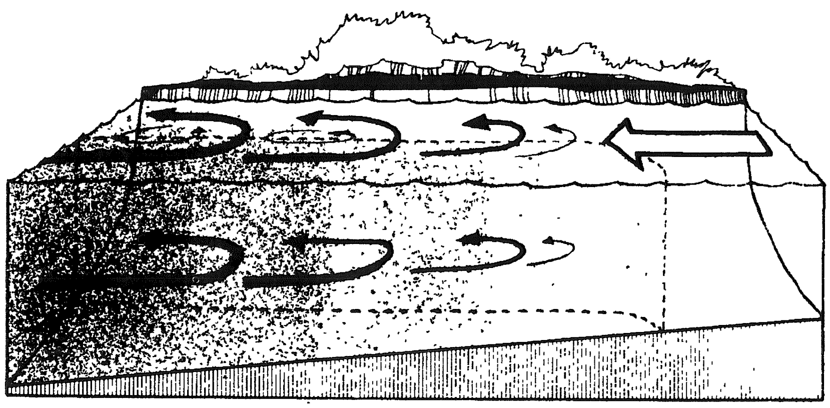
Ground-water temperatures may be substantially affected by the temperature of water injected through wells. Brashears (1941) found that on Long Island, water returned to the aquifer after use for air-conditioning resulted in a rise in temperature of water pumped from nearby production wells of as much as 6°C. Moreover, he noted a gradual increase in ground-water temperatures areally as recharge from this source increased.

Recharge from deep percolation generally shows more subtle effects on ground-water temperature than that induced from streams and is often barely detectable. Generally, the temperature of such percolating water is



SALT-WEDGE ESTUARY

PARTIALLY MIXED ESTUARY



VERTICALLY HOMOGENEOUS ESTUARY

Figure 7.—Stratification and circulation patterns for three types of coastal plain estuaries. (From Pritchard, 1955.)

modified by heat exchange as it moves through the unsaturated zone. Moreover, residence time of infiltrated water in the unsaturated zone may be fairly long because the infiltrating water generally displaces soil water already in place (Warrick and others, 1971). Thus, infiltration at land surface will result in water just above the capillary fringe being recharged to the ground-water body. Schneider (1962) inferred the effects of recharge from precipitation on the basis of deviation of a few tenths of a degree Celsius in the seasonal water-temperature trends for two wells tapping a shallow aquifer.

Temperature differences within the ground-water flow system due to recharge diminish within the aquifer with distance from the recharge source. The rate at which such temperature differences are dissipated depends upon the thermal conductivity and heat capacity of the solid-fluid complex comprising the aquifer and upon the velocity of the fluid as it affects heat dispersion. The various modes of heat transfer have been described in detail by Bear (1972, p. 641–643).

Ground-water movement results in areal temperature variations—due both to the effects of local recharge of water of different temperature than that of the ground water and to the interception of geothermal heat and its lateral transfer in the moving ground water. Supkow (1971) attributed much of the areal ground-water-temperature variation at the water table for Tucson basin (about 14°C) to these causes. Moreover, Cartwright (1968) and Birman (1969) proposed the use of temperature measurements at shallow depths to prospect for ground water, based at least in part on the effects of moving ground water on the geothermal gradient. The geothermal gradient also may be distorted by vertical ground-water movement. As noted by Sorey (1971), measured ground-water temperatures sometimes deviate by a few tenths of a degree Celsius from that described by a linear geothermal gradient.

Schoeller (1962) mentioned some secondary factors which under normal circumstances bring about only negligible changes in the temperature of the ground-water-flow regime. These include heat generated by friction of ground-water flow within the porous medium, temperature changes caused by the expansion of water brought up from great depths, and heat generated by chemical reactions. With regard to this latter factor, Hanshaw and Bredehoeft (1968) and Back and Hanshaw (1971) postulated that endothermic and exothermic chemical reactions can produce marked temperature changes in ground water. Lovering and Morris (1965) discussed the possibility that ground-water temperatures can be raised significantly by oxidation of sulfide deposits.

The injection or infiltration of radioactive or other polluting materials into the ground-water system may also result in a temperature anomaly. A dramatic change in the temperature of a spring near St. Louis, Mo., is attributed to a rise and fall of bacterial activity. The bacteria have been traced to organic matter leached from a nearby landfill (A. B. Carpenter, oral commun., 1973).

Part 2. Field Measurement

Two major factors need to be considered in planning and conducting field measurements of temperature. These factors are (1) proper selection of instruments and (2) proper field application and procedures. Discussions in this section, therefore, include, first, a description of equipment and, secondly, recommendations of methods and procedures for measuring temperature in the field.

Instruments

Instruments for measuring temperature consist of two basic parts—a sensor and a scaling device. The two components combined form a thermometer. For example, consider a mercury-filled thermometer. The mercury is a material that expands upon heating, and, when contained in a tube of glass that has a uniform bore, it becomes a sensor with approximately uniform response to temperature changes. When an etched scale is added to the mercury-in-glass sensor, the combined system becomes a thermometer. Some of the sensors used in temperature measurement and some of the thermometers which incorporate them are discussed in the subsections that follow.

Temperature sensors

A temperature sensor is a device which responds to the stimulus of heat and transmits a resulting signal. Even within the relatively narrow band of the temperature spectrum where the majority of water-temperature measurements are made, there are several well-established physical principles which are the basis for temperature sensors. It is therefore important that the potential user have an understanding of these sensors and of the physical principles underlying their operation, for this will help him make the proper selection when he has a temperature-measuring application. Only when one has an adequate understanding of temperature sensors can factors, such as sensitivity, accuracy, speed of response, expected useful life, cost and resistance to corrosion, sensitivity to vibration, and other conditions, be thoroughly evaluated. The material for this section on temperature sensors was obtained from Considine (1957) and Kallen (1961).

Liquid-in-glass

The liquid-in-glass sensor has been in use for over 200 years, and, although it is not generally used today for high-precision measurements, it is the most widely used device for temperature measurement. It consists typically of a thin-walled glass bulb joined to a class capillary stem closed at the opposite end. The bulb and part of the stem are filled with an expansive liquid. Almost any liquid can be used; however, the liquids most commonly used are mercury, mercury-thallium, gallium, alcohol, toluol, pentane, and the silicones. The better grades of sensors with metallic fillings have an inert gas under pressure above the liquid column. Nitrogen, argon, or carbon dioxide is generally used above mercury; nitrogen above mercury-thallium. This gas under pressure helps to prevent separations of the liquid in the capillary tube.

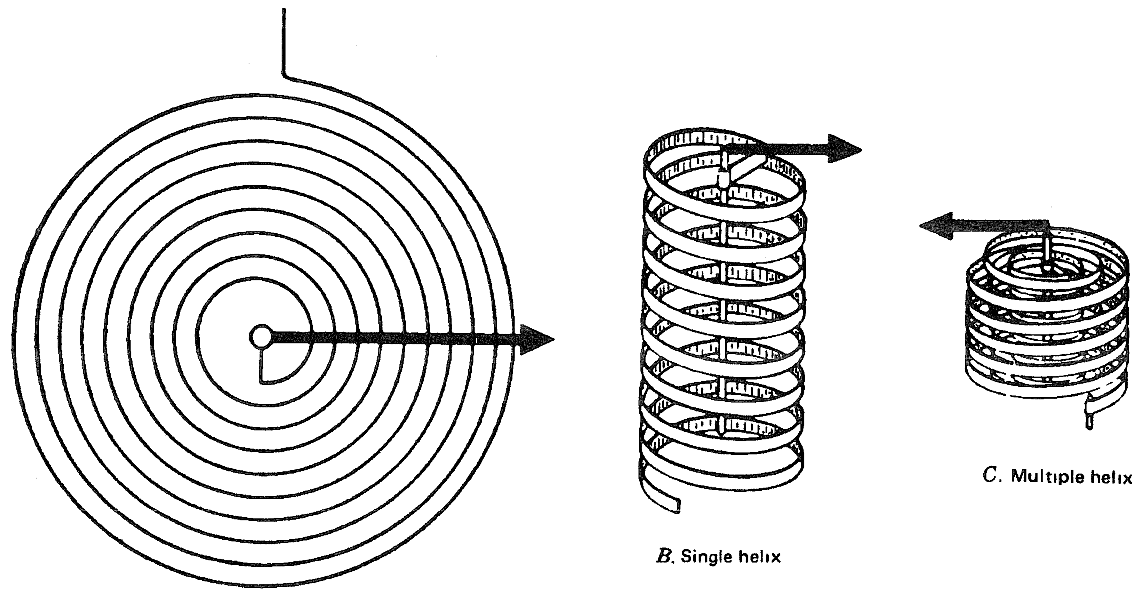
The liquid in the bulb expands or contracts in volume as its temperature rises or falls. This volume change is transmitted to the capillary tube, causing a change in the length of the liquid column in the tube. The physical principle on which this sensor operates is therefore very simple; however, the design, the choice of materials used, and the construction can be very complex and, consequently, have great influence on its quality. Although the cleanliness of the bulb, the capillary bore, and the liquid filling has a pronounced effect on the performance of the finished sensor, of equal importance is the choice of the glass from which it is manufactured and the correct annealing of the glass. If the bulb is made from unsuitable glass or the annealing is inadequate, significant changes in volume will occur, causing serious inaccuracies. Even with the best materials and design, gradual volume changes will continue for years; however, these will generally be limited to an equivalent inaccuracy of less than 0.1°C.

The capillary bores are usually round or elliptical. The smaller the capillary bore, the greater the change in elevation of the liquid level for a given change in temperature. However, there is a practical limit beyond which capillary forces will prevent a smooth advance or retreat of the liquid column. Particularly with a slowly changing temperature, the movement of the liquid meniscus may be found to occur erratically in significantly large steps.

Several factors contribute to the popularity and widespread use of the liquid-in-glass sensor. It is both simple in design and easy to use, as well as being very inexpensive. However, being made of glass, it is fragile. The thermal mass of the sensor is large; therefore, the time constant—that is, the time required to respond to a temperature change—is relatively long. The liquid-in-glass sensor is not commonly used as the basis of recording thermometers but is generally used as a part of portable nonrecording instruments.

Bimetallic

The bimetal temperature sensor is made up of two or more laminated strips of different



A. Flat spiral

Figure 8.—Principal types of elements in bimetal thermometers

metals, which, because of the different expansion rates of the components, causes it to change its curvature when subjected to a change in temperature. If one end of a straight bimetal strip is fixed, the other end deflects in direct proportion to a temperature change. The deflection for a given temperature change is proportional to the square of the length of the strip and is inversely proportional to the thickness of the strip. When the bimetal strip is wound into a spiral or helix and one end is fixed, the other end will rotate with a change in temperature.

Bimetallic elements are most commonly formed in either a flat spiral, a single helix, or a multiple helix (fig. 8). In these forms the signal transmitted is a rotary mechanical motion. If the design is proper the motion will be linear with temperature changes over the design range of the sensor.

Bimetallic sensors are rugged, but severe mechanical shock or vibration can cause distortion resulting in large shifts in their calibration. They present a large thermal mass and, consequently, have a relatively long time constant, approximately on the same order as that for liquid-in-glass sensors.

Filled-system

A filled-system temperature sensor consists of a bulb containing a gas or fluid whose physical properties change with temperature changes. These changes are transmitted to a Bourdon, bellows, or other suitable element through a connecting capillary tube. Filled-system sensors may be separated into two fundamental types—those in which the element responds to a volume change and those in which the element responds to a pressure change.

The systems that respond to volume changes are completely filled with a liquid. The liquid in the bulb expands with temperature changes to a greater degree than does the bulb metal, thereby producing a net volume change which is communicated to the detecting element.

The systems that respond to pressure changes are either filled with a gas or partially filled with a volatile liquid. Changes in gas or vapor pressure with changes in bulb temperature are communicated to the detecting element.

Filled-system temperature sensors are further classified by the Scientific Apparatus Makers Association into the following categories:

Class I. Liquid-filled systems:
- IA. Full compensation.
- IB. Compensation of the detecting element only.

Class II. Vapor-pressure systems:
- IIA. Designed to operate with the bulb temperature above the temperature of the remainder of the system.
- IIB. Designed to operate with the bulb temperature below the temperature of the system.
- IIC. Designed to operate with the bulb temperature above or below the temperature of the remainder of the system.
- IID. Designed to operate with the bulb temperature above, below, or at the temperature of the remainder of the system.

Class III. Gas-filled systems:
- IIIA. Full Compensation.
- IIIB. Compensation of the detecting element only.

Class V. Mercury-filled systems:
- VA. Full compensation.
- VB. Compensation of the detecting element only.

Although the physical principles upon which these sensors work are relatively simple, there are a number of causes which do affect their accuracy. In order to discuss these interferences, it is convenient to keep the above classification in mind.

Because the capillaries, detecting elements, and bulbs of all Class I, III, and V sensors are filled with actuating fluid or gas, all parts are sensitive to differences in ambient temperature. Therefore, serious system errors can result from ambient-temperature variations between components unless compensating means are employed. Classes IA, IIIA, and VA are fully compensated for such temperature variations by means of an auxiliary system which duplicates the primary system except for the bulb. Such an arrangement provides that an ambient-caused response is opposed by an equal and opposite response, thus compensating fully for ambient-temperature effects. Because of simplicity of construction, compensation of the detecting element only (Classes IB, IIIB, and VB) is frequently employed. In this type of compensation, the capillary bore is reduced in size to a point where system response to ambient-temperature variations is not seriously affected, in order to minimize the capillary-temperature error. The detecting element is then compensated by means of a bimetallic strip which provides a response opposing any ambient response of the element. Since the error caused by the capillary has only been reduced and not eliminated and since the longer the capillary the greater the error, sensors with this type of compensation are generally limited to relatively short capillary-tube lengths.

The only ambient temperature error in the vapor-filled system (Class II) is caused by the change in elastic modulus of the pressure detecting element with changing temperature. This error is very small and can usually be ignored.

A difference in elevation between the bulb and the detecting element can cause an appreciable error in all filled-system temperature sensors except the gas-filled type (Class III). Vapor-filled systems (Class II) and gas-filled systems (Class III) use pressure-sensitive detectors; consequently, they are affected by changes in barometric pressure.

The filled-system temperature sensor has the advantage that the bulb and detecting element can be separated by some distance. It is, however, like the bimetallic sensor, sensitive to severe shock, vibration, or other forms of mechanical abuse.

Thermocouple

The basis of one of the most commonly used temperature-sensing devices is the principle of thermoelectricity. Seebeck discovered in 1821 that when two dissimilar metals are welded together at one end and this junction is heated, a voltage is developed on the free ends.

There are two thermoelectric effects which combine to produce the electromotive force (emf) developed; one is known as the Peltier effect and the other as the Thomson effect. The Peltier effect dominates—the emf resulting solely from the contact of two dissimilar metals. Its magnitude varies with the temperature at the point of contact. The emf resulting from the less predominant Thomson effect is that produced by a temperature gradient along a single wire.

Considering the above effects, three thermoelectric laws have been formulated which characterize the behavior of thermocouples. They are as follows:

1. *Law of homogeneous circuit.*—An electric current cannot be sustained in a circuit of a single homogeneous metal, however varying in section, by the application of heat alone.
2. *Law of intermediate metals.*—If in a circuit of solid conductors, the temperature is uniform from any point P through all the conducting matter to a point Q, the algebraic sum of the thermoelectromotive forces in the entire circuit is totally independent of this intermediate matter and is the same as if P and Q were put in contact.
3. *Law of successive or intermediate tematures.*—The thermal emf developed by any thermocouple of homogeneous metals with its junctions at any two temperatures T_1 and T_3, is the algebraic sum of the emf of the thermocouple with one junction at T_1 and the other at any other temperature T_2 and the emf of the same thermocouple with its junctions at T_2 and T_3.

By combining these laws, it is apparent that leads of homogeneous metals connecting the thermocouple with the measuring instrument to not affect the emf developed by the thermocouple, provided that junctions of dissimilar conductors which are added to the circuit are all at the same temperature or that one junction of each pair of junctions between dissimilar metals is at the same temperature as the other junction of the pair.

The composition of thermocouples may be of any two dissimilar metals. However, there are several combinations of pure metals and alloys which are frequently used because they produce a reasonably linear temperature-emf relationship, and they develop an emf per degree of temperature change that is detectable with standard measuring instruments. Among these are copper-constantan, iron-constantan, chromel-alumel, and platinum rhodium-platinum.

Thermocouple sensors have an advantage in that they can be separated a considerable distance from the measuring instruments. However, great care must be taken in observing the laws previsously mentioned or errors will be caused by extraneous voltages produced by insertion of the electrical leads of different metals between the thermocouple and the measuring instrument. Although they have an extremely rapid time response, when used in water they must be sealed in a case, and this increases their thermal mass and, consequently, their time response. Thermocouples themselves are relatively inexpensive, but the measuring instrument used with them can be fairly expensive.

Resistance bulb

Resistance-temperature sensors are based upon the principle that metals (metallic) and semiconducting materials (thermistors) change in electrical resistance when they undergo a change in temperature. The change in electrical resistance of a material with a change in temperature is termed "temperature coefficient of the resistance" for the material. This coefficient is positive for most metals, and for pure metals the change in resistance with temperature is practically linear. The temperature coefficient for semiconductor material is negative, and the change in resistance with temperature is exponential.

Metallic.—As stated above, the resistance-temperature sensor, called the resistance bulb, depends on the inherent characteristics of metals to change in electrical resistance when they undergo a change in temperature. Resistance bulbs are manufactured in a number of shapes, the most common of which is a tubular-shaped stainless steel stem with the lower end sealed and the electrical leads protruding from the upper end. The resistance winding is located in the lower end of the stem, electrically insulated, but in good thermal contact with the stem.

The material from which the resistance element is wound must possess certain characteristics. It should have a high temperature coefficient of resistance, because the greater the resistance change per degree for a given value of resistance the greater the sensitivity of the element. It should have a high value of resistivity, for the higher the resistivity of the material, the more resistance for a given length of wire and, consequently, for a given size. It should remain stable, not changing its electrical characteristics over a long period of time. It should possess a linear resistance-temperature relationship, which greatly simplifies its calibration. It should be ductile and strong so that it can readily be drawn into fine wire and still possess strength for ruggedness in winding and adjusting.

Several metals meet the above criteria and are used in the manufacture of resistance bulbs. The three most commonly used are platinum, nickel, and copper, with platinum—except for its cost—being the most suitable of all metals.

After selection of the material, proper design and careful manufacture play important roles in the functional performance of a resistance sensor. As much of the metal as practical must be wound in as compact a configuration as possible. The winding must be encased in a protective housing or shield, usually a stainless steel tube that has one end closed for mechanical protection and has electrical insulation. The winding must also be insulated from the metal housing but must have good thermal coupling in order to respond rapidly to changes in surrounding temperatures and in order to dissipate what is referred to as self-developed heat caused by the flow of electrical current used in measuring its resistance value. In a well-designed resistor bulb, this self-developed heat will be properly dissipated into the medium being measured. The electrical leads from the winding itself to the measuring instrument should be low-resistance wire so that any change in their resistance plays an insignificant role in the total resistance of the sensor. In the best bulbs, a four lead arrangement is used such that the resistance value of the leads can be eliminated. In connecting the leads to the winding, usually a junction of two dissimilar metals, there exists a thermal junction and an emf is produced which would affect its reading. In a properly designed bulb the junctions will be located close to each other to eliminate any difference in temperature, and with no difference the algebraic sum of the developed emf's will equal zero.

Resistance bulbs have all the advantages of thermocouples, except that they are usually larger and have a slightly longer time constant. A resistance bulb basically measures temperature directly in that the resistance of the coil of wire is a direct function of its temperature, and the accuracy of this measurement is entirely unaffected by the temperature to which the measuring instrument is exposed. Resistance bulbs also have the advantage of greater sensitivity because the change of resistance per degree change in temperature is relatively large; hence, it is more easily measured than the microscopic change in voltage per degree change in a thermocouple.

Thermistors.—A thermistor is an electrical device made of a solid semiconductor with a high temperature coefficient of resistivity, which would exhibit a linear voltage current characteristic if its temperature were held constant. It changes electrical resistance markedly with temperature, the relationship usually being exponential.

Thermistors are made from a variety of metal oxides and their mixtures, including the oxides of cobalt, copper, iron, magnesium, manganese, nickel, tin, titanium, uranium, and zinc. The oxides, usually compressed into the desired shape from powders, are heat treated to recrystallize them, resulting in a dense ceramic body. Electrical contact is made by attaching wires by various means to opposite sides of the material. Thermistors are generally shaped as beads, rods, or disks.

Thermistors have many of the same advantages as metallic resistance sensors, and they are less costly. In addition, they are even more sensitive because of their high coefficient of resistivity, but for the same reason, self-developed heat is of greater significance in causing errors. They are not manufactured to the same degree of uniformity as metallic elements, and their resistance temperature is nonlinear; therefore, they must be calibrated at many points to achieve reasonable accuracy. They also have a tendency to age—that is, shift calibration with time—but developments in this are constantly improving their reliability.

Others

There are several other physical and chemical principles which are sometimes employed in measuring temperature. Most do not provide sufficient accuracy to be considered here; however, there is one temperature sensor, the quartz crystal, which will be discussed briefly. This sensor is based upon the sensitivity of the resonant frequency of a quartz crystal to temperature change. This change of resonant frequency is linear with respect to temperature. The quartz crystal is driven by an oscillator, the frequency of which is controlled by the crystal; therefore, a frequency that is linearly proportional to temperature is produced.

The quartz-crystal sensor has a number of advantages over other sensors. Its sensitivity is excellent, its linearity is excellent, and it provides a signal suitable for direct digital readout. However, in its present stage of development and manufacture, it is very expensive in comparison with other sensors and does not warrant this high cost for most field applications.

Thermometers

A thermometer is an instrument for measuring temperature, consisting of a temperature sensor and some type of calibrated scale or readout device. The comparative performance of temperature-measuring systems, both recording and nonrecording, are discussed in the following sections in order to provide a better understanding of the relative advantage and limitations of the various kinds of thermometers available. The material for this section on thermometers was obtained from Considine (1957) and Kallen (1961).

Nonrecording thermometers

All the temperature-sensing systems discussed in the preceding section can be and are used in nonrecording thermometers. When there are no additional requirements to consider, such as recording or fixed installation of instruments, simpler designs and lower costs are possible.

The liquid-in-glass sensor requires only the addition of a calibrated scale, usually etched on or enclosed within the stem to become a nonrecording thermometer. (See fig. 9*A*.) Those having an attached or removable scale generally are not considered suitable for scientific work. Liquid-in-glass thermometers are divided into two types—partial immersion and total immersion. This classification is used because the liquid in the column is a part of the total thermally responsive system and is affected by the temperature along its entire length. Partial-immersion thermometers have a line etched around the stem to indicate the exact immersion depth for maximum accuracy. Total immersion does not mean that all of the thermometer must be immersed, but that the bulb and all or nearly all of the liquid column should be immersed for maximum accuracy. In addition to the typical laboratory all-glass thermometer, there are several variations or special purpose liquid-in-glass thermometers available, the most common of which is the maximum-registering thermometer. The lower part of the capillary bore has a constriction, usually a wide slitlike opening, through which the liquid can easily be forced when heated, but when the bulb is cooled, the column breaks at the point of constriction. After a reading, the liquid can be forced back into the bulb by shaking. The clinical thermometer is of this type.

The liquid-in-glass thermometer is by far the most commonly used of all portable thermometers because of its low cost and relatively high degree of accuracy. Of course, accuracy depends upon the care with which the scale is etched and the length of the stem,

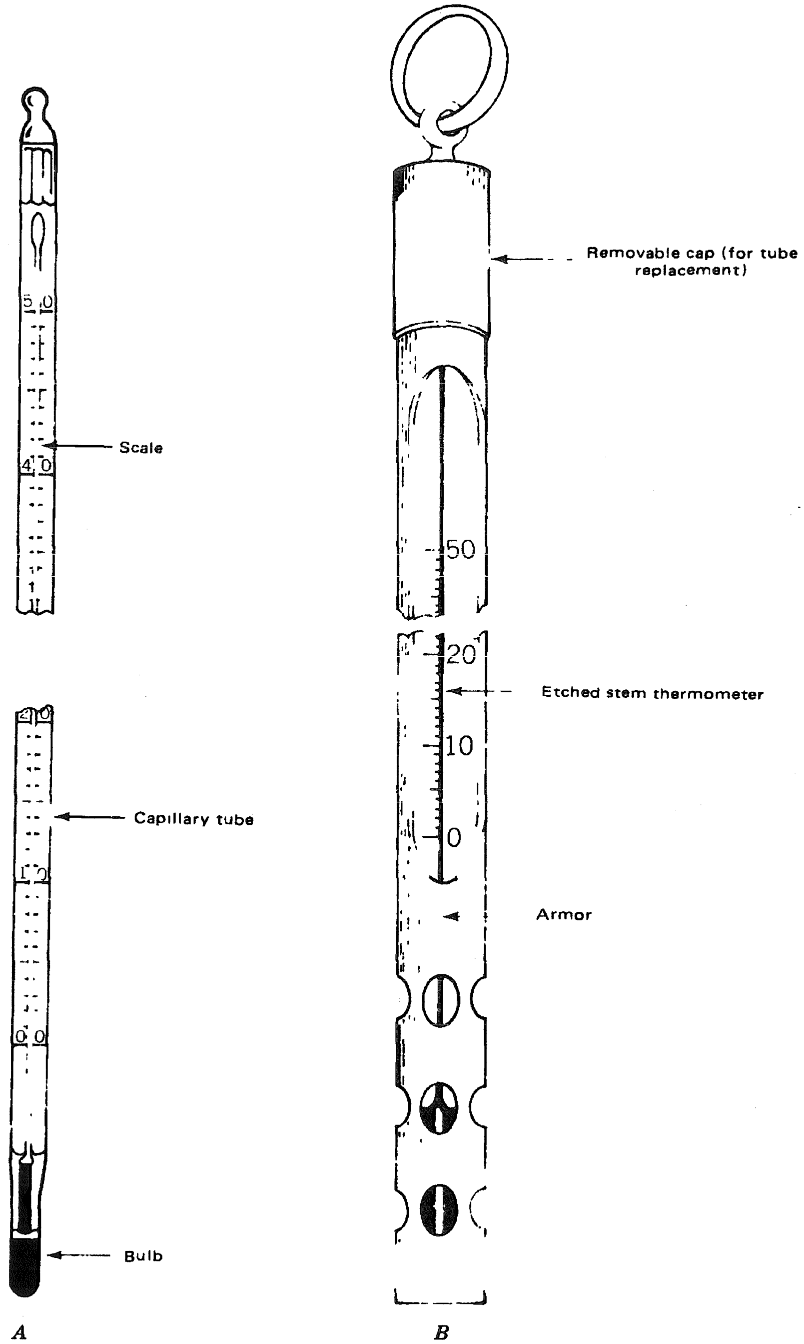


Figure 9.—Sketches showing various components of (*A*) an enclosed thermometer and (*B*) an armored thermometer.

which is, in turn, dependent upon the bore of the capillary. Being all glass, it is fragile, but protective metal sleeves or armor cases can be obtained for thermometers that are subjected to rough handling. (See fig. 9*B*.)

The maximum-minimum thermometer is a U-shaped liquid-in-glass thermomter in which the mercury column positions metal markers to indicate the two temperature extremes. The device indicates the temperature extremes but not their time of occurrence. A small magnet is used to reset the metal markers on the mercury columns. Possible errors when using the maximum-minimum thermometer are (1) the thermometer's response to the air temperature can reposition one of the metal markers if readings are not made quickly, (2) the scale for minimum temperature, which increases in a downward direction, can be misread, and (3) air temperature can affect registration, after it has been reset, if the thermometer is not quickly replaced in position in the water.

The bimetallic sensor, when wound into a spiral or helix, produces a rotary motion with changes in temperature. (See fig. 10.) This motion is transmitted to a pointer by a shaft mounted on precision-made bearings and guides which center the shaft with minimum friction. A scale graduated in degrees is fixed to the case.

Bimetal thermometers are rugged in construction and retain their calibration indefinitely unless they are subjected to abuse. Their accuracy, however, is not as good as that for the liquid-in-glass thermometer, being approximately one-half percent of full scale in the better grades. They are also generally more costly than liquid-in-glass thermometers.

Filled-system sensors, like the bimetallic, usually transmit a rotary motion for changes in temperature. (See fig. 11.) Although the angular movement for a given temperature change is smaller, it provides more force; therefore, a lever arrangement is normally used to magnify the movement of a pointer.

Although fundamental simplicity allows rugged construction, minimizing the possibility of damage during use, filled-system thermometers are not frequently used as portable instruments because the capillary tube is not highly flexible or convenient to handle.

The emf produced by a thermocouple may be read on a millivolt meter, potentiometer, or any other device for detecting and indicating small d.c. emf's. The simple millivolt meter is the least costly, and, for many applications, sensitivity and accuracy are adequate. However, for the best accuracy a potentiometer must be used. The potentiometer draws no current at balance and thus balances as if it had no resistance, whereas even the best millivolt meter still has enough resistance to cause some loading of the thermocouple.

The thermocouple has the advantage that the sensors can be separated from the indicator unit for some distance by a highly flexible electrical cable. There are, however, problems associated with the various junctions of different metals. Because of these problems, thermocouples are not frequently used as portable thermometers in water-temperature measurement unless a very rapid time response is required.

The equivalent temperature value of resistance sensors, either metallic bulbs or thermistors, can be read on a common bridge or other resistance measuring circuit. The conventional Wheatstone is most frequently used. For best accuracy, a null-balanced bridge circuit is used, and the adjusting mechanism of the slidewire is calibrated for temperature. Where less accuracy at a lower cost is an application requisite, deflectional-type circuits can be used. These simply consist of a circuit similar to the d.c. Wheatstone bridge and a meter indicating the amount of imbalance of the bridge. The readout is calibrated in temperature units.

The resistance-type thermometer also has the advantage that the indicator unit can be separated by some distance from the sensor by an electrical lead, but it must be remembered that resistance of the lead is measured by the instrument, and lead length cannot be changed without affecting calibration. Unlike the thermocouple, the accuracy of the resistance thermometer is unaffected by the ambient temperature to which the leads and junctions are exposed, and it is, in general, easier to operate and maintain.

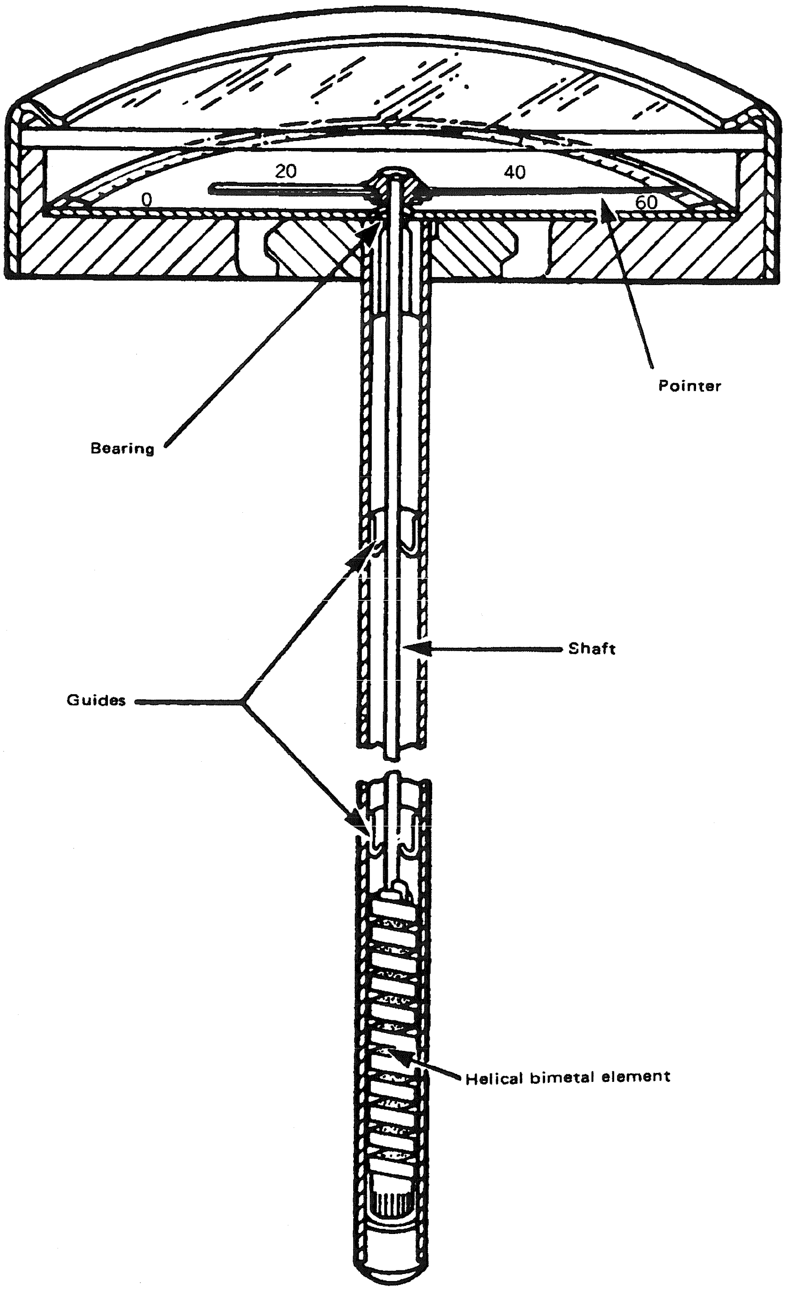


Figure 10.—Sectional view of thermometer with helical-type bimetal element.

As explained in the previous section, quartz-crystal temperature sensors, with their oscillators, generate a frequency proportional to temperature. In order to read this frequency, an electronic counter is usually employed. Readability is then within one pulse per second, which provides in the better thermometer a resolution of 0.00001°C. Accuracy is not the equivalent of resolution, but 0.01°C is easily obtained with proper calibration.

The counter of the quartz-crystal thermom-

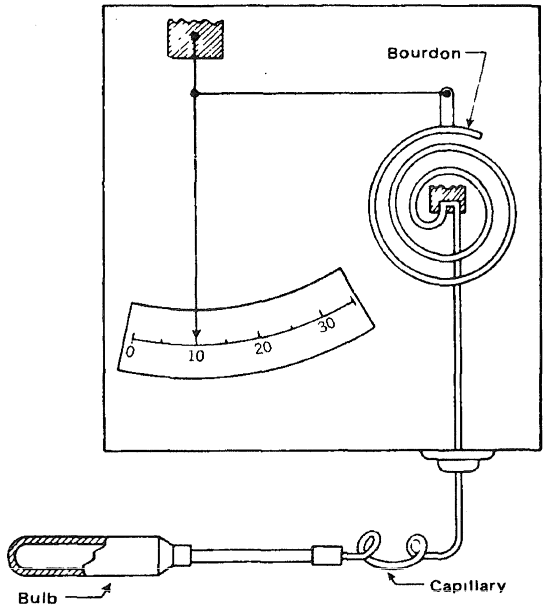


Figure 11 —Filled-system thermometer

eter also has the advantage that it can be separated from the sensor by an electrical lead without degradation of the signal. It is, however, because of its high cost, primarily useful in the laboratory where extreme accuracy is required.

In reviewing the available nonrecording thermometers, the following conclusion can be drawn concerning their application to the measurement of water temperature.

Liquid-in-glass thermometers provide good accuracy, on the order of ±0.1°C for laboratory grade, at the most economical cost. The sensor, however, cannot be separated from the scale.

Portable bimetallic thermometers are rugged and easy to read, and their costs compare with liquid-in-glass thermometers. However, their accuracy is usually on the order of from ±0.5° to ±1°C, and for this reason they generally are less desirable than liquid-in-glass thermometers for field measurement of water temperature.

Filled systems provide means of recording temperature at permanent installations with moderate cost, but, because of their bulkiness, they are not well suited to use as portable thermometers.

Resistance thermometers provide excellent accuracy, better than ±0.1°C, and long-term stability for the metallic type with proper readout instrumentation.

The thermistor, even with the deflection-type circuit, can provide accuracies better than ±0.3°C at the most economical price of any of the resistance types. Stability is not as good as with the metallic type, so calibration must be more frequent to maintain accuracy.

On any of the resistance types, the sensor can be located remotely from the readout instrumentation.

Thermocouple thermometers have many of the same advantages as resistance types, including accuracy in order of ±0.2°C, stability, and suitability for long leads. Because of their more complex circuits and needs for standard voltage references, their costs are usually higher than the costs of resistance thermometers.

If very rapid response (1 second or less) is required, the thermocouple thermomter is the most suitable because of its low thermal mass. The thermocouple sensor can also be located remotely from the indicator unit, but extreme care must be exercised with lead junctions.

Where extreme accuracy, on the order of ±0.01°C, is required, the quartz-crystal thermometer will provide this, but the cost is very high.

Portable recording thermometers

As is true of nonrecording thermometers, all the sensors described can and have been used as recording thermometers. Several, however, do not lend themselves nicely to portable recording instruments. The liquid-in-glass is very seldom used because the only method of recording is by photographing. Although the bimetallic produces a mechanical motion, the torque produced is so low that nothing more than a lightweight pointer should be attached to it. And the filled-system thermometer makes a rather unwieldy instrument for good portability because of its somewhat inflexible capillary tube.

All the electrical-type sensors lend themselves well to use as recording thermometers. Since the signal from the sensor is electrical, it is relatively easy to condition it to drive an electrical recorder. The electronic readout section and recorder can be located remotely from the sensors. The only connection necessary between the components is a highly flexible electrical cable.

The thermocouple produces a small d.c. emf which must be conditioned before it is of significant strength to drive a recorder. The most accurate means of reading an emf is a high-quality potentiometer. Although not of the highest precision, many electrical records are, in essence, reasonably good quality potentiometers which are driven to balance by an electromechanical servo mechanism. These recorders usually have an amplifier on their input to condition the signal to a sufficiently high level to drive the servo. Many other electrical recorders are simply millivolt meters, which also have an amplifier on their input to condition the signal so it is not overloaded. While the potentiometric recorder is a null-balance-type system which gives higher accuracy than the less costly deflection-type system, such as the millivolt recorder, the state of the art is sufficiently advanced so that either will give adequate accuracy for most water-temperature-measurement requirements.

The resistance-type sensors, both the metallic bulb and the thermistor, change the value of their resistance with changes in temperature. Their resistance value can be recorded by several methods. The null-balance Wheatstone bridge is the most accurate method and has again an electromechanical servo mechanism which drives the bridge to a balanced position and, at the same time, positions the recording device. A less expensive method is to read the imbalance of a bridge and record this imbalance on a millivolt recorder. The most frequently used method is to energize the sensor with a constant-current source and, using Ohms law, $E = IR$, record the voltage drop on a millivolt recorder. All these methods provide adequate accuracy for most water-temperature-measurement requirements.

In reviewing the available portable recording thermometers, the following conclusions can be drawn concerning their application to the measurement of water temperature.

Resistance-type thermometers can provide the most accuracy at the least cost.

The metallic bulb has an essentially linear relationship with temperature and, when used in a null-balanced system, can provide excellent accuracy and long-term stability.

The thermistor used either with the deflection bridge or constant-current-type circuit will provide accuracy on the order of ±0.3°C at the most economical cost. However, stability is not as good as with the metallic bulb, and more frequent calibration is required to maintain maximum accuracy.

The thermocouple will provide the most rapid time response but does require extreme care with lead junctions.

Fixed-installation recording thermometers

Several factors in addition to accuracy and speed of response should be considered when selecting a thermometer for recording temperature at a fixed installation. Long-term stability is certainly a desirable characteristic, for the instrument usually must operate unattended and without recalibration for periods of several weeks. Also, its resistance to corrosion, vibration, and other harmful conditions, as well as its cost and expected useful life must be considered. However, because it is to be a more or less permanent type of installation, more time and care can be devoted to the initial installation.

The filled-system thermometer is an instrument which does require more time and care in its installation, and for this reason it is almost never used except as a fixed-installation thermometer. The capillary tube is not as highly flexible as the electrical leads of a thermocouple or a resistance-type thermometer. The tube length must be fixed at the factory and is not readily altered in the field as is the length of the interconnecting leads of the electrical types. As stated in the section on filled-system sensors, all of Classes I, III, and V have liquid in the bulb, capillary, and detecting elements, and all parts are therefore sensitive to ambient-temperature changes; however, if full compensation (Classes IA, IIIA, and VA) is used, errors from this source can be eliminated. A difference in elevation between the bulb and the detecting element will cause an error in all filled-system instruments except the gas-filled type (Class III). This error can be corrected by careful calibration or by full compensation. The vapor-filled and gas-filled instruments (Classes II and III) use pressure-sensitive detectors and, consequently, are affected by changes in barometric pressure. These changes can be corrected by full compensation (a duplicate opposing system except for bulb). If care and proper correcting techniques are used with filled-system thermometers, they are accurate and reliable devices for measuring water temperature. They are, however, somewhat less convenient to use than the electrical-type thermometers.

As for the thermocouple and resistance-type thermometers, the same statements can be made here as appeared under the section on portable-recording thermometers. However, because the requirements for portability and, consequently, weight are not so severe, better quality circuits and recorders can be used. Of course, long-term stability is important, and, in this respect, the metallic-resistance element is the best. The advantages of greater accuracy and stability of the metallic resistance element over the thermistor more than offset its slight additional cost.

Recording systems commonly available provide a pen trace on a strip or circular chart. Recorders having 8-day circular charts may be used at frequently visited sites, but 30-day or continuous-strip-chart recorders are better suited to the normal station-visitation frequency. Because of the increasing demand for accurate current water-quality data, the U.S. Geological Survey has turned to the digital computer to eliminate the necessity of manually extracting data recorded on charts. Digital recording systems (fig. 12) have been developed that produce a punched paper tape that can be machine translated for the computer (Smoot and Blakey, 1966). Digital recorders coupled to servo-drive mechanisms are used for recording temperatures from a single sensor, and programable units are available for sequentially recording up to 10 different parameters.

Operation, maintenance and calibration

Probably the single most important contribution to the successful collection of accurate and representative water-temperature data is to have the operation of measuring systems performed by trained personnel. Observers should be familiar with methods of equipment calibration and routine maintenance.

All temperature-measuring instruments should be calibrated before use and periodically during use. Frequency at which recalibration is required will vary with instruments and must be determined by experiences of the operator. To calibrate, two waterbaths, one at 5°C, the other at 20°C, are necessary. The temperature of each waterbath should be monitored to the nearest 0.1°C with an ASTM standard or good-grade laboratory thermometer. Generally, the accuracy of all instruments should be within 0.5°C at both temperatures.

Liquid-in-glass thermometers, which require little routine maintenance, are calibrated by immersing them into each of the waterbaths. See page 22 for discussion of total-immersion and partial-immersion liquid-in-glass thermometers. The thermometers are held in the water until the mercury column no longer moves (no less than 60 seconds) and read without removing from the water. Before calibration they should be checked for possible separation of the mercury column and, when necessary, they should be cleaned but taking care not to scrub off the numbers on the glass.

Most fixed and portable temperature-measuring systems will have two calibration adjustments. These are the zero setting, which moves the temperature scale (or pen position) up or down, and the span setting, which expands or contracts the length of the temperature scale (or pen movement). For mechanical instruments, the zero setting is made by raising or lowering the pen arm, and the span setting is made by moving the position of the pen-arm pivot; for electrical instruments, the zero setting is made by changing the d.c.-voltage-bias potentiometer, and the span setting is made by changing the voltage-gain potentiometer (volts per °C).

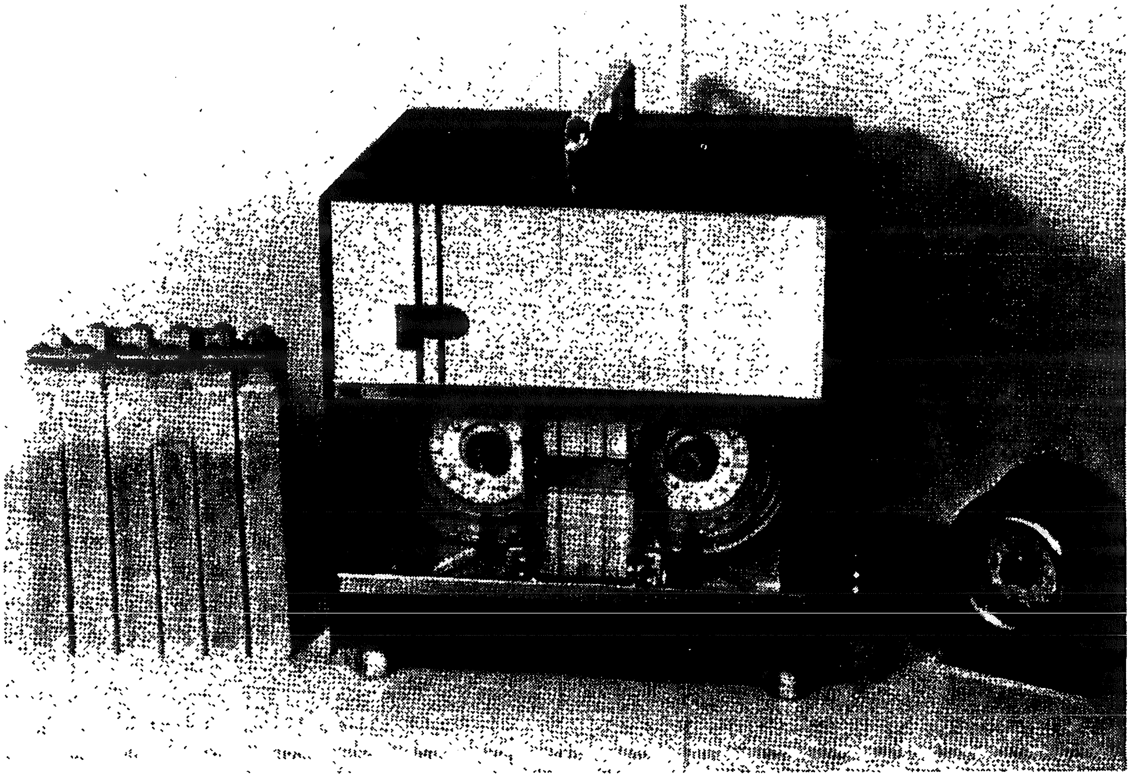


Figure 12.—Digital recorder. Photograph by L. H Ropes.

The following procedure, which may be modified to fit a particular instrument, should be used to calibrate a temperature-measuring system:

1. Place sensor in the 5°C waterbath and adjust the zero setting until the instrument indicates the temperature of this waterbath.
2. Place sensor in the 20°C waterbath and overcorrect the instrument by an amount equal to the difference between the temperature of this waterbath and the temperature indicated by the instrument (error) with the span setting.
3. Repeat steps 1 and 2 until the error is at or near zero. The instrument should now indicate the temperature of both waterbaths within 0.5°C (as closely as 0.005°C in some precision instruments).

When using calibrated portable systems in the field, batteries and electrical connections should be periodically checked and indicated water temperatures should be periodically compared with calibrated liquid-in-glass thermometer readings. These checks, which are most important when unusual temperature conditions occur, insure that the system is indicating accurate water temperatures.

Several important routine maintenance considerations for fixed sensor-recorder measuring systems are that:

1. A sensor covered by sediment or debris or one which has been physically damaged will not be responsive to temperature changes in the body of the flow.
2. Mechanical friction (or electrical malfunction) may prevent accurate recording of the signals transferred by the sensor to the recorder, and
3. The sensor-recorder system is subject to electrical-mechanical drift.

U.S. Geological Survey observers frequently read air temperature as well as water temperatures during each visit to field stations; therefore, they should obtain these temperature readings with a calibrated portable thermometer (liquid-in-glass generally preferred) using the following procedure, an example suggested by Robert Averett (written commun., 1970) for small, wadable streams:

1. Measure air temperature in the shade using a dry thermometer to minimize the risk of obtaining an erroneously low air-temperature reading due to evaporation.
2. Select a site in the stream where the water is moving and where the influence of tributaries is diminished because of mixing. Studies have shown that a temperature taken in main flow of the stream is usually representative of the entire water mass (Jones, 1965; Moore, 1967). During the summer when discharges are low, it may be necessary to wade into the center of the stream, or as far as possible in deep streams, to obtain the temperature. If sufficient mixing has not occurred, temperature observations must be obtained at several locations so that a discharge-weighted mean temperature can be computed. (See later section on field application and procedures for streams.)
3. Stand so that a shadow is cast upon the site chosen for collecting the temperature.
4. Hold the thermometer by its top and immerse it entirely in the water in the shadow area. Position the thermometer so that the scale can be read and hold the thermometer in the water until the liquid column no longer moves (no less than 60 seconds). Make certain the liquid column in the thermometer is not separated.
5. Without removing the thermometer from the water (to avoid wet-bulb cooling), read the temperature to the nearest 0.5°C, and record it in the field notes. If the water is too rough or too turbid to allow a reading in the stream, the temperature may be taken by filling a container with the water, immersing the thermometer in the container, and then reading the temperature. The container must be large enough to allow full immersion of the thermometer, and the walls of the container must be brought to the same temperature as the stream before it is filled with water for temperature determination. In addition, it must provide sufficient thermal mass to insure that the temperature of the water in the container does not change while the temperature is being recorded. A volume of at least a pint should be withdrawn for temperature measurement.

The observed water temperature is considered to be the true stream temperature and will be designated as TST. The next step is to repeat the above procedure (steps 3 through 5) in the water near the sensor. This is not the sensor temperature, but is the temperature of the water mass surrounding the sensor and will be designated as TNS (temperature near sensor). After recording this temperature the observer should check the thermograph recorder and note the indicated temperature. The recorder temperature is designated as TRC. The three temperatures should all be recorded in the field notes and also should be recorded on the temperature chart along with the date and time. Differences between TST and TNS will generally be diurnal or seasonal in nature. The recorder should, hence, be set to read TNS, and corrections should be made during the analysis of the record to account for differences between TNS and TST. This recording procedure will provide a clear record of problems at a given site and permits the recording of accurate temperatures at the higher flows, when TNS is likely to be representative of the true stream temperature (TST). Usually, changes in a recorder setting of less than 1°C should not be made unless the apparent error is verified by two or more field inspections.

After the observer has obtained and recorded the three reference temperatures, he should check and correct, if necessary, the recorder-chart time and the zero and span settings. Sensors should be checked, cleaned, and replaced if necessary. Sensor-recorder measuring systems should be recalibrated at least twice each year.

Field applications and procedures

Accurate temperature data are essential in order to document thermal alterations to the environment caused by the activities of man and by natural phenomena. This section on field applications and procedures presents guidelines for selection of suitable instrumentation and recommended procedures for the collection of temperature data in streams, lakes, estuaries, and ground water.

Streams

Objectives and accuracy requirements

A water-temperature station on a stream may be part of a network of continuously reporting stations or a temporary station (continuous or intermittent) for special localized studies, such as one for defining the effects of a heated discharge or a reservoir release. The water temperature reported for a station should represent the stream's mean cross-sectional temperature except at sites where complex temperature gradients exist. Generally, the accuracy should be within 0.5°C; however, special studies may dictate greater or lesser accuracy.

Selection of temperature measuring system

The type of temperature system to be used on a stream will depend upon the kind and frequency of data being sought. Measurements of surface temperature or temperature with depth at irregular intervals may be sufficient at some locations; however, at most locations it is desirable to put in a permanent installation at which the temperature is monitored continuously.

Hand thermometers used to obtain surface observations of water temperature and to check the setting of thermographs should be mercury filled and accurate within 0.5°C. It is essential that all hand thermomters be calibrated before use and checked periodically during use with an ASTM standard or good-grade laboratory thermometer. The recommended procedures to calibrate a hand thermometer are given in the section on operation, maintenance, and calibration of instruments (p. 28–30).

The maximum-minimum thermometer (p. 24) is an inexpensive device for obtaining temperature extremes but not their time of occurrence. James Mundorff (written commun., 1973) has used the maximum-minimum thermometer to obtain maximum and minimum temperatures between observations at a regular gaging station. A maximum-minimum thermometer is placed in a 1-foot (25-cm) length of 2½- or 3-inch (64- or 76-mm) diameter galvanized pipe, such as that used for gage-well intakes. This pipe can either be threaded and capped, or, if 2¹/₃-inch (64-mm) pipe is used, be bored for cross-bolts at both ends of the pipe. If the pipe is capped, it should be perforated with holes to allow free circulation of water. The encased thermometer is placed in the stream near the edge of water in the vicinity of the gage house and is fastened to the gage house with a short length of cable. The best location for placement is where the water is flowing but where the device is somewhat protected.

Portable water-temperature-measuring systems used for obtaining temperature profiles should be compact, rugged, and accurate within 0.5°C. Most portable systems utilize a thermistor as the temperature-sensing element and use dry-cell batteries to supply power needs. Both recording and nonrecording types are available. The temperature in nonrecording systems usually is obtained directly from an electrical meter or from a null-balancing system. Multiparameter systems incorporating measurements of temperature, salinity, and conductivity also are available. (See section on portable recording thermometers starting on page 26.)

The fixed water-temperature-measuring system (thermograph) used at continuous-recording stations should be stable and capable of sensing temperatures within 0.5°C for extended periods of time. The thermograph attachment on the Stevens A-35 water-stage recorder has been widely used at gaging stations (Moore, 1963). This instrument is accurate only within about 1°C, however. Temperature measuring systems incorporating a metallic resistance bulb are considered to be the best because they have a long-term accuracy of about 0.3°C. Thermistor and thermocouple sensors have an accuracy within the required limits, but they tend to shift in calibration with time. The temperature-measuring system can also be part of a multiparameter water-quality data-collection system (Cory, 1965; Anderson and others, 1970). Analog-recording systems provide a pen trace on a strip or circular chart, and digital recording systems produce a punched-paper or magnetic tape. (See p. 28.)

Site selection

When a water-temperature station is established, whether it is to be a recording or nonrecording station, care must be exercised to see that the site is suitable for observing water temperatures. Water-temperature records collected at gaging stations and at damsites provide for convenient access and operation but usually are not located on the basis of their suitability as temperature-measurement sites. The greatest problem at gaging stations is that temperature measurements are influenced by inflow from nearby upstream tributaries or reservoir releases. Water temperatures of outflow at dams are usually measured within the scroll case of one or more turbines, or at a gaging station a short distance downstream from the dam. Temperature data collected in the scroll case can be significantly higher than the average of the total outflow because of temperature stratification in the forebay, heat generated by turbulance, and heat conducted through the turbine shaft and dam.

Water-temperature stations should be located far enough downstream from tributaries or reservoirs to ensure that the waters at the station are completely mixed. Temperature profiles throughout the cross section at the proposed site should be made to test for horizontal and vertical homogeneity. (See page 33.) Checking the cross sectional distribution at just one season of the year may not be sufficient. The greatest likelihood of heterogenity in a cross section occurs in the summer when flows are extremely low. At that time, depths are shallow, turbulent mixing is of minimum intensity, and localized heating of the water may occur. In the spring, cool tributary water derived from snowmelt may not become completely mixed with mainstem waters generally for long distances below the tributary confluence.

Large streams may flow through zones of different temperature regimes. In addition, water flowing through secondary passages where velocities are low, such as sloughs, may gain or lose more heat than the mainstem water thereby, creating temperature gradients at the points of reentry with the main stream. Because of such situations on large streams, it may be necessary to locate a water-temperature station at a site where temperature gradients exist. A special localized study may also dictate a site where gradients exist; however, these sites should be avoided whenever possible.

Some locations may require more than one temperature station to adequately define the mean cross-sectional temperature. It is recommended that two stations be installed in the cross section whenever the horizontal or vertical variation in the water temperature exceeds 2°C more than 5 percent of the time. Some locations may require a period of time to determine if two temperature stations are necessary; hence, it may be desirable to install two stations immediately to insure proper data collection. The second station can be removed if it is later determined that it is not required.

Sensor location

Sensors for water-temperature or two-parameter (water temperature and specific conductance) measuring systems are usually housed in a perforated pipe mounted directly in the streamflow. The conductor wire from the sensor to the recorder is shielded in a metal conduit or plastic pipe.

The sensor must be properly located in the stream channel if the temperature sensed is to be representative of the mean water temperature in the cross section. The sensor must be located in flowing water, but it also must be adequately protected to minimize physical damage, it should not rest on the streambed, and it should not be in direct sunlight. Erroneous temperature registration may result if the sensor is exposed to air or becomes covered with silt or debris. Absorption of direct sunlight can cause the streambed of a shallow stream to be warmer than the water above it; hence, a sensor at the bed might register high. At a gaging station where both water temperature and stage records are collected, the sensor should not be located close to the stilling-well intake. Water in the gage well can be several degrees warmer or cooler than in the stream. Water leaving the gage well during a rapid drop in stage could cause a temporary error in the temperature record.

Sensors for multiparameter water-quality data-collection systems (including the temperature sensor) are housed in a flow-through chamber that receives a continuous flow from a submersible pump. The pumped flow rate must be sufficient to prevent water-temperature change. The pump may be mounted in the stream below the water surface by attaching it to a float arrangement, which rises and falls with the stage (Cory, 1965), or it may be mounted on a platform anchored to the streambed, as shown in figure 13 (Anderson and others, 1970). The float-type mounting is subject to damage by debris and ice. Divers equipped with scuba gear can place pumps on the bed; however, because this is expensive for installation and maintenance, the streambed-platform mounting is limited to wadable streams. Both types of mountings can be washed away.

Anderson, Murphy and Faust (1970) have used a stilling-well type of pump facility. (See fig. 14.) Pump servicing can be done on dry land except during extremely high water. The advantages of easy eccess and servicing with this type of pump facility are obvious; however, frequent cleaning of the stilling well and piping are necessary to remove sediment. High construction costs are an additional disadvantage. Existing structures, such as bridge piers or concrete bulkheads, also can be used to support a pumping facility. An installation of this type is shown in figure 15.

Special procedures

Assuming that the objective in measuring stream temperature is to collect data representing the stream's cross section, particular care has to be devoted to defining the mean and to verification that the data collected indeed represent the mean. At this time the reader should review the material on stream temperatures presented in the subsection on operation, maintenance, and calibration of instruments (p. 28–30), noting definitions of the terms "true stream temperature" (TST), "temperature near sensor" (TNS), and recorder temperature (TRC). The following paragraphs discuss in more detail the measurement and computation of mean temperature (TST).

The temperature distribution should be measured periodically throughout a section that is as close as possible to the temperature sensor in order to define any horizontal or vertical gradients. The required frequency for the cross-section measurements, which usually is low at most stations where TST can be represented by a single water-temperature measurement, is dictated by such factors as tributary inflow, reservoir releases, climatic elements, and channel geometry. At stations where temperature gradients exist all or most of the time, data will be needed as often as practicable to accurately compute the discharge-weighted mean temperature in the cross section (TST) and relate it to TNS; however, time, money, and measurement procedures limit the surveillance activity.

Two methods can be used to obtain temperature distribution data at a cross section. The most common method consists of obtaining vertical profiles by lowering the temperature sensor to predetermined depths at each of several verticals across the section. At most locations, 15 to 30 temperature observations (5 depths at 3 to 6 verticals) will be adquate; however, more observations may be required in large streams where tributary and secondary-channel flow is not well mixed with main-stem flow. In the other method, the sensor is towed successively across the channel at several different predetermined depths. This method is the most satisfactory

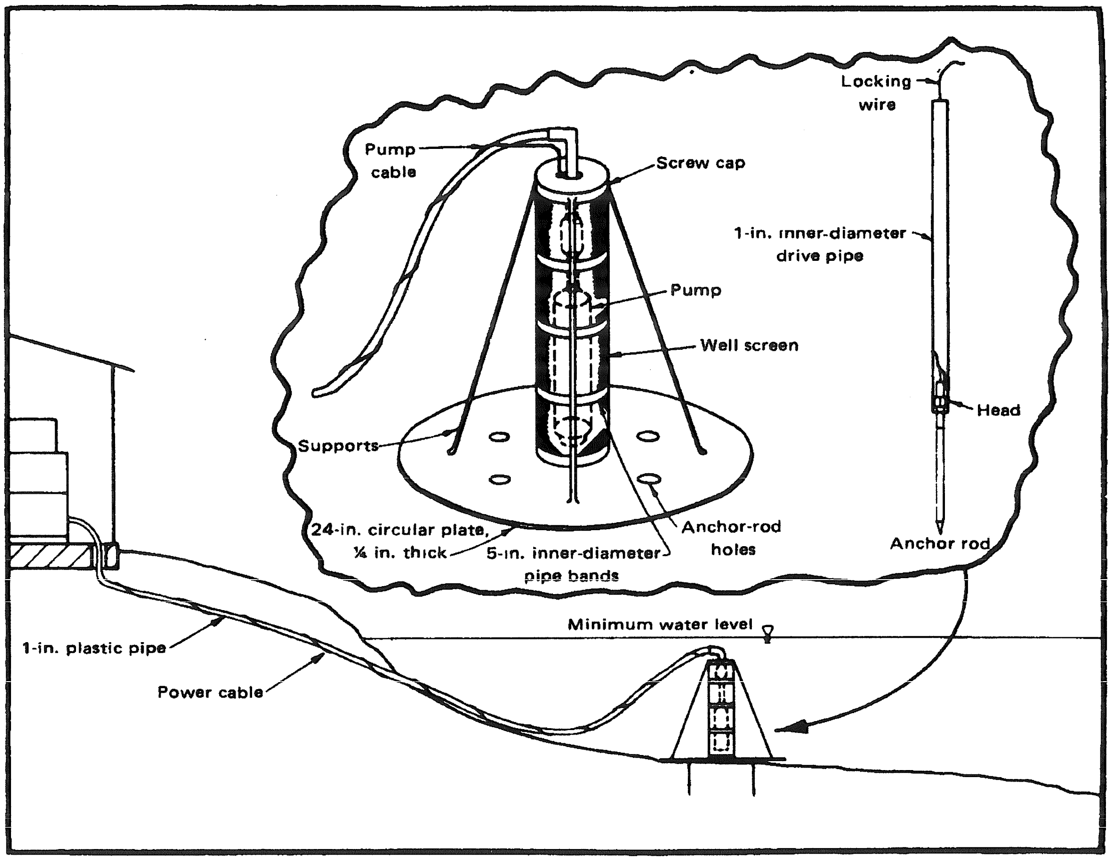


Figure 13.—Platform type of pump support. Platform is anchored by driven rods. (From Anderson and others, 1970, p. 267.)

for large channels. Once the temperature pattern is established at complex locations, the number of observations may be reduced by measuring at the most representative verticals in the cross section.

A stream cross section in which the observed temperature distribution varies over a 2.5°C range is shown in figure 16. The subsection lateral limits are positioned half way between each vertical. Normally, a location with a temperature range of this magnitude would not be selected for a temperature-measuring station, but the temperature-observation data from this cross section are ideal for demonstrating the cross-sectional computation of the average temperature, from the observations, the area-weighted mean temperature, and the discharge-weighted mean temperature.

The average temperature in the stream cross section (T_a) is the summation of the temperature observations (t_o) divided by the number of observations (n). The formula is

$$T_a = \frac{\Sigma\, t_o}{n} \,. \tag{8}$$

The area-weighted mean temperature in the stream cross section (T_{am}) is the summation of the products of the individual subsection areas (a) and average temperatures (t_a) divided by the total cross-sectional area (A). The formula is

$$T_{am} = \frac{\Sigma\, (a\, t_a)}{A} \,. \tag{9}$$

The discharge-weighted mean tempera-

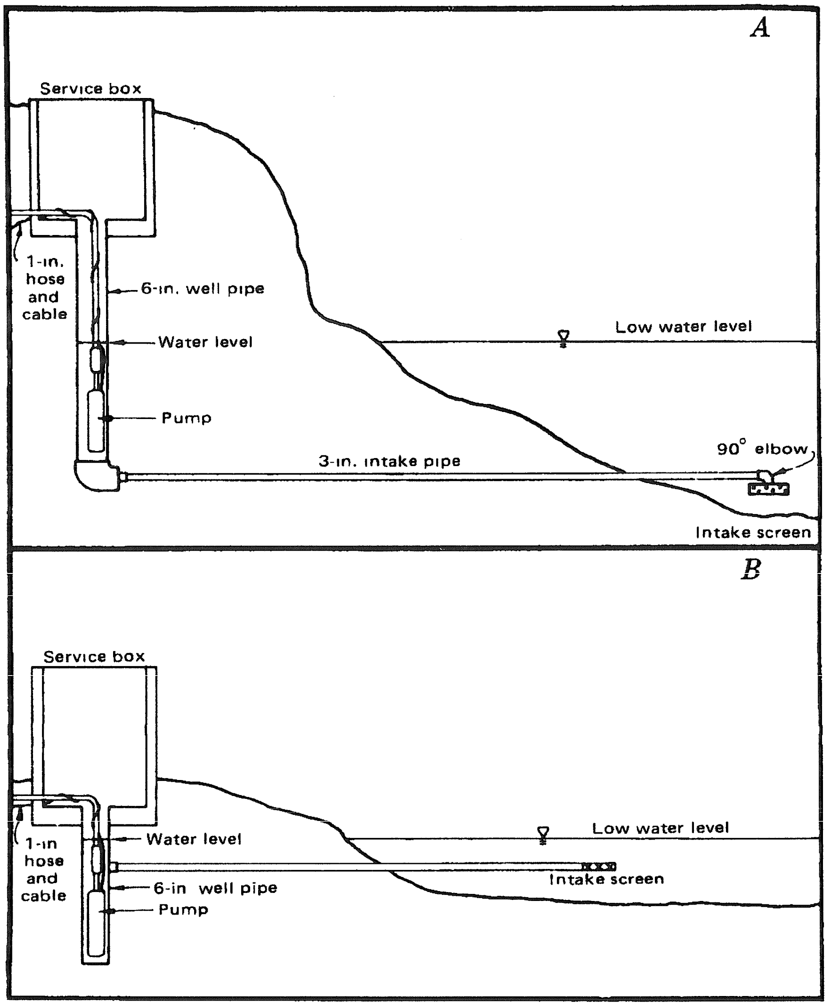


Figure 14 —Two examples of pumps supported within stilling wells. (From Anderson and others, 1970, p. 268.)

ture in the stream cross section (T_{qm}) is the summation of the products of the individual subsection discharges (q) and average temperatures (t_a) divided by the total stream discharge (Q). The formula is

$$T_{qm} = \frac{\Sigma\ (q\ t_a)}{Q} . \qquad (10)$$

An example of the computation of the cross-sectional mean temperature of a stream by the three methods is shown in table 5. The computed means, based on the data from figure 16, are 11.10°C by the observation-averaging method, 10.82°C by the area-weighting method, and 10.76°C by the discharge-weighting method. Since the differences between the means computed by the three methods are less than the 0.5°C-instrument-accuracy requirement at most locations, as in the above example, the preferred method of computation may vary among data users; however, the discharge-weighted mean is considered to be the best method to use when discharge data is available. Discharge data is readily available at

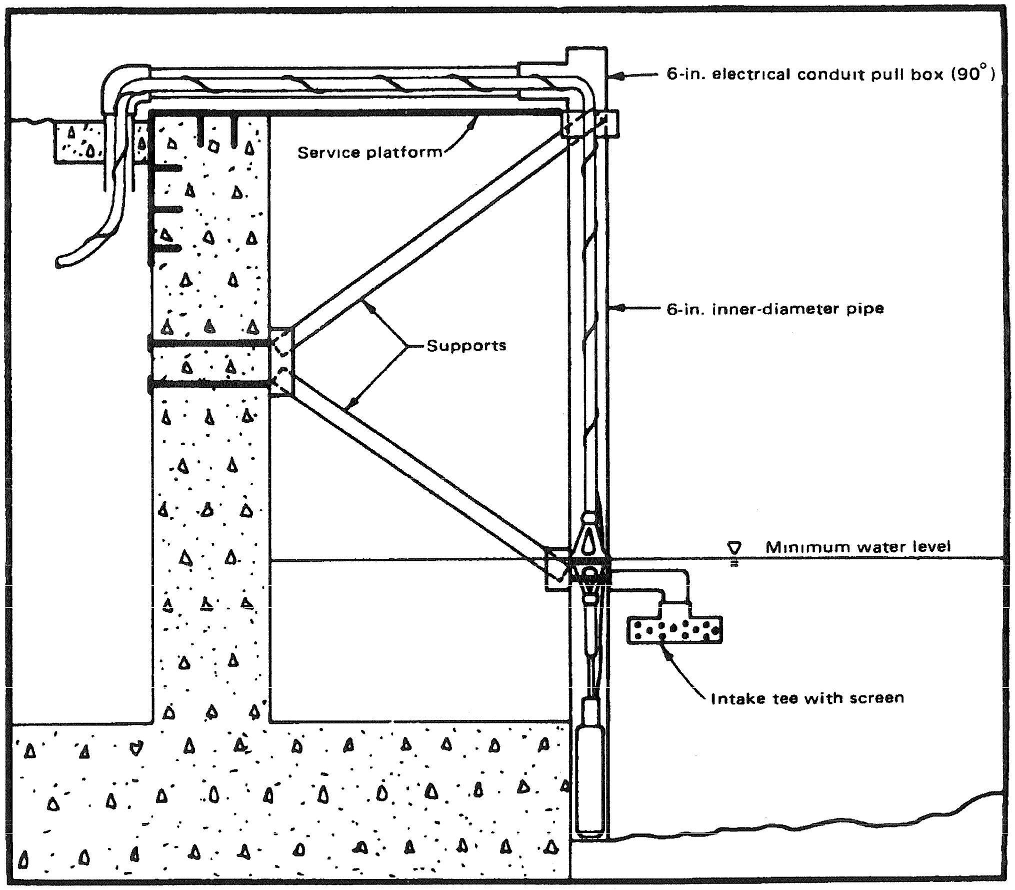


Figure 15.—Facility using bulkhead for pump support (From Anderson and others, 1970, p 269.)

temperature stations located at gaging sites, but at other locations discharge data must be obtained by measurements or indirect means. When the observation-averaging method is to be used, data should be collected at equal depth intervals rather than by equal numbers of samples. The equal-number sampling program, as shown in figure 16, biases the warmer, shallower areas.

Lakes and reservoirs

Objectives and accuracy requirements

Several applications are made of lake-temperature data; consequently, several different accuracy standards must be met. In order to determine if a lake water is suitable for swimming, water skiing, or fish-propagation, temperature-data requirements to within 1°C accuracy certainly are adequate. Unless there are reasons to consider a particularly cold or warm inflow, these requirements also can be met by a measurement at a single place on the lake surface, often near a shore point.

However, for some kinds of computations, such as evaporation measurement, much more accurate measurements of lake-surface temperature are necessary. In order to accurately compute the vapor pressure and back-radiation terms of evaporation computation it is necessary to know mean lake-surface temperature within 0.5°C or better, and it also is necessary to consider areal variations over the surface. Energy-budget computations of heat storage in a lake usually require measuring temperature at points in a vertical to an accuracy of 0.1°C.

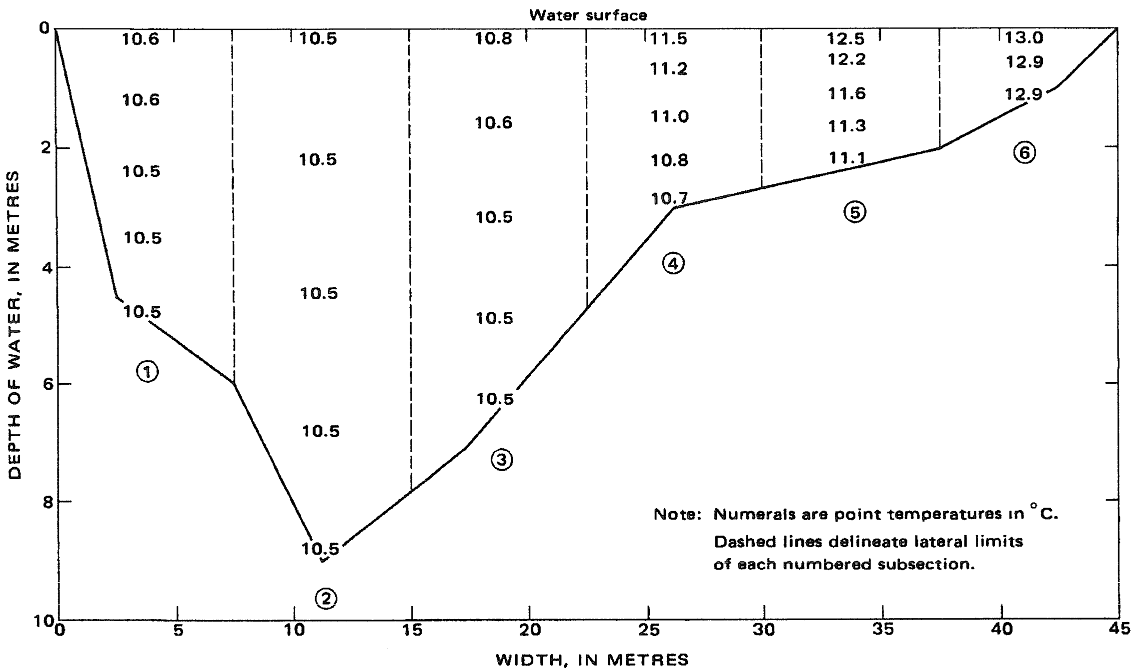


Figure 16.—Stream-temperature distribution in which the temperature varies 2.5° C throughout the cross section.

Table 5.—Computation of the cross-sectional mean temperature of a stream by three methods

Subsection No.	Mean depth (m)	Width (m)	Area (m^2)	Discharge (m^3/s)	Average temperature (°C)	Area times temperature	Discharge times temperature
1	4.3	7.5	32.2	13.5	10.54	339.39	142.29
2	7.8	7.5	58.5	34.7	10.50	614.25	364.35
3	6.4	7.5	48.0	26.4	10.58	507.84	279.31
4	3.4	7.5	25.5	12.3	11.04	281.52	141.31
5	2.4	7.5	18.0	7.7	11.74	211.32	90.40
6	1.2	7.5	9.0	2.7	12.93	116.37	34.91
Total	....	....	191.2	97.3	....	2,070.69	1,052.57
Mean temperature in °C	....	....	....	....	[1]11.10	[2]10.82	[3]10.76

[1]Average of temperature observations.
[2]Area-weighted mean
[3]Discharge-weighted mean.

Definition of mean lake temperature for evaporation computations or temperature modeling also requires a considerable degree of accuracy. Thermal stratification patterns must be measured to an accuracy of 0.1°C if such things as heat transfer through the thermocline are to be computed. On the other hand, if the only purpose of defining temperature at depth is to approximate a model or to estimate reservoir discharge temperature, measurements to within 0.5°C may be suitable.

In some lakes it is possible to ignore areal variations, particularly those lakes which are roughly circular in shape and which do not have large littoral areas. However, in a long narrow reservoir or a very large lake, or in a lake with large shallow areas near the shore, considerable variations in water temperature from place to place may be found at the surface and at depth, and these factors must be considered. If temperature modeling is to be the objective, it is necessary to define the extent of areal variations. However, for evaporation computations by the energy-budget method, it is necessary only to measure temperatures at enough different places to determine mean temperatures to an accuracy of 0.1°C.

Selection of temperature measuring system

It is obvious that the type of measuring system to be used on a lake will depend upon the kind of data being sought, the purpose for which the data are to be applied, and the accuracy requirements of the data user. The following paragraphs rather briefly describe some of the systems that can be used for measurements at a lake surface and measurements at depth, both single observation and recording.

Measurements at the surface.—Simple observations at the lake surface by an observer can be done with a hand-held thermometer. A liquid-in-glass, bimetallic, or resistance-type thermometer will fill this need. The instrument should be immersed to a depth of from 1 to 5 centimetres, allowed to equilibrate, and read with the bulb or sensing unit in place.

When it is necessary to record temperature at the surface continuously, liquid-filled, thermocouple-, or thermistor-type thermometers can be used. If the instrument is installed on a raft that is anchored on a lake, the liquid-filled system is particularly well suited because its rather short probe lead will easily reach from the raft to the surface of the water. When surface temperature is measured at the face of the dam or on a pier at a reservoir that has a considerable stage fluctuation, either the resistance-type or thermocouple-electric thermometer systems will work better because long leads can be better accomodated.

Recording at depth.—When the temperature at various depths is to be recorded, such as to define thermal stratification, either resistance- or thermocouple-type thermometers need to be employed. Several types of switching arrangements can be provided to switch from sensors at one depth to another. Below the surface, diurnal or even day-to-day changes are relatively small. Therefore, if an instrument is being used that makes only single depth measurements at intervals, it can be programed to measure below the surface at 6-hour or greater intervals. Investigators should remember that a.c. electrical power usually cannot be supplied to a raft station and that battery power must be used. Solar panels can be fitted to the raft to extend battery life between recharging.

Single observations at depth.—With proper equipment, it is relatively easy to measure the temperature at different depths of a lake for one-time or survey-type observations. These are the types of measurements commonly used in reconnaissance studies or by hydrologists making thermal surveys for evaporation measurements. The resistance-type thermometer, either recording or nonrecording, can be lowered from the side of a boat and read rather quickly at different points in the vertical. These types of instruments either can be equipped with recorders or the dial readings can be written down.

The bathythermograph (B–T) can also accomplish the job of obtaining a temperature profile from top to bottom. The B–T simultaneously measures depth and temperature by pressure transducer and by metal or liquid-filled systems. Readings are scribed on a glass plate within the instrument and must be placed in a special viewer in order to be read. Accuracy generally is within 0.5°C or better.

Oceanographic techniques can be employed to make rather precise measurements of temperatures at depth in a lake. Reversing thermometers, which are mercury thermometers equipped with a special type of curved tube, will provide readings within 0.01°C. Although these instruments are extremely precise, they must be lowered into place and brought back to the surface for each depth at which a reading is made, or several reversing thermometers may be rigged to the same sampling line. For most uses, the additional cost and inconvenience of the reversing thermometer over the resistance-type or thermocouple thermometer is not necessary to obtain desired accuracy and is not warranted.

Temperature-stratification patterns in lakes during summer seasons will almost always have warm water overlying cold water. For this reason, the maximum-minimum thermometers can be used for single observations of temperature and depth. For example, if the temperature of a lake is 25°C at the surface and its temperature at a depth of 20 metres (66 ft) is desired, the maximum-minimum thermometer can be zeroed and lowered to 20 metres (66 ft). After allowing time for the instrument to equilibrate, it can be brought to the surface, and the minimum temperature shown on the instrument can be assumed to be the temperature at depth of 20 metres (66 ft).

Site selection

No inflexible rule exists for deciding where to measure temperature on a lake surface. It is necessary to consider the shape of the lake surface, shape of the bottom, inflow and outflow patterns, accuracy requirements for the data, and prevailing wind patterns.

For most needs, surface temperature can be monitored at a single point. Generally, it is preferable to locate the monitoring instrument on a raft near the center of the lake; however, in a small lake with variable wind direction, the instrument could be mounted on a dam or at a shore installation. In a large lake, a multibasin lake, or one having a noticeable prevailing wind direction, it may be necessary to monitor temperature at more than one surface location.

When studying temperature distributions throughout a lake or reservoir, or sampling a lake for mean temperature for evaporation computations, it is generally recommended that at least 20 stations on the lake be considered. A common way of locating the stations is to divide the lake surface area into about 20 segments of about equal size and to locate one sampling station in approximately the center of each station. This will provide 20 measurements at the surface and at shallow depths but will only provide a very few measurements at or near the maximum depth of the reservoir. This technique is in keeping with accuracy requirements because there is considerably greater areal variation in temperature at or near the surface than there is at great depth.

Although a minimum of 20 stations is recommended for most studies of variations in lake temperature, in some lakes considerably fewer will suffice. Crow and Hettman (1973) analyzed data from Lake Hefner (Oklahoma) and determined that the optimum number of stations is 5, and that increasing the number from 5 to 19 resulted in an increase of accuracy of evaporation measurement of only 1 percent.

Sensor location

The sketch in figure 17 shows a raft assembly equipped with instruments for measurement at the surface and at depth, and for measurement of temperature of bottom sediment. Surface temperature is measured by a liquid-filled system having a probe only about 2 metres long. The probe is fastened beneath the raft with a device to hold it within the top 10 centimetres of the water. This instrument, located as shown, will give measurements of surface temperature with 0.5°C and will record variations continuously.

Temperatures at 6 points below the surface in the vertical are best measured by a resistance-type recording thermometer. Lead length for this type of intrument is not a critical factor, and measurements at intervals of several hours are considered to be accurate enough.

Thermocouples are suited for use in the probe set in the bottom sediments of the reservoir. A switching arrangement must be provided to measure the different thermocouple voltages at different intervals. On the instrument shown, no thermocouple reference is necessary because the deepest probe in the sediment can be considered as the reference junction. The raft, as shown in figure 17, is anchored by two different

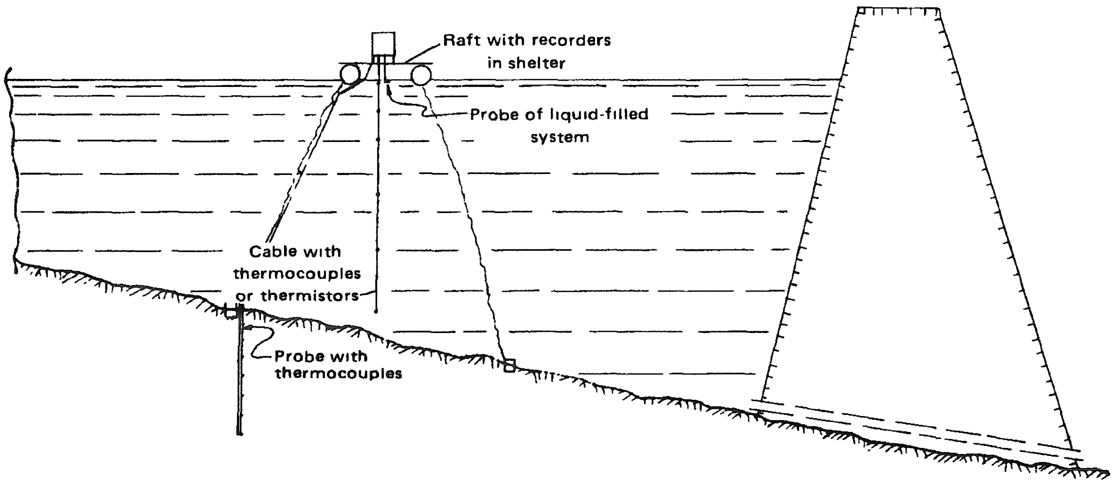


Figure 17.—Raft assembly for measuring temperature at the surface and at depth, and for measurement of temperature of bottom sediment in a lake.

anchors and anchor cables. This is necessary to avoid twisting and tangling of the wires for the depth- and sediment-temperature instruments. However, if only the surface-temperature measuring equipment is used on the raft, it may be possible to use only one anchor and anchor cable. It is desirable to include a piece of chain and swivel at the top end of the anchor cable, or a piece of chain between the anchor and anchor cable.

Equipment for measuring temperature can be mounted on the face of a dam in a manner somewhat similar to the way it is mounted on a raft. The sketch in figure 18 shows an arrangement by which a floating apparatus can be used to support a liquid-filled thermometer used to measure surface temperature only. Such an arrangement will satisfactorily provide a measure of temperature within the top few centimetres. A thermocouple or thermistor thermometer also can be mounted on the dam to measure temperature at several water depths. If there is considerable fluctuation in reservoir elevation, one or more of the sensors may be out of the water part of the time and be measuring air temperature. At a dam installation, prevailing winds may affect the data, and the temperature at the dam may not represent the mean at the surface or at different depths throughout the reservoir.

As mentioned previously, surface temperatures at a shore installation can be measured or some indication of temperature at depth can be gotten by setting instruments on a pier. Pier and shoreline installations should generally be avoided but under some circumstances may be used as the only resort. The largest potential problem of such an installation is caused by effects of shoreline currents and warming of water in littoral areas. In other words, data from a shoreline installation or from a shallow-water pier installation probably do not represent the conditions in the deeper parts of the lake.

Special procedures

Instrument calibration.—Calibration requirements for the purpose of measuring lake temperatures are very similar to calibration requirements for other uses. (See p. 28–30.) Resistance-type recording and non-recording instruments and liquid-filled systems should be compared with a high-grade mercury-in-glass thermometer. Resistance-type instruments used for temperature surveys should be calibrated at two points each time they are used and should have a complete range calibration at least twice a season. Liquid-filled recording systems should be checked against a mercury-in-glass

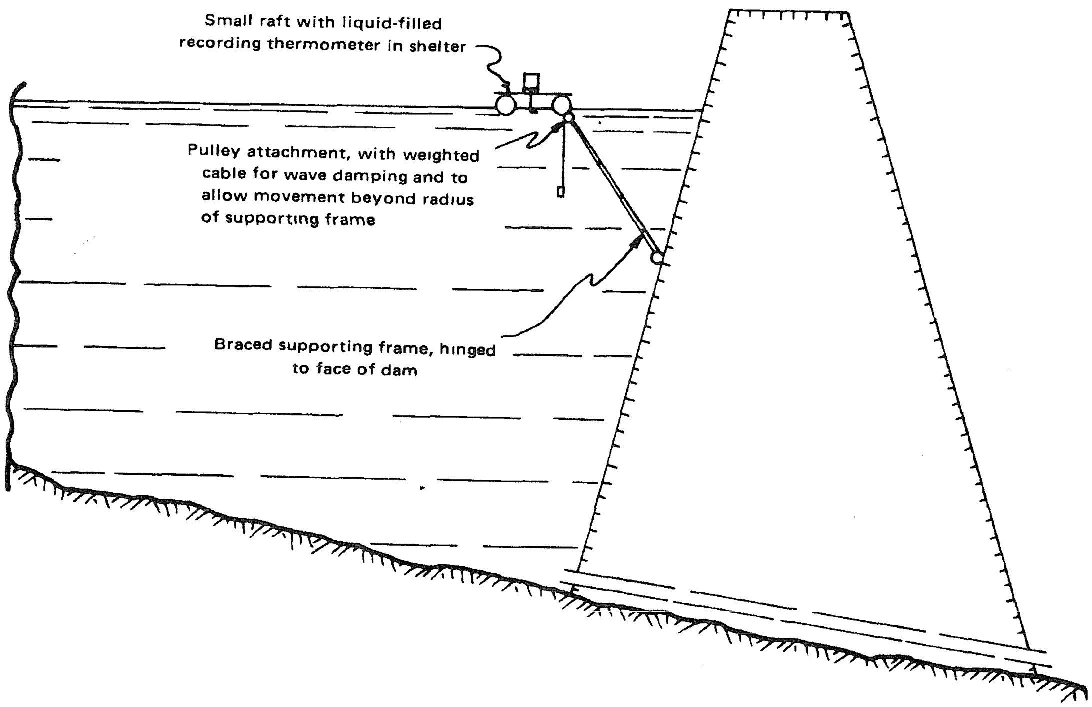


Figure 18 —Device to attach instrument raft at face of dam.

thermometer each time the chart is changed. Resistance or thermocouple units used to measure and record temperature at several depths should be compared with a profile measured with a nonrecording resistance-type thermometer.

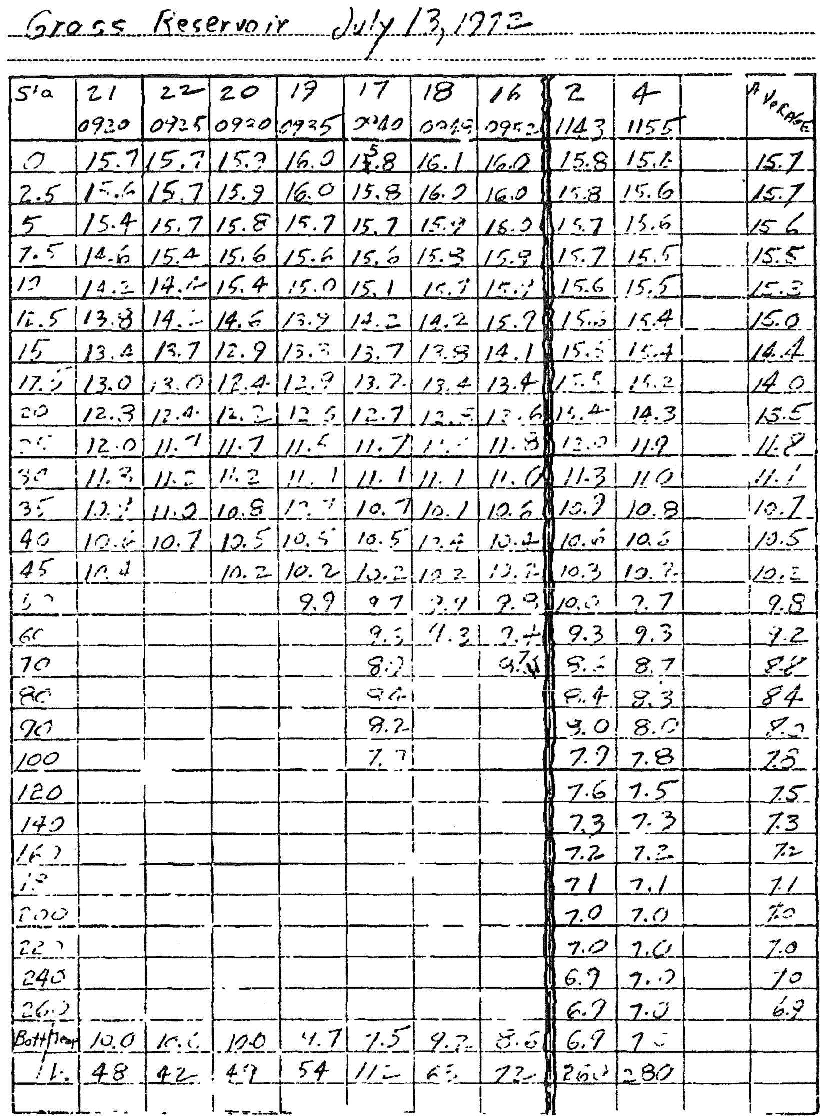
Recording instruments located on a raft or on the face of a dam should be "calibrated" to check for comparison with the mean temperature in the lake. This can be done by a 20-point survey of surface temperatures or of temperatures at surface and at depth. If data from the survey indicate that the temperature at the recording station is consistently higher or lower than the mean over the lake surface, it may be necessary to consider other points of measurement. The problem caused by a nonrepresentative station location can be corrected either by moving the station, by adding additional stations, or by establishing (if possible) a calibration relationship between the measured values and true mean temperature.

Computing mean temperature.—Many types of lake studies require that mean temperature of the water body be computed. These computations usually are made from the results of multiple-point surveys, as described earlier in this manual. Figure 19 shows part of a set of field notes from a survey of Gross Reservoir, Colo. Intervals of the depths of observations varied from 2.5 feet (0.76 m) near the surface to 20 feet (6.1 m) at greater depths. The far-right column of the note sheet has been used to show the mean temperature at each of the depths of observation.

Data from a thermal survey can be used to compute total heat storage by the relationship

$$\Theta = \int_0^H c\, T_z\, A_z\, dz, \qquad (11)$$

Θ = heat storage in the lake above a uniform base temperature of 0°C,
H = total depth,
c = heat capacity of the water, usually



Gross Reservoir July 13, 1972

Sta	21 0920	22 0925	20 0920	19 0935	17 0940	18 0945	16 0950	2 1143	4 1155		Average
0	15.7	15.7	15.9	16.0	15.8	16.1	16.0	15.8	15.6		15.7
2.5	15.6	15.7	15.9	16.0	15.8	16.0	16.0	15.8	15.6		15.7
5	15.4	15.7	15.8	15.7	15.7	15.9	16.0	15.7	15.6		15.6
7.5	14.6	15.4	15.6	15.6	15.6	15.3	15.9	15.7	15.5		15.5
10	14.2	14.6	15.4	15.0	15.1	15.7	15.9	15.6	15.5		15.3
12.5	13.8	[illegible]	14.6	13.9	14.2	14.2	15.7	15.6	15.4		15.0
15	13.4	13.7	12.9	[illegible]	13.7	13.8	14.1	15.5	15.4		14.4
17.5	13.0	13.0	12.4	12.9	13.7	13.4	13.4	[illegible]	15.2		14.0
20	12.3	12.4	12.2	12.6	12.7	12.5	13.6	14.4	14.3		15.5
25	12.0	11.7	11.7	11.6	11.7	[illegible]	11.8	12.0	11.9		11.8
30	11.3	11.2	11.2	11.1	11.1	11.1	11.0	11.3	11.0		11.1
35	10.9	11.0	10.8	[illegible]	10.7	10.1	10.6	10.9	10.8		10.7
40	10.6	10.7	10.5	10.5	10.5	10.4	10.2	10.6	10.6		10.5
45	10.4		10.2	10.2	10.2	10.2	10.2	10.3	10.2		10.2
50				9.9	9.7	9.9	9.9	10.0	9.7		9.8
60					9.5	9.2	9.4	9.3	9.3		9.2
70					8.9		9.4	[illegible]	8.7		8.8
80					8.6			8.4	8.3		8.4
90					8.2			9.0	8.0		8.2
100					7.7			7.9	7.8		7.8
120								7.6	7.5		7.5
140								7.3	7.3		7.3
160								7.2	7.2		7.2
180								7.1	7.1		7.1
200								7.0	7.0		7.0
220								7.0	7.0		7.0
240								6.9	7.0		7.0
260								6.9	7.0		6.9
Bott Temp	10.0	10.0	10.0	9.7	7.5	9.2	8.6	6.9	[illegible]		
Ft.	48	42	49	54	112	65	72	260	280		

Figure 19.—Part of a set of field notes from a temperature survey of Gross Reservoir, Colo.

assumed to be 1.0 calorie per °C per cm^3,

T_z = mean temperature over the horizontal cross-sectional area of the lake at a given level z, and

A_z = area of the horizontal cross-section at a given level z.

Solution of the above equation usually is performed by dividing the lake into horizontal layers and totaling the products of mean temperature and water volume for each layer.

Figure 20 shows a printout of the computer computation of heat storage and mean temperature in Gross Reservoir for the thermal survey recorded in the notes in figure 19.

The example shown in figure 20 uses rather unorthodox units for convenience. For example, heat storage in each computation layer is in acre-feet times °C, and total heat in the reservoir is shown as 415,715 A–F × °C.

GROSS RESERVOIR THERMAL SURVEY OF JULY 13, 1972

NOBS= 29 GHDAY= 7281.41

- DOBS = Depth of temperature observation below surface, here in feet
- GHO = Gage height (altitude) of observation, here in feet above sea level
- VOL = Volume of water in storage below GHO, here in acre-feet
- VOLINC = Volume of the layer between two GHO's, here in acre-feet
- TEMP = Observed temperature at DOBS, in °C
- TEMINC = Mean temperature in the layer between two GHO's, in °C
- HTINC = Heat in the layer (above 0°C base), here in acre-feet x °C

DOBS	GHO	VOL	VOLINC	TEMP	TEMINC	HTINC
0.0	7281.41	41568.		15.70		
			1021.		15.70	16034.
2.5	7278.91	40547.		15.70		
			1004.		15.65	15713.
5.0	7276.41	39543.		15.60		
			988.		15.55	15359.
7.5	7273.91	38555.		15.50		
			968.		15.40	14914.
10.0	7271.41	37587.		15.30		
			951.		15.15	14413.
12.5	7268.91	36635.		15.00		
			937.		14.70	13767.
15.0	7266.41	35699.		14.40		
			921.		14.20	13082.
17.5	7263.91	34777.		14.00		
			906.		13.75	12453.
20.0	7261.41	33872.		13.50		
			1764.		12.65	22319.
25.0	7256.41	32107.		11.80		
			1702.		11.45	19492.
30.0	7251.41	30405.		11.10		
			1640.		10.90	17875.
35.0	7246.41	28765.		10.70		
~~	~~	~~	~~	~~	~~	~~
160.0	7121.41	4721.		7.20		
			1582.		7.15	11313.
180.0	7101.41	3138.		7.10		
			1213.		7.05	8551.
200.0	7081.41	1925.		7.00		
			880.		7.00	6157.
220.0	7061.41	1046.		7.00		
			581.		7.00	4069.
240.0	7041.41	464.		7.00		
			340.		6.95	2362.
260.0	7021.41	125.		6.90		
			124.		6.90	858.
295.4	6986.01	0.		6.90		
			41568.			415715.

AREA= 411.7 ACRES 0.16662E 11SQUARE CM HEAT=0.51278E 15CAL

ENERGY STORAGE= 30775.CAL/SQCM AVE TEMP=10.00DEGREES C

Figure 20 —Printout of computation of heat storage and mean temperature in Gross Reservoir, Colo.

The value of total heat in storage is shown converted to 0.51278×10^{15} calories, or a mean storage of 30,775 cal/cm². Average temperature of 10.00°C was found by dividing the total heat (415,715 A-F × °C) by the volume of the reservoir (41,568 A-F).

Estuaries

Objectives and accuracy requirements

Water temperature in an estuary fluctuates annually, seasonally, diurnally, and spatially. Circulation and thermal patterns vary from estuary to estuary. (See p. 12.) Because of the complexities of the temperature gradients, a water-temperature-reporting station on an estuary is usually useful only for providing data for special localized studies, such as defining the effects of a heated discharge at a point within the estuary. Generally, the accuracy of each temperature reported should be within 0.5°C. The collection of synoptic data over tidal cycles is required to define thermal patterns near a reporting station or to define longitudinal temperature patterns within the estuary.

Selection of temperature measuring system

Any portable water-temperature-measuring system used in an estuary must be accurate to within 0.5°C and, because of the complex temperature gradients, be capable of responding to temperature changes rapidly enough to permit the measurement of complete vertical temperature profiles in a short time. Most systems that meet these requirements utilize a thermistor as the temperature-sensing element and use dry-cell batteries to supply power needs. Both recording and nonrecording types are available.

In estuarine studies, multiparameter systems incorporating measurements of temperature and conductivity are often used. Salinity data, determined from the temperature and conductivity data, facilitate the analysis of estuary circulation patterns. In the Columbia River estuary, a temperature-conductivity-measuring system and a velocity system for measuring velocity from a moving boat (Prych and others, 1967) was used to rapidly define velocity, temperature, and salinity profiles throughout the total depth. Outputs from the sensors were recorded on magnetic tape with a system that consisted of a scanning voltmeter coupled to a tape unit. This magnetic-tape data-acquisition system permitted automatic data handling but is bulky and requires a 110-volt electricity supply.

The fixed water-temperature-measuring system (thermograph) used at continuous recording stations should be stable and capable of sensing temperatures within 0.5°C for extended periods of time. Temperature-measuring systems incorporating a metallic resistance-bulb sensor are considered to be the best, and such systems can also be part of a multiparameter water-quality data-collection system. (See p. 32, under "Streams.")

Site selection

Most estuary water-temperature stations are located at special study sites, and the instruments are mounted on existing structures. For water temperatures at a station to most represent the thermal patterns in an estuary, the station should be located in a central location where the flow is relatively deep and fast. Tidal flats and other areas where velocities and depths are low exhibit the greatest diurnal and wind-induced temperature fluctuations (p. 13).

Sensor location

Sensors for water-temperature or two-parameter (water temperature and specific conductance) measuring systems are usually housed in a perforated pipe mounted directly in the water, whereas sensors for multiparameter water-quality data-collection systems (including the temperature sensor) are most often housed in a flow-through chamber which receives a continuous supply of water from a submersible pump. The proper placement of the sensor and (or) pumping systems are described in the section on streams. (See p. 32–33.)

Vertical temperature gradients can be defined with multisensor or multipump-intake systems at several points in the vertical. Anderson, Murphy, and Faust (1970) used motor-operated ball valves to direct the inflowing sample from different points in the depth to the sensor unit. Cory and Nauman (1968) used a multiparameter system that had a floating pump with an intake 1 foot below the water surface and a temperature sensor fixed 1 foot above the bed. When multisensor or multipump-intake systems are used, digital recorders coupled to programable servo-drive mechanisms are used for recording each sensor output. (See p. 28.)

Special procedures

Temperature sensors are nearly trouble free; however, in the saltwater environment of an estuary, continuous maintenance is required to insure proper operation of recorders and other types of sensors (Nauman and Cory, 1970). Condensation of water vapor in the marine environment causes a salt film to deposit on all equipment. The salt accelerates corrosion of mechanical parts and electrical contacts, thereby creating mechanical binding and increased electrical resistance (Bromberg and Carames, 1970).

Observers should follow the same maintenance and calibration procedures as given in the section on streams (p. 33). An estuary station will require more frequent servicing, including the washing of sensors with freshwater to prevent the buildup of salt deposits, to assure the collection of continuous and accurate temperature data. The complex temperature gradients prohibit the determination of the mean cross-sectional water temperature in most estuaries; however, the thermal patterns near the reporting station may be defined by the collection of synoptic profile data over tidal cycles.

Ground water

Objectives and accuracy requirements

As with streams, lakes, and estuaries, the accuracy required for ground-water-temperature measurements depends upon the intended use of the data. If the measurements are made to determine suitability of the water for domestic, municipal, or industrial use, an accuracy of 1°C is adequate. A standard laboratory mercury thermometer that is accurate to 0.5°C can be used for this purpose. Other more sophisticated instrumentation generally used in ground-water studies is usually accurate to less than 0.1°C (Sass and others, 1971).

In many studies that involve determining rate and direction of ground-water movement from temperature data, the accuracy of the absolute temperature is not of great importance, but a high level of precision is needed to accurately measure temperature gradients. It is possible under ideal conditions to measure water temperature with a precision of 0.0005°C. However, a practical limit for the precision of water temperatures measured in boreholes has been found to be about 0.01°C (Sorey, 1971). This appears to be adequate for most purposes. If higher precision is required, it may be attainable by using extreme care both in calibration of the temperature detector and in application to field use.

Selection of temperature measuring system

The kind of measuring system to use will depend upon the problem at hand, the accuracy requirements, the frequency of sampling, and the location of the data points. In some instances, it may be desirable to install a temperature recorder. In other instances, a single measurement at a given location is adequate.

There are several different ground-water temperature detectors, including, for example, mercury thermometers, thermocouples, and resistance thermometers. The thermistor, and type of resistance thermometer, is frequently used in borehole thermometry. Perhaps the simplest and least expensive equipment for measuring ground-water temperature with accuracy sufficient for many purposes is the mercury thermometer. A standard laboratory partial-immersion mercury thermometer can be used to measure the temperature of water discharging from wells or springs.

A good device for temperature measurements just below the water table in boreholes or wells is the maximum-minimum thermometer (p. 24), which costs only a few dollars, is readily available, and is easy to use. It is especially useful for reconnaissance work, in which an accuracy of about 0.5°C is adequate and only one or two readings in a well are needed. One disadvantage is that continual raising and lowering of the thermometer to get readings at different depths becomes tedious and tends to disrupt the thermal stratification of water in the well. The possibility of thermometer breakage presents a pollution hazard. In addition, thermometers of this type are pressure sensitive, so measurements taken at depth may be significantly in error. To avoid this effect, the thermometers can be placed in a pressure tube, sealed to prevent entrance of water (Birch, 1947.)

A commonly used system for borehole-temperature measurements consists of a multiconductor cable and hoist, a probe that contains a temperature transducer, and a resistance-measuring system. The multiconductor cable and hoist can be hand or power driven, depending upon the depth to which temperature measurements are to be made. The location of the probe below land surface is obtained from a depth indicator located on the reel. Temperature transducers usually consist of a number of thermistor beads encased in a probe some 6 inches (15 cm) in length and 1 inch (2.54 cm) in diameter. The thermistors are arranged to give maximum sensitivity and preferably, but not necessarily, a linear output. The linear output allows one to read the temperature directly in degrees Celsius. The thermistors are semiconductors which have a large temperature coefficient of resistance (about -4 percent/°C). It is this fact which is the principle behind their use as temperature detectors; hence, some variation of the Wheatstone bridge is often used to measure the resistance across the thermistors. Details of a typical arrangement for temperature measurement in wells are given by Sass and others (1971). Units adequate for most purposes are available commercially at a cost of about $200 (Olmsted, oral commun., 1973).

The logging unit just described has advantages over the maximum-minimum thermometer in that many more measurements can be taken in a shorter period of time with a much higher degree of precision. Thermal stratification of water within the well is less likely to be upset as the probe is lowered slowly and is not pulled back to the surface to get a reading.

The amount of time needed to attain a stable reading at any given point depends upon the distance from the surface, where the temperature gradient is steepest, and upon the heat capacity and initial temperature of the probe. Usually, 1 to 3 minutes is adequate.

A thermistor probe device that may be used to provide a continuous log of temperature with depth is also available (Keys and Brown, 1975). The device detects temperature-related resistance changes in the thermistor through a voltage-controlled oscillator. The pulses may be integrated by a rate meter to provide an analog record of pulse counter. The probe used by Keys and Brown is electrically and thermally stable, and they were able to repeat temperature measurements in a borehole with 0.02°C.

Site selection

Ground-water temperatures may be measured in unused wells, pumping wells, discharging springs, mines, or any other accessible location, depending on the purpose of the measurements. Usually, for reasons of cost, the hydrologist is restricted to collecting data at existing sites or installations.

If a temperature profile in a well is to be measured to study slowly moving ground water, considerable care must be taken in selecting the observation well. It is preferable that the well be idle for a number of years and that it not be disturbed in any way. There should not be any circulation within the well bore, such as from one screened interval to another, or along the outside of the casing. Wells that have been backfilled with cement should be avoided because cement, upon curing, generates heat for years after installation. This generated heat may be of sufficient magnitude to upset the local thermal gradient. A metal well casing may distort the local temperature profile because of its high thermal conductivity. Another important consideration is the well diameter, because thermal gradients will induce vertical convection in the fluid within the well bore of large-diameter wells (Sammel, 1968).

Preferably, the wells should be 2 inches (50.08 cm) or less in diameter for a temperature profile.

Despite the apparent violation of many of these considerations, Sorey (1971) obtained satisfactory results from many wells. Just the same, it is wise to keep these points in mind when planning a ground-water-temperature study.

More reliable results probably can be obtained by using wells especially designed for temperature measurements. Again the design will depend somewhat upon the purpose for which the data are to be used. For most studies, wells should be drilled below the depth of seasonal-temperature variation as well as below it. (Such data may provide useful information, such as thermal diffusivity of the near-surface materials and whether local ground-water recharge is taking place.) A plastic pipe with no perforations, either sealed at the bottom or fitted with a well point and a screen, may be used. Plastic has the advantage that its thermal conductivity more closely represents that of the natural porous medium than does steel. A well point and screen are used if it is desired to measure water levels.

The annulus between the well and casing should be backfilled with a material other than cement that prevents the circulation of water. A soil that contains clay may bridge and cause gaps in the annulus.

If the casing is sealed at the bottom, it is filled with water to the desired level. This may be above the water table if measurements of temperature in the unsaturated zones are desired.

A newly drilled hole usually upsets the thermal regime in the vicinity of the well because of the drilling process. This may result in the generation of heat by friction or, in a thermal area, may cool rather than heat the materials near the hole by rapid circulation of the drilling fluid. It is best to monitor the temperature profile after completion of the drilling to determine when it has come into thermal equilibrium with its surroundings. This may take from days to months, depending upon the thermal properties of the materials and the degree by which the thermal regime is upset.

Sensor location

When measuring the temperature of discharging wells or springs, placement of the sensor generally presents little problem. Care must be taken to avoid extraneous effects, such as heat exchange between water and the pump or the atmosphere (Schneider, 1962).

When taking a temperature profile in a well, the sampling interval must be decided upon. This depends primarily upon the thermal gradient in the well. Steeper gradients require a shorter distance between measuring points. A 10-foot (3-m) interval will provide sufficient data to accurately represent the thermal profile in most instances, but, if it is desired to relate the thermal profile with lithology, a 2-foot (0.6-m) interval may be necessary.

The depth to which temperature measurements should be made depends upon requirements of the problem. To be in the range of the geothermal gradient undisturbed by seasonal-temperature fluctuations, measurements should be made below about 20 m (66 ft). Above about 10 m (33 ft), the influence of surface temperature produces high thermal gradients that cause instability in all but very small diameter wells.

Special procedures

Mercury thermometers require little maintenance, but thermistor temperature-measuring systems require considerably more. Batteries, electronic equipment, and electrical connections in these systems invariably require checking to insure that they are in good working order. The thermistor probes should be checked to see if their response has changed because of thermal shock, aging, or other factors. The probes should be checked frequently for leaks, as water will make a thermistor inoperative. See additional material in the subsection on operation, maintenance, and calibration of instruments (p. 28–30).

Commercially available temperature-detecting units are calibrated at the factory. However, precision required in ground-water-temperature measurements is often such that recalibration is necessary. The systems used by Sorey (1971) were calibrated with platinum resistance and mercury thermometers to a precision of 0.005°C. Thermistor probes tend to be very stable with passage of time if properly cared for. They have drift rates of about 0.01°C/yr or less and, hence, need recalibration only occasionally.

Part 3. Data Presentation

Observation and monitoring schemes described in earlier parts of this report provide new data in a relatively crude form. Single observations by an observer or a fieldman may be penciled notes in a fieldbook or on observer forms. Charts from analog-type recorders are simply an inked or scribed line on a piece of paper. Digital recorders will produce either a magnetic or a punched tape, which is difficult to read or totally unintelligible and unusable without special processing.

On the other hand, the user of temperature data requires information in a more usable and more interpretable form. Publication of raw data is common and must be in a form that is suitable to a rather wide variety of users. Research data often have special format needs, but, again, the purpose is to provide the information in a form that it can be put to the best use.

This section presents information on the reduction of raw field data, application of corrections, and forms of publication.

Reduction and correction

An ideal temperature-measuring system would produce data ready to publish without exerting additional effort. However, considering the state of the art of instrumentation today, this dream is probably not to be realized for some time.

The job of reducing temperature data breaks down into two basic operations—removal of error caused by imperfect equipment and conversion of the recorded instrument output to numeric values. The procedures differ with types of equipment, but the following discussion is designed to provide some general guidelines.

Correcting instrument error

Perfectly operating instruments that are serviced by a careful operator generally require very little correction in their record. Realistically, however, there are errors that creep into all the records, owing to drift of the instrument or to failure of different parts of the mechanism, such as the timing devices. The most common error probably is drift between servicing. An instrument may be left operating in good calibration but will drift out of calibration over several days of operation. This is the reason that it is important to make a calibration check of an instrument before it is readjusted.

Figure 21 shows two examples of the type of error that may be found when an instrument is calibrated. Constant error through the calibration range is most common, with a displacement of the same number of degrees at all temperatures. Nonuniform error is not so common but is found frequently enough that the two-point calibration is justified. (See p. 28.) Not shown, but also possible, is a curvilinear calibration whereby an instrument is nearly in calibration over part of its range, but deviates significantly in another part. This type of error is rather infrequent and, therefore, generally does not justify calibrating at more than two points in the instrument range.

Corrections can be applied to the records of analog recorders at the same time the records are reduced. If a constant error of 2°C is found at the end of a 2-week period, and if the instrument was in adjustment at the beginning of the period, the 2°C error should be prorated over time, in increments of 0.5°C. Nonuniform error over the calibration range is a little more difficult to correct, and the correction usually is best applied by assuming a constant rate of drift at each end of the calibration curve. For example, if the nonuniform error shown in figure 21 developed over a period of 2 weeks, the 2°C error at 15°C could be assumed to have been 1°C at the end of the first week.

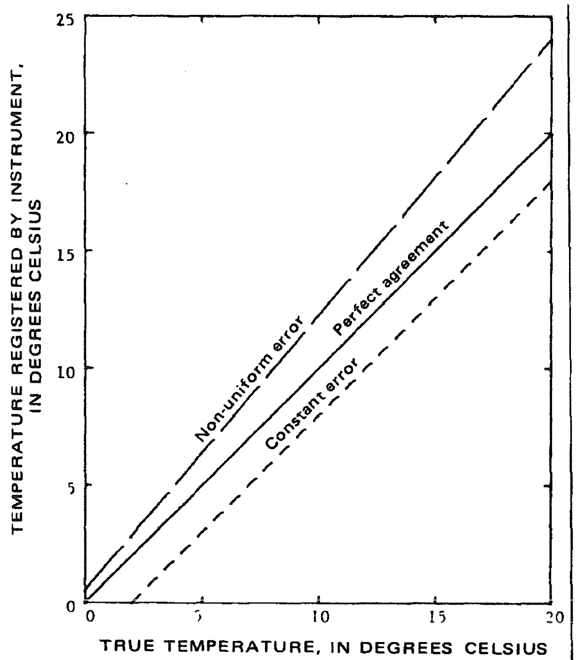


Figure 21.—Types of thermometer calibration curves.

Records from digital- and magnetic-recording instruments are corrected in many different ways, depending upon the types of programs available. The systems are too complex and too widely varied to allow detailed discussion in this report. However, everyone who prepares programs for reducing the data from these types of instruments should (1) provide for correcting uniform and non-uniform errors over the range of the instrument and (2) provide for time distribution of the error over the periods between times of calibration of the instrument.

Faulty timers, skipped punches, and other equipment weaknesses frequently cause time errors in recorded data. These usually are corrected by assuming that the drift took place at a constant rate between the times the instrument was serviced. For example, an instrument that was found running 2 hours slow after 2 weeks of operation would be assumed to have lost time at the rate of about 8.6 minutes per day. An instrument found with it's clock stopped generally is assumed to have operated on time until the clock stopped. The most difficult problem to correct probably is the one caused by a clock which stopped and then restarted during the period of operation. This phenomenon is rather common in cold weather. Unless correlations with other kinds of data can be provided to determine approximately when the clock stopped and started, there is no good way to correct the record.

Although temperature corrections can be complex, they are rather easy to apply. For example, if daily mean temperatures are being determined, the daily range is relatively small, and the rate of drift is linear, corrections can be applied directly to the mean without breaking down the record on an hour-by-hour basis. On the other hand, if the temperature records are being used to determine such things as the mean temperature of a lake, the vertical temperature curve should be corrected before the weighting according to volumes at different temperatures is made.

Data reduction

Conversion of chart traces, punched tapes, or magnetic signals to numeric values falls under the general title of data reduction. Magnetic and punch tapes have the advantage of being machine reducible, but a cretain amount of editing and error correction almost always is necessary. Programs for reduction by machine are complex and vary too much from one machine to another to discuss in considerable detail here. Most include provisions for correcting recorder error and for editing data when pieces are missing or questionable. Most programs for reduction by machine allow for listing data for short intervals, determining daily means, and listing daily maximums and minimums. In principal, they are not unlike the procedures for reduction of chart records by hand, as described in the following paragraph.

Chart data often can be reduced rather rapidly if the instruments record at a workable scale suitable to meeting the intended format of the report. For example, a chart record obtained in order to determine daily maximum and minimum, and mean, can

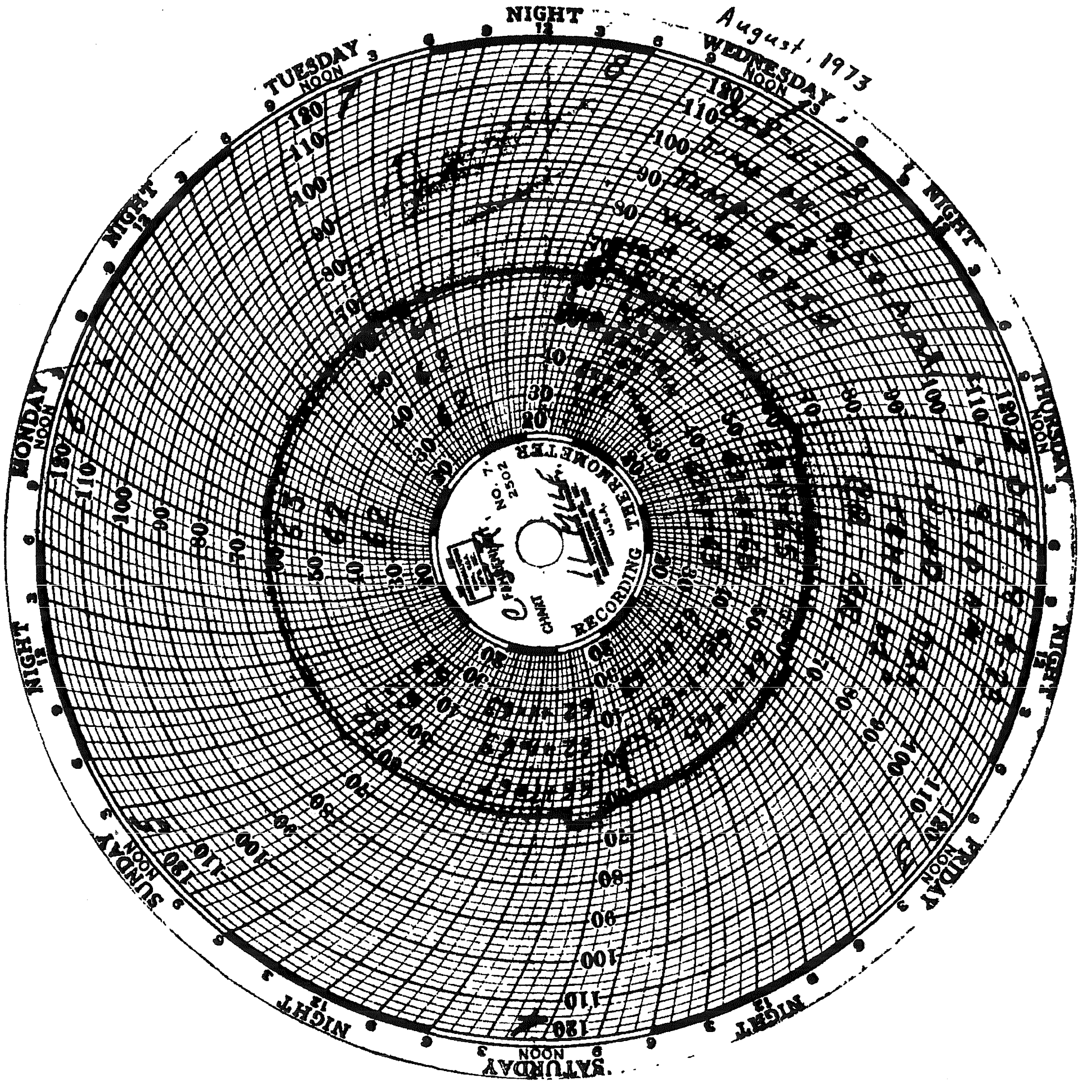


Figure 22.—Circular chart showing data reduced by hand for daily maximum, minimum, and mean temperature.

operate at a relatively slow speed. Figure 22 shows a circular chart from which the data have been reduced for daily maximum, minimum, and mean. Daily fluctuations are relatively small, and the mean can be determined rather quickly by inspection of the chart.

When data on a body of water are collected by several recording instruments or by observations at several sites, the reduction of data from each recording instrument should be treated separately. Procedures for computing mean temperature in a cross section or in a lake, or for making analyses of the data are included in the earlier section of this report on field applications (p. 34) or in the following subsection on publications.

Presentation and publication

What to publish

There obviously is great variability in the needs for temperature data. As a consequence, there will be a rather broad set of rules as to what type of data the investigator should present to his readers. Research or interpretive reports often contain a great deal of data from a relatively small area, such as a reach of stream, a lake, or an estuary. Investigators may wish to show that streams have diurnal or cross-sectional variation and to report these, but in other streams simple daily means may be adequate to represent the phenomenon they are discussing. Temperatures in estuaries vary in three spatial dimensions and in time. They are extremely complex to report if the whole four-dimensional picture is to be presented. In ground-water studies, the long-term variations are often important, but, at times, the simple variations with depth adequately represent what the investigator is trying to show. At times, very very small temperature differences are important in ground-water studies, but the actual temperatures of the water are relatively unimportant.

Lakes, like estuaries, may need to have differences shown in three dimensions and over either short or long time periods. For other types of needs, lake reports may need to show only mean surface-temperature data.

Data reports representing information on many stations are different from the research reports in that they often have to compromise and present information for someone else's interpretation. The researcher in writing a paper on temperature can choose which data are relevant to the phenomenon he is demonstrating, but the person preparing a data report should arrange the data so that they can be interpreted by someone else. User needs are important but are widely variable. Data reports, because they contain a great deal of material, often must consider economy of preparation and presentation. It also is important that the information contained in data reports represent field conditions and show anomalous conditions, such as unusually hot or cold spots.

The following paragraphs present some guidelines that might be used in deciding what types of temperature data to be published.

Stream temperatures.—If diurnal variations and variations in the cross section at the measuring station do not exceed 2.0°C more than 5 percent of the time, publish time-weighted daily mean temperatures. Report to the nearest 0.5°C.

If diurnal variations are greater than 2.0°C more than 5 percent of the time, publish maximum, minimum, and time-weighted mean temperatures for each day. Report to the nearest 0.5°C.

If cross-section temperatures at a stream station vary more than 2°C for more than 5 percent of the time, publish records for more than 1 measuring point (p. 32), and treat each record as a separate station record. Use the 2°C-diurnal-variation criterion stated previously in deciding whether or not to publish maximum and minimum values for the day.

In the case of multiple channels, where sufficient data are available, report temperature measured in each channel and the discharge-weighted mean. The format shown in figure 23 may be used to present data from a stream with measurements in two different channels. Note that the table allows for reporting maximum and minimum at station 2 where the diurnal variation is greater than 2.0°C. The right-hand column on the table is used to report the discharge-weighted mean temperature for the cross section. This type of presentation allows the showing of extreme data in a divided channel; it also presents heat-load data which may be important.

Temperature-profile data collected in a stream cross section may be included as a supplementary table in the report or (as noted in the report) held in the files for inspection. The format shown in figure 24 may be used to present data comparing temperature at the sensor with maximum, minimum, and mean values in the cross section.

Many periodic or nonrecording data are collected on streams by investigators, hydrographers, and observers. These data should be presented as they are recorded and not be assumed to be mean daily or mean cross-sectional data. Proper qualifications should be made in the report to describe how the data were collected. If a tabular form of presentation is used, reporting of time of observation should be considered if there is reason to believe that the temperature has a diurnal

Date	Water temperatures in °C				
	Station 1 mean	Station 2			Discharge-weighted mean
		Maximum	Minimum	Mean	

Figure 23.—Tabular format for presenting stream temperatures from two measuring stations in a cross section. Station 1 has a diurnal variation less than 2°C, and station 2 varies more than 2°C at least 5 percent of the time.

Date	Discharge (cfs)	Width (ft)	Mean depth (ft)	Water temperatures (°C)			
				In cross section			At thermograph sensor
				Maximum	Minimum	Mean	

Figure 24.—Tabular format for comparing temperatures at the sensor with maximum, minimum, and mean temperatures in the cross section.

variation. Formats of presentation are discussed in the subsection that follows, and examples are given in figures 28 and 29.

Lakes and reservoirs.—Report the surface temperatures measured at a raft or shore station, with a description of the site where the data were collected. Report as daily mean temperature to the nearest 0.5°C. If diurnal variations at the station are greater than 2.0°C for 5 percent of the time or more, report maximum, minimum, and daily mean temperatures.

If conditions on the lake require more than one recording station for surface temperature, report the data from each station separately.

When subsurface temperatures are recorded on a continuing basis, report only as daily mean temperatures at the depth of observation. Occasionally, large variations may occur from internal waves (vertical movement of the thermocline); however, these data are generally not valuable to the data user and should not be reported.

Intermittent measurements of lake temperatures at several stations and several depths are common, such as with thermal surveys. These data should be published as they are collected, reporting to the accuracy of the temperature-measuring system (usually to the nearest 0.5° or 0.1°C). If areal variations in the lake are relatively small, it often is possible to combine the measurements from several stations into one mean vertical profile of lake temperature.

Estuary temperatures.—When temperature in an estuary is measured at a single station, criteria for reporting data are basically the same as for reporting data in streams. That is, if diurnal variations and variations in the cross section at the measuring station do not exceed 2°C more than 5 percent of the time, publish daily mean temperatures. Report to the nearest 0.5°C. Generally, diurnal fluctuations will be greater than 2.0°C more than 5 percent of the time, in which case publish maximum, minimum, and daily mean temperatures. Report to the nearest 0.5°C.

If an estuary station records temperatures at more than one level or at more than one point in the estuary, report each point of measurement as a separate table of data, or combine into the same table using a format similar to that shown in figure 23. The discharge-weighted mean column shown in figure 23 will not apply to an estuary situation.

If temperature profiles have been measured in an estuary cross section, include those data as a supplementary table in the report.

Periodic or spot measurements of temperatures normally are not collected at an estuary site, because they do not have a great deal of value unless they are related to the variations with time and space. As a general rule, do not report periodic or spot measurements made at an estuary station.

Ground-water temperatures.—The safest rule to follow in reporting ground-water temperatures is report all data. The variations in temperatures from the top to the bottom of a well may be considerable, and sufficient recorder-chart data to define the temperature variation or all of the point-measurement data should be shown. The same is true in reporting data from several different wells. Do not attempt to average data from several different wells; rather, report them on a map or in a table.

Tabular format

Usually it is easier and more economical to publish temperature data in tables than in any other format. The formats are easy for readers to grasp, tables can often be compiled by computer and printed from computer copy, and hand-typed tables can be typed on preprinted columnar formats.

A previous subsection of this report outlined criteria for selection of the kind of data to publish. The examples and brief discussions that follow are designed to guide the investigator in presenting those data in tabular form.

Daily values.—Figure 25 is an example of the format used in the data reports on water quality published for each state by the U.S. Geological Survey. Note that the headnotes of the table show details on the period of available record, extremes, and other remarks. The record shown is part of a continued table

PLATTE RIVER BASIN

06764000 SOUTH PLATTE RIVER AT JULESBURG, COLO.--Continued

EXTREMES, 1970-71.--Continued
Water temperatures: Maximum, 21.0°C Aug. 22, 23; minimum, freezing point on many days during December to March.
Period of record.--Specific conductance: Maximum daily, 3,270 micromhos Jan. 12, 1971; minimum daily, 348 micromhos Aug. 15, 1968.
Water temperatures (1946-49, 1950-71): Maximum, 34°C July 28, Aug. 1, 1953, July 7, 18, 1963; minimum, freezing point on many days during winter period.

REMARKS.--Samples for specific conductance and temperature collected from channel no. 2 (06763990). For monthly chemical analyses considered applicable to this site, see record for South Platte River near Julesburg, Colo. (sta. 06764200).

TEMPERATURE (°C) OF WATER, WATER YEAR OCTOBER 1970 TO SEPTEMBER 1971

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	14.5	4.5	4.5	1.0	1.0	3.5	6.5	10.0	8.0	11.0	10.0	11.0
2	12.0	3.5	2.0	0.0	0.0	2.0	12.0	4.5	9.0	14.5	14.5	12.0
3	14.5	2.0	3.5	0.0	1.0	1.0	10.0	5.5	10.0	10.0	9.0	15.5
4	13.5	3.5	1.0	0.0	0.0	4.5	6.5	5.5	9.0	13.5	8.0	10.0
5	13.5	3.5	1.0	0.0	0.0	4.5	5.5	4.5	8.0	11.0	8.0	15.5
6	13.5	4.5	4.5	0.0	0.0	4.5	12.0	2.0	10.0	11.0	8.0	20.0
7	9.0	10.0	3.5	1.0	0.0	0.0	9.0	2.0	6.5	12.0	6.5	14.5
8	4.5	5.5	2.0	0.0	0.0	0.0	14.5	4.5	9.0	8.0	8.0	5.5
9	5.5	4.5	3.5	0.0	1.0	8.0	15.5	4.5	8.0	10.0	8.0	11.0
10	8.0	4.5	1.0	0.0	4.0	8.0	11.0	4.5	8.0	9.0	14.5	5.5
11	8.0	9.0	1.0	0.0	3.5	6.5	10.0	1.0	8.0	15.5	9.0	8.0
12	6.5	6.5	1.0	0.0	2.0	4.5	12.0	2.0	10.0	11.0	10.0	10.0
13	10.0	8.0	0.0	0.0	4.0	8.0	15.5	4.5	9.0	10.0	10.0	4.5
14	9.0	4.5	0.0	0.0	5.5	2.0	11.0	4.5	8.0	10.0	18.0	4.5
15	5.5	2.0	2.0	0.0	5.5	3.5	18.0	4.5	5.5	13.5	9.0	4.5
16	4.5	3.5	0.0	1.0	4.5	4.5	14.5	10.0	5.5	10.0	10.0	4.5
17	12.0	4.5	1.0	0.0	3.5	10.0	15.5	9.0	10.0	11.0	10.0	3.5
18	8.0	8.0	1.0	1.0	4.5	4.5	15.5	4.5	10.0	13.5	11.0	9.0
19	10.0	8.0	0.0	0.0	4.5	1.0	13.5	2.0	12.0	8.0	10.0	9.0
20	9.0	2.0	0.0	1.0	3.5	4.5	13.5	4.5	12.0	9.0	10.0	4.5
21	10.0	4.5	0.0	1.0	1.0	5.5	15.5	10.0	11.0	10.0	9.0	13.5
22	10.0	3.5	0.0	1.0	0.0	4.5	10.0	8.0	14.5	9.0	21.0	10.0
23	10.0	0.5	0.0	1.0	0.0	2.0	9.0	5.5	12.0	9.0	21.0	6.5
24	9.0	2.0	0.0	1.0	0.0	1.0	13.5	4.5	14.5	9.0	9.0	10.0
25	9.0	4.5	0.0	0.0	5.5	1.0	10.0	5.5	14.5	10.0	10.0	12.0
26	5.5	4.5	0.0	2.0	3.5	12.0	4.5	5.5	13.5	6.5	12.0	11.0
27	5.5	4.5	1.0	0.0	0.0	14.5	6.5	5.5	11.0	8.0	10.0	12.0
28	6.5	4.5	0.0	4.5	0.0	4.5	9.0	5.5	10.0	8.0	15.5	13.5
29	9.5	3.5	1.0	2.0	---	9.0	11.0	6.5	9.0	6.5	11.0	11.0
30	12.0	4.5	1.0	4.5	---	8.0	3.5	6.5	10.0	4.5	11.0	13.5
31	4.5	---	0.0	1.0	---	15.5	---	5.5	---	6.5	10.0	---

Figure 25.—Tabular presentation of daily mean temperatures in a stream (From U.S. Geological Survey, 1972, p 24.)

which showed records of specific conductance on a previous page. The previous page of the table also contained details on station location and drainage area. Sizes of differences in day-to-day temperatures shown in figure 25 suggest that maximum and minimum daily values should be shown for this station in order to satisfy the 2°C variation criterion specified in this manual.

Figure 23 showed an example of a tabular format for showing maximum, minimum, and mean daily temperatures for stations having diurnal variations of more than 2°C. In contrast, figure 26 is an example of a table showing only maximum and minimum values for each day and is a less desirable format than the one shown in figure 23. The example in figure 26 shows a simple way of reporting data for more than one data point (surface and bottom), but when using such a technique the writer should be careful to define where the measuring points are located.

Daily values of temperature measured at several levels in a reservoir are shown in the example in figure 27. Values shown in the example are readings taken once a day rather than daily means, and the time the readings were made is also shown.

Observations at irregular intervals.—Temperature of streams, lakes,

STATISTICAL SUMMARIES

UNITED STATE

GEOLOGICAL

TABLE 1.—WATER QUALITY AT PATUXENT RIVER BRIDGE, MARYLAND

	DATE			TEMPERATURE DEG C SURFACE		BOTTOM	
WEEK	MO	DA	YR	MAX	MIN	MAX	MIN
01	01	01	66	7.3	5.5	6.8	5.4
01	01	02	66	7.8	6.7	7.3	6.3
01	01	03	66	7.3	6.7	7.4	6.6
01	01	04	66	7.1	6.2	7.1	6.5
01	01	05	66	6.7	5.7	6.8	6.3
01	01	06	66	6.9	6.3	6.7	6.4
01	01	07	66	6.7	6.3	6.7	6.5
EXTREME				7.8	5.5	7.4	5.4
AVERAGE				7.1	6.2	6.9	6.2

Figure 26.—Tabluar presentation of maximum and minimum daily temperatures of an estuary. Note that weekly mean values also are shown (From Cory and Nauman, 1968, p 29)

estuaries, and ground water often are measured by observers who visit measuring stations at irregular intervals of time. When these observations are published, it is necessary to show the date of each measurement, and, often, the time of the measurement. Decisions of whether to show time in the published records should be based on criteria similar to the 2° rule used in deciding if maxima and minima should be shown for daily values. If, in the judgement of the investigator, the diurnal variation at the station exceeds 2°C on more than 5 percent of the days of observation, time should be shown. Figures 28 and 29 show examples of tables listing measurements at irregular intervals. Figure 28 includes two forms of presentation, and it can be assumed that the 2° rule was not used in selecting the format of presentation. The upper part of figure 29 includes a graphical presentation which will be described in more detail in a later subsection of this manual.

Summary reports.—It often is necessary to summarize records over rather long periods of time by presenting mean, maximum, and minimum temperatures on weekly, monthly, or even annual basis. Computer printouts of the temperature data shown in figure 26 included weekly extremes and averages. The example in figure 30 is a summary of maximum, minimum, and mean values on a monthly basis for several years of record. Care has been taken in the example to distinguish that the data shown represent different methods of measuring or recording, so that the data user can decide for himself the extent of sampling error in the data.

Remarks concerning accuracy.—In order to provide the reader with information on the accuracy of reported data, it is recommended that a statement on accuracy be included with each published record. Such a statement could go with "Remarks" in the heading of tables like those shown in figures 25 or 29.

A suggested wording of a remark on accuracy is "Records represent water temperature at sensor within 0.5°C. Temperature at the sensor was compared with the average for the river by temperature cross-section on (give date or dates). A maximum variation of 2.5°C was found within the cross

TABLE 116

WATER TEMPERATURE (°F)
Detroit Reservoir, Oregon

Day	Observed		Thermohm Elevations (Upstream Face of Dam)																Reservoir Surface						
	Hour (PST)	Pool elev.	1192	1217	1242	1267	1292	1317	1342	1367	1392	1417	1442	1467	1492	1517	1542	1567	At Dam at Hours of 06	10	14	18	20	Ave.	@ I Bo
1	1625	1503.7	44	44	43	43	45	45	51	54	54	54	55	56	56							57			
2	1715	1502.3	44	44	43	44	45	46	51	53	54	55	55	55	55							56			
3	1715	1500.6	44	44	43	44	45	45	51	53	54	55	55	55	55							56			
4	1645	1498.2	44	44	43	44	45	46	51	54	54	54	55	55	55							54			
5	1610	1496.9	43	44	44	44	45	46	51	54	54	54	54	55	54							54			
6	1640	1495.6	44	43	43	44	45	46	51	53	54	54	54	54	54							54			
7	1630	1493.7	44	43	43	44	45	49	50	52	53	53	54	55	54							54			
8	1635	1492.3	44	44	44	44	45	47	50	52	53	53	54	54	54							54			
9	1800	1490.9	44	44	44	44	45	47	50	52	53	53	53	54											
10	1800	1489.7	44	44	44	44	45	48	50	52	53	53	53	53											
11	1735	1490.4	44	43	44	44	45	48	50	52	52	53	53	53											
12	1800	1489.9	43	42	44	44	45	48	50	[illegible]			[illegible]	[illegible]											
						44	45	[illegible]																	

Figure 27 —Tabular presentation of temperatures measured once daily at several different depths in a reservoir. (From U S. Corps of Engineers, 1968, table 116.)

WATER QUALITY DATA, WATER YEAR OCTOBER 1970 TO SEPTEMBER 1971

DATE	DIS-CHARGE (CFS)	TEMP-ERATURE (DEG C)	SILICA (SIO2) (MG/L)	DIS-SOLVED CAL-CIUM (CA) (MG/L)	DIS-SOLVED MAG-NE-SIUM (MG) (MG/L)	SODIUM (NA) (MG/L)	PO-TAS-SIUM (K) (MG/L)	BICAR-BONATE (HCO3) (MG/L)	SULFA (SO (MG
OCT.									
08...	896	6.0	13	53	15	19	2.0	144	
NOV.									
05...	602	3.0	14	64	19	23	2.2	164	
DEC.									
22...	389	2.0	14	43	13	19	1.9	176	
JAN.									
19...	449	2.0	13	61	19	28	2.9	162	
FEB.									
16...	312	8.5	15	67	21	28	2.6	177	
MAR.									
05...	344	3.0	13	62	19	26	3.1	162	
13...	324	13.0	12	65	21	31	2.8	17'	
APR.									
06...	515	11.0	11	47	14	20	2.6	'	
MAY									
17...	966	15.0	8.7	36	9.6	14	1.8		
JUNE									
03...	1320	18.5	9.7	33	8.8	11	1.3		
JULY									
09...	1860	19.0	8.0	25	6.3	8.5	1.4		
AUG.									
30...	1250	20.0	10	39	9.8	13	2.2		
SEP.									
14...	417	20.0	13	61	18	25	2.6		

INSTANTANEOUS SUSPENDED SEDIMENT AND PARTICLE SIZE, WATF
(METHODS OF ANALYSIS: B, BOTTOM WITHDRAWAL TUBE; C, CHEMICALLY D
V, VISUAL ACCUMULATION TUBE; W, I

DATE	TIME	WATER TEMP-ERA-TURE (°C)	DISCHARGE (CFS)	CONCEN-TRATION (MG/L)	SUSPENDED SEDIMENT DISCHARGE (TONS/DAY)	PERCE' .0r
OCT 8, 1970	1130	6.0	896	84	203	
21......	1345	10.0	820	42	93	
NOV 5......	1100		602	35	57	
20......	1100	4.0	510	557	76'	
DEC 3......	1340		477	21	'	
8......	1500		500	35		
23......	1430		397	114		
JAN 8, 1971	1400		248	40		
19......	1030	2.0	449	72		
FEB 7......	1615	1.5	282	32		
16......	1435	8.0	312	25		
MAR 5......	1015	3.0	344	20		
15......	1325	7.0	324	26		
APR 6......	1345	11.0	515	61		
29......	1230	18.0	397	29		
MAY 14......	1600	16.5	723	61		
25......	1200		644	24'		
JUN 3......	1400	18.5	1200	2'		
14......	1315	16.5	1490	'		
JUL 9......	1545	19.0	1880			
19......	1215		1810			
AUG 10......	1200		924			
30......	1820	20.0	1210			
SEP 14......	1530	20.0	417			
28......	1500	17.0	401			

Figure 28.—Tabular presentations of stream temperatures measured at irregular intervals Note that bottom table shows time of the instantaneous values. (From U.S. Geological Survey, 1972, p 30.)

section." If measurements are available for several different dates, it is advisable to include a summary in the format of figure 24 as part of the record.

Graphical presentation

Data presented in graphical form are almost always easier for the reader to understand and interpret than tables of data. This

YELLOWSTONE RIVER BASIN

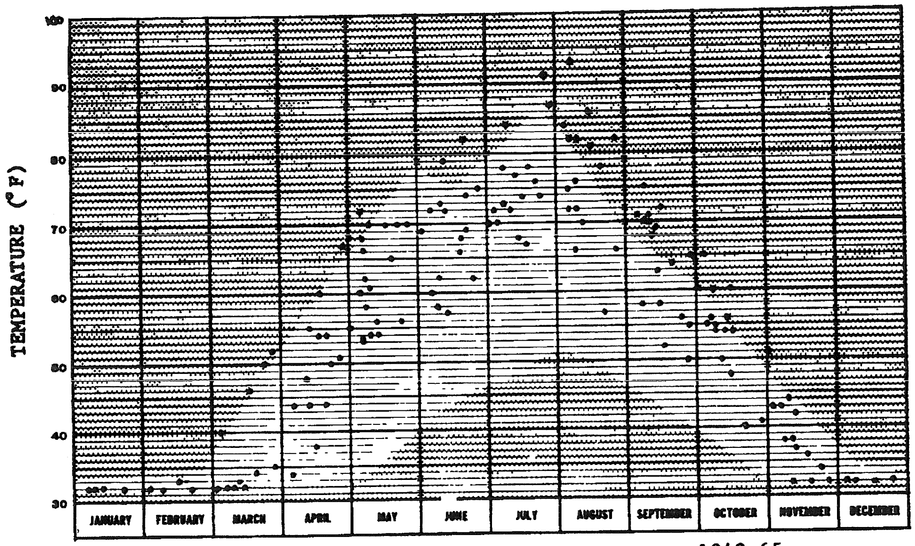
194. Tongue River at Miles City, Mont. (6-3085)

Location.--At gaging station, lat 46°21', long 105°48', in SE¼ sec.23, T.7 N., R.47 E., on right bank 4 miles south of Miles City and 8 miles upstream from mouth. Altitude of gage is 2,370 ft (by barometer).

Drainage area.--5,379 sq mi.

Water temperature records available.--157 spot observations made at time of discharge measurements during period April 1949 to December 1965. Once-daily observations made during period April 1949 to December 1965 published in reports of the Geological Survey.

Extremes.--Discharge 1938-42, 1946-66: Maximum, 13,300 cfs June 15, 1962; no flow July 9-19, Aug. 13, 14, Sept. 28, 1940.
Water temperatures 1949-65: Maximum observed, 93°F Aug. 8, 1961; minimum, freezing point on many days during winter months.



Spot observations of water temperatures, 1949-65.
The unshaded area delineates the range between the highest and lowest monthly temperatures from once-daily observations, 1949-65.

Water temperatures at time of discharge measurements

Date	Time	°F	Date	Time	°F	Date	Time	°F	Date	Time	°F	Date	Time	°F	Date	Time	°F
January			February			March			April			May			June		
5-61	1450	32	13-61	1750	32	30-52	1630	35	26-49	1600	67	26-49	1600	70	9-49	1130	72
16-62	1700	32	11-63	1600	33	27-53	1200	50	17-50	1530	54	11-50	0950	54	19-49	1100	62
8-63	1350	32	5-64	0930	32	17-54	1500	46	11-51	1000	38	25-50	0830	56	6-50	1420	72
8-64	1455	32	2-65	1600	32	11-55	1430	33	23-51	1400	51	1-51	1745	68	20-50	1440	75
6-65	1530	32				24-56	0930	34	16-54	1600	60	9-51	1430	62	8-51	0845	62
						30-60	1545	52	9-55	1830	55	16-51	1600	70	2-53	1630	69
						10-61	0830	32	18-56	1130	50	7-52	1700	66	17-53	1930	74
						13-62	1600	32	8-57	1600	48	18-53	1600	65	17-54	1610	69
						4-63	1505	40	8-58	0900	44	7-54	1730	72	9-55	1645	57
						2-64	1630	32	17-59	1600	44	6-55	1400	60	8-56	1430	73

Figure 29 —Combined tabular and graphical presentations of stream temperatures measured at irregular intervals (From Aagaard, 1969, p 438)

WATER TEMPERATURES FROM ONCE DAILY DATA, DEGREES CELSIUS

YEAR		OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.
1958	MAXIMUM:	19	12	9	9	11	11	17	20	27	29	30	26
	MEAN:	13	9	7	7	9	8	12	16	21	26	26	23
	MINIMUM:	11	4	5	4	7	5	6	10	15	20	24	18
1959	MAXIMUM:	24	16	11	14	11	11	17	21	27	29	27	25
	MEAN:	19	11	9	8	7	9	13	18	24	27	25	20
	MINIMUM:	14	7	7	4	3	7	10	13	21	24	23	17
1961	MAXIMUM:	18	12	9	10	11	12	13	17	27	28	27	24
	MEAN:	15	8	7	7	8	8	11	13	22	27	25	21
	MINIMUM:	13	6	3	3	6	7	7	9	16	24	23	19
1962	MAXIMUM:	16	10	8	7	9	10	13	19	25	28	27	26
	MEAN:	13	7	5	4	7	7	11	14	22	24	24	21
	MINIMUM:	12	3	3	2	2	4	9	12	18	22	21	18
1963	MAXIMUM:	18	14	11	11	11	11	13	19	27	28	27	26
	MEAN:	13	10	7	4	10	9	9	14	22	25	24	23
	MINIMUM:	9	6	2	1	8	7	7	8	17	20	22	20
1964	MAXIMUM:	21	14	9	7	8	11	17	22	27	28	27	23
	MEAN:	16	9	7	5	7	8	12	16	22	25	25	22
	MINIMUM:	12	6	4	3	4	6	7	10	16	21	22	18
1965	MAXIMUM:	19	16	12	9	9	12	15	16	26	24	26	26
	MEAN:	16	8	6	6	7	10	11	13	21	23	24	23
	MINIMUM:	15	3	4	3	6	7	7	9	18	21	21	21
1966	MAXIMUM:	19	16	8	8	8	12	15	22	25	27	27	26
	MEAN:	17	10	5	5	6	8	10	15	21	24	25	22
	MINIMUM:	14	5	2	3	5	3	8	11	15	21	23	18
1968	MAXIMUM:	20	15	8	9	11	13	17	22	24	27	28	28
	MEAN:	16	12	5	5	9	9	12	17	21	23	24	21
	MINIMUM:	13	7	2	2	6	7	9	13	16	20	18	16
1958-	MAXIMUM:	24	16	12	14	11	13	17	22	27	29	30	28
1968	MEAN:	15	9	6	6	8	8	11	15	22	25	25	22
	MINIMUM:	9	3	2	1	2	3	6	8	15	20	18	16
	DAYS OF RECORD:	88	172	208	223	224	252	216	170	106	85	82	65

WATER TEMPERATURES FROM THERMOGRAPH DATA, DEGREES CELSIUS

YEAR		OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.
1967	MAXIMUM:	24	16	**	7	**	12	12	16	17	**	**	**
	MEAN:	17	13	**	5	**	8	9	12	13	**	**	**
	MINIMUM:	12	10	**	1	**	4	6	8	10	**	**	**
1967	MAXIMUM:	24	16	**	7	**	12	12	16	17	**	**	**
	MEAN:	17	13	**	5	**	8	9	12	13	**	**	**
	MINIMUM:	12	10	**	1	**	4	6	8	10	**	**	**
	DAYS OF RECORD:	31	19	0	10	0	29	30	31	7	0	0	0

WATER TEMPERATURES FROM PERIODIC DATA, DEGREES CELSIUS

PERIOD OF RECORD		OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.
1956-68	MAXIMUM:	21	16	12	13	11	12	17	19	27	27	28	27
	MEAN:	16	9	7	6	7	8	10	13	20	24	25	22
	MINIMUM:	13	6	2	3	4	4	7	8	13	21	17	18
	DAYS OF RECORD:	14	35	46	47	44	16	17	17	23	24	24	12

Figure 30 —Tabluar presentation of several years' temperature data from a stream Note that the data are divided according to the measurement techniques (From Blodgett, 1970, p 35)

subsection presents some examples of graphical presentation of temperature data which are intended to provide guidance in preparing reports.

Temperatures of streams.—Thermographs showing temperature on the ordinate scale and time on the abscissa scale probably are the most common way of presenting stream temperatures. Data from recording thermographs or a plot of daily mean temperatures can be presented as a continuous line on the graph, but intermittent readings should be shown as plotted points. Figure 29 is an example of a way of presenting the results of spot measurements as well as showing the long-term extremes.

Variations in temperature along the length of a stream also can be advantageously shown graphically. Figure 31 is an example of a simple form of presentation showing data from several stations collected at different times. Figure 32 depicts a more complex form of showing temperature variations both with time and with distance along a stream.

Cumulative-frequency distribution of water temperatures might be considered in analyzing to determine effectiveness of a stream for cooling, for use as a fishery, or for other uses. Ward (1963) has adapted a method of cumulative analyses to stream temperature data to make the type of presentation shown in figure 33. Techniques similar to those described by Searcy (1959) for constructing flow-duration curves can be applied to temperature data to construct cumulative-frequency relationships.

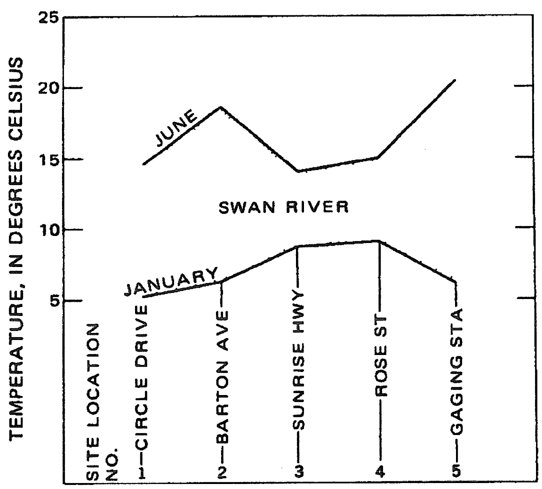


Figure 31 —Graphic presentation of longitudinal temperature profiles in a stream. (From Pluhowski, 1970, p. D42)

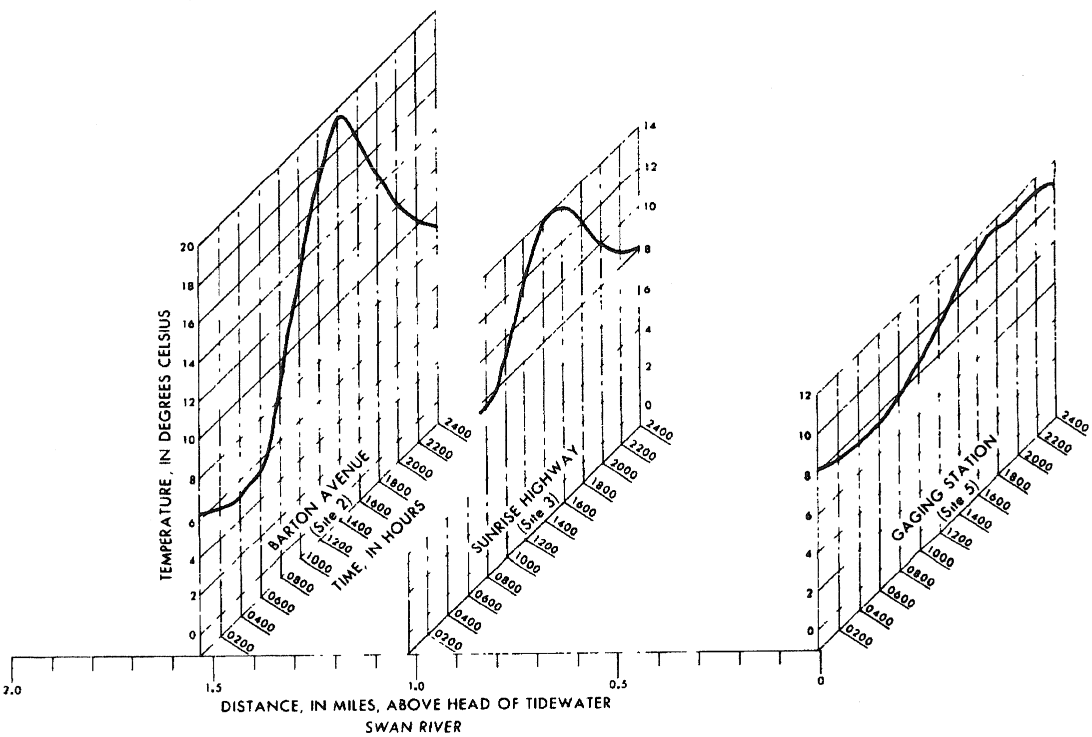


Figure 32 —Complex graphical depiction of variations of stream temperature with time at several sites. (From Pluhowski, 1970, p. D35.)

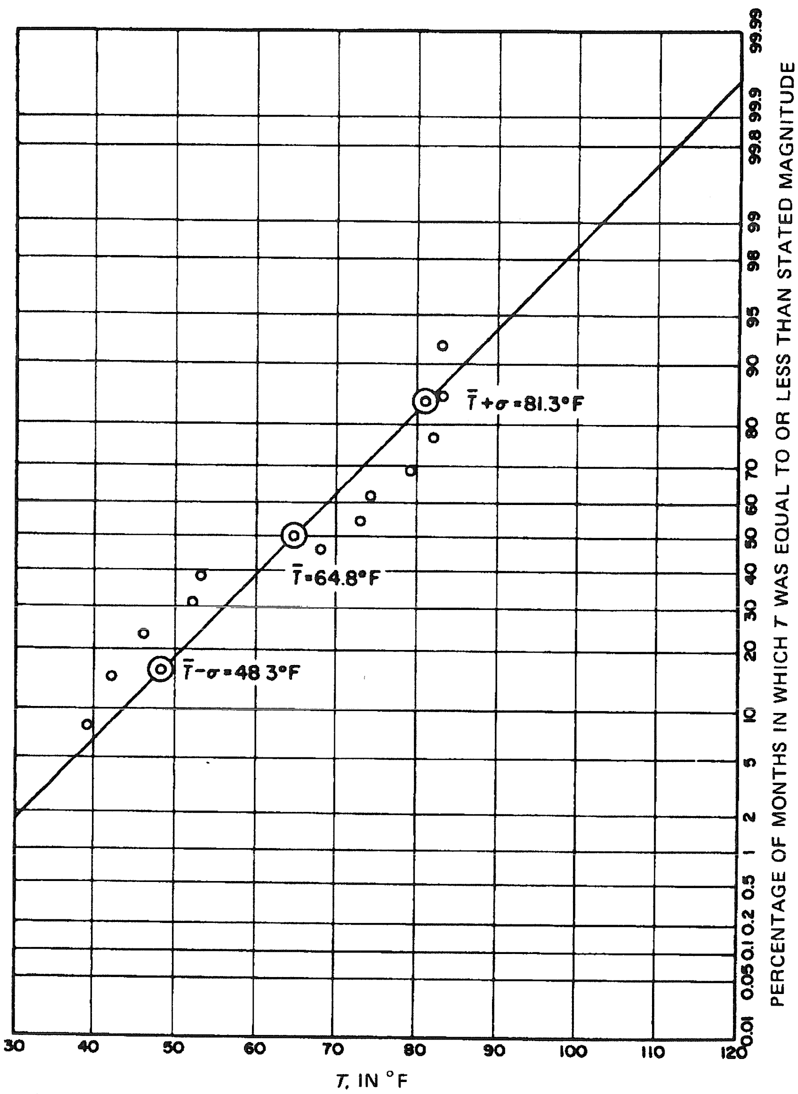


Figure 33 —Cumulative frequency of stream temperature (From Ward, 1963, p 10)

Lakes.—Variations of temperature with time at the surface of a lake, or at other points in the lake can be represented by a temperature versus time plot of the type described for streams. These data also can be subjected to frequency analyses of the type reported in the preceding paragraph.

Variations with depth often must be shown in reporting lake temperatures. Figure 6 is an example of a common way of reporting temperatures of lake water. The particular example shown presents data for several different times, which usually is easy to accomplish because of the systematic way in which the temperatures in lakes change. Figure 34 is another form for showing changes of lake temperatures with time. The type of presentation in figure 34 is particularly well suited to showing annual patterns.

Estuaries.—Depending upon conditions,

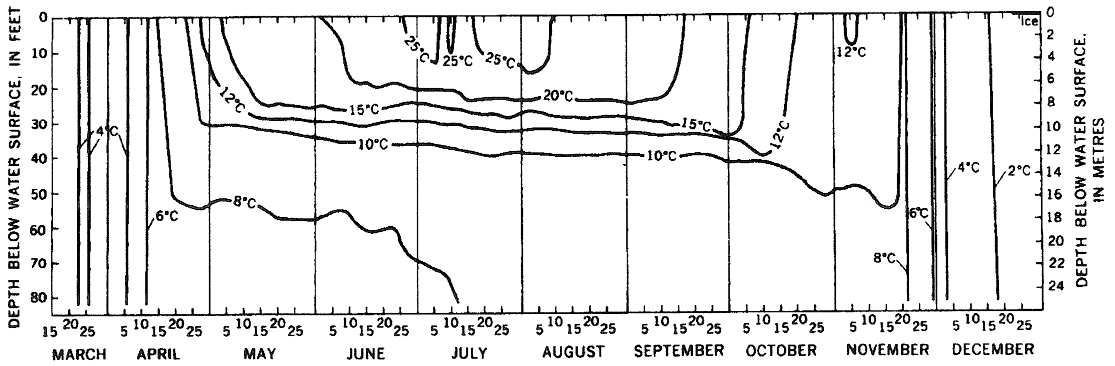


Figure 34.—Temperature variations in a lake represented by isothermal lines in a depth versus time graph. (From Ficke, 1972, p. A5.)

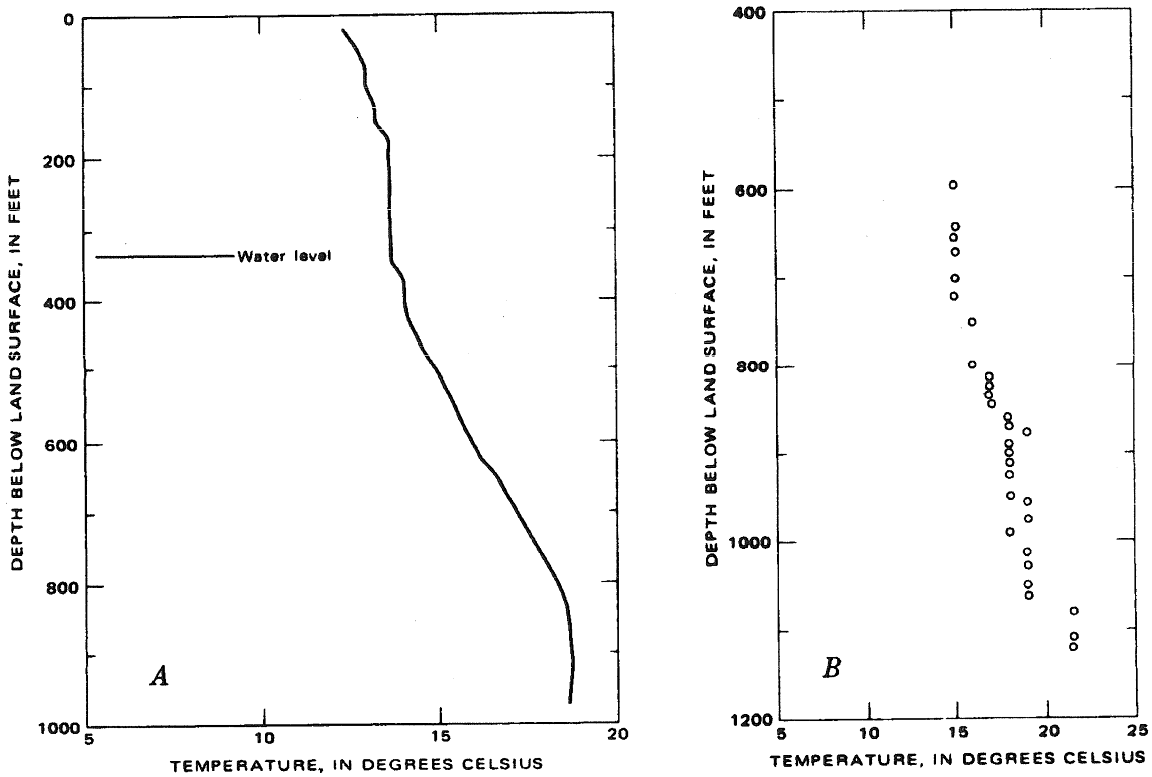


Figure 35.—Graphical presentation of temperature variations in well. *A*, Continuous trace from a recording logger. *B*, Observations of temperature of water discharged during the drilling of a well. (From Ficke and others, 1974, p 62, 110.)

temperatures of estuaries can be reported using the methods presented for reporting stream or lake data, or a combination of these. Figure 32 is well adapted to estuary data and can be modified to show temperature at more than one depth or at more than one point in the cross section simply by adding additional lines to the isometric graphs. The format of figure 34 also can be applied to estuarine data to show variations in a tidal cycle, using a greatly expanded time scale.

Ground water.—Graphs often are far superior to tables in showing temperatures of ground water because they can show small, subtle changes which would require elaborate tables. Temperatures in wells often are recorded by logging devices, rather than by measurements at discrete points, and it is a relatively simple task to reduce the logs to page-size graphs. Graphical presentations of data from loggers should show continuous lines. Data from measurements at discrete points can be shown as continuous lines if the measurements are closely spaced, but should be shown as plotted points if the author feels they cannot be reasonably connected. Examples in figure 35 include both data from a logger and data at specific depths. In fact, the data in figure 35*B* do not represent temperature of water at a particular depth, but instead show temperatures of water discharged from a drillhole at the depth shown on the ordinate scale. The water actually entered the hole at several levels, and the data help point out the zones that contribute water.

Data from different times of measurement can be shown in the same graph, as was done in figure 6, provided there are great enough changes between times of measurement to keep the curves from plotting on top of each other. In addition to temperature profiles in wells, a graphical presentation commonly used is a map showing temperatures at a given depth or geologic horizon. Other graphical presentations include thermal gradient versus depth, areal variation in thermal gradient for a given depth range, and temporal variations in temperature of a spring or well. A great opportunity still exists for authors to apply imagination in developing new techniques to present temperature data for ground water.

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