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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.

CONTENTS

FIGURES

TABLES

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

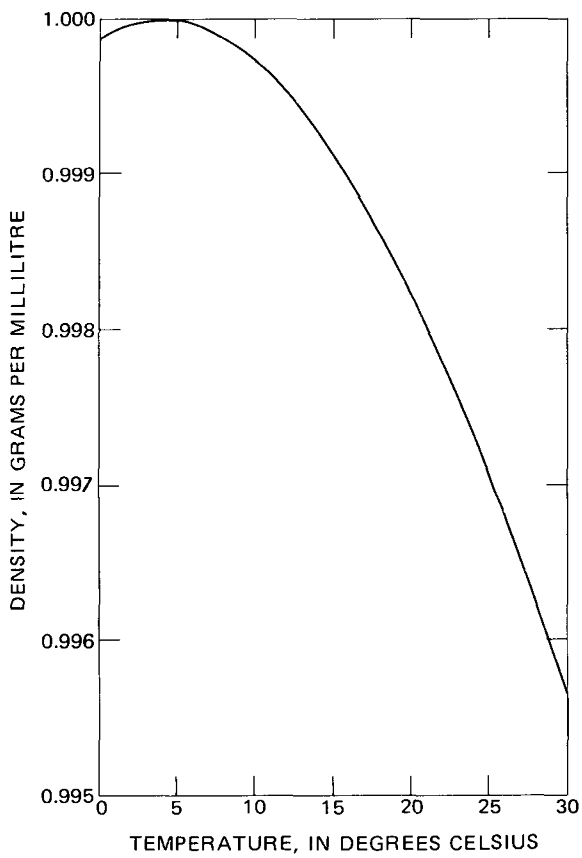


Figure 1.—Temperature-density relationship of water at 1 atmosphere (760 mm Hg (0°C)) pressure

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 mircoorganism 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

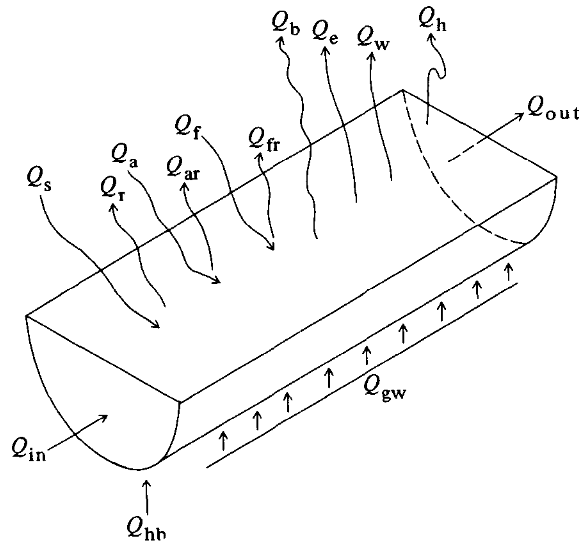


Figure 2.—Principal energy components in the heat balance of small streams. See text for explanation of symbols. (Modified from Pluhowski, 1972.)

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

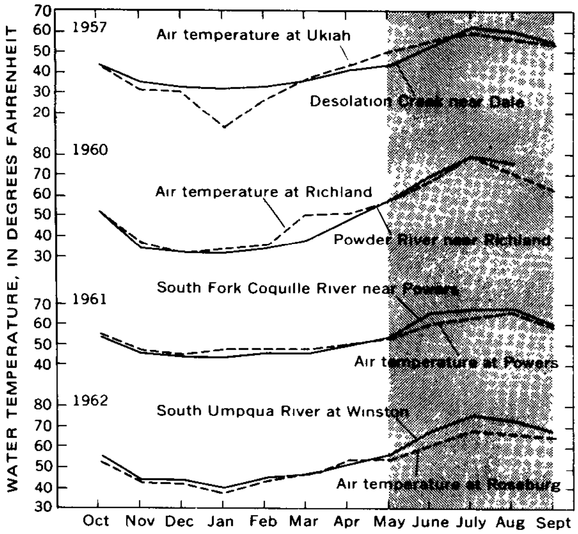


Figure 3.—Comparison of monthly mean air and water temperatures for selected east-west-oriented streams in Oregon. (Summer months patterned. From Moore, 1967, p. K21.)

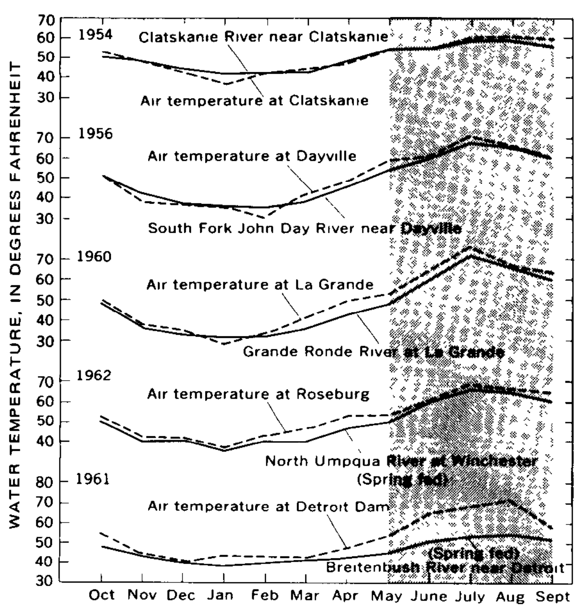


Figure 4.—Comparison of monthly mean air and water temperatures from selected spring-fed or north-south-oriented streams in Oregon. (Summer months patterned. From Moore, 1967, p. K22.)

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

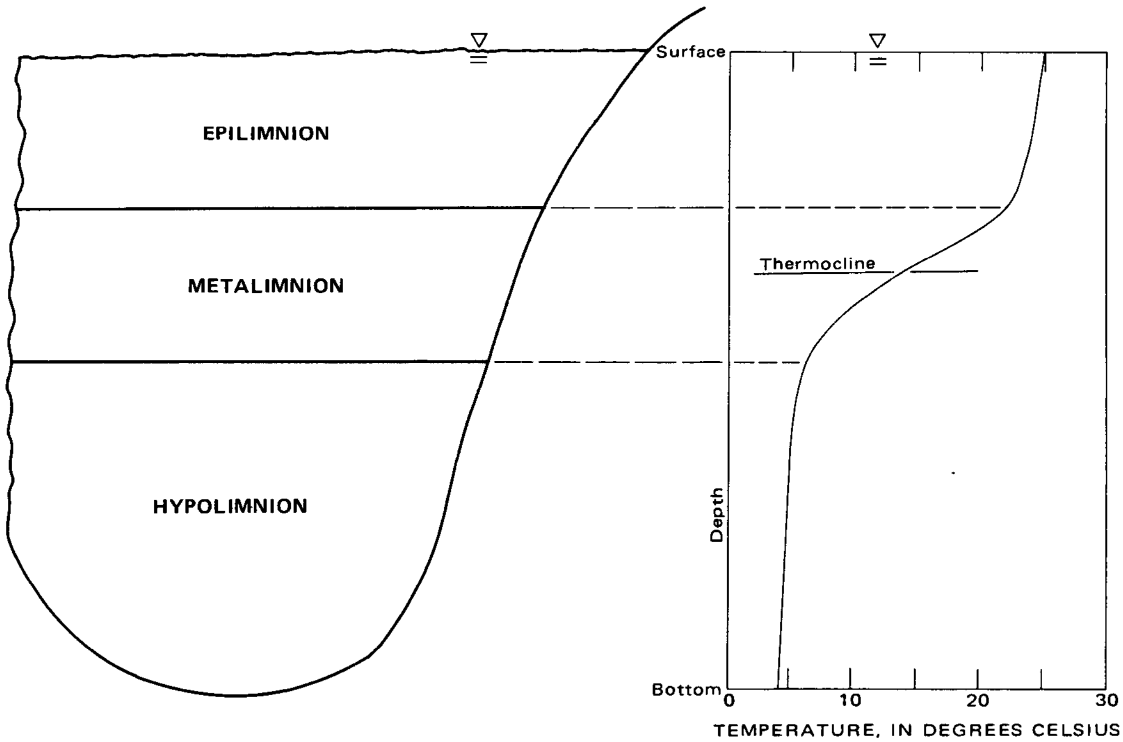


Figure 5 —Zones of a thermally stratified lake

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.

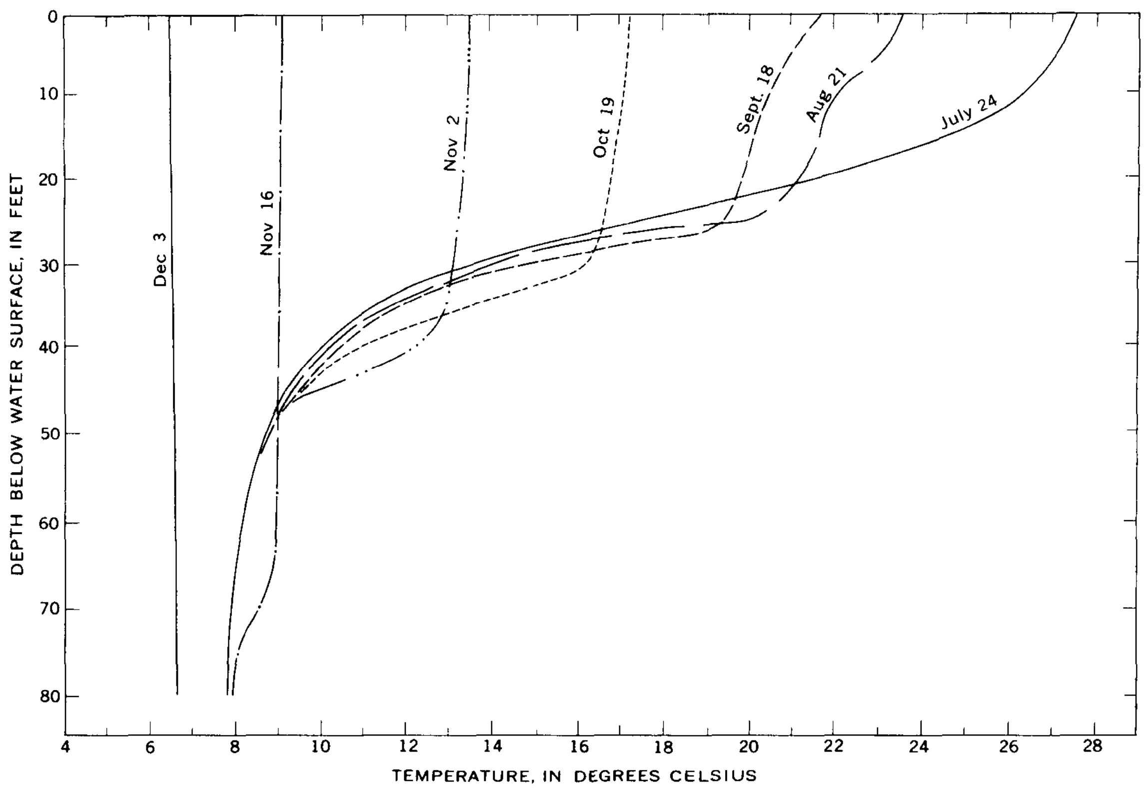


Figure 6.—Water-temperature profiles averaged from measurements at 21 locations on Pretty Lake, Ind., during the summer and autumn of 1963 (From Ficke, 1965, p C200.)

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 estuary 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.

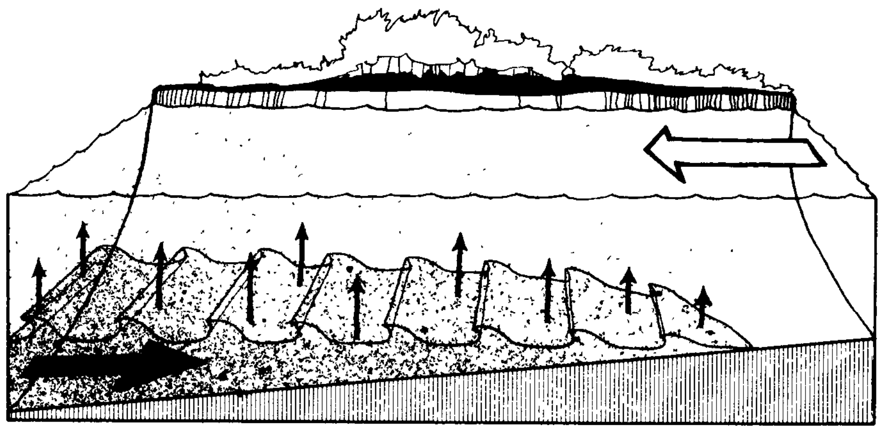
Because of heat conduction from the land surface, very shallow ground water will show diurnal and seasonal temperature variations of about the same magnitude as those observed for surface-water bodies. However, due to the insulating properties of the Earth, these variations are greatly attenuated with 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.

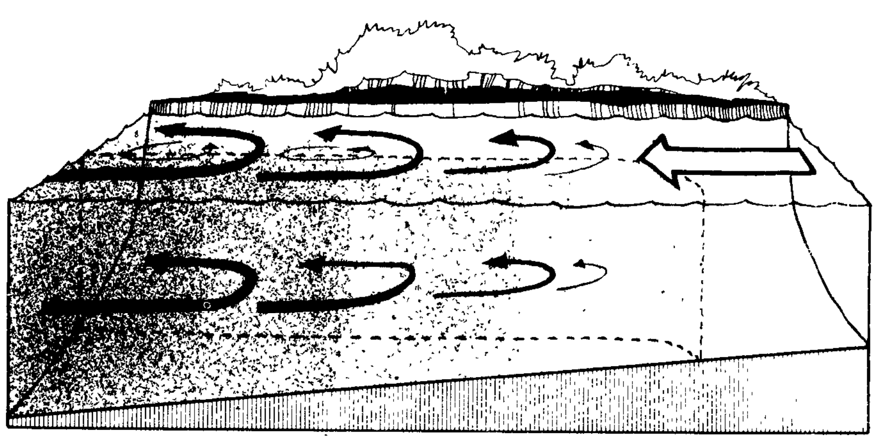
Ground-water temperatures may be substantially affected by the temperature of water injected through wells. Brashears (1941) found that on Long Island, water returned to the aquifer after use for air-conditioning resulted in a rise in temperature of water pumped from nearby production wells of as much 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