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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

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BOOK 1

COLLECTION OF WATER DATA BY DIRECT MEASUREMENT

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 2½-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

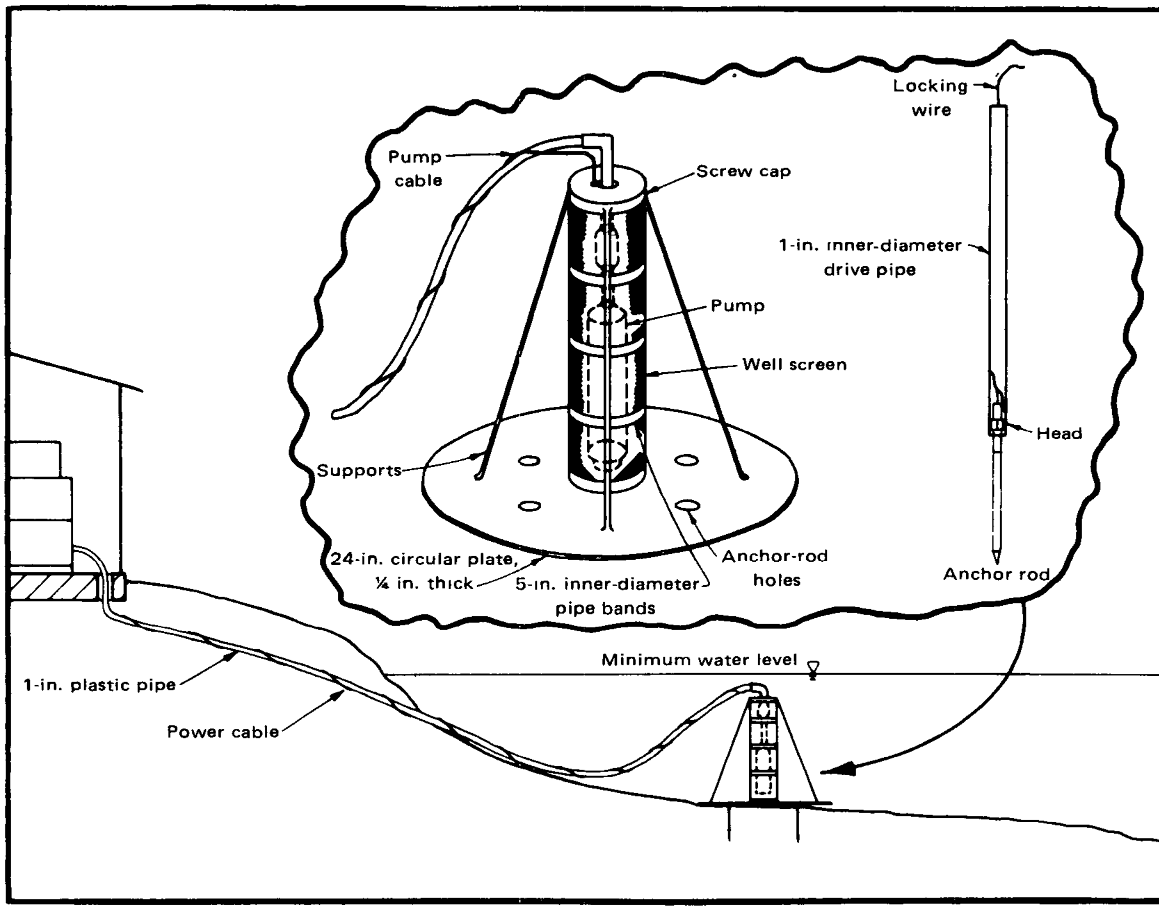

Figure 13.—Platform type of pump support. Platform is anchored by driven rods. (From Anderson and others, 1970, p. 267.)

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

$$T_a = \frac{\Sigma\, t_o}{n}. \qquad (8)$$

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

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

The discharge-weighted mean tempera-

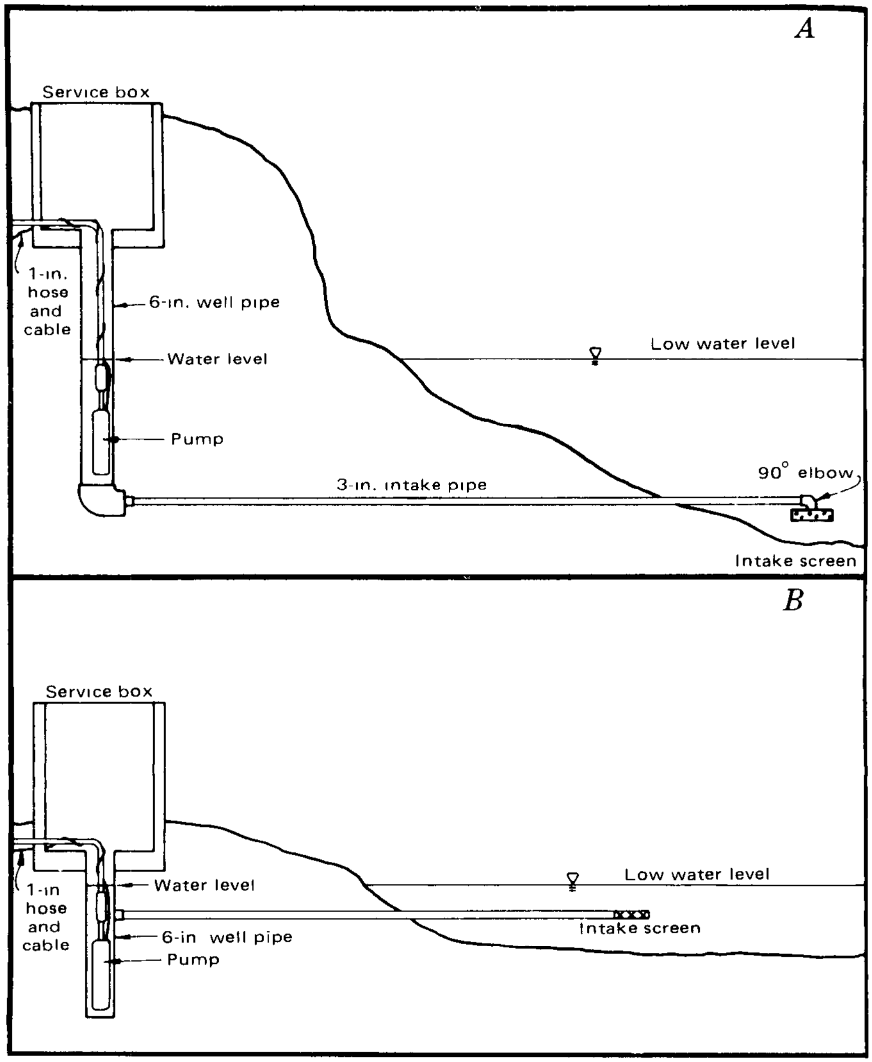

Figure 14 —Two examples of pumps supported within stilling wells. (From Anderson and others, 1970, p. 268.)

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

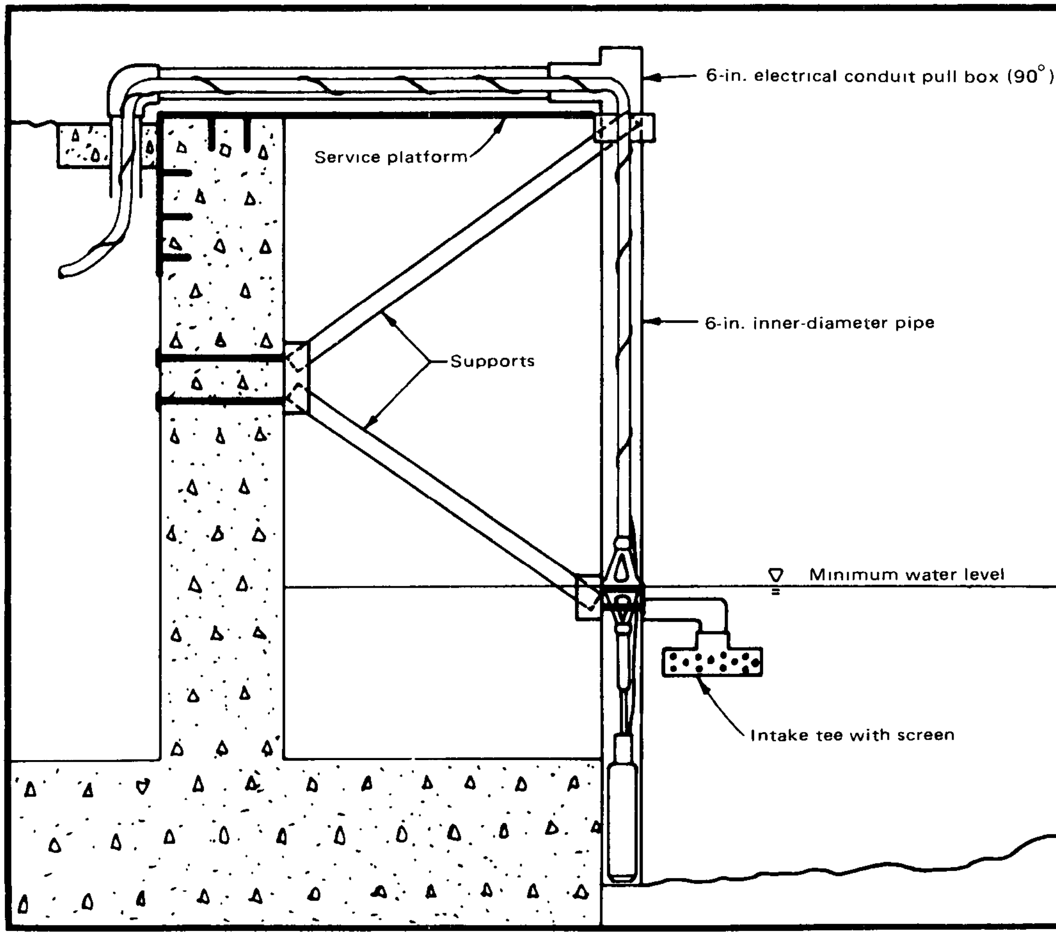

Figure 15.—Facility using bulkhead for pump support (From Anderson and others, 1970, p 269.)

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.

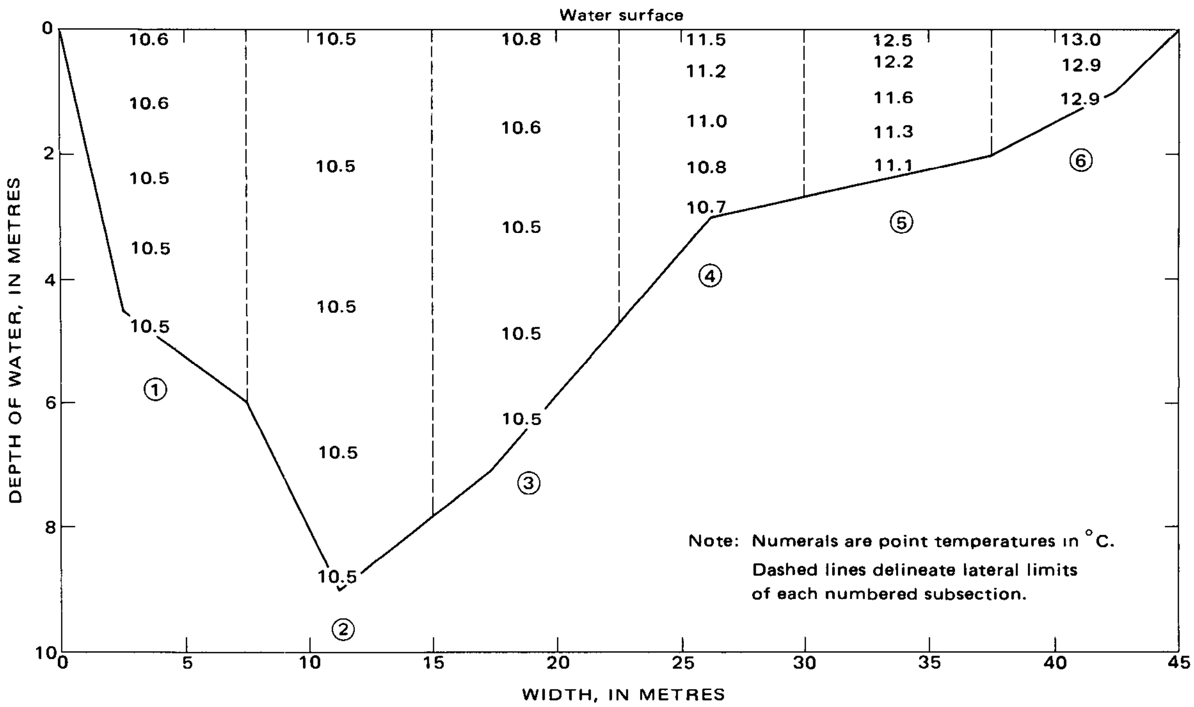

Figure 16.—Stream-temperature distribution in which the temperature varies 2.5° C throughout the cross section.

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 Hcttman (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

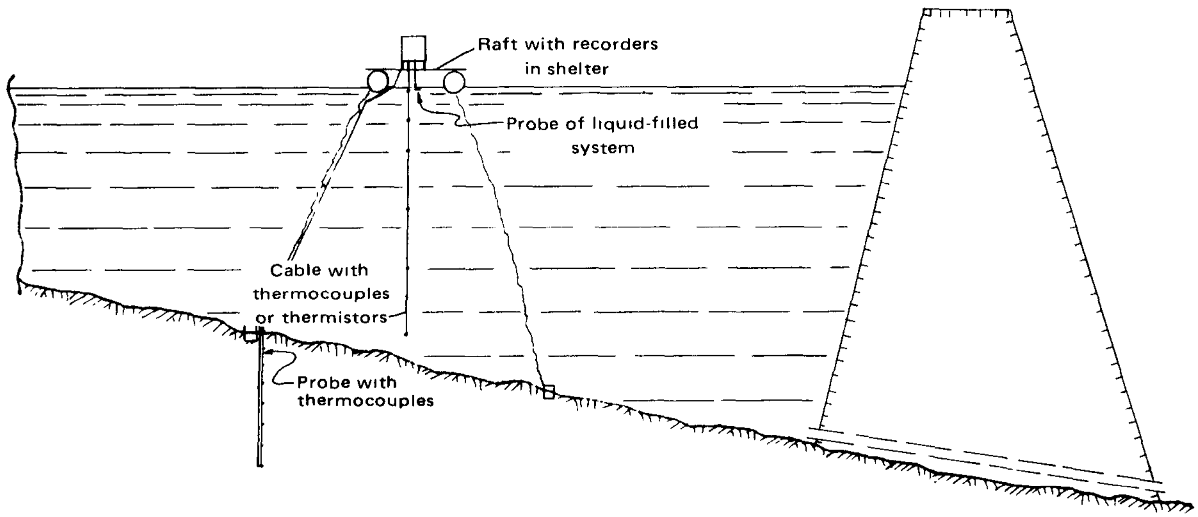

Figure 17.—Raft assembly for measuring temperature at the surface and at depth, and for measurement of temperature of bottom sediment in a lake.

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 nonrecording 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

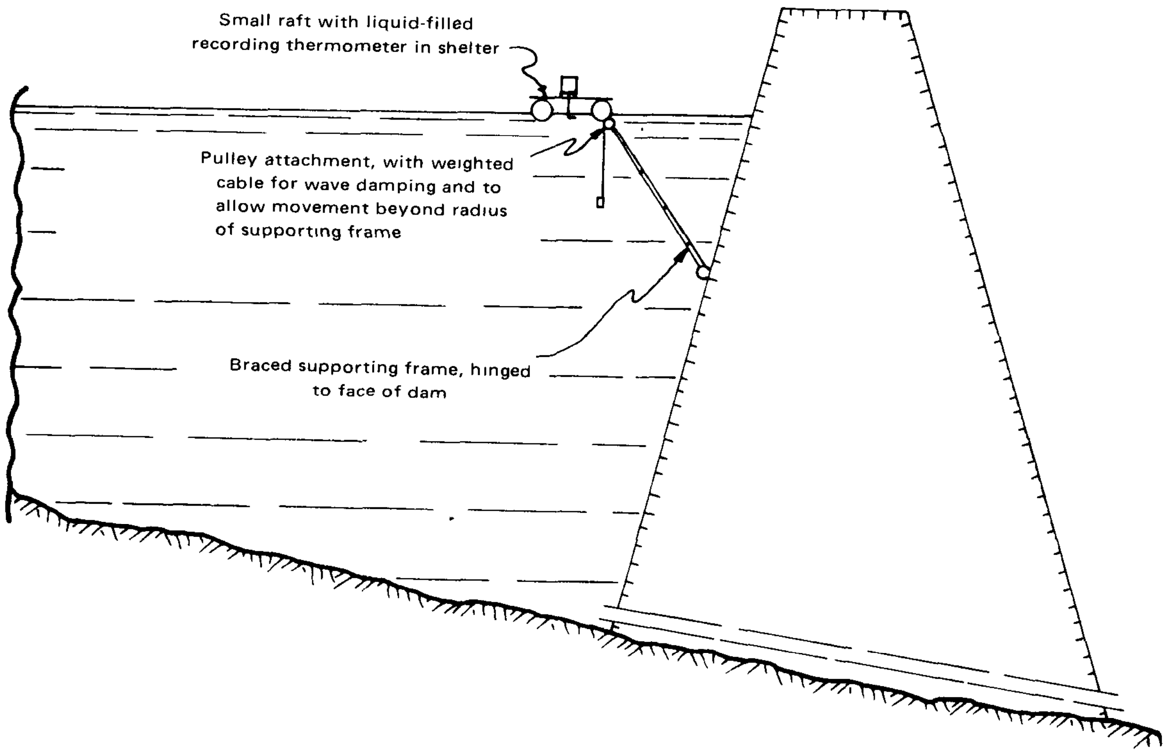

Figure 18 —Device to attach instrument raft at face of dam.

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 non-representative 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 0952	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	16.2	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.[illegible]	15.4	15.0	15.1	15.7	15.[illegible]	15.6	15.5		15.3
12.5	13.8	14.[illegible]	14.6	13.9	14.2	14.2	15.2	15.3	15.4		15.0
15	13.4	13.7	12.9	13.[illegible]	13.7	13.8	14.1	15.[illegible]	15.4		14.4
17.5	13.0	13.0	12.4	12.9	13.2	13.4	13.4	15.5	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	11.5	11.7	11.[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.[illegible]	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	9.3	9.4	9.3	9.3		9.2
70					8.9		8.7	8.8	8.7		8.8
80					8.6			8.4	8.3		8.4
90					8.2			8.0	8.0		8.0
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
Bottom	10.0	10.0	10.0	9.7	7.5	9.2	8.6	6.9	7.0		
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	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.

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

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.