HYDROLOGY FOR ENGINEERS

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PREFACE

The publication in 1949 of "Applied Hydrology" was well received, and that book has found extensive use as a text in schools of engineering. No single book can meet all needs, and "Hydrology for Engineers" has been written specifically to serve as an elementary text. The emphasis throughout is on quantitative methods of arriving at answers to hydrologic problems. The handbook approach, as exemplified by the many empirical formulas widely used in the early days of hydrology, has been avoided.

"Hydrology for Engineers" is not a mere condensation of "Applied Hydrology." While there is much similarity in the organization, the text has been completely rewritten. Where appropriate, new methods and concepts developed since 1949 have been included. The experience of the authors in teaching hydrology over several years has been utilized as a basis for selecting topics to be included and methods of presentation.

The student should find hydrology an interesting subject but one much different from most of his engineering courses. The natural phenomena with which hydrology is concerned do not lend themselves to rigorous analyses such as are possible in engineering mechanics. There is, therefore, a greater variety of methods, more latitude for judgment, and a seeming lack of accuracy in problem solutions. Actually, the accuracy of sound hydrologic solutions compares favorably with other types of engineering computations. Uncertainties in engineering are frequently hidden by use of factors of safety, rigidly standardized working procedures, and conservative assumptions regarding properties of materials.

The authors gratefully acknowledge the splendid cooperation of their many friends and colleagues whose helpful suggestions have added much to this text. Special appreciation goes to Walter T. Wilson and David Hershfield of the U.S. Weather Bureau for review and comments on frequency analysis, to Professor Stanley N. Davis of Stanford University for his helpful review of the chapter on groundwater, and to T. J. Nordenson of the Weather Bureau for many suggestions. Professor J. B. Franzini of Stanford reviewed the entire manuscript, and many of his worthwhile suggestions are incorporated in the final text. Miss Dianne Linsley prepared the final manuscript.

CONTENTS

1

INTRODUCTION

Hydrology is that branch of physical geography which is concerned with the origin, distribution, and properties of the waters of the earth. Engineering hydrology includes those segments of the very broad field of hydrology pertinent to the design and operation of engineering projects for the control and use of water. The boundaries between hydrology and other earth sciences such as meteorology, oceanography, and geology are indistinct, and no good purpose is served by attempting to define them rigidly. Likewise, the distinctions between engineering hydrology and other branches of applied hydrology are vague. Indeed, the engineer owes much of his present knowledge of hydrology to agriculturists, foresters, meteorologists, geologists, and others in a variety of fields.

1-1. The hydrologic cycle. The concept of the *hydrologic cycle* is a useful, if somewhat academic, point from which to begin the study of hydrology. This cycle (Fig. 1-1) is visualized as beginning with the evaporation of water from the oceans. The resulting vapor is transported by moving air masses. Under the proper conditions, the vapor is condensed to form clouds, which in turn may result in precipitation. The precipitation which falls upon land is dispersed in several ways. The greater part is temporarily retained in the soil near where it falls and is ultimately returned to the atmosphere by evaporation and transpiration by plants. A portion of the water finds its way over and through the surface soil to stream channels, while other water penetrates farther into the ground to become part of the earth's groundwater supply. Under the influence of gravity, both surface streamflow and groundwater move toward lower elevations and may eventually discharge into the ocean. However, substantial quantities of surface and underground water are returned to the atmosphere by evaporation and transpiration before reaching the oceans.

This description of the hydrologic cycle and the schematic diagram of Fig. 1-1 are enormously oversimplified. For example, some water which enters surface streams may percolate to the groundwater, while in other cases groundwater is a source of surface streamflow. Some precipitation may remain on the ground as snow for many months before melting releases the water to the streams or groundwater. The hydrologic cycle is a convenient means for a rough delineation of the scope of hydrology as that portion between precipitation on the land and the return of this water to the atmosphere or the ocean. The hydrologic cycle serves also to emphasize the four basic phases of interest to the hydrologist: precipitation, evaporation and transpiration, surface streamflow, and groundwater. These topics are the subject of much more detailed discussion later in this text.

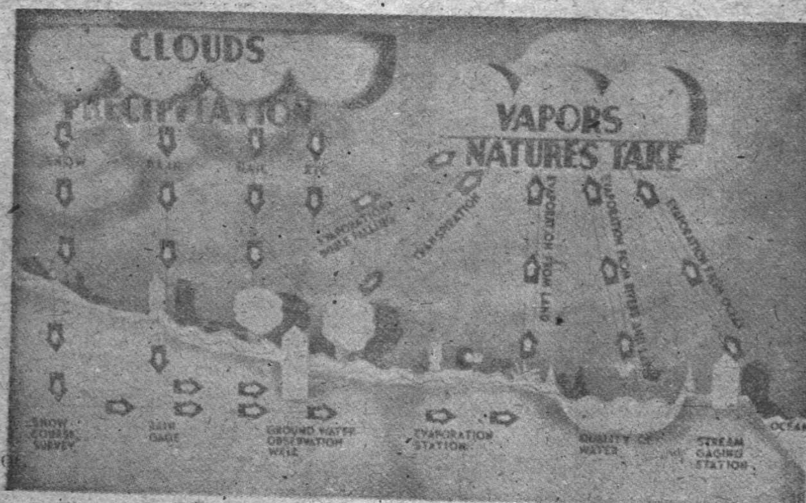

FIG. 1-1. The hydrologic cycle. *(Courtesy of U.S. Geological Survey.)*

If the discussion of the hydrologic cycle gives any impression of a continuous mechanism through which water moves steadily at a constant rate, this impression should be dispelled at once. The movement of water through the various phases of the cycle is most erratic, both in time and area. On occasion, nature seems to work overtime to provide torrential rains which tax surface-channel capacities to the utmost. At other times it seems that the machinery of the cycle has stopped completely and, with it, precipitation and streamflow. In adjacent areas the variations in the cycle may be quite different. It is precisely these extremes of flood and drought that are often of most interest to the engineering hydrologist, for many of our hydraulic engineering projects are designed to protect against the ill effect of extremes. The reasons for these climatic extremes are found in the science of meteorology and should be understood, in broad detail at least, by the hydrologist. This aspect of hydrology is discussed in the following chapter.

The hydrologist is interested in more than obtaining a qualitative understanding of the hydrologic cycle and measuring the quantities of water in transit in this cycle. He must be able to deal quantitatively with the interrelations between the various factors so that he can accurately predict the influence of man-made works on these relationships. He must also concern himself with the frequency with which the various extremes of the cycle may occur, for this is the basis of economic analysis which is, or should be, the final determinant for all hydraulic projects. The final chapters of this text deal with these quantitative problems.

1-2. History. The first hydraulic project has been lost in the mists of prehistory. Perhaps some prehistoric man found that a pile of rocks across a stream would raise the water level sufficiently to overflow the land which was the source of his wild food plants and thus water them during a drought. Whatever the early history of hydraulics, abundant evidence exists to show that the builders understood little hydrology. Abandoned irrigation projects the world over, including Indian works in the southwest United States dating from about A.D. 1100, are believed to be evidence of developments inadequate to sustain a permanent civilization.

Early Greek and Roman writings indicate that these people could accept the oceans as the ultimate source of all water but they could not visualize precipitation equaling or exceeding streamflow. Typical of the ideas of the time was a view that sea water moved underground to the base of the mountains. There a natural still desalted the water and the vapor rose through conduits to the mountain tops where it condensed and escaped at the source springs of the streams. Leonardo da Vinci (ca. A.D. 1500) seems to have been one of the first to recognize the hydrologic cycle as we accept it today, but Perreault of France offered the first recorded proof about A.D. 1650. Using crude instruments, he measured the flow of the Seine River and found it to be only one-sixth of the precipitation. About A.D. 1700 the English astronomer Halley confirmed that oceanic evaporation was an adequate source of moisture for precipitation.

Precipitation was measured in India as early as the fourth century B.C., but satisfactory methods for measuring streamflow were a much later development. Frontinus, water commissioner of Rome in A.D. 97, based estimates of flow on cross-sectional area alone without regard to velocity. In the United States, organized measurement of precipitation started under the Surgeon General of the Army in 1819, was transferred to the Signal Corps in 1870, and finally to a newly organized U.S. Weather Bureau in 1891. Scattered streamflow measurements were made on the

Mississippi River as early as 1848, but a systematic program was not started until 1888 when the U.S. Geological Survey undertook this work. It is not surprising, therefore, that little quantitative work in hydrology was done before the early years of the twentieth century, when men such as Horton, Mead, and Sherman began to explore the field. The great expansion of activity in flood control, irrigation, soil conservation, and related fields which began about 1930 gave the first real impetus to organized research in hydrology, as the need for more precise design data became evident. Most of our present-day concepts of hydrology date since 1930. Hydrology is, therefore, a young science with many important problems only imperfectly understood and much research still ahead.

1-3. Hydrology in engineering. Hydrology is used in engineering mainly in connection with the design and operation of hydraulic structures. What flood flows may be expected at a spillway or highway culvert or in a city drainage system? What reservoir capacity is required to assure adequate water for irrigation or municipal water supply during droughts? What effect will reservoirs, levees, and other control works exert on flood flows in a stream? These are typical of the questions which the hydrologist is expected to answer.

Large organizations such as Federal and state water agencies can maintain staffs of hydrologic specialists to analyze their problems, but smaller offices often have insufficient hydrologic work for full-time specialists. Hence, many civil engineers are called upon for occasional hydrologic studies. It is probable that these civil engineers deal with a larger number of projects (without regard to size) than do the specialists, although in respect to annual dollar volume the situation may be reversed. In any event, it seems that knowledge of the fundamentals of hydrology is an essential part of the civil engineer's training.

1-4. The subject matter of hydrology. Hydrology deals with many topics. The subject matter as presented in this book can be broadly classified into two phases: data collection and methods of analysis and application. Chapters 2 to 6 deal with the basic data of hydrology. Adequate basic data are essential to any science, and hydrology is no exception. In fact, the complex features of the natural processes involved in hydrologic phenomena make it difficult to treat many hydrologic processes by rigorous deductive reasoning. One cannot always start with a basic physical law and from this determine the hydrologic result to be expected. Rather, it is necessary to start with a mass of observed facts, analyze these facts statistically, and from this analysis establish the systematic pattern that governs these events. Thus, without adequate historical data for the particular problem area, the hydrologist is in a difficult position. The collection of hydrologic data has been the life work of many hydrologists and is a primary function of the U.S. Geological Survey and the U.S. Weather Bureau. It is important, therefore, that the student learn how these data are collected and published, the limitations on their accuracy, and the proper methods of interpretation and adjustment.

Generally, each hydrologic problem is unique in that it deals with a distinct set of physical conditions within a specific river basin. Hence, the quantitative conclusions of one analysis are often not directly transferable to another problem. However, the general solution for most problems can be developed from the application of a few relatively standard procedures. Chapters 6 to 12 describe these procedures and explain how they are utilized to solve specific phases of a hydrologic problem. Chapter 13 summarizes the preceding material by describing how the various steps are combined in the solution of typical engineering problems.

BIBLIOGRAPHY

Hydrology Handbook, *ASCE Manual* 28, 1949.

Johnstone, Don, and W. P. Cross: "Elements of Applied Hydrology," Ronald, New York, 1949.

Linsley, R. K., M. A. Kohler, and J. L. H. Paulhus: "Applied Hydrology," McGraw-Hill, New York, 1949.

Mead, D. W.: "Hydrology," 1st ed., McGraw-Hill, New York, 1919 (revised by H. W. Mead, 2d ed., 1950).

Meinzer, O. E. (ed.): "Hydrology," Vol. IX, Physics of the Earth Series, McGraw-Hill, New York, 1942 (reprinted Dover Publications, New York, 1949).

Meyer, A. F.: "Elements of Hydrology," 2d ed., Wiley, New York, 1928.

Wisler, C. O., and E. F. Brater: "Hydrology," Wiley, New York, 1949.

PROBLEMS

1-1. List the agencies in your state which have responsibilities of a hydrologic nature. What is the special problem of each agency?

1-2. Repeat Prob. 1-1 for Federal agencies.

1-3. List the major hydraulic projects in your area. What specific hydrologic problems did each project involve?

2

WEATHER AND HYDROLOGY

The hydrologic characteristics of a region are determined largely by its climate and its geological structure. Among the climatic factors that establish the hydrologic features of a region are the amount and distribution of precipitation; the occurrence of snow and ice; and the effects of wind, temperature, and humidity on evaporation and snowmelt. Consequently, the design and operation of hydraulic projects involve meteorological considerations. Hydrologic problems in which meteorology plays an important role include determination of probable maximum precipitation and optimum snowmelt conditions for spillway design, forecasts of precipitation and snowmelt for reservoir operation, and determination of probable maximum winds over water surfaces for evaluating resulting waves in connection with the design of dams and levees. Obviously, the hydrologist should have some understanding of the meteorological processes determining a regional climate. The general features of climatology are discussed in this chapter. Because of its special importance in hydrology, precipitation is treated separately and in more detail in Chap. 3.

THE GENERAL CIRCULATION

2-1. Thermal circulation. If the earth were a nonrotating sphere, a purely thermal circulation (Fig. 2-1) would result. The equator receives more solar radiation than the higher latitudes. Equatorial air, being warmer, is lighter and tends to rise. As it rises, it is replaced by cooler air from higher latitudes. The only way the air from the higher latitudes can be replaced is from above—by the poleward flow of air rising from the equator. The true circulation differs from that of Fig. 2-1 because of the earth's rotation and the effects of land and sea distribution and land forms.

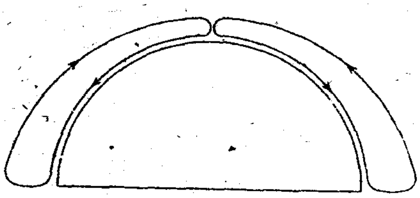

FIG. 2-1. Simple thermal circulation on nonrotating earth (Northern Hemisphere).

2-2. Factors modifying the thermal circulation. The earth rotates from west to east, and a point at the equator moves at about 1500 fps while one at 60° lat. moves at one-half this speed. From the principle of conservation of angular momentum, it follows that a parcel of air at rest relative to the earth's surface at the equator would attain a theoretical eastward velocity of 2250 fps (relative to the earth's surface) if moved northward to 60° lat. Conversely, if a parcel of air at the North Pole were moved southward to 60° lat., it would reach a theoretical westward velocity of 2250 fps. However, wind speeds of this magnitude are never observed in nature because of friction. The force that would

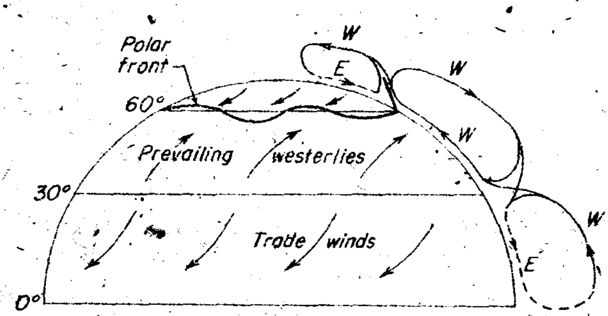

FIG. 2-2. General circulation of Northern Hemisphere.

be required to produce these changes in velocity is known as the *Coriolis force*. This apparent force always acts to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

The observed pattern of the general circulation in the Northern Hemisphere is shown in Fig. 2-2. Unfortunately, the physical reasons for this circulation are only partly known. The rising equatorial air acquires an eastward component as it moves northward. At about 30° lat., it tends to subside because of cooling. The subsiding air splits into two currents, one moving southward as the northeast *trade winds* and the second continuing northward and eastward.

In the polar cell, loss of heat in the lower layers results in subsidence, the subsiding air spreading southward and westward. As it moves southward the air is warmed, and at about 60° lat. it rises and returns poleward as a southwesterly current aloft.

In the middle cell the southwesterly current in the lower layers meets the southern edge of the polar cell and is forced upward over the colder westward-moving air. This circulation would result in an accumulation of air in the polar cell were it not for outbreaks of excess polar air southward.

The idealized circulation of Fig. 2-2 implies belts of low pressure (surface) at the equator and at about 60° lat. where warmer air is rising.

Similarly, high pressure would be expected at about 30° lat. and at the poles. This pressure pattern (Fig. 2-3) is greatly distorted by the effects of water and land masses. These effects are the results of differences in the specific heats, reflectivity, and mixing properties of water and land and of the existence of barriers to air flow. Heat gains and

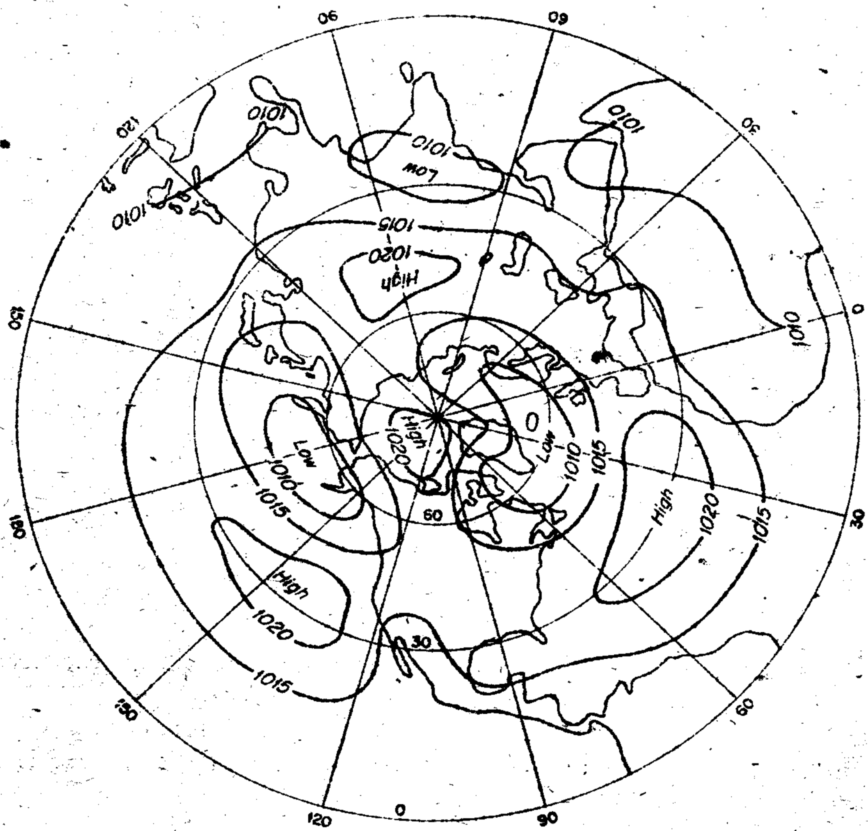

FIG. 2-3. Mean-pressure pattern of the Northern Hemisphere.

losses are distributed through relatively great depths in large bodies of water by mixing, while land is affected only near the surface. Consequently, land-surface temperatures are far less equable than those of the surface of large bodies of water. This condition is further emphasized by the lower specific heat of the soil and its higher albedo, especially in winter when snow cover reflects most of the incident radiation back to space. In winter there is a tendency for the accumulation of cold dense air over land masses and warm air over the oceans. In summer, the situation is reversed.

2-3. Migratory systems. The semipermanent features of the general, or mean, circulation (Fig. 2-3) are statistical and at any time may be distorted or displaced by transitory, or migratory, systems. Both semipermanent and transitory features are classified as cyclones or anticyclones. A *cyclone* is a more or less circular area of low atmospheric pressure in which the winds blow counterclockwise in the Northern Hemisphere. *Tropical cyclones* form at low latitudes and may develop into violent *hurricanes* or *typhoons* with winds exceeding 75 mph over areas as large as 200 mi in diameter. *Extratropical cyclones* form along *fronts,* the boundaries between warm and cold air masses. Such cyclones are usually larger than tropical cyclones and may produce precipitation over thousands of square miles. An *anticyclone* is an area of relatively high pressure in which the winds tend to blow spirally outward in a clockwise direction in the Northern Hemisphere. Details on the general circulation and on the structure of cyclones and anticyclones can be found in meteorological textbooks.

TEMPERATURE

2-4. Measurement of temperature. In order to measure air temperature properly, the thermometers must be placed where air circulation is relatively unobstructed and yet they must be protected from the direct rays of the sun and from precipitation. In the United States thermometers are placed in white, louvered, wooden boxes, called *instrument shelters* (Fig. 2-4), through which the air can move readily. The shelter location must be typical of the area for which the measured temperatures are to be representative. Because of marked vertical temperature gradients just above the soil surface, the shelters should be about the same height above the ground for the recorded temperatures to be comparable. In the United States shelters are set about 4½ ft above the ground.

There are about 6000 stations in the United States for which the Weather Bureau compiles temperature records. Except for a few hundred stations equipped or staffed to obtain continuous or hourly temperatures, most make a daily observation consisting of the current, maximum, and minimum temperatures. The *minimum thermometer,* of the alcohol-in-glass type, has an index which remains at the lowest temperature occurring since its last setting. The *maximum thermometer* has a constriction near the bulb which prevents the mercury from returning to the bulb as the temperature falls and thus registers the highest temperature since its last setting. The *thermograph,* with either a bimetallic strip or a metal tube filled with alcohol or mercury for its thermometric element, makes an autographic record on a ruled chart wrapped around a clock-driven cylinder. Electrical-resistance thermometers, thermocouples, gas-bulb thermometers, and other types of instruments are used for special purposes.

2-5. Terminology. A knowledge of terminology and methods of computation is required in order to avoid misuse of published temperature

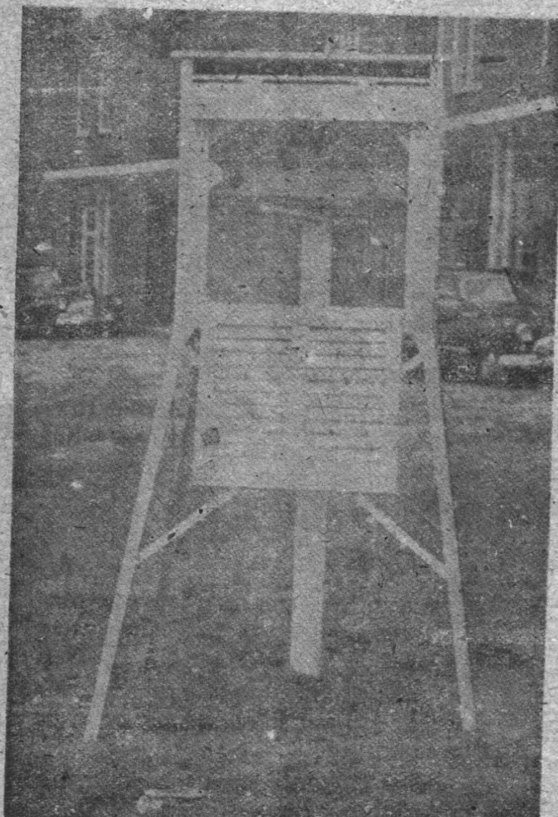

FIG. 2-4. Instrument shelter with maximum and minimum thermometers and psychrometer. (U.S. Weather Bureau.)

data. The terms *average*, *mean*, and *normal* are all arithmetic means. The first two are used interchangeably, but the *normal*, generally used as a standard of comparison, is the average value for a particular date, month, season, or year over a specific 30-yr period (1921 to 1950 as of 1958). Plans call for recomputing the 30-yr normals every decade, dropping off the first 10 yr and adding the most recent 10 yr.

The *mean daily temperature* is the average of the daily maximum and minimum temperatures. In the United States, this yields a value usually less than a degree above the true daily average. Once-daily temperature observations are usually made about 7 A.M. or 5 P.M. Temperatures are published as of the date of the reading even though the maximum or minimum may have occurred on the preceding day. Mean temperatures computed from evening readings tend to be slightly higher than those from midnight readings. Morning readings yield mean temperatures with a negative bias, but the difference is less than that for evening readings.[1]

The *normal daily temperature* is the average daily mean temperature for a given date computed for a specific 30-yr period. The *daily range* in temperature is the difference between the highest and lowest temperatures recorded on a particular day. The *mean monthly temperature* is the average of the mean monthly maximum and minimum temperatures. The *mean annual temperature* is the average of the monthly means for the year.

The *degree day* is a departure of one degree for one day in the mean daily temperature from a specified base temperature. For snowmelt computations, the number of degree days for a day is equal to the mean daily temperature minus the base temperature, all negative differences being taken as zero. The number of degree days in a month or other time interval is the total of the daily values. Published degree-day values are for heating purposes and are based on departures below 65°F.

2-6. Lapse rates. The *lapse rate*, or vertical temperature gradient, is the rate of change of temperature with height in the free atmosphere. The mean lapse rate is a decrease of about 3.6 F° per 1000 ft increase in height. The greatest variations in lapse rate are found in the layer of air just above the land surface. The earth radiates heat energy to space at a relatively constant rate which is a function of its absolute temperature. Incoming radiation at night is less than the outgoing, and the temperature of the earth's surface and of the air immediately above it decreases. This surface cooling sometimes leads to an increase of temperature with altitude, or *temperature inversion*, in the surface layer. This condition usually occurs on still, clear nights because there is little turbulent mixing of air and because outgoing radiation is unhampered by clouds. Temperature inversions are also observed at higher levels when warm air currents overrun colder air.

In the daytime there is a tendency for steep lapse rates because of the relatively high temperatures of the air near the ground. This daytime heating usually destroys a surface radiation inversion by early forenoon. As the heating continues, the lapse rate in the lower layers of the air steepens until it may reach the *dry-adiabatic* lapse rate (5.4 F° per 1000

[1] W. F. Rumbaugh, The Effect of Time of Observation on the Mean Temperature, *Monthly Weather Rev.*, Vol. 62, pp. 375–376, October, 1934.