HANDBOOK OF

Water Resources and Pollution Control

EDITED BY

HARRY W. GEHM and

JACOB I. BREGMAN

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Preface

Technology as it relates to water is in rapid evolution. This is due primarily to new national policies and goals toward improved water quality which take expression as federal and state water pollution control regulations. The ability to meet their requirements is, in many instances, dependent upon the development of new technologies or refinement of those which have been practiced in the water field for many years. This situation has sparked intensified research and development programs which are in turn contributing to the technological evolutionary process.

Another result of expanding federal and state control of water quality is that many public officials as well as private citizens, untrained in the field, have been thrust into positions of water management responsibility. Others have acquired new responsibilities under increasingly stringent regulations which expand their scope of operation. Personnel at all levels of government are charged with solving water-related problems which are entirely new to their experience. Elected officials, planners, and those appointed to decision-making boards or commissions at the local level, too, are confronted, many for the first time, with the necessity to make difficult choices among pollution control alternatives.

It was in this climate that this book on water was written. It responds both to changing technology and the needs of those who will employ it. The book embraces the constant principles of the scientific and technical disciplines involved in water pollution control and within their framework, changing control technologies. The sciences covered which either affect or are affected by water pollution are global hydrology, water chemistry, microbiology, aquatic biology, and the waste assimilative capacity of streams.

Advanced techniques for treatment of both municipal and industrial wastes, many of which are still in experimental stages, are presented. These techniques, for the most part, are designed not only to reduce pollution loads, but to increase available water supplies through the reuse of reclaimed wastewater.

Advanced techniques of cost allocation among users of joint municipal/industrial waste treatment facilities are also discussed along with alternative methods of recovering costs. Joint treatment is frequently undertaken to obtain economies of scale, and federal law now requires industry to pay its full share of treatment in plants constructed with federal funding.

The chapter on acceptable techniques for disposing of sludge resulting from waste treatment is of increasing importance as populations grow, treatment requirements become more stringent, and more solids are removed. This is one of the most difficult and expensive facets of dealing with municipal and industrial wastewaters.

The book, however, is not confined to wastewater, its treatment, and reuse. It addresses water supply and use as well, both for human and industrial needs. These chapters are especially appropriate in an era when water supply concerns have often been overshadowed by preoccupation with wastewater problems.

As a guide to potential water demand, data are presented on actual water use by nearly 200 public water supplies in the U.S., information which is not tabulated in one source elsewhere. The treatment and distribution of potable water are covered in two chapters. The former presents the most modern practice in the preparation of potable water and provides a basis for meeting future requirements. The chapter on distribution will be especially useful to those responsible for extending water systems to serve burgeoning metropolitan areas. This is also true of the chapter "Wastewater in the City," which is concerned with projecting anticipated quantities of sewage, how to confine it, and how to remove it from its source.

The potential for increasing the world's usable water supply through desalination of seawater is explored. This chapter discussed theoretical, practical, and economic considerations of the more promising processes of desalination.

Innovative techniques for beneficial use of thermal discharges from power plants are described. These include increased-productivity greenhouses for vegetables as well as flowers, improved livestock production, and space heating.

The book closes with a section-by-section analysis of the 1972 Amendments to the Federal Water Pollution Control Act which establish, for the foreseeable future, the goals anticipated to be achieved in the nation's drive toward clean waterways. It is imperative that engineers understand the law and its requirements in order to gauge the magnitude of the effort and the technology it will require.

Two important areas are not covered individually by chapters in this volume, although they are indirectly addressed in other chapters. One is the federal drinking water standards which are presently undergoing a thorough revision within the Environmental Protection Agency. The other is federal water quality criteria for various uses of water which are similarly being revised. Sufficient change is anticipated that discussion of the existing standards would, in both cases, serve no useful purpose in this reference volume.

Recognized experts were selected to author the chapters in their specialty areas. We extend our deep appreciation for their contributions in the full knowledge that this "extracurricular" assignment placed a heavy burden on already busy schedules.

Our especial thanks go to Mrs. Gene Beeland of WAPORA, Inc., technical editor of the *Handbook of Water Resources and Pollution Control*, who for over three years has borne the day-to-day responsibility for its production. She has dealt with over 3000 pages of manuscript, over 200 permissions to publish copyrighted materials, author schedules, and the myriad other details attendant to a project of this scope. The book would not be a reality today without her assistance.

H. W. GEHM
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Editors

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1

Hydrology

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THE WATER CYCLE

Since very ancient times it has been empirically known that there is a water cycle—a series of recurring events that can be depended on to repeat themselves. The water cycle (hydrological cycle) is the central concept of hydrology, the science of water. Water circulates naturally through five principal realms—oceans, atmosphere, lakes and rivers, icecaps and glaciers, and underground. Hydrology concerns water and its behavior in all these realms.

Air and water are the most mobile physical elements of the earth system, and this mobility permits the water cycle to operate. Constant circulation of water from ocean to atmosphere (evaporation), from the atmosphere to land areas or directly back to the ocean (precipitation), and from the land back to the ocean and atmosphere (runoff and evaporation) may be called the planetary water cycle. Within it are many regional and local subcycles. For practical reasons, most resource-oriented studies of water have concerned regional and local phenomena. However, as water supply and water quality problems proliferate, they must be viewed in a larger context—national, continental, and even global.

Large-scale phenomena of the hydrological cycle may seem to be far removed from the purview of sanitary engineers, most of whom are concerned with specific local or regional problems. However, large-scale phenomena are critical, whether we deal with water as a supply resource or as a vehicle for the transportation of wastes. Worldwide contamination of oceans and the atmosphere is a good example. Where water and air are concerned, events in any part of the world are consequences of events in all other parts of the world. Because the water cycle is a global phenomenon, it will be considered from that standpoint.

A serious handicap to all who work with water is the inadequacy of meteorological and hydrological forecasting for periods of more than a few hours. Forecasting can be improved through better means for interpreting meteorological data, but more and better data from large areas also are needed. This was one of the reasons for establishing the IHD (International Hydrological Decade, 1965-1974), a joint effort of more than one hundred nations to improve hydrological knowledge. The IHD is symbolic. It is a special decade during which attention turned from man's frail waterwheels to the great waterwheel of nature—the global hydrological cycle.

Oceans and Seas. Hydrologists generally treat the world ocean as though it were only of peripheral interest to hydrology. For local studies this is generally true, except in coastal areas where salt water invades river estuaries and may also invade coastal aquifers. The ocean, however, is tremendously important in the hydrological cycle.

The world ocean contains about 317×10^6 mi^3 of water (Table 1-1). A more significant characteristic of the ocean, however, is its vast expanse of 139.5×10^6 mi^2. The ocean averages 2.27 mi in depth but the widths of the main oceans are 900 to 2500 times that amount. Because of this geometry and the great heat-storage capacity of the ocean, the sea-atmosphere interface is the most important of all interfaces involved in the hydrological cycle. The system ocean-atmosphere-continents is a great heat engine driven by solar energy. Solar energy and the oceans form a giant natural water-distillation plant and the atmosphere provides the water-distribution system. Owing to its immense reserve of thermal energy, circulation of oceanic water, coupled with atmospheric circulation, provides the climate-control system of the world.

Thermal energy transactions, including evaporation, occur throughout the world ocean. Therefore, the entire ocean area is a source of atmospheric vapor and hence of precipitation on land. The total volume of oceanic water is about 3000 times the annual volume of oceanic evaporation. Hence, the average residence time of water molecules in the sea is about 3000 years. Residence in abyssal zones is much longer and in shallow zones much less.

Heat Fluxes. Heat is the driving force of the water cycle, and evaporation is the first stage of the cycle. The solar constant may be defined for present purposes as solar radiation per unit area reaching the top of the atmosphere on a surface perpendicular to the solar beam. The "top" of the atmosphere cannot be defined precisely in terms of altitude because it varies with latitude and air movements. In general, it is the level above which no significant absorption or backscattering of radiation occurs. Solar energy which reaches the earth eventually

TABLE 1-1. Estimated Long-Term Average Value for Elements and Parameters of the Water Cycle[a]

Parameter	Volume (mi^3)	Equivalent Depth[b]	Average Residence Time
Atmospheric water	3.1×10^3	1.0 in.	10 days
World ocean	$317{,}000 \times 10^3$	1.6 mi	>3,000 yrs
Freshwater lakes	30×10^3	9.6 in.	Days to 100s yrs
Saline lakes and inland seas	25×10^3	8.0 in.	Days to 100s yrs
Swamps and bogs	8.6×10^3	2.8 in.	Days to yrs
River channels	0.41×10^3	0.13 in.	~2 weeks
Soil water; vadose water	16×10^3	5.1 in.	Days to yrs
Groundwater	$1{,}000 \times 10^3$	26 ft	Days to 100,000s yrs
Icecaps and glaciers	$7{,}300 \times 10^3$	196 ft	Days to 100,000s yrs
Permafrost	Unknown	Unknown	Unknown
Biological water	0.17×10^3 [c]	0.04 in.	Days to weeks

[a]Adapted from Nace.[1]
[b]Computed as though it were spread uniformly over the entire earth.
[c]Some estimates are as high as 1.2×10^3 mi^3.

is reradiated into space as heat. Meanwhile, circulation of oceans and the atmosphere distributes the heat around the earth.

Differential heating is the key to the entire cycle. Heating is different at different latitudes, at different seasons, and at different times of day. Heating of land areas differs from that at sea. Within land areas it differs depending on soil color, type of vegetation or lack of it, and so on *ad infinitum*. Heating of the ocean also is differential. The results of these and other differentials are imbalances of thermal energy, which cause imbalances of density or pressure energy, and these in turn contribute to air flow and ocean currents. Friction, the earth's rotation, and gravity also have profound effects. The Coriolis force, for example, operating because of the earth's rotation, sets up the principal wind patterns in the lower atmosphere.

Solar radiation is generally treated as the sole source of heat that drives the water cycle because heat conducted to the earth's surface from its interior is negligible by comparison. A commonly used value for the solar constant (S) is 2.0 ± 0.04 ly (langley; 1 ly = 1 gm-cal/cm^2). Only part of the atmosphere receives radiation at any one time, and little of its outer surface is perpendicular to the incident radiation. Using a solar constant value of 2.0 ly/min, total energy intercepted by the earth in unit time is 2.55×10^{18} cal/min.[2] Total energy intercepted by the earth is equal to $\pi r^2 S$, where r is the mean radius of the earth (6.371×10^8 cm) and S is the solar constant of 2 ly:

$$\pi r^2 S = 2.55 \times 10^{18} \text{ cal/min} \qquad (1)$$

About 30 percent of the incident radiation is reflected and scattered in space by clouds and atmospheric constituents; 17 percent is absorbed by the same media; 22 percent reaches the earth's surface as diffuse sky radiation; and 31 percent reaches the surface as direct-beam radiation. Thus, about 53 percent of intercepted solar radiation actually reaches the earth's surface.

If the intercepted energy were spread uniformly over the full spheroidal surface of the earth, the average intensity of radiation per unit area and time ($\overline{E}_s$) at the top of the atmosphere would be only one-fourth of the solar constant:

$$\overline{E}_s = \frac{\pi r^2 S}{4 \pi r^2} = \frac{S}{4} = 0.5 \text{ ly/min}$$
$$= 263 \times 10^3 \text{ ly/yr} \qquad (2)$$

Owing to absorption, backscattering, and other losses, the effective radiation for producing evaporation is 0.078 ly over the oceans and 0.098 ly over the earth's surface as a whole.[3]

The mean global values are significant for the global hydrological cycle. The distribution of energy, however, is not uniform and the average values cannot be applied in local or regional studies. At the equator, for example, the annual value of $\overline{E}_s$ is about 2.4 times that near the poles. A good summary of the energy cycle of the earth is contained in Ref. 4.

Vapor Fluxes. The flow of vapor in air is called a vapor flux. According to a recent estimate,[5] the earth's mean upward flux of water (evaporation, which includes transpiration) is about 1000 mm/yr (about 1250 mm/yr from the sea and 410 mm/yr from land). Many other estimates are extant and the differences among them are significant, but no means is available to judge which estimate is "best." For working purposes, the following values probably are acceptable:

World average
1016 mm = 39.8 in. (125,000 mi^3)
Oceanic area
1230 mm = 48.4 in. (107,800 mi^3)
Land
480 mm = 18.9 in. (17,200 mi^3)

The implication of three to four significant figures is, of course, erroneous. They are retained only for bookkeeping purposes. According to this estimate only about 14 percent of world evaporation is from land areas. The methods and problems of measuring and estimating oceanic evaporation and precipitation and the current state of knowledge have recently been analyzed and described.[6]

Because of the accessibility of inhabited land areas, the state of knowledge there is somewhat better than for the oceans but still is unsatisfactory. Estimation of terrestrial evaporation is a formidable problem because no generally acceptable or usable method is available for direct measurement of evaporation for areas larger than a few hundred square feet. A commonly accepted value for evaporation, averaged for the conterminous United States, is 21 in.

Advective atmospheric vapor fluxes have attracted considerable attention in recent years, but they need much more study. Analysis of vapor flux divergences is a relatively new method for indirect determination of net precipitation and evaporation, but stations for determination of vertically integrated vapor fluxes are far too few for hydrological purposes.

A study of vapor transport over the North American air space[5] indicated that vapor inflow exceeded outflow by about 210×10^9 gm/sec in winter, this being the excess of winter precipitation over evaporation. Summer outflow exceeded inflow by about 80×10^9 gm/sec, representing excess of summer evaporation over precipitation.

Table 1-2 is derived from an analysis[7] which shows the total annual flux of water vapor into and out of the conterminous United States during each of 2 years. The differences between income and outgo were 2420 and 2240×10^{12} kg/yr in the 2 years, respectively. This is equivalent to 11.8 in. or less of yearly precipitation over the United States. Actual precipitation of water derived from oceanic sources cannot be computed in that way from such generalized data, but the computation is a way of giving meaning to the amounts of water involved.

TABLE 1-2. Vapor Flux over the United States[a]

Source or Destination	Flux (10^{12} kg/yr) 1961-62[b]	1962-63[b]
Pacific Ocean to West Coast	4,320	4,480
Gulf of California to Southwest	670	730
Gulf of Mexico to midcontinent	4,580	3,790
Totals, income	9,570	9,000
East Coast to Atlantic Ocean	6,480	6,260
Midcontinent to Canada	670	500
Totals, outgo	7,150	6,760
From West Coast across Rocky Mountains (and their southern extension) into midcontinent and Canada	4,420	4,800

[a]Compiled from a figure by Rasmusson.[7]
[b]Each year is from May through April.

Evaporation of a single molecule of water is a simple process in which the molecule is torn free from others after absorbing radiant energy. Gross evaporation from ocean surfaces or land surfaces, however, is a result of complex reactions among water, soils, vegetation, air, and radiation. It occurs wherever water is available and the air adjacent to it is not already saturated. Evaporation occurs even at freezing temperatures and the great icecaps, glaciers, sea ice, and perennial snow fields of the world are not immune. By the process of sublimation, ice and snow may vaporize without passing through a liquid phase. Sublimation accounts for about 10 percent of evaporation from snow and ice fields, but it is probably largely offset by hoar frost deposited by the reverse process (W. J. Campbell, personal communication, June 14, 1970).

Evaporation from free water surfaces such as ponds and lakes cannot be measured directly, even by calculation from stage-capacity tables and from measurement of surface inflow and outflow. Measurement of each factor has inherent errors. In addition, a water body may lose by seepage into the ground or gain by effluent seepage of groundwater. Wind has a great effect on evaporation from water surfaces because it removes humid air and commonly introduces drier air. Floating pans containing water do not give a true measure of lake evaporation because the protruding rim of the pan changes the wind pattern and hence the eddy diffusion above the pan.

Similarly, land pans do not give a true measure of lake evaporation because air near the surface over land generally is less humid than that over a lake. Experimental evidence indicates that under many conditions lake evaporation is about 70 percent of evaporation from the U. S. National Weather Service Class A land pan. The highest reported pan evaporation rate in the United States is about 155 in. at a location in Death Valley, California, in the year ending on May 1, 1959. Weather Service data indicate that average annual Class A pan evaporation ranges from 140 in. in parts of the arid Southwest to only 25 in. in the far Northwest and Northeast. Recommended pan coefficients range from 60 to 80 percent depending on location.[8] Evaporation is measured regularly at only about 540 stations in the United States, and records for periods longer than 40 years are available for only about 54 stations.

Vegetation has an important role in the water cycle. Plants send their roots into the soil, withdraw water, transpire it, and thus put the root zone of the earth in communication with the atmosphere. No satisfactory method is available for differentiating direct evaporation from plant transpiration, so the term evapotranspiration has been coined to designate the combined processes. Transpiration is evaporation, and so long as the two types of evaporation cannot be estimated or measured separately, evapotranspiration is a useless term.

Measurement of evaporation from lysimeters is a common and useful practice to obtain data for estimating local evaporation from vegetated areas. For large areas, however, evaporation must be computed on the basis of theory, using observations of insolation, temperature, duration of daylight, wind, and other factors. These calculations generally yield a value that expresses potential evaporation, the amount of evaporation that would occur if water were plentiful, as in a pond or water-saturated land area. Soil, however, is seldom fully saturated. Actual evaporation in most land areas is less than the potential, commonly much less. From dry soil it approaches nil.

The percent saturation of the air with water vapor is called the relative humidity. Humidity varies with time, place, and altitude. At a given time and place, the amount of liquid water equivalent in the overlying column of air is called the precipitable water content.

Air masses of varying humidity may move upward and downward as well as laterally. Vertical humidity profiles can be obtained by various rocket-borne or balloon-borne sensors. Knowing the direction and speed of air movement, vertically integrated horizontal vapor fluxes may be determined. With a sufficient number of determinations around an area, the net vapor balance may be determined.

Thus far, such determinations have been made in research and experiments, but not routinely. The results indicate that the method is reliable, within acceptable limits, only for areas of about 200,000 mi^2 or more. Little success has been achieved with smaller areas. The method does not define either precipitation or evaporation. Rather, it discloses the net vapor balance. That is, if a given amount of vapor moves into an area, and a different amount moves out, it can be determined whether evaporation exceeded precipitation, or the reverse.

Precipitation. Precipitation is the beginning of the land phase of the water cycle. Disposition of the precipitated water depends on many factors such as rate of rainfall or snowfall, rate of snow melt, topography, vegetation, nature and condition of the soil or rock at the land surface, and relative humidity.

Worldwide, the estimated number of rain gauges of all kinds in operation is somewhat more than 100,000, and the number of snow gauges is about 25,000. This is an average of 1 gauge per 460 mi^2 of land area. Understandably, therefore, it is difficult to estimate total precipitation on land areas, much less for the vast area of the world ocean. None but crude approximations can be achieved. A commonly accepted value for average annual precipitation averaged for the conterminous United States is 30 in.

For many purposes in meteorology and hydrology, standard elevated rain gauges are sufficiently accurate. They are not adequate for careful quantitative hydrology. The hydrologist needs to know how much precipitation actually reaches the ground, not how much is caught in a vessel some distance above ground.

Pit gauges, with the aperture at ground level, have been widely used in the United Kingdom, the Soviet Union, and elsewhere. They are considered to be superior to elevated gauges for measuring rain, but they have little value for measuring snowfall.

Contrary to the common working assumption, rainfall measured at individual gauges is not truly representative of the area between gauges. Even where gauge networks are relatively dense (on the order of 1 per 40 mi^2, as in Japan and Western Europe), measured rainfall is about 2×10^{-10} of the total areal amount. In most areas it is 10^{-11} to 10^{-13} or even smaller. Many thunderstorm cells are only 2 to 4 mi in horizontal diameter, so many rain showers cannot be measured accurately by an ordinary station network.

For the earth as a whole, averaged for long periods of time, the amount of atmospheric moisture is constant. Average long-term precipitation, therefore, must equal evaporation, though the distribution of precipitation differs from that of evaporation. World average precipitation probably is about as shown below:

World total
  1016 mm = 39.8 in. (125,000 mi^3)
Ocean area
  1138 mm = 44.8 in. (99,800 mi^3)
Land area
  724 mm = 28.5 in. (25,200 mi^3)

According to this estimate, only 20 percent of all precipitation falls on land areas.

Precipitation has been observed systematically more widely and during longer periods of time than most other meteorological parameters. Much of the early work was done by individuals to satisfy personal curiosity. For some parts of the eastern United States, a few data are available even for pre-Revolutionary periods. However, very few systematic records are available for periods longer than 100 years. Coverage is sparse in many parts of the conterminous United States, especially in wilderness and high-altitude areas. No data are available for vast areas of Alaska. Puerto Rico, on the other hand, has the most intensive network of observations of any area of comparable size in the Western Hemisphere.

The most common rain gauge in the United States during many years has been a cylindrical tube about 2 ft high, with a horizontal circular catchment orifice 8 in. in diameter. The depth of rainfall is measured with a calibrated dip stick. This gauge is still the standard for routine measurement of daily precipitation in regional observation networks. More complicated equipment is available to measure and record rates of precipitation and other factors in experimental areas.

Observational coverage in the United States and elsewhere is being improved constantly, but it is unlikely that coverage ever will be adequate for precise estimation of precipitation. The U. S. National Weather Service and other agencies maintain only about 10,500 permanent precipitation gauges, of which only 5500 have records longer than 40 years.[9] Coverage by 1 gauge per square mile would require more than 3×10^6 gauges for the conterminous states. This still would sample only about 0.3×10^{-6} percent of the total area.

Gauge records are generally biased toward the low side.[10] Experience with standard rain gauges[11] indicates that they are generally negatively biased about 1.5 percent owing to evaporation, adhesion to the instrument, and several other factors. In addition, gauges in exposed positions may be in error by 5 to 80 percent, depending on wind speed. No absolute measurement of precipitation is possible at present, and field measurements are only comparative.

The physics and hydrodynamics of precipitation are beyond the scope of this discussion. It is necessary, however, to reconcile the small amount of atmospheric moisture with the comparatively large volume of precipitation.

Firstly, atmospheric moisture is being constantly renewed by evaporation and advection. Secondly, for most of the world, precipitation is a rare event in terms of hours per year during which it occurs. At Paris, France, a fairly typical temperate zone location, average annual duration of precipitation is 577 hr, or about 7 percent of the time.[12] Thirdly, the air mass in a storm contains considerably more than the global average of moisture. Finally, the atmosphere is on the move and moisture is renewed in the area over which rain-producing conditions persist.

Intensity of precipitation is an important factor, because the disposition of precipitation among evaporation, infiltration, and runoff is strongly affected by the rate of precipitation. Precipitation of low intensity and long duration has the advantage that there is ample opportunity for infiltration. Total precipitation of an inch or so during a few hours may produce little or no direct runoff. The same amount of rain within a few minutes may produce heavy runoff.

Interception. Much precipitation is intercepted by vegetation and evaporates without ever reaching the ground. This is called interception loss. Many studies of the phenomenon have been made but no wholly satisfactory means have been developed for estimation of regional interception. Rain gauges generally are purposely sited in the open, where they theoretically measure total precipitation. Only for experimental purposes are companion gauges placed under tree canopies.

Although it is considered that open-space rain gauge records are generally biased on the low side, the bias may be accentuated in forested areas in terms of precipitation that actually reaches the ground. The extent of permanent interception depends strongly on the intensity and duration of precipitation. Heavy precipitation quickly saturates foliage and, if continued, full precipitation after saturation reaches the ground. This is called throughfall. Light precipitation of short duration may only wet the vegetation and no moisture will reach the ground except in open areas. Light precipitation during an extended period, however, may largely reach the ground.

Some good data on interception are available for experimental areas, but only estimates are available for large areas. Owing to the variables noted above, it is readily apparent that direct measurement of large-area interception is impossible.

The amount of interception varies with the nature of the foliage and bark of the vegetation. Some intercepted precipitation may be absorbed by foliage and bark, and a certain amount is required to wet leaves and bark before throughfall and stemflow occur. Wind, by shaking leaves, may cause greater throughfall than would occur without wind. Specialists in this field commonly consider that 0.02 to 0.10 in. of rain is necessary for throughfall to occur, depending on the type and height of vegetation. It may be assumed that a nearly equal amount evaporates from foliage after the storm. In addition, some water may evaporate from foliage even while rain is falling.

Most interception is satisfied by rain falling in the early part of a storm. However, many storms yield only small amounts of precipitation and, where vegetation is dense, interception may amount to 25 to 50 percent.[13]

Some observers believe that interception of snow by conifer forests is highly significant. A sizable fraction of snowfall may be intercepted and evaporate without reaching the ground. Various studies of conifer forest areas report annual interception rates of 4 to 15 in. of precipitation and amounts of up to 38 percent of total precipitation.[14] Hardwood forests intercept little snow.

In one experiment, snowpack accumulation under trees was 30 percent less than in the open. In other experiments, rainfall interception ranged from 100 percent from a rain shower of 0.01 in. to 16 percent for showers of 0.5 to 1.0 in.[15]

On the other hand, it has been noted[16] that calculation of an energy budget for snow in the trees shows that little energy is available for sublimation. Also, the moisture gradient is small and very little snow actually evaporates. The whole topic of interception, especially of snow, needs much more study.

Infiltration. Infiltration, the movement of water downward through the soil surface, is an elusive parameter in the hydrological cycle and it can be measured directly only in small experimental plots. Various kinds of soil moisture probes are available with various degrees of accuracy. Some of them, by their very presence, disturb the soil so that they do not correctly define infiltration under natural conditions.

Infiltrometers have been also widely used to determine rates and amounts of infiltration. Again, the infiltrometer itself disturbs natural conditions and the results may be erroneous.

Infiltrometers in some areas show no deep infiltration where other lines of evidence indicate that infiltration must occur.

Infiltration is one of the more critical phenomena of the hydrological cycle for several reasons. Where the rate is slow, the ratio of runoff to infiltration is high and restoration of soil moisture is low. Where the surface soil is highly permeable, infiltration may be rapid and runoff from a light but steady rain may be negligible. No recharge of groundwater by deep percolation can occur until the moisture demand of the soil mantle has been satisfied. Thereafter, further infiltration leads to deep percolation and groundwater recharge.

Infiltration rates in very tight soil range from 0.0 to 0.5 in. water/hr. In very permeable soils, rates may range up to several inches per hour.

Deep Percolation. Deep percolation refers to the process whereby water percolates downward below the soil or root zone and may reach the water table. In order for percolating water to reach the water table, the supply of water must exceed the field capacity of the soil and subsoil. In this zone, capillary forces dominate when the earth material is not saturated. At the saturation and near-saturation levels, however, gravitational forces dominate and water can move downward to recharge groundwater in the zone of saturation.

The hydrodynamics of deep percolation is not well understood, but the fact of deep percolation is well recognized. Direct recharge by vertical percolation downward through permeable earth is widespread where the supply of water from precipitation is adequate. Where the soil and subsoil are poorly permeable, recharge may be small even in areas of high precipitation.

Arid areas and semi-arid areas contain some very large aquifers, but some of them receive very little direct annual recharge. An example is the Ogallala Formation of the Southern High Plains of Texas and New Mexico. Estimates of the average annual rate of recharge are in the range of a few tenths of an inch. The aquifer is geologically isolated and receives no replenishment of water by underflow from surrounding sources. The huge amount of water in this aquifer is an inheritance from the past, when a wetter climate prevailed.

Another great aquifer, the basalt aquifer of the Snake River group in southern Idaho, probably receives only a few tenths of an inch annually by direct infiltration of precipitation. However, the aquifer has copious sources of replenishment: several rivers which debouch onto the plain from surrounding mountains sink into the basalt and disappear. Mass underflow of groundwater from surrounding mountains into the plain must be significant in amount. Some reaches of the main stream of the area, the Snake River, are perched above the water table, to which the river loses water by seepage. Some reservoirs and lakes also are leaky. Finally, excess water applied to irrigated areas finds its way to the water table.

Gravel-filled valleys in arid areas are another special case. Rain and melting snow in adjacent mountains feed streams which are perennial in the hard-rock mountains but disappear when they reach their permeable alluvial cones or fans. Some of the water may be disposed of by deep percolation, but in some cases the water is sufficient merely to a wet shallow layer of alluvium from which the water evaporates.

No direct measurement of deep percolation is possible, but several methods are available for estimation. One of the most common is to observe fluctuations of the water table, represented by the water levels in observation wells. Following a rainstorm or melting of snow, water levels will rise after a lag period that depends on the permeability of the soil and the depth to water. If the porosity of the aquifer is known or estimated, the rise in water table, suitably adjusted for previous moisture content, can be converted to equivalent depth or volume of water added.

Relatively little is known about rates of deep percolation except in local areas. A study on Long Island, New York showed that beneath one recharge basin in coarse sand and gravel the downward rate of movement averaged 5 ft/hr.[17] In a recharge basin with a few feet of head of water in the basin, the rate of infiltration and hence of downward percolation would be higher than through undisturbed land surfaces in many areas.

No infallible method is available for accurate estimation in large areas. Under natural conditions during long periods of time, natural discharge of groundwater equals natural recharge. Natural discharge is through seeps and springs, by evaporation where the water table is at shallow depth, and by transpiration where plant roots reach the water table or the capillary fringe above it. It would not be possible to measure all these parameters. Several indirect methods have been used to estimate recharge in the Southern High Plains of New Mexico.[18] Results from each method differed, but they seemed to converge on a value of about 0.5 in./yr. In arid areas, deep percolation may be nil in most years. In humid areas it may amount to several inches or more per year.

Groundwater Underflow. Underflow is the lateral movement of groundwater, whether in confined or unconfined aquifers. Rates of underflow cover a wide range, depending on the permeability of the aquifer, the rate of recharge, and the hydraulic gradient. In coarse sand and gravel, rates of 50 to 60 ft/day are considered to be in the upper range. Rates in cavernous limestone and basalt may be higher, and even under low gradients rates may average 20 to 40 ft/day. In less permeable materials such as sand, silt, and clay, rates are much less, ranging down to a fraction of a foot per day or nil.

Flow rate is not a direct function of porosity. Clay, for example, is among the most porous of earth materials, with porosities up to 60 percent. However, the pores are so small that capillary and molecular forces dominate and may prevent gravity flow.

Rates of flow have only been sparsely studied in artesian aquifers. The water from artesian wells is derived by elastic compression of the aquifer. In a non-artesian well, a dye or other tracer may be introduced in one well and its time of arrival observed in another well down gradient. In the artesian situation, the tracer would have to be introduced under pressure. This would disrupt the pressure gradients in the aquifer and the time of appearance of the tracer in another well would not be indicative of natural rates of movement.

Application of specialized techniques permits estimation of movement rates and residence time of water in some aquifers. Analysis of ^{14}C in dissolved carbon compounds in groundwater is an example. Results for water from various deep aquifers in North Africa and Arabia indicate residence times in the range of 20,000 to 30,000 years. These indicate movement rates on the order of a few hundred feet per year from distant recharge areas in the plateaus and mountains. These rates are consistent with the known properties of the aquifer such as permeability and pressure gradients.

Rate of movement of water in an aquifer should not be confused with rate of transfer of changes in hydraulic head. Transfer of head is analogous to what occurs when there is a sudden influx of water at the head of a reservoir. This influx creates a surge or bore whose celerity depends on its height and the depth of water below and ahead of it. Under some circumstances celerities of many miles per hour may be achieved. Flow over the spillway of a dam may increase within a few minutes after the influx of water while the new water itself is still at the head of the reservoir.

Analogous phenomena occur in unconfined aquifers. An influx of recharge water in one area may create a so-called recharge wave which is propagated outward from the area. The aquifer material, however, has a damping effect on the wave, and the lower the permeability the greater the damping. Even in highly permeable material, the celerity may be no more than a few hundred feet per day through short distances. Recharge waves generally are completely damped out within a few miles, often much less. Meanwhile, the recharge water remains at or near the place where it entered the aquifer. The recharge wave is merely a transfer of head.

In terms of rate of circulation, subsurface water-bearing materials may be grouped in several zones; as described below.

Zone of Rapid Circulation. The zone of rapid circulation extends from the land surface downward a few tens or hundreds of feet. It includes the soil zone, vadose zone and zone of relatively shallow unconfined groundwater. Water of meteoric origin in this zone has a residence time of a few hours or days to a few years. Natural discharge from this zone is a principal source of water that sustains the flow of streams during rainless periods (base flow).

Zone of Delayed Circulation. In the zone of delayed circulation the water is generally fresh and of meteoric origin; it may be unconfined but commonly is confined under artesian pressure. While the water circulates rather freely, circulation is delayed and residence time of water in the aquifer may range from a few decades to a few centuries. The depth to or through this zone may range from a few hundred to a few thousand feet.

Zone of Lethargic Circulation. The zone of lethargic circulation contains water which is largely or wholly of meteoric origin but which has been out of the normal hydrological cycle during many hundreds or thousands of years. The water commonly is highly saline. Its movement is generally considered to be hydrodynamic, but geochemical osmosis and electrochemical forces also may operate. Such waters commonly are at depths exceeding 5000 ft, but they may occur within the upper few hundred feet. For practical purposes, most of these waters may be considered to be nonparticipants in the modern hydrological cycle.

Other Zones. Other zones (stagnant and dry) exist, but they are of no concern in the water cycle. They may be of interest as zones for the storage of radioactive and industrial liquid or gaseous wastes.

Exceptions occur in all of the depth and circulation zones noted above. Saline water, for example, occurs at shallow depth in large areas and may feed saline springs, as in the Permian Basin in the southwestern United States.

Groundwater Outflow. Under natural conditions, most unconfined aquifers are full to overflowing. Overflow occurs through springs and seeps and by diffused percolation into stream channels. Were this not so, many streams would be dry during rainless periods. At high-flow and flood stages of rivers, some surface water seeps into river banks and becomes groundwater. When river stages fall, the water returns slowly to the river. Bank storage and return flow were first recognized and described, though not named, 300 years ago,[19] but the phenomena received relatively little study until modern times.

The important phenomenon of base flow has been studied chiefly in connection with flow-duration analyses of streams. It has been largely neglected as a means of estimating the sustained annual yield of aquifers, although it could be helpful in that respect. Conjunctive use of groundwater and surface water inevitably will become widespread. This will require much more attention to groundwater flow, including contributions to base flow in streams.

In some places the discharge of groundwater through springs is spectacular. An example is the springs along the valley walls of a 40-mi reach of the Snake River in southern Idaho. The aggregate average discharge of these springs is about 6000 ft^3/sec. One group, the Thousand Springs, alone discharges about 750 ft^3/sec.

The existence of oceanic shoreline and submarine springs has been known since antiquity. For the most part, these have been treated as curiosities. However, it is now known that they have considerable importance in some localities. An outstanding example is Hawaii, where an aerial survey by infrared imagery disclosed the existance of at least 219 springs with discharges sufficiently large to affect noticeably the temperature of the receiving seawater. Discharge from individual longshore springs of Hawaii range up to 238×10^6 gpd (2260 ft^3/sec.)[20]

Longshore and submarine springs have been found at many other places: along the Atlantic and Gulf coasts of Florida, many Mediterranean countries, in the Red Sea, along the shore of Normandy in the English Channel, in the West Indies, near the Sandwich Islands, and elsewhere. It has been estimated[21] that about 2×10^9 m^3 (70.6×10^9 ft^3) of water discharges annually through coastal and submarine springs in the karstic areas of Greece; this is about 22 percent of estimated annual groundwater recharge (9×10^9 m^3 = 318×10^9 ft^3).

The karstic area is about 45,000 km^2 (17,380 mi^2), island karst included. Karst is a distinctive type of landform in regions of