these two methods of computation, and these, on a small scale, might well be undertaken in the hydraulic laboratory of an engineering college.

Prob. 141*a*. A canal from a river to a power house is two miles long, its bed is on a slope of 1/10 000, and c is 70. When the water is in uniform flow, the depth D is 6.0 feet, and the discharge is 800 cubic feet per second. If there be a power house which takes 1000 cubic feet per second, find the probable depth of water at the entrance to its forebay.

Prob. 141*b*. Show that the last formula in Art. 135, when reduced to the metric system, becomes $v = v' + 6.1\sqrt{rs}$.

Prob. 141*c*. A stream 181 meters wide and 5 meters deep has a discharge of 1318 cubic meters per second. Find the height of backwater when the stream is contracted by piers and abutments to a width of 96 meters.

Prob. 141*d*. Which has the greater discharge, a stream 1.2 meters deep and 20 meters wide on a slope of 3 meters per kilometer, or a stream 1.6 meters deep and 26 meters wide on a slope of 2 meters per kilometer?

Prob. 141*e*. A stream 2 meters deep is to be dammed so that water shall be 4 meters deep at the dam. Its slope is 0.0002 and its channel is such that the metric value of c is 39. Compute the distance to a section up-stream where the depth of water is 3.6 meters.

CHAPTER 11

WATER SUPPLY AND WATER POWER

Art. 142. Rainfall

All the water that flows in a stream has at some previous time been precipitated in the form of rain or snow. The word "rainfall" means the total rain and melted snow, and it is usually measured in vertical inches of water. The annual rainfall is least in the frigid zone and greatest in the torrid zone; at the equator it is about 100 inches, at latitude 40° about 40 inches, and at latitude 60° about 20 inches. There are, however, certain places where the annual rainfall is as high as 500 inches, and others where no rain ever falls. In the United States the heaviest annual rainfall is near the Gulf of Mexico, where 60 inches is sometimes registered, and near Puget Sound, where 90 inches is not uncommon. In that large region, formerly called the Great American Desert, which lies between the Rocky and Sierra Nevada mountains, the mean annual rainfall does not exceed 15 inches, and in Nevada it is only about $7\frac{1}{2}$ inches. The amount of rainfall in any locality depends upon the winds and upon the neighboring mountains and oceans.

Fig. 142*a*.

The standard type of rain gage used by the U. S. Weather Bureau has a diameter of 8 inches. The rain falling into the gage passes down through the funnel shown in Fig. 142*a* and into the small cylinder A, the area of which is one-tenth that of the gage. One inch of rainfall therefore will give a depth of 10 inches in the cylinder A and small falls can thus be accurately measured. As the cylinder A fills it overflows into the body of the gage *B*, and when measured is simply poured into the cylinder *A* after the water it contains has been measured and poured out. These gages should be read each day in order that the loss due to evaporation may not become excessive and introduce material errors. Other forms of rain gages which record on a chart each one-hundredth of an inch of rainfall at the time when it falls are made. Such gages are of particular use in determining the rate of rainfall and the time of the fall rather than its total quantity.

At any place the rainfall in a given year may vary considerably from the mean derived from the observations of several years. Thus, at Philadelphia, Pa., the mean annual rainfall is about 42 inches, but in 1890 it was 50.8 inches and in 1885 it was only 33.4 inches. Similarly at Denver, Col., the mean is about 14 inches, but the extremes are about 20 and 9 inches. When a very low rainfall occurs, that of the year preceding or following is also apt to be low, and estimates for the water supply of towns must take into account this minimum annual rainfall. The distribution of rainfall throughout the year must also be considered, and for this purpose the rainfall records of the given locality should be obtained from the publications of the U. S. Weather Bureau as well as from all other available sources and be carefully discussed. In making plans for a water supply it should be the aim to store a sufficient quantity so that an ample amount will be available at the end of the driest period which is likely to occur. In Table 142 are shown the average rainfalls at a number of places in the United States for the four seasons and for the year; in estimates for very wet years about 25 percent may be added to these values, while for very dry years about 25 percent may be subtracted.

As illustrating the variations from the mean rainfall which may be expected at any place the following example is given. The mean rainfall at Philadelphia is about 42 inches, and the following are some of the values for various years: 29.6 inches for 1825, 30.2 inches for 1881, 61.3 inches for 1867, and 55.5 inches for 1840.

TABLE 142. RAINFALL IN THE UNITED STATES *

City	Length of Record. Years	Rainfall in Inches				
		Spring	Summer	Autumn	Winter	Annual
Vicksburg	32	15.9	12.0	10.3	15.6	53.8
Charleston	33	10.6	20.1	12.5	10.2	53.4
Little Rock	24	14.5	11.2	10.5	13.4	49.6
Portland	32	10.7	3.0	11.9	20.0	45.6
New York	33	10.6	12.3	10.8	11.1	44.8
Boston	31	11.2	10.5	11.1	10.9	43.7
Cairo	22	11.4	10.4	9.1	10.7	41.6
Cincinnati	33	9.9	10.9	7.9	9.7	38.4
Key West	33	5.5	12.6	14.5	5.3	37.9
Cleveland	33	8.5	10.2	9.0	7.9	35.6
Chicago	33	8.7	10.1	8.2	6.4	33.4
Detroit	33	7.9	10.1	7.6	6.6	32.2
Omaha	33	8.8	13.3	6.4	2.3	30.8
St. Paul	31	7.4	11.4	7.0	2.8	28.6
San Antonio	18	7.7	8.4	7.0	5.3	28.4
San Francisco	32	5.7	0.2	4.4	12.2	22.5
Bismarck	29	5.8	8.3	2.7	2.0	18.8
Spokane	23	4.1	2.7	4.7	6.8	18.3
Salt Lake City	30	5.9	2.0	3.8	4.1	15.8
Los Angeles	28	1.7	0.0	5.6	8.1	15.4
Santa Fé	30	2.7	6.2	3.3	2.0	14.2
Denver	31	5.4	4.4	2.2	1.7	13.7
Helena	24	4.0	3.9	2.8	2.6	13.3
Yuma	28	0.4	0.4	0.6	1.3	2.7

The annual rainfall at any locality seems to vary in cycles, but no law of such variation, if any there be, has yet been discovered. The manner of variation at Philadelphia and New York is shown in Fig. 142*b*, the curves being obtained by plotting for each year a value for the rainfall which is one-third of the sum of the rainfalls for that year, the preceding year, and the following year. The curves are not drawn to exactly follow the plotted points, but are smoothed out in order to better illustrate the probable variations.

* From Records of U. S. Weather Bureau to 1910.

The distribution of rainfall from place to place is also subject to many variations, some local and others general in their nature. Among them may be mentioned both the topography and the

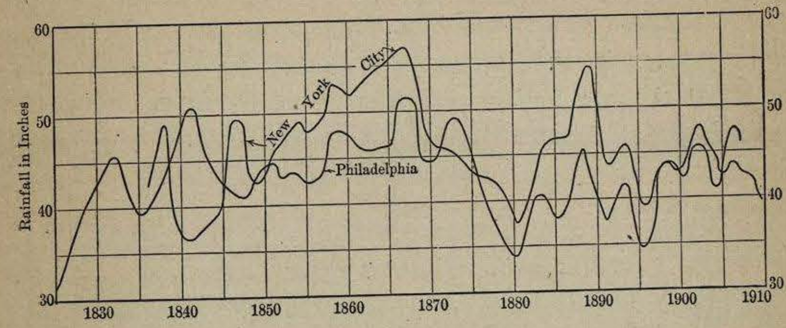

Fig. 142*b*.

altitude of the country and their relation to the prevailing wind direction. The presence of large bodies of water in the neighborhood also has its influence.

As examples of such variations in rainfall there may be mentioned the Esopus and Catskill watersheds in New York.* Their areas are nearly the same, they both drain into the Hudson River from the west, and their centers are not more than 25 miles apart, yet the rainfall on the former is about 20 percent greater than on the latter. As one other example there may be mentioned the rainfall at "Number 4" in northern New York in the Western Adirondacks and Avon on the Genessee River 23 miles south of Lake Ontario. These two stations are but 145 miles apart, yet the average yearly rainfall at the former is 50.4 inches, while at the latter it is only 27.0 inches. In determining the rainfall at any point or for any given area all available records must be examined and all other collateral evidence carefully analyzed, particularly in cases where estimates of the stream flow are to be based on estimates of the rainfall.

Prob. 142. Consult the "Instructions for Voluntary Observers," published by the United States Weather Bureau, and describe a method of determining the amount of rainfall contained in a given depth of snowfall. In making reports how much rainfall on the average is to be taken as representing a snowfall of 12 inches?

* Monthly Weather Review, March, 1907.

Art. 143. Evaporation

After rain has fallen evaporation from both land and water surfaces at once begins and continues until all of the rainfall has passed off into the atmosphere, where it is condensed into clouds and again falls as rain, thus completing the cycle. Like rainfall the evaporation is to be measured in inches of depth. Various experiments on the evaporation from water surfaces have been made, and a number of the results which have been derived are shown in Table 143*a*.

Table 143*a*. Monthly and Yearly Evaporation from Water Surfaces

Place	Evaporation in Inches												
	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Boston, Mass.*	0.96	1.05	1.70	2.97	4.46	5.54	5.98	5.50	4.12	3.16	2.25	1.51	39.20
Rochester, N.Y.†	0.52	0.54	1.33	2.62	3.93	4.94	5.47	5.30	4.15	3.16	1.45	1.13	34.54
Emdrup, Denmark ‡	0.70	0.50	0.90	2.00	3.70	5.40	5.20	4.40	2.60	1.30	0.70	0.50	27.90
Lee Bridge, England §	0.75	0.60	1.07	2.10	2.75	3.14	3.44	2.85	1.61	1.06	0.67	0.57	20.61
GraniteReef, Arizona ¶	4.25	4.40	5.25	7.00	9.50	12.00	12.75	12.50	11.00	8.31	6.56	4.22	97.74
Birmingham, Ala. ¶	1.50	1.50	2.25	4.45	5.91	7.28	7.36	7.34	6.00	4.00	2.25	1.50	51.34
Klamath, Oregon ¶	0.50	1.25	3.57	6.64	7.15	6.99	8.01	9.21	6.13	2.50	1.00	0.50	53.45

Evaporation from land surfaces is dependent on the character of the soil, on the extent and character of the forestation and cultivation, and in a considerable measure on the general steepness of the surface, for on this is dependent the time in which evaporation can act. In a steep country the rainfall rapidly runs into

* Transactions, American Society of Civil Engineers, vol. 15.
† Annual Reports, Rochester, N.Y., Board of Water Commissioners.
‡ Hydrology, Beardmore, London, 1862.
§ Proceedings, Institution Civil Engineers, vol. 45.
¶ Engineering News, June 16, 1910.

the streams, while in a flat country it passes off more slowly, and the amount of the evaporation is thus increased.

Experiments on the evaporation from earth, from short grass and long grass surfaces have been made, and some results are shown in Table 143*b*.

TABLE 143*b*. MONTHLY AND YEARLY EVAPORATION FROM LAND SURFACES

Place	Evaporation in Inches												
	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Lancashire, England,* from earth	0.64	0.95	1.59	2.59	4.38	3.84	4.02	3.16	2.02	1.28	0.81	0.47	25.65
Cumberland, England,† from earth	0.95	1.01	1.77	2.71	4.11	4.25	4.13	3.29	2.96	1.76	1.25	1.02	29.21
Emdrup, Denmark,* from short grass	0.70	0.80	1.20	2.60	4.10	5.50	5.20	4.70	2.80	1.30	0.70	0.50	30.10
Emdrup, Denmark,* from long grass	0.90	0.60	1.40	2.60	4.70	6.70	9.30	7.90	5.20	2.90	1.30	0.50	44.00
Rothamsted, England,‡ from earth	0.45	0.60	0.88	1.53	1.69	1.92	2.26	1.95	2.11	1.70	0.98	0.61	16.68

The evaporation from any particular watershed is dependent on the temperature, the humidity, the altitude, the area of the watershed, and the area of the water surface on it. The evaporation is dependent also on the wind velocity, the inclination or slope of the watershed, its geological character, its forest cover, and its state as regards cultivated areas. The total amount of evaporation is also dependent on the rainfall, and varies with it. The distribution of the rainfall throughout the year greatly influences the evaporation; a heavy winter and a light summer rainfall will together show a small annual evaporation.

* Hydrology, Beardmore, London.

† Fanning, Treatise on Water Supply Engineering, New York, 1878.

‡ Proceedings Institution Civil Engineers, vol. 105.

In the Atlantic States it may be said that the annual evaporation from land surfaces is about 45 percent and that from water surfaces about 60 percent of the annual rainfall, so that about one-half of the rainfall reaches the streams and may be utilized. In the arid regions west of the Rocky Mountains the percentages of evaporation are much higher, as indicated in Table 143*a*.

Many attempts to deduce a formula which will take account of the various factors which influence evaporation have been made but without definite success. The problem is a very complicated one. Vermeule has deduced the formula

$$E = (15.5 + 0.16\,R)(0.05\,T - 1.48)$$

where R is the annual rainfall and E the annual evaporation in inches, and T is the mean annual temperature in Fahrenheit degrees.* If $T = 49°.6$, this becomes $E = 15.5 + 0.16\,R$, which is a mean value for New Jersey and neighboring states; if T be 47°, the evaporation is 10 percent less, and if T be 52°, it is 10 percent more, than this mean. The evaporation in different months varies greatly, the mean monthly temperature being the controlling factor. The following are average values given by Vermeule for the vicinity of New Jersey, where the mean annual temperature is 49°.6; r representing mean monthly rainfall and e mean monthly evaporations in inches:

Jan.,	$e = 0.27 + 0.10r$	July,	$e = 3.00 + 0.30r$
Feb.,	$e = 0.30 + 0.10r$	Aug.,	$e = 2.62 + 0.25r$
March,	$e = 0.48 + 0.10r$	Sept.,	$e = 1.63 + 0.20r$
April,	$e = 0.87 + 0.10r$	Oct.,	$e = 0.88 + 0.12r$
May,	$e = 1.87 + 0.20r$	Nov.,	$e = 0.66 + 0.10r$
June,	$e = 2.50 + 0.25r$	Dec.,	$e = 0.42 + 0.10r$

To obtain the monthly evaporations for places of mean annual temperature T, the values found for e are to be multiplied by $0.05T - 1.48$. Thus, if there be 8 inches of rain in July, $e = 5.40$ inches, and if the mean annual temperature be 56°, this is to be increased by 32 percent. Vermeule's formulas for evaporation were deduced from a consideration of the relation between the rainfall and the observed flows of a number of streams in the New England and Middle States. They take account of the effect of unequal distribution of the rainfall

* U. S. Geological Survey of New Jersey (Trenton, 1894), vol. 3, p. 76.

throughout the year and give results which agree well with actual gagings if care be taken to determine a proper factor for each watershed to which they are applied.*

Like rainfall the evaporation varies greatly, even in regions not widely separated. In Art. 142 the difference in the rainfall on the Esopus and Schoharie watersheds in New York State was referred to. The evaporation on the Esopus will probably average about 15 inches per year, while on the Catskill it is not far from 19 inches, a difference of over 20 percent in a distance of less than 30 miles.

Experiments on evaporation are of interest and value, but the best results as to its amount are determined by taking the difference between the amount of the rainfall and the results of measured stream flows. In this manner all of the factors are taken account of and the most accurate results obtained. Experiments made by collecting the rainfall in pans and measuring the depth of water from time to time are not highly reliable, since the size of the pan influences the results. It has been shown by the U. S. Department of Agriculture that the evaporation from a pan 2 feet in diameter is about 75 percent, that from a pan 4 feet in diameter is about 50 percent, and that from a pan 6 feet in diameter is about 30 percent greater than the evaporation from a large pond or lake.†

Prob. 143. The rainfall on a watershed of 850 square miles is 44.8 inches. Assuming a seasonal distribution as at New York (Table 142) compute the evaporation by Vermeule's formula.

Art. 144. Ground Water and Runoff

When the ground is frozen and the precipitation does not accumulate in the form of ice and snow, the runoff from a watershed is closely equal to the rainfall minus the evaporation. If three inches of rain falls per month and one-third of this evaporates, the runoff will be nearly 2 cubic feet per second for each square mile of the watershed. The discharge due to a heavy rainfall occurring in a short period or to the melting of snow may be twenty or thirty times as great. A rainfall of 10 inches occurring in two days, if three-fourths of it is delivered at once to the streams, will give a flood discharge of about 100 cubic feet per

* Monthly Weather Review, March, 1907.

† American Civil Engineers' Pocket Book, 1911, p. 1286.

second per square mile of watershed area. It is not usually necessary to consider these flood discharges in estimates for water supply and water power, except in order to take precautions against the damage they may cause.

In Table 144*a* are shown some observed flood flows of various small and large streams in the United States.

Table 144*a*. Observed Maximum Flood Flows*

Stream and Place	Watershed Area Square Miles	Cubic Feet per Second per Square Mile
Starch Factory Creek, New Hartford, N.Y.	3.4	209
Mad Brook, Sherburne, N.Y.	5.0	262
Mill Brook, Edmeston, N.Y.	9.4	241
Sawkill, near mouth, N.J.	35.0	229
Rock Creek, Washington, D.C.	77.5	126
Ramapo River, Mahwah, N.J.	118.0	105
Esopus, Olive Bridge, N.Y.	238.0	110
Great River, Westfield, Mass.	350.0	152
Raritan River, Bound Brook, N.J.	879	59
Mora River, La Cueva, N.M.	159	140
Delaware River, Lambertville, N.J.	6 500	54
Susquehanna River, Harrisburg, Pa.	24 030	19

Data such as those in Table 144*a* are of use in proportioning overflows and waste-weirs for reservoirs and in fixing on the length of overfall dams in rivers. Numerous formulas have been proposed, but data such as actual observations are to be preferred in making designs of this character. In each particular case all available information must be considered, including the traditions as to the past highest water, and then after making due allowance for all of the conditions which influence the rapidity of runoff from the watershed, a liberal factor of safety must be applied.

Runoff may be defined as the difference between the rainfall and the evaporation if in the latter be included all of the water which fails to reach the streams. The runoff of a stream can

* Taken largely from American Civil Engineers' Pocket Book, New York, 1911.

be determined by measuring the flow over a weir (Chap. 6) or by daily gage height readings in connection with a discharge curve which has been determined by gagings of the flow at various water stages (Art. 131). The runoff is usually expressed as a percentage of the rainfall, thus if F be the rainfall, E the evaporation, and R the runoff, all in inches, then $R = F - E$, and as a percentage of the rainfall the runoff is $100(F - E)/F$.

In Table 144*b* are shown some observed values of the rainfall and runoff on a number of streams in the United States.

TABLE 144*b*. OBSERVED RAINFALL AND RUNOFF *

Stream and Place	Area of Watershed Square Miles	Rainfall in Inches	Runoff	
			Percent of Rainfall	Cubic Feet per Second per Square Mile
Sudbury, Boston, Mass.	75.2	45.77	48.6	1.64
Connecticut, Hartford, Conn. . . .	10 234.0	44.69	56.5	1.86
Croton, Old Croton Dam, N.Y. . .	338.0	48.38	50.8	1.81
Upper Hudson, Mechanicsville, N.Y.	4 500.0	39.70	59.0	1.72
Perkiomen, Philadelphia, Pa. . . .	152.0	47.98	49.2	1.74
Potomac, Point of Rocks, Md. . . .	9 650.0	36.86	38.6	1.05
Savannah, Augusta, Ga.	7 294.0	45.41	48.9	1.63
Upper Mississippi, Pokegama Falls .	3 265.0	26.57	18.4	0.36

The gagings which have been made and are being continued by the U. S. Geological Survey on many streams all over this country furnish a vast fund of information concerning the runoff of streams. The results of these gagings are published in the various Water Supply and Irrigation Papers of the Survey, and are to be consulted wherever questions involving the runoff of streams are being considered.

During the spring the ground is filled with water which is slowly flowing toward the streams, and this ground water is the main source of the runoff from a watershed during the dry months. The velocity of flow of this ground water varies directly as the slope of its surface, for this velocity is so slow that no losses

* From American Civil Engineers' Pocket Book, New York, 1911.

occur in impact (Art. 90). When the slope of the surface of the ground water becomes zero, the streams are dry if there be no rainfall. The discharge of a stream in a dry season hence depends upon the depth and slope of the ground water, and this in turn depends upon the previous rainfall; the topography of the country, and the character of the soil.

While data regarding rainfall and evaporation will furnish valuable information regarding the mean annual flow of a stream, they will usually fail to indicate the mean discharge during different months. For this purpose the study of discharge curves and gage heights (Art. 134) is important, and if there be none for the stream in hand, it will be necessary to make a few gagings at different stages of water and to collect information regarding the lowest stages that have been observed in dry years.

In irrigation work quantities of water are often estimated in terms of a convenient unit called the acre-foot, which is the quantity which will cover one acre to a depth of one foot, namely, 43 560 cubic feet. The discharge of a stream is often stated in acre-feet per day. One acre-foot per day is 0.5042 cubic feet per second, or one cubic foot per second is 1.983 acre-feet per day. One acre-foot of water is 325 851 U. S. gallons, and 1 000 000 gallons is 3.0689 acre-feet. One inch of rainfall per month is, very closely, 0.9 cubic feet per second per square mile.

In irrigation estimates the "duty" of water is to be regarded. This is defined as the number of acres that can be irrigated by a supply of one cubic foot per second, and it usually ranges from 60 to 100 acres. An inverse measure of duty is the number of vertical inches of water required to irrigate any area, this usually ranging from 18 to 24 inches per year. The acre-foot is also frequently used in statements of duty of water. The methods of measuring the water by orifices and modules in terms of the miner's inch unit have been explained in Art. 55.

The hydraulics of irrigation engineering differs in no respect from that of water supply and water power. Water is collected in reservoirs or obtained by damming a river, and it is led by a main canal to the area to be irrigated, and there it is distributed through smaller lateral