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FORESTS AND WATER IN THE LIGHT OF SCIENTIFIC INVESTIGATION

BY

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Object of the Report

Of all the direct influences of the forest the influence upon the supply of water in streams and upon the regularity of their flow is the most important in human economy. Yet so many are the factors which play related parts in this influence, so great is the difficulty of observing them with precision, and so wide the range of economic interests affected, that considerable divergence of opinion has arisen on the subject. This, however, if prompted by a sincere desire to reach the bottom of a complicated and vital problem, can only be productive of results of the highest scientific value.

There is, perhaps no other problem facing the American people to-day which demands such care in the scientific accuracy of its data and conclusions as does the relation between forests and water. It is imperative, therefore, that no final conclusions be drawn in regard to this relation until ample, reliable, and critically revised evidence upon which to base them is available. A national policy which, though considering the direct value of forests as a source of timber, fails to take full account also of their influence upon erosion, the flow of streams, and climate, may easily endanger the well-being of the whole people.

This paper aims to bring together impartially all the well-established scientific facts in regard to the relation of forests to water supply. Such a critical statement of our present knowledge of this subject should be helpful in separating what is definitely known of this relation from that which still needs to be determined.

Methods of Determining the Influence of Forests Upon Stream Flow

The influence of the forest on stream flow can be determined in two ways: (1) By actual measurements, continued for sufficient time, of the total discharge and of the high and low stages of rivers having drainage areas essentially similar in regard to precipitation, geologic formation, topography, and soil, but differing in the amount of forest cover, and (2) by determining, through the measurement of individual factors, the total amount of water available for stream flow.

The first method, since it deals directly with the measurement of water, may properly be called the hydrometric method; while the

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other, which deals chiefly with the physical and mechanical effects of the forest upon evaporation, run-off, etc., may be termed the physical method. The first method studies the final result of all the factors affecting stream flow as they are shown in the behavior of the stream. It is the most direct, and would be the most practical, provided all the conditions of the watersheds studied, except forest cover, were essentially similar. Since, however, such similarity between wastersheds is seldom met with in nature, this method, which has frequently been employed by engineers, is particularly liable to error. Further, the existing hydrometrical data are incomplete, for the hydrographic method requires the nicest observations, extending over a considerable period of time. The defects of the method in this regard were well brought out at the International Milan Congress of Hyrographic Engineers of 1905, as shown in the summary of the papers presented there.

The ideal application of this method would consist in comparing the regimen of a stream flowing from a completely forested watershed with the regimen of the same stream after its forest cover has been removed. As a control area there ought to be another watershed, exactly similar in character, on which the forest cover remains unchanged while that on the one under experiment is being removed. To make such a comparison thorough and accurate the topography, geological formation, and character of the soil of the two watersheds should be surveyed, and each watershed then equipped, at different elevations, with ordinary and self-registering rain gauges, as well as with instruments for measuring evaporation, wind velocity, level of ground water, and especially the flow of the stream during different seasons of the year. This would yield reliable information as to the influence of forest upon stream flow for regions having similar soil, climate, and character of forest. Such experiments, however, with the exception of one now being conducted at Emmenthal, Switzerland, by the Swiss experiment station, and one at Wagon Wheel Gap, Colo., by the Forest Service, in cooperation with the Weather Bureau, have never been made in any part of the world. The most common practice, especially with engineers, has been to compare the run-off from drainage areas in the same general region, of which one may have more forest cover than the other. If the comparisons were based on equally large numbers of stream gaugings and dependable meterological records, and the drainage areas compared were similar in regard to topography and soil, the average results might assume some practical value. Unfortunately, however, reliable gaugings for a given stream too often can not be supplemented by reliable meterological data for the same region. Therefore, while there is no end to the material gathered in this way, it is often contradictory at best showing only tendencies, and failing to determine with any accuracy the nature and extent of the influence which the forest has upon stream flow.

The second method analyzes separately the influence of the forest upon each of the different factors affecting stream flow, and the final effect of the forest upon stream flow is deduced from the combined effect on all the factors. While less direct, this method lends itself more readily to experimentation, and has been largely employed by foresters.

Since a large amount of reliable data concerning the influence of the forest upon the amount of precipitation over forested and unforested drainage areas upon evaporation, surface run-off, percolation, etc., have been obtained by this method, it will be discussed first.

PART I.—RESULTS BY THE PHYSICAL METHOD

Forests and Climate

The influence of forests upon climate has been a subject of investigation for a long time, and is not settled yet. Now and then this influence has been exaggerated, thus leading to the other extreme of denying it entirely. In discussing the subject, therefore, one has to be very careful in selecting facts and in drawing conclusions from them.

The physical and physiological processes which accompany any plant growth must necessarily reduce the temperature of the air, at least during the vegetative period. First, because the leaves evaporate water. Second, because the heat of the sun is consumed in this evaporation, and the plant can not become heated to the same extent as, for instance, a rock or soil without any vegetative cover. Similarly, the ground under plants can not become greatly heated on account of shading. Third, the surface from which heat radiates at night is much greater when vegetation is on the ground than when the ground is bare. The cooling effect on the air by crops has been experimentally proven. For every pound of dry substance produced it has been found that corn evaporates 233 pounds of water and turnips 910 pounds.

Under good cultivation an acre may produce about 7 tons of dry substance. If the evaporation of water be only five hundred times more than the amount of dry substance produced, then an acre will evaporate during the vegetative period about 3,500 tons of water. This example shows the extent to which ordinary crops can contribute to the moisture content of the air and the cooling which accompanies this evaporation. Forests, being the most highly developed form of vegetable life, exert this influence in the greatest degree.

The first systematic observations upon the effect of forests on climate were made in Bavaria. The climatic influences first observed were those which are least changeable from year to year and which are fairly uniform over large areas, namely, the temperature and humidity of the air, evaporation, temperature of the soil, and percolation of the water into the ground.

Temperature of the Air

Table 1 gives the results of early observations upon the temperature of the air outside and inside the forest carried on in central Italy,[1] eastern France,[1] in the mountains of Alsace, Bavaria,[2] and eastern Prussia.[3] The stations inside and outside the forest were

[1] Woeikov, A. I. The climates of the world (in Russian). St. Petersburg, 1884.
[2] Ebermayer, E. Die physikalischen Einwirkung des Waldes auf Luft und Boden. Berlin, 1873.
[3] Muttrich, A. Jahresbericht uber due Beobacht ungsergebnisse der im Konigreich Preussen und in den Reichslanden eingerichteten forstlich-meteorologischen Stationen, 1875, 1876.

scarcely a mile apart. The differences between the temperature of the air outside and inside the forest are shown by plus and minus. Plus indicates that the temperature in the forest is higher; minus, lower than in the field.

TABLE 1.—*Temperature of air in the forest compared with that in the open*

	Central Italy	Eastern France	Mountains of Alsace	Bavaria	Eastern Prussia
February-April:	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*
Average of daily maximum		−1.44	−1.98	−0.90	−1.26
Average of daily minimum		+1.44	+3.42	+.36	+.18
Mean temperature			+.72	−.54	−.54
May-July:					
Average of daily maximum	−7.38	−5.76	−4.50	−3.96	−2.52
Average of daily minimum	+2.88	+2.16	+3.42	+1.98	+.90
Mean temperature	−2.16	−1.8	−.54	−1.62	−.72
August-October:					
Average of daily maximum	−6.48	−4.68	−3.42	−5.76	−2.88
Average of daily minimum	+1.98	+2.34	+4.32	+2.88	+.36
Mean temperature	−2.34	−1.08	−.36	−1.44	−1.26
November-January:					
Average of daily maximum		−1.62	+1.62		−.54
Average of daily minimun		+1.08	+3.06	+2.16	−.36
Mean temperature		−.18	+2.34	+1.08	−.36
Entire year:					
Average of daily maximum		−3.42	−2.26	−2.70	−1.8
Average of daily minimum		+1.8	+3.6	+1.8	+.36
Mean temperature		−.72	+.72	−.54	−.72

This table brings out clearly the moderating influence of the forest upon temperature of the air. In the forest the maximum temperature is always lower, and the minimum temperature higher, than outside. More recent observations extending over long periods in France, Germany, Austria, Switzerland, and other countries have confirmed the earlier results.

The yearly mean temperature at equal elevations and in the same locality has invariably been found to be less inside than outside a forest. In a level country this difference is about 0.9° F. It increases, however, with altitude, and at an elevation of about 3,000 feet is 1.8° F.

The monthly mean temperature is less in the forest than in the open for each month of the year, but the difference is greatest during the summer months, when it may reach 3.6° F., while in winter it does not often exceed 0.1° F.

The daily mean temperature shows the same difference, but to a greater degree. During the hottest days the air inside the forest was more than 5° F. cooler than that outside, while for the coldest days of the year the difference was only 1.8° F.

The temperature of the air within the forest is, therefore, not only lower, but also subject to less fluctuation than in the open.

It is in tropical and subtropical regions that the influence of the forest upon the temperature of the air is probably greatest. In northern British India, in latitude 24°–27° N., the mean annual temperature for the year varies but little with latitude. In winter the rainfall is very scant, and in summer very abundant. Before the rainy season the valleys of northern India have a period of extreme hot weather and drought. On the whole, the temperature and the dryness are moderated by proximity to the sea.

The country along the Ganges, and in general to the west of the lower extension of Brahmaputra, is almost treeless, while in Assam, along the middle extension of Brahmaputra, there are large forests. A comparison of temperatures at these places, made by Woeikov,[4] and given in Table 2, shows clearly the influence of the forest upon the temperature and humidity of the air. Of the places named, Brahmaputra lies at 24° N., the others between 25° and 27° N. The arrangement is from west to east.

TABLE 2.—*Difference in temperature and humidity between treeless and forested regions, British India*

Locality	Distance from sea	Mean temperature				Absolute maximum temperature	Relative humidity (per cent)			
		April	May	June	July		April	May	June	July
Treeless region:	*Miles*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*				
Lucknow	526	86.18	91.94	91.58	86.72	114.44	30	36	54	74
Benares	367	86.36	91.76	91.04	85.46	113.00	41	60	81	82
Patna	267	86.54	88.52	88.52	84.56	112.28	------	------	------	------
Berhampur	168	84.28	86.18	84.56	83.66	111.38	52	60	75	79
Forested region:										
Goalpara	265	77.36	78.62	80.42	81.86	95.18	66	77	85	84
Sibsagar	345	74.30	77.54	82.76	83.30	96.08	81	82	83	83

The figures in the table indicate that forests play a much greater part in moderating the temperature in the hot and dry months of April and May than does proximity to the sea. The same thing holds for the relative humidity, especially in Sibsagar, which is the center of the forested region. The most striking influence of the forest is the lowering of the absolute temperature maxima. Proximity to the sea has but little effect upon this, but as soon as the forest region is reached, the absolute maximum temperature is at once decreased by about 15° F. Especially striking is the difference in the average temperature in May between Benares and Goalpara. The distance between the two places is only 462 miles, the latitude about the same, and the intervening country level. Both are at considerable distances from the sea, yet the difference in the average temperatures for May is 13° F., or about 1° for every 35 miles. This difference in temperature Woeikov explains by the presence of forest in Goalpara.

Woeikov further cites observations in the basin of the Amazon River, which possesses the largest forest area in the world. The middle and upper extensions of the Amazon River are about 621 miles from the Atlantic Ocean and are separated from the Pacific Ocean by very high mountains. At such great distances from the ocean, and so close to the equator, one would naturally expect to find very high temperatures and great dryness. Yet there the average temperature of the warmest month and the absolute temperature maxima are not greater than at the sea, and even not as high as the temperatures often experienced in middle latitudes. This is shown in Table 3.

[4] Woeikov, A. I. The climates of the world (in Russian). St. Petersburg, 1884, p. 321.

TABLE 3.—*Temperature and relative humidity in Amazon River basin and at points on or nearer the coast*

Locality	Altitude	Latitude	Distance from Atlantic Ocean	Temperature			
				Mean annual	Average for the warmest month	Absolute maximum	Annual mean relative humidity
	Feet	°	*Miles*	° *F.*	° *F.*	° *F.*	*Per cent*
Para		1½	62	80.6	81.86		
Manaos	121	3	714	78.98	80.6	97.26	80
Iquitos	311	3½	130	76.64	78.26	90.32	83
Pernambuco	11	8		78.26	80.78	89.06	72
San Antonio on the Madeira		9	1,087	78.8	80.6		

Woeikov attributes this remarkably moderate temperature of the Amazon Basin to the cooling effect of the forest, due to the enormous evaporation of water from the soil and plants in the Tropics. He assumes that in tropical countries covered with luxuriant forest vegetation the rainfall is seldom less than about 60 inches a year. So thick usually is the mass of decayed leaf litter and fallen and half-rotted trees in the forest that most of the rainfall is absorbed by the soil, and only a small portion runs off from the surface. Even allowing one-third of the annual precipitation for surface run-off, there is still transpired by the plants and evaporated by the soil a layer of water about 40 inches high. About 35.5 cubic feet of water are given off from every 10.7 square feet, and in the evaporation of this amount of water 606,500 calories of heat are consumed. The cooling of the air due to this evaporation explains why, in the vast tropical forests, the temperature of the air never becomes as high as it is even in middle latitudes.

The evaporation of water from forests differs from evaporation from water surfaces in that, while forests are, during the day, continually using up heat by converting it into latent heat through transpiration, bodies of water are directly heated by the sun's rays, becoming, as it were, temperature reservoirs. Interior seas and lakes in the Tropics are often heated considerably above 82°, and even 86° F., increase the temperature of the lower air when it is cooler than the water.

The total area of the leaves is so great that at night they cool off quickly. When they have reached the dew-point temperature, vapor of the air condenses on their surface. A part of the water which has been transpired during the day is thus brought back to be transpired again next day. The forests may therefore be likened to a self-feeding boiler, the water from which is evaporated into the air at the expense of the heat of the sun and surrounding air.

TEMPERATURE OF THE SOIL

Forests influence the temperature of the soil in almost the same way as they do that of the air. The differences in temperature outside and inside the forest, however, as a comparison of Tables 3 and 4 will show, are greatest in the case of soil.

This is readily explained by the fact that the temperatures of bodies of air near one another tend to become equalized by the passage of air currents. Moreover, the surface of the soil is heated directly by the sun, while the air receives its heat chiefly from the surface of the soil, so that the difference between the temperature of the soil in the forest, where the ground is at least partially protected from heat, and that outside of the forest, where no such protection exists, is especially pronounced. This difference is not limited to the surface of the soil, but is manifest at a considerable depth.

TABLE 4.—*Difference in soil temperatures inside and outside the forest*

	February–April		May–July		August–October		November–January		Mean annual	
	At surface	At a depth of 35.5 inches	At surface	At a depth of 35.4 inches	At surface	At a depth of 35.4 inches	At surface	At a depth of 35.4 inches	At surface	At a depth of 35.4 inches
	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*	° *F.*
Mountains of Alsace	−1.8	+0.90	−14.04	−5.04	10.26	−5.76	+0.54	−1.26	−6.30	−2.70
Bavaria	−3.24	−1.44	−8.10	−7.02	−4.68	−5.4		−.18	−3.96	−3.96
Do	−2.34	−1.08	−8.28	−7.38	−4.68	−5.4	+.54	−.18	−3.78	−3.6
Eastern Prussia	−2.34		−7.92	−6.48	−4.14	−3.96	+2.34	+1.62	−2.88	−2.16

In winter soil temperatures of the forest and field differ but little. The temperature of the soil in the forest is even somewhat higher, especially where snow lies on the ground for several months, when the difference is considerable. In eastern Prussia, for instance, it amounts to almost 3.6° F. The fluctuations of soil temperature in the forest, therefore, are much smaller than in the field. The moderating influence of the forest upon the temperature of the surface of the soil becomes especially marked when the maximum and minimum temperatures for the entire year are compared. (Table 5.)

TABLE 5.—*Fluctuation of soil temperatures inside and outside the forest*

	Outside the forest			Inside the forest		
	Maximum	Minimum	Fluctuation	Maximum	Minimum	Fluctuation
	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*	°*F.*
Bavaria (6 stations)	84.02	12.92	71.10	71.24	18.14	50.10
Mountains of Alsace	86.00	23.00	63.00	63.32	27.68	35.64
astern Prussia (2 stations)	81.68	6.44	75.24	64.58	16.52	48.06

More recent observations upon the temperature of the soil inside and outside of the forest yielded results very similar to the earlier ones. These later results show that the forest soil is warmer in winter by 1.8° F. and cooler in summer by from 5.4° to 9° F. than soil without a forest cover, and that this holds true for a depth of as much as 4 feet. In the spring, and especially in the summer, the forest soil is cooler than that of open land. In the fall and winter, however, it is warmer, but the degree of difference is always less than in summer.

Observations in 1892 and 1893 at L'Adlisberg, near Zürich,[5] showed that under the complete cover of a young beech stand the average temperature of the soil from April 1 to November 1 was from 9° to 12.6° F. lower than in the open on level ground, and from 10.8° to 18° F. lower than on ground sloping toward the south, but otherwise almost identical. On August 24, 1894, the soil on an open southerly slope attained a temperature of 91.4° F. Under the forest, close by on the same slope, the temperature was only 63.3° F. A cover of young beeches thus produced a soil temperature lower by about 28.1° F. The temperatures were taken at a depth of 2 inches; at the surface the difference was still greater.

The influence which forest cover has upon the freezing of the ground was well brought out by 21 years' observation in Germany,[6] as shown in Table 6.

TABLE 6.—*Freezing of soil inside and outside the forest*

Stations	Altitude, nature of soil, and composition of forest	Depth to which soil freezes		Difference	Depth of frost in forest soil in per cent of depth in the open
		Outside the forest	Within the forest		
		Inches	*Inches*		*Per cent*
Haguenau (Alsace)	Rhine Valley, 492 feet; gravelly sand mixed with humus; Scotch pine.	19.7	8.3	11.4	42
Eberswalde (near Berlin).	160 feet; sandy soil mixed with humus; Scotch pine.	27.6	18.5	9.1	67
Neunath (Lorraine)	Plateau, 164 feet; lime rock; beech	8.7	5.9	2.8	68
Melkerei (Alsace)	Moderate southeast slope, 3,114 feet (167 feet below summit of slope); decomposed granite; beech and fir.	17.7	13.0	4.7	73

Thus, the soil under the forest may remain soft when the ground in the open is frozen hard to some depth. If it does freeze it is to a depth of from one-half to less than three-fourths that in the open.

RELATIVE HUMIDITY

In the summer the relative humidity of the air is higher in the forest than in the open; first, because the transpiration of water by the leaves appreciably increases the moisture content of the air within or near the forest; and, second, because the temperature of the air in the forest is lower, and therefore nearer its saturation point. This difference is usually between 4 and 10 per cent, but in some places may be as much as 12 per cent. In regions of heavy snow there is practically no difference in the relative humidity during the spring, when the snow melts. Table 7 shows the difference between the relative humidity of the air outside and inside the forest for different months of the year.

[5] Bühler, A. Beobachtungen an den forstlich-meteorologischen Stationen, 1892, 1893. (Mitteilungen der Schweizerischen Centralanstalt für das forstliche Versuchswesen, 1895, vol. 4, pp. 34, 94.)

[6] Schubert, J. Der jährliche Gang der Luft- und Boden-Temperature im Freien und in Waldungen. Berlin, 1900.

TABLE 7.—*Relative humidity inside and outside the forest*

	February–April		May–July		August–October		November–January		Entire year	
	Outside the forest	Inside the forest	Outside the forest	Inside the forest	Outside the forest	Inside the forest	Outside the forest	Inside the forest	Outside the forest	Inside the forest
Mountains of Alsace	80	85	68	75	78	84	85	89	77	84
Bavaria	80	84	70	80	78	85	87	90	79	85
Eastern Prussia	84	85	64	68	76	81	90	92	78	82

PRECIPITATION

The water which reaches the ground and becomes available for vegetation and stream flow comes from two chief sources—first, rain, snow, hail, etc., which form in the upper strata of the air; and, second, dew, hoarfrost, and similar condensations of the air moisture which form on the surfaces of foliage, branches, and trunks, and also on the surface and in the interior of the soil when these are colder than the surrounding air.

EFFECT UPON LOCAL PRECIPITATION

Observations upon the influence of forests on local precipitations began as early as the middle of the last century, but systematic observations did not start until the second half of the sixties (Bavaria, France, and Switzerland), and in many places are still being carried on. In a few cases these observations do not show any essential difference in the amount of precipitation over forest and over open fields. Most of them, however, demonstrate beyond doubt that the amount of precipitation over forests [7] is greater.

This excess of precipitation over forested areas varies from a fraction of 1 per cent to 25 per cent. Such wide variation is due partly to differences of geographic situation, altitude, character of the forest, etc. At the forest experiment station at Nancy, 33 years' observations show an average excess of precipitation on forested areas of 23 per cent, while Ebermayer in Germany, Bouvard at Moumal,

[7] Blodget, Lorin. Climatalogy of the United States. Phila., 1857; Lorenz-Liburnau, Josef Roman von. Resultate forstlich-meteorologischer Beobachtungen insbeondere in den jahren 1885–1887, pt. 1–2. Wein, 1890–1892. (Mittheilungen aus dem forstlichen Versuchswesen Österreichs, Heft. 12–13); Bühler, A. Beobachtungen an den forstlich-meteorologischen Stationen Adlisberg, etc., 1889–1897. (Schweizerische Centralanstalt für das forstliche Versuchswesen. Mittheilungen, 1891–1898, v. 1, pp. 201–282; v. 2, pp. 61–126; v. 4, pp. 34–173; v. 5, 22–190; v. 6, pp. 18–28); Bühler, A. Die Niederschläge im Walde. (Schweizerische Centralanstalt für das forstliche Versuchswesen. Mittheilungen, 1892, v. 2 pp. 127–160); Hamberg, H. E. De l'influence des forêts sur le climat de la Suède, pt. 4–5. Stockholm, 1896; Blanford, H. F. Influence of the Indian forests on the rainfall. (Asiatic society of Bengal. Journal, pt. 2, 1887, v. 56, pp. 1–15); Studnička, F. J. Grundzüge der Hyetographie des Königreichs Böhmen. (Archiv für naturwissenschaftliche Landésdurchforschungen von Böhmen, 1887, v. 6, No. 3); Fritsch, Karl. Zur Frage über den Einfluss des Waldes auf den Regen. (Zeitschrift der Oesterreichischen Gesellschaft für Meteorologie, 1867, v. 2, pp. 230–235); Krutzch, H. Ueber den Einfluss der Waldungen auf die Regenverhältnisse der gemässigten Zone. (Tharander forstliches Jahrbuch, 1855, v. 11, pp. 123–141); Fautrat, L. Observations météorologiques faites de 1874 à 1878. Paris, 1878; Ebermayer, E. W. Untersuchungs-Ergebnisse über die Menge und Vertheilung der Niederschläge in den Wäldern. (Forstlich-naturwissenschaftliche Zeitschrift, 1897, v. 6, pp. 283–301); Müttrich, A. Bericht über die Untersuchung der Einwirkung des Waldes auf die Menge der Niederschläge. Neudamm, 1903; Hann, Julius. Wald und Regen. (Zeitschrift der Oesterreichischen Gesellschaft für Meteorologie, 1867, v. 2, pp. 129–136); Kopezky, Richard. Wald und Niederschläge. (Centralblatt für das gesamte Forstwesen, May, 1899, v. 25, pp. 195–213, 243–253); Zacher, Gustav. Ueber den Causalnexus von Wald und Regen. (Oesterreichische Viertel-jahresschrift für Forstwesen, 1890, v. 40, pp. 103–108); and others in Russian.

and Blandford in India compute it as being 12 per cent. Some meteorologists are inclined to ascribe the difference in the amount of precipitation over forests and open fields to the imperfection of the rain gauges. Hellman's [8] experiments, for instance, showed that the ordinary rain gauge in a wind of medium velocity registers 19 per cent less of precipitation than actually falls. It is possible that rain gauges in the forest, being protected from wind, will catch more rain and therefore show a greater amount of precipitation than when placed in the open. That the greater amount of precipitation over forest areas as compared with open fields can not, however, be ascribed entirely to this, has been clearly brought out by Müttrich, who, during four years of careful observation with Hellman's improved rain gauges, found that the difference of precipitation in the forest and outside the forest still amounted to 6 per cent.

French observers are practically unanimous in recording a larger amount of precipitation over forests than over fields. This conclusion is the result of experiments carried on at the forest school at Nancy, in the forests of Haye, by Fautrat in the forest of Halatte (Oise), and by de Pons in the forest of Troncais (Allier). Most of those carried on in Germany, Austria, Russia, and India have forced similar conclusions.

Regular observations taken at Nancy for 33 years since 1866, at stations inside, on the edge of, and outside the forest, show that, without exception, more rain has fallen inside than outside the forest, and that during 8 or 10 years more rain fell on the edge of the forest than outside. If the amount of the rainfall at the center of the forest be designated as 100, then the amount of rainfall at the edge of the forest would be represented by 93.9 and the rainfall outside the forest by 76.7.

The difficulty of bringing out clearly the influence which forests have upon precipitation results from the fact that the bulk of the forests are in the mountains. Altitude, as is well known, has a definite relation to the amount of precipitation, and unless this influence is eliminated that of the forest can not be clearly determined. To neutralize this altitudinal influence Prof. R. Weber [9] has grouped (Table 8) precipitation data obtained during a period of 10 years (1876–1885) at Prussian forest stations situated at different altitudes, together with average figures obtained by Dr. van Bebber [10] from 192 ordinary weather stations within the respective regions at corresponding altitudes but outside the forest.

TABLE 8.—*Precipitation within and outside of the forest at different altitudes*

	Altitude (feet)					
	3–300	330–650	980–1,300	1,970–2,300	2,300–2,600	3,000–3,250
	Inches	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
Stations in the forest (R. Weber)	25.9	26.2	29.4	42.9	55.5	69.9
Ordinary stations (Dr. van Bebber)	25.5	22.9	27.4	36.0	38.6	37.9
Difference	.4	3.3	2.0	6.9	16.9	32.0
Per cent	1.25	14.2	7.3	19.0	43.7	84.2

[8] Hellman, G. Resultate des Regenmessungs-Versuchsfeldes bei Berlin, 1855 bis 1891. (Meteorologische Zeitschrift, 1892, v. 9, pp. 173–181.)

[9] Weber, R. Die Aufgaben der Forswirtschaft (in Lorey's Handbuch der Forstwissenschaft, 1903, v. 1, pp. 1–102).

[10] Bebber, J. van. Die Regenverhältnisse Deutschlands. München, 1877.

This table shows that, while the rainfall at the forest stations situated in the plains of north Germany exceeds the average for such lands by only 0.4 of an inch, or 1.25 per cent, the excess at moderate altitudes of from 328 to 656 feet amounts to 14.2 per cent. At elevations between 1,970 and 2,300 feet the difference is increased to 19 per cent, between 2,300 and 2,600 feet to 43.7 per cent, and between 3,000 and 3,250 feet to 84.2 per cent. These figures seem to show that the influence of the forest upon precipitation increases with the increase in altitude. Therefore, while it is true that mountains affect precipitation, wooded mountains affect it to a still greater degree. On the other hand, it is not true, as it was for many years commonly believed to be, that the rainfall chart is practically identical with the contour chart. In reality the matter is not so simple.

Angot, in his "Régime des pluies de la peninsule iberique," published in the Annales du Bureau Meteorologique de France, 1893, brings out most strikingly the fact that denuded mountains do not always cause moisture-laden winds to precipitate their moisture. An examination of the monthly and annual mean precipitation during the months of June, July, and August shows it to have an entirely different character from that during the preceding months. In June the fall is from 1 to 2 inches in the northern part of the peninsula and less than 1 inch in the southern part. In July and August only from four-tenths to 1 inch falls in the north and less than four-tenths of an inch in the south. "These three months, therefore, are the driest months, yet," says Angot, "the wind generally blows from the sea during this period, but owing to the excessive heat of the soil the moisture-laden clouds, on arriving inland, are further heated and are therefore further than ever removed from the saturation point. In all this mountainous region, which covers the Provinces of Granada, Jeon, and Murcia, in spite of the proximity of the sea, in spite of the entire absence of mountain ranges to the west which might precipitate the moisture before it reaches here, in spite of the presence within the region of the high peaks, some having an elevation of from 6,500 to 16,400 feet, the rainfall during July and August does not exceed four-tenths of an inch. It is certain that if these mountain ranges, which stretch between Sierra Nevada and Sierra Segura, were wooded instead of being absolutely bare and dry, the precipitation in the southeast of Spain would be increased, and there would be no fear of the disastrous floods which at times occur in the basin of the River Segura."

Wooded mountains, therefore, increase precipitation to a much greater degree than denuded mountains. This effect is especially marked during summer months, and as Fautrat's[11] observations show, the effect is greater over coniferous than over broadleaf forests. The greater effect of coniferous forests upon the amount of precipitation can not be due to transpiration, since coniferous forests, as is well known, transpire less than broadleaf forests. According to Henry,[12] this greater concentration of vapor over coniferous forests must be due to the fact that the crowns of conifers intercept a greater

[11] Fautrat, L. Observations météorologiques faites due 1874 à 1878. Paris, 1878, p. 21.
[12] Henry, E. Sur le rôle de la forêt dans la circulation de l'eau à la surface des continents. Paris, 1902, p. 14.

amount of precipitation and therefore return into the atmosphere larger quantities of water than broad-leafed trees. Fautrat's observations in 1876 showed that while the soil under broadleaf forests received 16.7 inches, the soil under coniferous forests received only 11 inches. Therefore 5.7 inches, or 20,608 cubic feet per acre, were retained by the crowns of the conifers and returned into the atmosphere. Similar results were obtained by him in 1877.

Dr. Paul Schreiber,[13] a noted meteorologist, after working up elaborate meteorological data for Saxony, came to the conclusion that in a region completely covered with forests the influence of the forest in increasing precipitation would be equal to elevating the region 650 feet. A comparison by Prof. R. Weber of the precipitation data for seven years at the French weather stations at Cinq Tranchées and at Amance is shown in Table 9. The two stations lie on an oolitic plateau near Nancy at an elevation of 1,246 feet above the sea. That at Cinq Tranchées is located on a pasture surrounded by large forest areas, while the one at Amance is in a region practically stripped of forest. The results are given for the four seasons of the year.

Table 9.—*Precipitation over forest pasture and in treeless region, France*

	Spring	Summer	Fall	Winter	Total
	Inches	*Inches*	*Inches*	*Inches*	*Inches*
Cinq Tranchées (forest station)	6.3	7.4	7.6	8.3	29.6
Amance (not in forest)	5.9	6.5	6.2	7.0	25.5
Difference	.4	.9	1.4	1.3	4.1

The greater excess of precipitation over the forest pasture during fall and winter when the clouds are very low is no doubt the result of condensation due chiefly to the mechanical obstruction offered to the moisture-leaden strata of air.

During the four-year period from 1874 to 1877, Fautrat and Sartiaux conducted experiments on precipitation in the 12,500-acre state forest of Halatte. The experiments were carried on in the space above the tops of trees; in one case 23 feet above a hardwood forest, and in another 10 feet above a coniferous forest, with similar observations in the open. The observations yielded the following results:

	Above tree tops	In the open	Difference
	Inches	*Inches*	*Inches*
Broadleaf	25.8	24.8	1.0
Coniferous	26.3	24.0	2.3

Dr. Müttrich[14] observed at the meteorological station at Lintzel in the Luneburg heath the influence which the planting of a forest in the open waste land has upon the amount of precipitation. Plant-

[13] Schreiber, P. Die Einwirkung des Waldes auf Klima und Witterung. (Tharander forstliches Jahrbuch, 1899, v. 49, pp. 85–204.)

[14] Müttrich, A. Ueber den Einfluss des Waldes auf die Grösse der atmosphärischen Neiderschläge. Zeitschrift für das gesamte Forstwesen, 1892, v. 24, pp. 27–42.)

ing was begun in 1877. At that time the region was made up of cultivated land, 12 per cent; heath, 85 per cent; and forest, 3 per cent. After the planting was finished the proportion of forest land had been increased to 80 per cent, and that of heath and agricultural land reduced to 10 per cent each. Regular observations on the amount of precipitation were begun in 1882, and the figures for each year thereafter compared with those for five neighboring stations where conditions had, of course, remained unchanged. For the years 1882–1888, inclusive, the precipitation at Lintzel, expressed in per cent of the average for the five other stations, was 81.8, 86.3, 95.2, 99.8, 100.6, 103.7, and 103.9, respectively. As compared with that at any one of the other stations, in fact, the precipitation at Lintzel showed a steady increase for the seven-year period. This demonstration of the effect of forest cover upon local precipitation is particularly striking.

A most direct proof, however, of the effect of forests in increasing local precipitation is afforded by observations following forest planting in the steppes of southern Russia. Between 1845 and 1863 over 5,000 acres of forest were planted in an entirely open situation in the high steppes (prairies). About 1892 two meteorological stations were established for determining in a most accurate and thorough manner the climatic influence of the forest. One station was located on the open steppe and the other in the forest. At the first the average annual precipitation during the period between 1893 and 1897 was found to be 17.9 inches, while in the newly established forest it was 22.2 inches, or 23.9 per cent more, in spite of the fact that the station in the open was located somewhat higher than the one in the forest. In addition, eight parallel observations on precipitation in the open and in the forest, carried on elsewhere, showed that the influence of the forest upon the amount of precipitation was greatest at the time of heavy rains, but was also well marked during the dry periods of the year. Thus, while the amount of precipitation at stations in the open during the summer of 1895 was 8.3 inches, that at the forest stations was 9.7 inches, or 16.4 per cent greater. These observations tally with similar ones taken in 1894 and 1895 by J. Klingen in the open steppe and in the neighboring forest of Chrinovsky, in the Government of Voronej.

TABLE 10.—*Precipitation on the open steppe and in pine and oak forest*

	Total for the year		Total for the growing season	
	1894	1895	1894	1895
	Inches	*Inches*	*Inches*	*Inches*
In the open steppe	13.9	14.1	12.0	7.6
In a pine forest	19.9	19.8	15.0	10.1
In an oak forest	21.3	20.7	13.9	10.3
Excess in pine forest over the open, actual	6.0	5.7	3.0	2.5
Excess in pine forest over the open ... per cent	43.0	40.0	25.0	32.0
Excess in oak forest over the open, actual	7.4	6.6	1.9	2.7
Excess in oak forest over the open ... per cent	53.0	46.0	16.0	36.0

The effect of forests upon precipitation, as shown from the data brought together by such meteorologists as Woeikov and Blanford, is even greater in tropical and subtropical climates than in temperate regions. Thus, for British India, Woeikov shows that the forest cover exerts a greater influence upon precipitation than does proximity to the ocean.

TABLE 11.—*Precipitation in forested and treeless regions, British India*

Locality	Distance from sea	Precipitation			
		April	May	June	July
Treeless region:	*Miles*				
Lucknow	526	0.2	0.7	5.0	15.5
Benares	367	.2	.5	5.0	12.9
Patna	276	.4	1.0	6.0	10.9
Berhampur	168	2.2	3.9	9.5	10.1
Forested region:					
Goalpara	265	5.8	13.0	25.3	19.6
Sibsagar	345	10.2	12.0	15.5	15.9

H. F. Blanford, meteorologist to the Government of British India, regards Woiekov's statement as too sweeping, but admits that the forest is one of the elements which contributes to the amount of precipitation over Assam Valley. He furnishes a very striking evidence of the effect of forest protection upon increase in precipitation. In part of the central Provinces of British India a forest area of about 600,000 acres has been protected for a number of years (since 1875) from fire. As a result there appeared, under the thin stands of trees, a dense young growth. Complete precipitation records were kept at seven stations from 1865 or 1867 up to the present time. A comparison between the precipitation before 1875 and after 1875 (Table 12) shows a marked increase in the latter period for the same area.[15]

TABLE 12.—*Precipitation over protected forest area, British India*

Weather stations within the protected region	Observations begun	Mean annual precipitation		
		Before 1875	After 1875	Difference
		Inches	*Inches*	*Inches*
Badnur	1867	39.83	47.83	+8.00
Chhindwara	1865	41.43	48.48	+7.05
Seoni	1865	52.07	54.76	+2.69
Mandla	1867	53.58	56.32	+2.74
Burha	1867	64.51	71.65	+7.14
Bilaspur	1865	41.85	54.81	+12.96
Raipur	1866	51.59	54.41	+2.82
Average	--------	49.27	55.47	+6.20

Practically all observations, then, tend to show that there is an increase in the total amount of precipitation over wooded areas as compared with that over barren or deforested ones. One reason for this is undoubtedly the tendency of moisture-bearing currents to precipitate their moisture more readily above or near the forests than

[15] Brandis, D. Regen and Wald in Indien. (Meteorologische Zeitschrift, 1887, v. 4, p. 375.)

over bare or cultivated fields at the same elevation, due to the dampening and chilling effect of the forest upon the atmosphere, which induces a greater condensation of the water vapor.

That the air over forests contains a much larger amount of moisture than that over bare or cultivated fields is to-day a proven fact, based both on actual observations in the upper air strata and determinations of the quantities of water evaporated by the forest. The latest experiments by Russian agronomists and foresters, corroborated by similar observations in France and Germany, have shown conclusively that in level or slightly hilly regions (where the stratification of the rock is horizontal and the ground waters are stagnant, as, for example, in the steppes of Russia or the landes of Gascony) the forest has a desiccating effect upon the ground, causing the water table to be lower under forest than in adjoining open fields. Professor Henry, in his recent investigations upon the effect of forests upon ground waters in level country, found that the minimum depression of the water table produced by the transpiration of forest trees in the Mondon forest near Luneville, France, amounts to 11.8 inches. With a porosity of the soil strata ranging between 45 and 55 per cent, such depression would correspond to a rainfall of 5.9 inches, which amounts to 21.443 cubic feet per acre.

This amount of water given off by the forest into the air obviously contributes greatly to the moisture content of the atmosphere above the forest. Dr. Franz R. von Höhnel,[16] of the Austrian forest experiment station at Mariabrunn, after observations carried on for a period of three years (1878–1880) upon the amount of water transpired by forests, found that one acre of oak forest, 115 years old, absorbed in one day from 2,227 to 2,672 gallons of water per acre, which corresponds to a rainfall of from 0.09 to 0.115 per day, or 2.9 to 3.9 per month. Taking the period of vegetation as five months, the absorption of water would be 158,895 cubic feet, which represents a rainfall for this period of 17.7 inches. This amount of water is given off through transpiration from the leaves and does not include the physical evaporation from the surface of the twigs, branches, and leaves. These figures, while only approximate, give an idea of the enormous quantities of water given off by forests into the air, which has justly given them the name of the "oceans of the continent."

As a matter of fact, small clouds are frequently observed hanging persistently over forested areas in the presence of a fairly strong wind. If all the moisture given off by the forest could be made visible as a fog, heavily forested areas would appear enveloped by a damp mist, more dense over coniferous than over broadleaf forests.

That the vertical influence of the forest extends to a height far greater than 100 or 200 feet has been proven by observations taken during balloon ascensions. Thus Renard, commander of engineers and subdirector of the Central Military Balloonist Institute of France, states that the effect of the forest upon the temperature of the upper strata of air has been repeatedly felt during ascensions at an elevation of nearly 5,000 feet over the forest of Orleans, which has

[16] Höhnel, F. R. von. Ueber die Transpirationsgrössen der forstlichen Holzgewächse. (Mitteilungen aus dem forstlichen Versuchswesen Oesterreichs, 1881, v. 2, pp. 47–90, 275–296.)

an area of 75,000 acres. This influence is scarcely felt over field crops, and it is obvious that the difference can not be due to the greater height of the trees, which at best reach but a little over 100 feet on an average. It can be accounted for only by the greater amount of water given off by the forest and the lower temperature above it.

The condensation of vapor on the surface of the leaves in the form of dew, hoarfrost, etc., in northern latitudes, according to C. E. Ney.[17] is from 0.4 to 0.8 inch a year. It is much more in southern latitudes, especially in tropical forests. The condensing capacity of many tropical forests, because of the extreme dampness of the air within them, is so great that during every clear and still night drops of dew fall continuously from the leaves as in rain. (This is also the case in the redwood belt on the Pacific coast.) Thus part of the moisture which is evaporated from the leaves during the day is condensed during the night, and the dews in the forest in all latitudes are so heavy that they dampen the soil under the leaves.

Condensation formed within the soil may be omitted from this discussion, judging from the results of local observations over limited areas, since there seems to be no difference in this respect between open field and forest.

Another reason for greater precipitation over forests may be the mechanical action of the trees themselves. When a cloud in the mountains passes through a forest, the branches and the leaves of the trees retard its movement. It comes, therefore, into a state when it can no longer retain its moisture in suspension, just as a river carrying sediment deposits part of it as soon as the rapidity of its flow is diminished. The moisture from such clouds is intercepted by the forest in the form of mist or drops of dew or crystals of hoarfrost on the branches and foliage of trees.

The mechanical action of the forest is especially important in the case of snow. The influence of forests upon the amount of snow has been especially studied in Russia, where in some places more than 30 per cent of all the precipitation is in that form. During heavy storms the forests not only catch more snow than do large open fields, from which it is blown away, but they prevent it drifting. There is always more snow deposited within the forest than in nonforested areas, except in depressions and protected places where snow accumulates. In regions where the snowfall is heavy the amount of snow that accumulates in the forest, and especially in small openings within the forest, is often so great that gauges located even under the crowns of trees contain more snow than those located in large open places, in spite of the fact that snow is very readily retained by the branches, especially in coniferous forests, and that part of the snow thus retained by the trees gets into the rain gauges only at the time of thawing, and therefore can not be accurately recorded. The results of many years of observations in Russia upon the accumulation of snow in the forest and outside if it have conclusively shown that young forests, deciduous forests, and small openings within the forest collect nearly twice as much snow as open fields.

After all, it really matters very little for the final result whether the increased precipitation over the forest is due to its influence upon

[17] Ney, C. E. Der Wald und die Quellen. Tübingen, 1893.

the condensation of vapor in the air or to the mechanical action of its branches and leaves. The fact remains that forests receive more precipitation than open fields.

PRECIPITATION OVER CONTINENTS

The effect of the forest upon local precipitation, however, is insignificant as compared with its effects upon the precipitation over the interior of continents.

The moisture given off into the atmosphere by forests is carried great distances over the country or out to sea before it appears as rain; yet, owing to the enormous quantities of water given off by the forest, the amount of moisture in the air, and consequently the chance for rain, is increased. So widely distributed is this influence, however, that even the most exact observations could never determine its extent. The great drawback to local observations, on the other hand, is that the neighboring open areas, the climate of which is compared with that of the forest, are themselves under the influence of the forest.

Prof. Lorentz Liburnau, at the end of his book on Forest, Climate, and Water, remarks that his data and conclusions apply only to the influence which the forest exerts while it exists, but do not extend to conditions which may arise from its complete destruction. "If, for instance, according to our observations in the Carpathian foothills, it appears that the influence of the forest upon the neighboring country is only insignificant, this does not indicate that a complete destruction of all the existing forests will produce here also only insignificant climatic changes. Very likely, if the forest were completely destroyed, the difference would be much greater than that which now exists between the climate of the forest and its neighboring areas."

Source of atmospheric moisture over the land.—While definite observations to show the relation between the forest and the climate of continents are still lacking, there are many theoretical considerations which strongly point to a distinct influence of the forest, especially upon the climate of large continents of a level character.

The accompanying maps, on which the direction of the prevailing winds is indicated by arrows and the mean precipitation by lines, one typical of the summer period and the other of the winter, show a most intimate relation between the prevailing winds and precipitation in the eastern half of the United States. A high meteorological authority in this country states that the "precipitation in the eastern half of the United States is from the aqueous vapor that is raised up from the vast waters to the south and southeast of the continent," and that "the supply is inexhaustible." [18]

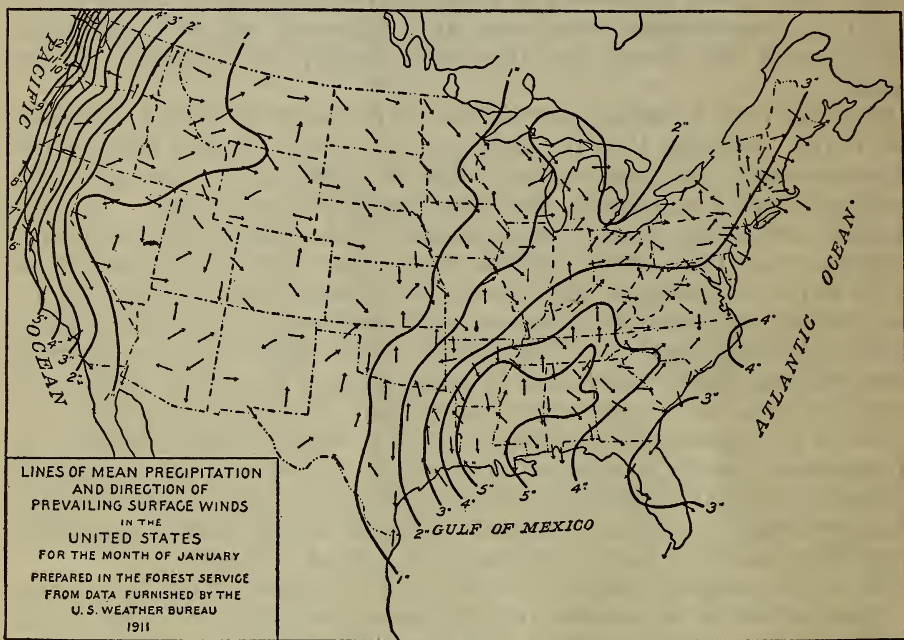
If by this is meant that the precipitation over the eastern part of the United States is derived entirely from evaporation from the Gulf of Mexico and the Atlantic Ocean, the statement is not entirely correct. It is true that the southern winds which prevail all over the eastern United States during the summer pass over the Atlantic Ocean and the Gulf of Mexico and reach the land loaded with mois-

[18] Moore, W. L. A report on the influence of forests on climate and on floods. Washington, D. C., 1910.

ture. As soon, however, as they reach the land, part of the moisture is precipitated, and as they move farther inland they become drier and derive their moisture more and more from the evaporation from the land.

Of the 44,015,400 square miles of land surface of the earth 79 per cent drains directly toward the ocean and 21 per cent forms an inclosed inland area without ocean drainage. The 79 per cent may be called the peripheral area of the earth's surface, and the importance of the evaporation from it is, on the whole, very great.

Prof. Ed. Brückner[19] computes the "continental vapor" evaporated from this peripheral area to be about 21,000 cubic miles (20,871.3 cubic miles). It plays, therefore, even a more important part in supplying moisture to the air than does the vapor directly evaporated from the ocean. Brückner estimates that the peripheral regions of



LINES OF MEAN PRECIPITATION AND DIRECTION OF PREVAILING SURFACE WINDS IN THE UNITED STATES FOR THE MONTH OF JANUARY

PREPARED IN THE FOREST SERVICE FROM DATA FURNISHED BY THE U. S. WEATHER BUREAU 1911

the continents are capable of supplying seven-ninths of their precipitation by evaporation from their own areas. If the evaporation from land plays such an important part in the precipitation over areas adjoining the ocean, it becomes still more important at some distance from the ocean. It may be assumed, therefore, that the moisture which is carried by the winds into the interior of vast continents, thousands of miles from the ocean, is almost exclusively due to continental vapor and not to evaporation from the ocean.

In the interior closed basins the precipitation and evaporation are, as a rule, equal.

The circulation of water on the earth's surface may be shown in the form of a balance sheet, as follows:

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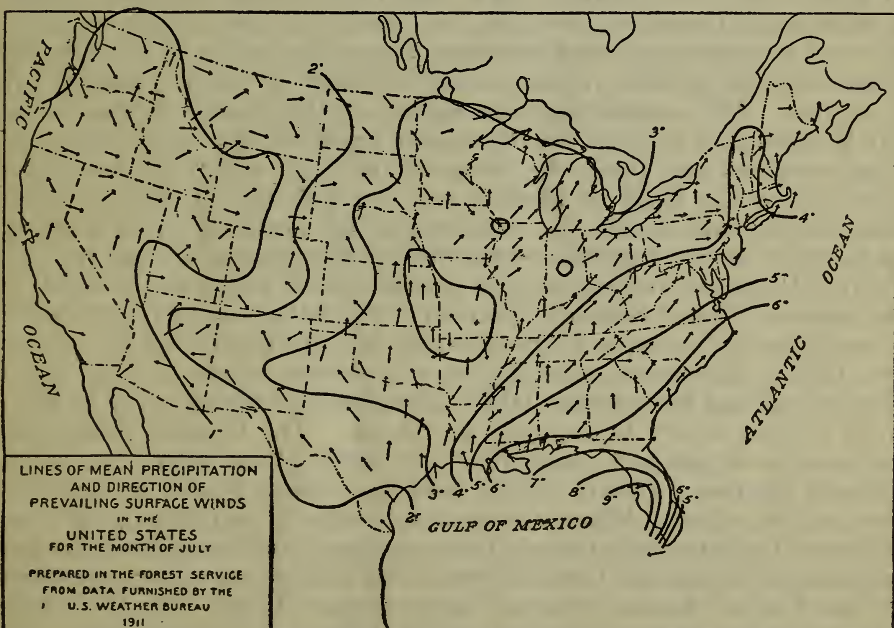
[19] Brückner, E. Die Bilanz des Kreislaufs des Wassers auf der Erde. (Geographische Zeitschrift, v. 6; also in La Pedologie (Russian), 1905, v. 7, No. 3.)

Balance sheet—Circulation of water on the earth's surface

	Cubic miles	Depth, in inches	Per cent
A. Entire earth surface (196,911,000.59 miles):			
Evaporation from water surfaces	92, 121	29. 5	80
Evaporation from land surfaces	23, 270	7. 5	20
Precipitation on entire earth surface	115, 391	37. 0	100
B. Oceans (141,312,600 square miles):			
Evaporation from oceans	92, 121	41. 3	100
Amount of ocean vapor carried to the land (net [1])	5, 997	2. 8	7
	86, 124	38. 5	93
C. Peripheral land area (44,015,400 square miles):			
Ocean vapor (net)	5, 997	8. 7	29
Continental vapor from the peripheral land surface	20, 871	29. 9	100
Precipitation over the peripheral land area	26, 868	38. 6	129
D. Closed interior basins with no drainage to the ocean (11,583,000 miles):			
Evaporation from closed basins	2, 399	13. 0	100
Precipitation over closed basins	2, 399	13. 0	100

[1] The difference between the amount of vapor that escapes from land to the ocean and from the ocean to land.

An analysis of these figures discloses the fact that one-fifth of the entire vapor on the earth's surface comes from evaporation on land;



that only 7 per cent, or 5,997.5 cubic miles, of all the water evaporated from the oceans enters into the precipitation over land; and that 78 per cent of all the precipitation that falls over the peripheral land area is furnished by this area itself.

Where is evaporation on land greatest? The evaporation from a moist, bare soil is, on the whole, greater than from a water surface, especially during the warm season of the year when the surface of the soil is heated. Soil covered only with a dead vegetable cover evaporates moisture much more slowly than a bare soil or an open water surface. On the other hand, a soil with a living vegetal cover loses moisture, both through direct evaporation and absorption by its vegetation, much faster than bare, moist soil.

The more highly developed the vegetal cover the faster is moisture extracted from the soil and given off into the air. In this respect the forest is the greatest desiccator of the soil. The experiments of Otozky, which have been fully confirmed by many observers in other countries, have conclusively shown that the forest, on account of its excessive transpiration, consumes more moisture, all other conditions being equal, than a similar area bare of vegetation or covered with some herbaceous growth.

The amount of water consumed by the forest is nearly equal to the total annual precipitation—in cold and humid regions less and in warm and dry regions somewhat greater. This enormous amount of moisture, which is later given off into the air by the forest, may be compared to clouds of exhaust steam thrown into the atmosphere, and must necessarily play an important part in the economy of nature. If the south and southeast winds, in their passage toward the north, northwest, and northeast, in the spring and summer, did not encounter the vast forest areas bordering the shores of the Gulf of Mexico and the Atlantic coast, and those of the Southern Appalachian, and, therefore, were not enriched with the enormous quantities of moisture given off by them, the precipitation in the Central States and the prairie region would probably be much smaller than it is now. The central interior region of the United States is the battle ground of two titanic forces, one harmful, the other beneficial. The beneficial one takes the form of the mild and humid summer winds from the Gulf of Mexico and the Atlantic Ocean, which at their height extend into the continent as far north as North Dakota, as far west as the foothills of the Rocky Mountains, and as far east as New England, and during the prevalence of which the rainfall in the eastern United States is heaviest. The other and harmful force is made up of the warm chinook winds which blow out of the northern Rocky Mountains, and the dry westerly winds of the upper Mississippi and the western lake region, both of which carry in their wake serious injury to orchards and fields. The Central States and the prairie region are geographically at the point where the battle between the two forces is fiercest, and the victory is now on one side, now on the other. When the humid southerly winds extend their influence far into the interior of the continent and overpower the dry continental winds, the Central States and prairie region, the granary of the United States, produce large crops. When the dry winds overpower the humid southerly winds there are droughts and crop failures.

As soon as the moisture-laden winds from the Gulf reach the land and encounter irregularities they are cooled and begin to lose part of their moisture in the form of precipitation. As long as the air currents remain saturated with moisture the slightest cooling or irregularity of the land that causes them to rise will result in precipitation. But as they move inland and become drier the remaining moisture is given off with difficulty and precipitation decreases. The sooner the humid air currents over land are drained of their moisture, the shorter, of course, is the distance from the ocean over which abundant precipitation falls. If precipitation over land depended solely on the amount of water brought by the prevailing winds directly from the ocean, rainfall would, of course, be confined only to a narrow belt close to the sea. Not all the water that is precipitated, however, is lost from the air current. A large part of it is again evaporated from the land into the atmosphere. The moisture-laden air currents, therefore, soon lose the moisture which they obtain directly from the ocean, but in moving farther into the interior absorb the evaporation from the land. Hence, the further from the ocean the greater is the proportion which evaporation from the land forms of the air moisture. In fact, at certain distances inland practically all the moisture of the air, or at least as great a part as that formed originally by the water evaporated direct from the ocean, must consist of that obtained by evaporation from the land.

In the case of the central and plain States, then, what would be the effect upon precipitation of complete or even partial destruction of forests in the Atlantic plains or in the southern Appalachians? Since the mean temperature in the eastern portion of the United States drops rapidly from north to south, the moisture-laden air currents, upon reaching the land, would be cooled off and rapidly drained of their moisture within a comparatively short distance from the ocean. The sandy soil so characteristic of the southern pine belt of the Gulf and South Atlantic States would rapidly absorb the rain, without returning much of it into the atmosphere. The rain which fell upon the slopes of the mountains would rapidly run off into the streams. While the removal of the forest might increase the evaporation from the ground itself, yet the more rapid run-off and the absence of transpiration by the trees would reduce the total amount of water evaporated into the atmosphere. The land, even if taken up for agriculture, could never return such large quantities of rain into the atmosphere as the forests did. The result would be that less moisture would be carried by the prevailing winds into the interior of the country, and therefore less precipitation would occur there.

Regarding Sweden, an eminent meteorological authority, Doctor Hamberg,[20] says:

"The excess of evaporation which the forest vegetation of Sweden furnishes to the atmosphere above what the same area would furnish if it were covered only with herbaceous vegetation must, of course, be very considerable. If this aqueous vapor remained in the forest and returned to the land in the form of rain, it would be extremely beneficial. But winds carry it on and spread it in all directions with such rapidity that its beneficial influence for our country (Sweden) remains very doubtful."

The forests of Sweden have, however, an important influence upon the precipitation of the countries to the east, into which the prevailing winds blow, since in regions far removed from the ocean the feeding of the atmosphere by local evaporation has an important

[20] Hamberg, H. E. De l'influense des forêts sur le climat de la Suède. Stockholm, 1885–1897.

bearing upon the humidity and amount of precipitation. "On the continents, in countries like central Siberia," says Hamberg, "forest vegetation must influence, of course, the humidity of the air. It returns to the atmosphere in the form of vapor the water collected and conserved in the forest which otherwise would run off. It lowers the temperature of the air. As a result of these two causes, the relative humidity of the air must increase, and with it must also increase the inclination to precipitation in the form of rain or snow."

Whether mountain forests have the same effect as forests in level countries upon the precipitation of the regions into which the prevailing winds that pass over them blow, is difficult to determine. The problem is complicated by the fact that high mountain chains themselves exert an influence upon precipitation and the direction of the winds, not only by presenting a mechanical obstruction to the free passage of the air, but also on account of the difference in temperature on the different slopes. A moist current of air in passing over a mountain chain undergoes several changes. In ascending it becomes cooler, the temperature of air not fully saturated decreasing 1° F. for every 182 feet of ascension. At the same time, the water-holding capacity of the air decreases until the saturation point is reached, and fogs, clouds, and precipitation begin to form. Further cooling of the air in its upward course is counteracted to some extent by the heat that is separated in the process of condensing vapor, and from then on proceeds only at the rate of about 0.5° F. for every 182 feet of ascension. After the air current has passed the crest of the mountain and lost an amount of moisture in ratio to the degree to which it has been cooled, it descends on the leeward side and becomes heated. In its descent it absorbs the fogs and clouds, and in this process takes on some heat. Further heating goes on at the rate of 1° F. for every 182 feet of descent.

The more moisture the air loses in ascending a mountain the greater is the amount of heat it can absorb in descending. If, for instance, a current of saturated air, before ascending, had a temperature of 50° F., and the crest over which it passed was 9,900 feet high, then, on the leeward side at the same altitude at which it began to ascend, it would have a temperature of 77° F. and, provided no moisture is absorbed in the descent, a relative humidity of 21 per cent.[21] At other obstructions met by the same current of air the same changes would take place, though on the next chain of mountains new precipitation begins, as a rule, only at an altitude equal to that of the crest of the previous mountain chain over which the current of air has passed.

Professor Mayr[22] has shown that wherever, as on the Pacific coast, in the Rocky Mountains, and in Caucasus and Turkestan, there are several parallel chains of mountains at right angles to the moist air current, each chain higher than the previous one, the forest on each consecutive mountain chain does not extend below an altitude equal to that of the preceding chain. Between the mountain chains are treeless, dry valleys.

As a rule the moist air currents passing over wooded slopes, being chilled, deposit most of their precipitation on the windward side.

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[21] Klossovsky, A. V. Osnovl meteorologii. Odessa, 1910, p. 48.
[22] Mayr, H. Waldungen von Nord Amerika, Munich, 1890.

It is only in exceptional cases, such as when the air is not fully saturated, or when warm currents rise from below, that the air current, instead of depositing moisture, becomes enriched with moisture and carries it over the crest to the regions lying beyond. This may occur on southern slopes, which are likely to be warm. The influence of wooded windward slopes upon the humidity of the region to the leeward side of the mountains therefore varies. It is apparent, however, that while the forests in the mountains have a marked influence upon local precipitation, their influence upon the humidity of regions lying to the leeward can not, on the whole, be very great.

SUMMARY OF EFFECTS OF FORESTS UPON CLIMATE

Accurate observations, continued for many years in different parts of the world, establish with certainty the following facts in regard to the influence of forests upon climate:

The forest lowers the temperature of the air inside and above it. The vertical influence of forests upon temperature extends in some cases to a height of 5,000 feet.

Forests increase both the abundance and frequency of local precipitation over the areas they occupy, the excess of precipitation, as compared with that over adjoining unforested areas, amounting in some cases to more than 25 per cent.

The influence of mountains upon precipitation is increased by the presence of forests. The influence of forests upon local precipitation is more marked in the mountains than in the plains.

Forests in broad continental valleys enrich with moisture the prevailing air currents that pass over them, and thus enable larger quantities of moisture to penetrate into the interior of the continent. The destruction of such forests, especially if followed by weak, herbaceous vegetation or complete baring of the ground, affects the climate, not necessarily of the locality where the forests are destroyed, but of the drier regions into which the air currents flow.

While the influence of mountain forests upon local precipitation is greater than that of forests in level countries, their effect upon the humidity of the region lying in the lee of them is not very great.

Forests as Conservers of Precipitation

WATER AVAILABLE FOR STREAM FLOW

All the water precipitated over an area covered with vegetation does not go to swell the underground drainage which feeds the springs and the regular flow of streams. Some of it is dissipated before it has a chance to reach the lower strata. A part (i) is intercepted by the branches and leaves of vegetation and is evaporated from them into the air; another part (e) is evaporated from the surface of the soil; a third part (r) runs off from the surface of the slopes into the valleys below; and a fourth part (t) is absorbed by plants and used by them for the building up of tissue and transpiration. Finally, a surplus (S), which is left over and above the amount absorbed by plants and evaporated by the soil, filters through into the ground and enriches the water which goes to supply the streams. Thus the water balance of any given area may be expressed in the form of an equation, in which $P=i+e+r+t+S$, and the amount of precipitation available for stream flow may then be expressed as $S=P-(i+e+r+t)$. Thus it is evident that, since the water available for streams is the amount which is left over and above that evaporated, transpired, and lost through surface run-off, the smaller the loss of atmospheric precipitation, the greater will be the amount of water that penetrates into the ground and becomes available for stream flow. Hence, to determine the effect of forests upon stream ffow, it is necessary first to determine whether a greater or less amount of precipitation is dissipated in a forested than in a treeless region.

In a level country, where there is practically no surface run-off, the only sources of loss of water to the streams are interception by vegetation, evaporation from the soil, and transpiration. The water available for stream ffow in a level country, therefore, may be represented by the equation $S=P-(i+e+t)$. In mountainous regions, on the other hand, surface run-off is one of the largest sources of loss to ground waters, and the hydrophysical influence of the forest in mountainous country is therefore essentially different from that in level country.

EFFECT OF FORESTS IN LEVEL REGIONS

The forest, all other conditions being equal, has an influence distinct from that of any other vegetable cover upon the amount of precipitation lost to the streams. This influence varies, of course, with the kind of forest, just as the influence of field crops or of bare soil varies in accordance with the character of each.

INTERCEPTION BY TREE CROWNS

On bare ground—for instance, on a plowed field—it is self-evident that no water is lost through interception by vegetation. In a field or meadow from which the grass or crops have been removed interception by the vegetal cover is very slight. It is greater on fields with growing crops, and is greatest in the forest, especially when the trees are in leaf.

Many experiments have been carried on in different parts of the world to determine the amount of water intercepted by the crowns of trees. The results obtained vary considerably with the character of the trees, their age, density of crown, the amount and severity of precipitation, velocity and direction of the wind, etc. The amount of water retained by tree crowns is, however, not much greater than that retained by a meadow of dense grass or cultivated plants at the time of their full development. Ney [23] estimates, on the basis of the average number and weight of beech leaves shed, that the aggregate foliage of a middle-aged beech forest on 1 acre would occupy 8.4 acres, and on the basis of the average yield of straw and hay, that the aggregate area occupied by the foliage of cereals would be 7.4 acres; of clover, 5.6 acres; and of meadow grass, 4.8 acres. Though cultivated plants present less surface per acre than do beech leaves,

[23] Ney, C. E. Der wald und die Quellen. Tübingen, 1893.

the latter offer more mechanical hindrances to the run-off of the water. It is very likely, therefore, that during the summer months cultivated fields retain as much water as does a beech forest.

For the entire year, however, the tree tops intercept more water than field crops, which are present for only a few months. The foliage in deciduous forests, on the other hand, remains intact for six months, and in coniferous forests all the year around. In deciduous forests, even when the foliage is gone, the branches still prevent a portion of the precipitation from reaching the ground directly. As a result of a great number of investigations,[24] it may be assumed that coniferous forests intercept more precipitation than broadleaf forests. Under average conditions a spruce forest will intercept about 39 per cent of the precipitation, a broadleaf forest about 13 per cent. The amount of precipitation intercepted is the smallest in a young stand and greatest in a middle-aged one. This fact is clearly brought out by investigations conducted by Doctor Bühler in Switzerland in dense beech stands of different ages. The figures given in table 13 are averages for two to three years' observations:

TABLE 13.—*Interception of precipitation by tree crowns in beech stands of various ages*

	Age of stand			
	20 years	50 years	60 years	90 years
	Per cent	*Per cent*	*Per cent*	*Per cent*
Proportion which reached the ground	98	73	77	83
Proportion retained by the tree crowns	2	27	23	17

The interceptive influence of forests is much greater in light than in heavy rains. It is evident, therefore, that all the figures which show the interceptive influence of tree crowns have a value only for the place and time that the measurements were taken, and for this reason can not be of general application. In regions where the precipitation is in the form of heavy or prolonged rains the ground under the forest, no matter whether the latter is deciduous or coniferous, will receive as much or nearly as much water as the bare ground, while in regions where the rains are neither heavy nor of long duration a large portion of the precipitation will remain in the tree crowns and escape the soil.

[24] Hoppe, E. Hegenmessung unter Baumkronen, Vienna, 1896; Fautrat, L. Influence comparée des bois feuillus et des bois résineux, sur la pluie et sur l'etat hygrométrique de l'air (Académie des science, Paris, Comptes rendus, 1877); Fautrat, L. Observations météroligique faites de 1874 à 1878. Paris, 1878; Krutzsch, H. Ueber den Einflus der Waldungen auf die Regenverhältnisse der germässgten Zone. (Tharander forstliches Jahrbuch, 1855, v. 11, pp. 123–141); Ebermayer, E. Die physikalischen Ein wirkung des Waldes auf Luft und Boden. Berlin, 1873; Bühler, A. Die Niederschläge im Walde. (Schweizerische Centralanstalt für das forstliche Versuchswesen. Mitteilungen, 1892. v. 2. pp. 127–160); Ney, C. E. Ueber die Messung des an den Schäften der Bäume herabfliessenden Regenwassers. (Mitteilungen aus dem forstlichen Versuchswesen Oesterreichs, 1894, no. 17, pp. 115–125); Johnen, A. Comparative Beobachtungen der Neiderschläge nach Fautrat's Methode. (Centralblatt für das gesamte Forstwesen, 1878, p. 16–19); Riegler, W. Beobachfungen über die Abfuhr meteorlogischen Wassers entang den Hochstämmen (Mitteilungen aus dem forstlichen Versuchswesen Oesterreichs, 1881, v. 2, pp. 234–246); Mathieu, J. Météorologie comparée, agricole et forestière. Paris, 1878; Ebermayer, E. Untersuchungs-Ergebnisse über die Menge und Vertheilung der Niederschläge in den Wäldern (Forstlich natürwissenschaftliche Zeitschrift, 1897, v. 6, pp. 283–301).

Of the precipitation intercepted by branches and leaves, however, only a part is evaporated into the air and so lost to the soil; the rest runs along the branches and trunks down to the ground. The amount of precipitation which reaches the ground along the twigs and trunks varies with the species, the bark, and character of branching. Thus, in a coniferous forest, the amount of precipitation which reaches the ground along the branches and trunks is very small (0.7 to 3 per cent), while in deciduous forests, under average conditions, it is about 15 per cent. Ney, after deducting from the amount of precipitation retained by the tree crowns the amount of water which runs down the trunks and branches, computed the loss of precipitation for the whole year, through interception by the crowns, to average for beech forests, 15 per cent; for pine, 20 per cent; and for spruce, 33⅓ per cent. Mathieu, at Nancy, on a basis of 11 years' observations, found that a forest of blue beech intercepts by its foliage and returns into the atmosphere on an average 8.48 per cent, and in winter only 5.85 per cent of the precipitation.

That portion of the precipitation which is prevented from reaching the ground directly is, however, not lost to the forest. Its evaporation increases the relative humidity of the air, which, together with the lower temperature within the forest, results in the condensation, especially in a coniferous forest, of a great deal of moisture, in the form of fog, dew, and hoarfrost.

Thus, though the forest, more than any other vegetable cover, intercepts atmospheric precipitation and prevents it from reaching the ground, the amount of precipitation thus lost is offset, except in dense, old stands of pure spruce, by the greater precipitation over the forest and the greater condensation of vapor within it in the form of dew, hoarfrost, etc.

EVAPORATION FROM THE SOIL

The influence of the forest upon evaporation has been determined for both water and soil surfaces. Numerous experiments on evaporation from water surfaces outside and inside the forest [25] have been carried on in France, Germany, and Russia. All these give practically the same result, namely, that evaporation from a free water surface is two and a half times greater outside the forest than inside.

Though investigations on the evaporation of water from soil surfaces were begun in the eighteenth century, and there are on record at least 50 different experiments, the results are less conclusive than those relating to the evaporation from free water surfaces.[26] According to the most accurate investigations, evaporation from bare soil in the open, under average conditions, amounts to about 50 per cent of precipitation. This ratio, however, varies within very wide limit. Ebermayer [25] and Wollney,[27] whose experiments are among the most accurate, determined in one case the evaporation from a bare sandy soil in the open to be 33.6 per cent of the precipitation,

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[25] Ebermayer, E. Die physikalischen Einwirkung des Waldes auf Luft und Boden. Berlin, 1873.

[26] Ezera, K. Untersuchungen über den Einflus der physikalischen und chemischen Eigenschaften des Bodens auf dessen Verdunstungsvermögen. Erlangen, 1844; Mangin, A. Influence des forêts sur le régime des eaux. (Revue des eaux et forêts, 1869.)

[27] Wollney, E. Des Einfluss der Pflanzendecke und der Beschattung auf die physikalischen Eigenschaften des Bodens. Berlin, 1877.

and that from a clayey soil, 50.8 per cent. In another experiment, where the kind of soil was not given, the evaporation was 49.4 per cent. Comparative observations on the amount of water evaporated by soil within the forest and in the open have been carried on chiefly by Professor Ebermayer. These observations were made only during the summer on soils always kept at the point of saturation. The absolute figures, therefore, must be taken with considerable caution, but the ratio between the evaporation from soil in the forest and from a similar soil in the open which they show is extremely important. This is that the evaporation from forest soil without a cover of leaf litter is 39 per cent, and with a cover of litter 15.4 per cent of the amount evaporated by a similar soil in the open. If the same ratio holds for winter, then, within the forest, a soil covered with leaf litter evaporates only 7.7 per cent, and one without litter 19.5 per cent of the total annual precipitation.

It is fair to assume that in a pine forest which thins out with age the evaporation from the soil will be above the average. In a beech or other deciduous forest, with heavy, dense foliage, it will be less than the average.

Ney [28] determines the evaporation from the soil in a beech forest with leaf litter to be 6 per cent of the precipitation, without a leaf litter 15 per cent; in a pine forest with a leaf litter 15 per cent, without leaf litter 24 per cent; in a spruce forest with leaf litter 8.1 per cent, without leaf litter 19.5 per cent.

The evaporation from soil in an open field covered with some vegetation has never been accurately determined, but, according to Ney, it scarcely exceeds one-third of the precipitation.

These results only confirm what one would expect of the influence which the forest has upon evaporation. The rate at which water is evaporated from the surface depends on the temperature of the air and soil, relative humidity of the air, movement of the air, and character of the soil cover. It has already been pointed out that the temperature of the air throughout the entire year and that of the soil in summer is lower within the forest than in the open, and that the relative humidity, especially in the summer, is greater in the forest than outside of it.

Wind.—The wind exercises a great influence on evaporation, both in summer and winter, by constantly renewing the air in contact with the moisture-containing surface. By breaking the force of the wind and checking the circulation of air, a forest cover reduces the evaporation of water or snow from the forest soil.

Mr. F. H. King,[29] of the agricultural experiment station of the University of Wisconsin, carried on in 1894 a number of interesting experiments to determine the effect of winds upon the rate of evaporation within and outside the sphere of influence of woods. The first series of experiments was made to the northwest of Plainfield, on a piece of ground planted to corn, south of a grove of black oaks having an average height of from 12 to 15 feet. At the time of the experiment there was a gentle breeze from a little west of north. The results showed in one case that the evaporation at 20 feet from the

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[28] Ney, C. E. Der Wald und die Quellen. Tübingen, 1893.

[29] King, F. H. Influence of woods on the rate of evaporation and amount of moisture in the air over fields to the leeward of them. (Wisconsin—Agricultural experiment station. Bulletin 42, 1894, pp. 14–19.)

wood was 17.2 per cent less than at 120 feet. In another case, at three stations located within 60 feet of the woods, the amount of evaporation was 24 per cent less than at three stations located between 280 and 320 feet away from the woods. Another experiment near the town of Almond, to the south of an oak grove 80 rods square, in a field sowed to oats and wheat, showed that the amount of evaporation increased until a point 300 feet from the woods was reached. Here the evaporation was 17.7 per cent greater than at 200 feet and 66.6 per cent greater than at 20 feet from the woods, the difference being due entirely to the protection from the wind afforded by the forest.

Observations made by the Forest Service on the influence of windbreaks[30] upon crops have shown that the per cent of moisture saved within an area twelve times as wide as the height of the trees may amount at different wind velocities to from 11 to over 40 per cent.

Character of soil cover.—As already shown, the soil cover in the forest, composed of a mulch of fallen leaves and humus, reduces considerably the amount of moisture evaporated from the ground. Experiments conducted by Professor Ebermayer for five years (1869–1873) in Bavaria demonstrated that a layer of fallen leaves is capable of reducing evaporation from the soil by 24 per cent. Thus, while the average evaporation from the soil in the forest deprived of leaf litter during the summer months (May to September) amounted to 39 per cent of that in the open, the evaporation from the same soil covered with a fairly deep layer of leaf litter was only 15 per cent of that in the open. In other words, while the forest cover alone diminished the evaporation from the ground by 61 per cent, the forest cover, together with the leaf litter, reduced it by 85 per cent.

Evaporation from soil in the open decreases greatly, of course, with increase in altitude; yet the forest cover, together with the leaf litter still exercises its influence, although the difference between the evaporation in the open and that in the forest at high altitudes is not so great as at lower ones.

The lower summer temperature of the soil and air in the forest, the greater relative humidity of the air, the checking of strong air currents, together with the double protection afforded to the soil by the mulch of fallen leaves and humus and the tree tops, tend to reduce the direct evaporation from the soil in the forest to practically a negligible quantity as compared to that in the open.

TRANSPIRATION

Besides the loss of water through direct evaporation from the soil, a large amount is returned to the atmosphere by the transpiration of leaves. This may be called physiological evaporation, in distinction from physical evaporation, since it is essential to the physiological function of the tree.

Loss of water through transpiration is one of the most complicated physiological processes. Although the problem has received a great deal of attention and has been studied by a large number of investigators, the exact quantities of water transpired by different trees and

[30] Bates, C. G. Windbreaks: their influence and value. Wash., D. C., 1911. (U. S.—Dept. of Agriculture—Forest service. Bull. 86.)

plants are still unknown. What the experiments thus far have established are the comparative amounts transpired by different plants. Of the experiments carried on upon the amount transpired by forest trees those of Wollny, Höhnel, and Bühler are the most valuable, since they were carried on for long periods of years and with the utmost care.

Höhnel determined the consumption of water by forest trees by repeated weighings of the pots containing them, and determined the loss of water through transpiration by the difference between successive weighings.

In Table 14 are brought together the results of Höhnel's experiments. The table is of especial interest in that it gives the comparative water consumption of different species. The figures are only for the vegetative season and show the number of pounds of water transpired for every pound of dry-leaf substance.

TABLE 14.—*Amount of water transpired by different forest trees per pound of dry-leaf substance*

	1878	1879	1880
	Pounds	*Pounds*	*Pounds*
Birch	679. 87	845. 13	918. 00
Ash	566. 89	983. 05	1, 018. 50
Hornbeam	562. 51	759. 01	871. 70
Beech	472. 46	859. 50	913. 80
Maple (Spitzahorn)	462. 87	517. 22	611. 80
Maple (Bergahorn)	435. 77	618. 30	703. 80
Elm	407. 31	755. 00	822. 80
Oak	283. 45	622. 21	691. 50
Oak (Zerreiche)	253. 33	614. 22	492. 20
Spruce	58. 47	206. 36	140. 20
Scotch pine	58. 02	103. 72	121. 05
Fir	44. 02	77. 54	93. 80
Austrian pine	32. 07	99. 92	70. 05

Thus, during the vegetative period, birch and ash trees transpire for every pound of dried-out leaves from 567 to 1,019 pounds of water—more than do any other forest trees; beeches and maples from 436 to 914 pounds; oaks from 253 to 692 pounds; and conifers, which transpire least, from 32 to 206 pounds. The difference in the amount of transpiration in the different years is explained by the fact that the years 1879 and 1880 had more rain and therefore more water penetrated the soil.

Höhnel estimates that a fully stocked beech stand, 115 years old, consumes from 1,560 to 2,140 tons of water per acre, or 1.15 acre-feet per year. The last means that if the water were spread over an acre it would have a depth of 1.15 feet. If an acre contains 526 trees from 50 to 60 years old, the water consumption is only 1,026 tons per acre, or 0.70 acre-foot; and if it contains 1,620 trees, only 35 years old, the consumption is as low at 321.5 tons per acre, or 0.23 acre-foot. Höhnel expressed the quantities of water that were transpired in 1880 in per cent of the precipitation of that year. He found that elm transpired 43½ per cent, beech 25 per cent, and birch 40 per cent of the precipitation. In 1878 and 1879 the per cent of transpiration was smaller.

Wollny, in observations carried on for six years, determined the amount of water transpired by different species of trees in pots, containing identical amounts and kinds of soil, by measuring the amounts of water which percolated through the pots. He found that spruce transpires, on an average, during the year 37.9 per cent of the annual precipitation and birch 27.8 per cent; but that during the vegetative period the amount transpired by the two species is almost the same, spruce 33 per cent and birch 32.1 per cent.

Ney[31] computed, on the basis of Höhnel's results, the amount transpired during the entire vegetative season by beech as 10.8 inches, spruce 8.3 inches, and pine 2.9 inches; or, for the forest in general, 7.3 inches. This, expressed in per cent of the total precipitation (31.5 inches), would be 23.2. In the case of coniferous trees the amount transpired during the winter must be taken into account, so that the transpiration of pine for the entire year would be 3.1 inches (10.2 per cent of the total precipitation) and for spruce 9.1 inches (28.9 per cent of the total precipitation).

TOTAL AMOUNT OF WATER LOST TO STREAMS

Loss of water to streams through interception by tree crowns and ground cover, by evaporation from the ground, and by transpiration, in a level country with no surface run-off, may be summed up for different kinds of forest, as in Table 15.

TABLE 15.—*Loss of water to streams in forests in level country (annual precipitation 31.5 inches)*

	Interception by forest cover	Evaporation from soil	Transpiration	Total loss	Total loss of annual rainfall
With leaf litter:	*Inches*	*Inches*	*Inches*	*Inches*	*Per cent*
Beech	6.7	1.9	10.8	19.4	61.5
Pine	9.4	2.8	3.1	15.3	48.6
Spruce	12.1	2.6	9.1	23.8	75.6
Average	9.4	2.4	7.7	19.5	61.9
Without leaf litter:					
Beech	4.7	4.7	10.8	20.2	64.1
Pine	6.3	7.6	3.1	17.0	54.0
Spruce	10.5	6.1	9.1	25.7	81.6
Average	7.2	6.1	7.7	21.0	66.7

On the basis of Wollny's and Riesler's experiments Ney has determined the total annual loss of water from field crops through interception of precipitation by the plants, evaporation from the soil, and transpiration to be as shown in Table 16.

TABLE 16.—*Loss in water to streams from field crops*

	Total loss	Annual precipitation (31.5 inches)
	Inches	*Per cent*
Meadow (overflowed)	41.6	132.1
Potato field	13.5	42.9
Grain field	25.3	80.3
Field crops in general	19.4	61.6

[31] Ney, C. E. Wer Wald und die Quellenbildung. (Forstwissenschaftliches Centralblatt 1901, p. 452.)

On bare soil in level country the only loss is from evaporation from the soil. This amount has been found to be on an average about 50 per cent of the precipitation.

The figures given, which are corroborated by daily practical experience, shows that in a level country a soil covered with vegetation of some kind surrenders to the ground waters a much smaller amount of water than bare soil with no vegetation at all, and a forest, at least a spruce forest, less than field crops. The only vegetative cover which uses up more water than a spruce forest is an overflowed meadow, which can draw upon a supply of water in addition to the precipitation. That any vegetable cover in a level country tends to reduce the amount of water available for stream flow is clearly shown by numerous experiments. In the United States King[32] has demonstrated this for corn. During the growing seasons of 1899 and 1890 the mean height of ground water under corn was lower than that under fallow land. From this he inferred that corn exerts a measurable influence in depressing the height of ground water lying at a depth of over 7 feet below the surface.

Recent experiments in Russia by Ototzky and others, taken with those by German and French investigators, have brought out the fact that in a level country with ground waters not in motion the humidity of the forest soil, which is very great at the surface, rapidly decreases with depth. According to Ebermayer, this desiccating influence extends under spruce stands to 31.5 inches, and, according to Russian investigators, even to from 10 to 13 feet. The forest, like any other vegetable cover, desiccates the layer of soil within which its roots are active, and since the roots of forest trees go to a much greater depth than the roots of cultivated crops, this has led to the conclusion that forest cover absorbs more moisture, and therefore desiccates the soil to a greater depth, than any other vegetal cover.

These investigations, of which those carried on by Professor Henry in the forest of Mondon, near Luneville, France, must be considered the most conclusive, have established with sufficient accuracy that in the forests of a level country in a temperate or cold climate, where the geological strata are homogeneous and horizontal, and the ground water is, therefore, not in motion, and where there is no surface runoff, (1) the water table is lower under the forest than outside during every season of the year, and (2) this depression is more marked in regions with deficient precipitation than where the precipitation is great.

Ototzky's and Henry's experiments can not, however, be generalized for all species and for all level countries of the world, since there are species and level regions where just the reverse is true. Thus, for instance, in level tropical regions, where the heat is intense, and the bare soil, though it may receive large quantities of rain, is subject to great evaporation, the soil under forest cover, in spite of intense transpiration, may contain more moisture than that in the open, especially since transpiration in tropical climates during the period of rest, which occurs in the hot season (equivalent to the winter of the Temperate Zones), is considerably reduced, while evaporation, which follows physical laws, is especially intense at that time.

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[32] King, F. H. Observations and experiments on the fluctuations in the level and rate of movement of ground water. (U. S.—Weather bureau. Bulletin 5, 1892, p. 32.)

B. Ribbentrop[33] reports that wells from 6 to 10 feet deep, dug within the forest plantations in the suburbs of Madras, near Trichinopoli, British India, contain water during the hottest season, while neighboring wells, 15 feet deep, outside of the forest, and rivers in the vicinity, are entirely dry during the hot months. This is due to the enormous evaporation from the bare soil during the hot months, evaporation which is much greater than the transpiration from the forest cover.

It is also true, as Ney has shown, that, from the consumption of water by different forest trees, it may be inferred that in a level country the cutting away of such forests as beech or spruce may even lead to an increase in ground waters. The cutting away of pine forests in a level country would, however, be injurious to ground waters unless the soil should remain entirely bare, for any other vegetation which would take the place of pine would consume a larger amount of water and, therefore, tend to lower the ground water to a greater extent than the pine forests.

The lowering effect on ground waters of the forest is well known from practical experience. The afforestation of the swamp lands of southern France, called the Landes, with maritime pine, brought about a lowering of the water table. In Italy the water table in swampy regions in Europe the drainage ditches, which before afforestation were always full of water, after planting became entirely dry.

As a net result of all these experiments in different parts of the world, it must be admitted that a difference exists between the hydrophysical influence of the forest in the plains and that of forests in the mountains and hills. In the plains the forest, because of its desiccating effect upon the soil:

(1) Constitutes an effective means of draining and drying up swampy lands, the breeding places of malaria and swamp fevers. The reforestation of the Landes, Sologne, the Pontine marshes, and a hundred other examples prove this.

(2) It draws moisture from a greater depth than does any other plant organism, thus affecting the unutilized water of the lower horizontal strata by bringing it again into the general circulation of water in the atmosphere, and making it available for vegetation.

(3) While it lowers to some extent the subterranean water level, it has no injurious effect upon springs, since these are practically lacking in the level countries with horizontal geological strata where its lowering influence has been chiefly noted.

(4) It refreshes the air above it and increases the condensation of moisture carried by the winds, thus increasing the frequency of rains during the vegetative season.

EFFECT OF FOREST IN MOUNTAINOUS REGIONS

INTERCEPTION, EVAPORATION, AND TRANSPIRATION

In mountainous regions, as already shown, the amount of precipitation increases within certain limits with elevation. The denser the

[33] Ribbentrop, B. Influence of forests on the climatic conditions and fertility of a country. (In his Forestry in British India, 1900, pp. 39–59.)

forest cover, the greater is this increase. Forests in the mountains receive more precipitation than forests at lower altitudes in the same region.

The loss of precipitation through interception (i) by tree crowns and humus in mountainous regions, while it has never been measured accurately, is accepted to be less than in level regions, first, because in the mountains precipitation more often falls in heavy showers, and second, because a larger part of it is in the form of snow.

In mountain forests the loss through direct evaporation (e) from the soil is considerably less than in forests of a level country, because of the lower temperatures at higher altitudes.

The amount of water transpired (t) by a forest in the mountains is also less, for the vegetative period is shorter, the temperature lower, and there is, in consequence, less growth per unit of area. This is well illustrated by the variation in the amount and weight of leaves produced by the same species at different altitudes. At an elevation of 450 feet, 1,000 beech leaves have an aggregate surface of 36.7 square feet, but at an elevation of 4,500 feet this falls to 9.8 square feet. Not only the surface and weight of the same number of leaves decrease with increase in altitude, but the ash content decreases as well. At a height of 450 feet, the ash content of beech leaves is 9.91 per cent, and of fir needles 10.19 per cent. At an elevation of 3,500 feet, that of beech is 4.03 and of fir 3.58 per cent.

Thus in mountain forests everything tends to reduce loss of precipitation, through interception, evaporation, and transpiration, to a minimum, and, consequently, to increase the amount of water available stream flow.

Observations carried on in forests over a broken topography, where the geological strata are not horizontal, and the ground waters therefore in motion, and where there is a surface run-off, have failed to establish any lowering of the water table under the forest. On the contrary, Hartmann,[34] hydraulic engineer of the State of Bavaria, who carried on these investigations in cooperation with the Bavarian Forest Service at the initiative of the International Association of Forest Experiment Stations, found that the water table at Mindelheim (altitude 2,000 feet) was nearer the surface in the forests than outside.

SURFACE RUN-OFF CONVERTED TO SEEPAGE

In the mountains the greatest source of loss of precipitation is through surface run-off (r), and the most important influence which a forest cover has is in reducing this.

A German investigator of high standing (Ney) estimates the amount of water which the forest cover saves to the soil by reducing the surface run-off and changing it to underground seepage to be as follows: For forests at low altitudes where the rains are not heavy and the soil is less subject to freezing, 20 per cent; for forests of moderate altitudes, 35 per cent; and for mountain forests, 50 per cent of the precipitation.

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[34] Ebermayer, E., and Hartmann, O. Untersuchungen über den Einfluss des Waldes auf den Grundwässerstand. Munich, 1904.

Measurements of surface run-off made in 1860 by Jeandel, Cantegril, and Bellot[36] in the Vosges, show that the surface run-off from the wooded slopes is only about half as much as that from deforested slopes, while, from the former, the underground seepage is greater and the flow of the streams more regular.

Such an authority as Huffel[36] states that under ordinary conditions of rainfall there is practically no surface run-off from wooded watersheds having an abundant leaf litter.

The saving of precipitation effected in this way by the forest is more than sufficient to offset whatever loss may be sustained through transpiration or interception by tree crowns. This is clearly brought out by the following facts: The entire loss of water from forested areas at moderate altitudes, even on the steepest slopes, is about equal to that from forest in level country.[37] Ney places this at 19.4 inches or 61.5 per cent of the precipitation (31.5 inches). Cultivated fields on similar slopes have been computed to lose, through interception by vegetable cover, evaporation from the soil, transportation, and surface run-off, 24.9 inches, or 79 per cent of the precipitation, and bare surfaces 27.2 inches, or 86.4 per cent. The higher the altitude, the steeper the slope, the heavier the rainfall, and the greater the precipitation, the more marked will be the difference. This holds true, not only for such species of trees as beech or pine, the entire loss of water from which is less than that from cultivated fields, but also for spruce. Although in a level country a spruce forest consumes more water than do cultivated fields, at high elevations, where the precipitation is from 43 to 47 inches, it consumes only 9.2 inches, or 21.5 per cent of the total precipitation, less than open fields and nearly 15.7 inches or 34 per cent less than bare surfaces.

The ability of the forest to check surface run-off is greatest when the ground beneath is covered with an unbroken leaf litter. A forest without leaf litter, on slopes at moderate altitudes, has little effect in checking run-off. The entire loss of precipitation from such a forest was found to be 26.9 inches, while that from bare surface in the same situation was 27.2 inches. Hence, for a forest to exercise its most beneficial effect upon run-off, it must not be burned over, grazed, or otherwise interfered with in its normal function.

That a normal forest in the mountains saves more water for stream flow than any other vegetal cover or any bare surface is shown also by the abundance of springs in mountain forests.

This difference in the hydrological influence of the forest in level country and in the mountains makes clear how unfounded is the contention occasionally expressed that if the forests are to control stream flow it is necessary to keep them not only on the headwaters of the stream but also on their lower levels, since the latter form by far the largest part of the drainage basin. As carefully conducted experiments have shown, the presence of forests at low levels, especially spruce, may impoverish the ground waters instead of enriching them. At best the influence would be the same of that of agricultural soil kept in good tillage. A forest in the mountains, on the other hand, actually conveys more water to the ground than does any other vege-

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[35] Jeandel, F., Cantegril and Bellot. Études expérimentales sur les inondations. Paris, 1862.

[36] Huffel, G. Études expérimentales sur les inondations. Paris et Nancy, 1862.

[37] Ney, C. E. Der Wald und die Quellen. Tübingen, 1893.

tal cover. The greatest influence of a forest upon stream flow, therefore, is at high altitudes, where precipitation is heaviest, slopes steepest, and erosion easiest. Even if good agriculture, as sometimes claimed, could have there the same effect upon erosion and absorption of water as forest cover, which it has not, the fact would be of no practical value, since agriculture at high altitudes is, as a rule, impracticable.

Reduction of surface run-off means both an increase of underground seepage and prevention of erosion, two important factors in the regulation of stream flow. The action of mountain forests in protecting the soil against erosion and in increasing underground seepage at the expense of surface run-off is the result of their ability to lessen the severity of rainfall, to retard the melting of snow, to offer mechanical obstacles to surface run-off, to hold the soil together, to keep it in a permeable state, to increase its volume by constantly adding new soil, and to absorb large quantities of water by its leaf litter.

Severity of rainfall checked.—The amount of water which filters into the ground depends, for one thing, upon the length of time the water remains in contact with the soil. For slopes of the same gradient this, in turn, depends upon the duration of the rain or on the time the snow takes to melt. Imbeaux [38] found, for deforested or poorly forested watersheds near Mirabeau, that during three exceptional rainfalls the surface run-off from slopes of the same gradient constituted in one case 33 per cent, in another 39 per cent, and in a third 42 per cent of the precipitation, while during less heavy rains this per cent fell to 22 and in light rains to 18. Other figures obtained at the confluence of the Durance with the River Rhone were close to those obtained at Mirabeau but somewhat smaller. For the Danube, near Vienna, Lauda, the Central Hydrographic Bureau, using the same method, found that for the period between July 28 and August 14, 1897, the surface run-off formed 42 per cent of the precipitation.

The forest modifies both the severity and the duration of the rainfall. By its foliage and branches it breaks the force of the rain, so that the water reaches the soil without violence and at the same time prolongs its duration. After a storm water continues to drip from the leaves and twigs for one or two hours. The water in the forest, therefore, falls more quietly and for a longer time and has thus a better chance to be absorbed by the soil.

Melting of snow retarded.—The rapid melting of the snow in the spring, especially when the ground is frozen or is saturated with water, favors surface run-off and lessens seepage. In this country the systematic measurement of snow in the mountains has but recently been begun by the Weather Bureau in cooperation with other bureaus, and it will be several years before definite results are obtained.[39] Such measurements, however, have been made in other countries, and the influence of the forest upon the melting of snow has been thoroughly determined by experiment, especially in Russia, where snow forms a large portion of the precipitation and affects most vitally the flow of streams:

[38] Imbeaux, E. Essai programme d'hydrologie. (Zeitschrift für Gewässerkunde, 1898–1899, v. 1, pp. 68–91, 225–278; v. 2, pp. 220–248, 257–274.)
[39] U. S.—Department of Agriculture—Weather Bureau. Instructions No. 76.

At the Imperial Agronomic Institute at Moscow measurements on the amount of snow that reaches the ground in the forest have been carried on for five years, both by means of rain gauges and directly by measuring the snow cover in the forest before its melting. These measurements show very clearly that the species, density, and age of the forest have a direct influence upon the amount of snowfall that reaches the ground. Thus, while in a birch stand between 70 and 75 years old only from 4 to 5 per cent of the total snowfall is prevented from reaching the ground, in dense spruce stands the tree crowns retain from 50 to 55 per cent. In other words, only about half as much snow reaches the ground in a dense spruce forest as in the open. This is brought out in Table 17.

TABLE 17.—*Interceptive influence of forests on snowfall*

	Number of areas examined	Number of measurements of snow depth	Number of snow samples weighed	Thickness of snow			Water equivalent of snow depth	Amount of water per acre
				Minimum	Maximum	Average		
				Inches	*Inches*	*Inches*	*Inches*	*Cubic feet*
1. Young plantations (2 to 4 years old) and small clearings within the forest	20	259	7	15.4	26.8	21.9	5.1	18,420
2. Birch forest (35 to 75 years old)	11	377	27	18.9	26.8	22.2	5.0	18,290
3. Oak forest (25 to 90 years old)	2	62	3	19.7	27.2	23.5	5.6	20,148
4. Pine forests	32	887	56	11.4	19.7	15.5	3.1	11,255
Young (25 to 35 years old)	25	662	43	11.4	19.7	15.2	3.1	10,417
Old (60 to 90 years old)	7	225	13	11.8	19.3	16.4	3.2	11,497
5. Spruce forest (25 to 35 years old)	21	460	29	6.7	13.8	9.7	2.1	7,711
6. Pine forest with admixture of birch (65 to 75 years old)	4	6	3	14.2	22.8	20.0	4.4	15,753
Pine forest with admixture of larch (25 to 35 years old)	3	74	2	11.4	16.5	15.2	3.1	11,230
Pine forest with admixture of spruce (35 years old)	5	157	9	8.7	15.7	12.9	2.9	10,391
7. Spruce forest with admixture of larch	3	57	2	8.3	21.7	14.1	3.1	11,103
8. Cultivated field	1	332	8	5.1	22.4	13.0	3.1	11,281

Thus an acre of broadleaf forest (birch 35 to 75 years old and oak 25 to 90 years old) will contain per acre about 41 per cent more snow water than a pure pine forest (20 to 90 years old); 60 per cent more than a pure spruce forest; or an average of about 50 per cent more than coniferous forests in general. The table shows also that the age of the stand has an important influence upon the amount of snow on the ground. Thus young pine stands contain from 9 to 10 per cent more snow than older pine stands (60 to 90 years old). The important fact which these figures show, however, is that young forests, deciduous forests, and small openings within the forest collect nearly twice as much snow as open fields, while dense, pure spruce forests contain less than open fields.

Upon the comparative loss of snow through drifting or evaporation from forested and from unforested areas there exists comparatively little data. This is due chiefly to the great difficulty of making satisfactory measurements on the wind-blown and constantly shifting snow in the open. Such meteological observations and empirical data as do exist, however, agree in showing that the loss of snow in the forest during thaws in the winter and from other causes is much less than that outside. This is due, as in the case of aqueous precipitation, to the protection afforded by the forest cover from the direct rays of the sun and from radiation, to the lesser circulation of the forest air, and to the narrower range of temperature inside the forest than outside. Because of this protection from the sun and wind and also because of the partial retention of the spring rains by the forest cover the melting of snow in the forest continues for three, four, and five weeks longer than in the open.

The influence of forests in retarding the melting of snow has been demonstrated with especial precision in a 10 years' series of observations carried on at the Imperial Agronomic Institute at Moscow. These show that the period of snow melting lasts within the forests from 26 (1904) to 57 (1902) days, while snow in the open disappears within 6 or 7 days. Thus in 1908 the melting of snow, which began April 12, lasted in the forest until May 15 (34 days), but in the fields, pastures, and all other open places surrounding the institute only until April 22 (11 days), while in the more exposed fields the snow had all disappeared as early as April 18, 7 days after it had begun to melt. The retention of snow in the forest until May 15 was in spite of the fact that after April 22 there were frequent warm rains.

The rapidity with which snow melts in the forest varies with the species and with the density, age, and location of the stand. This variation has been found to hold true from year to year, irrespective of the weather at the time of melting. The snow disappears first of all from clearings in the forest, simultaneously with its disappearance from open fields. Next it disappears from young forest plantations, in which the tree tops have not yet begun to touch each other; then from thin oak forests on southerly slopes and old, open pine forests; then from dense stands of birch on northerly slopes; later from pine; and last of all from spruce. Thus in 1908 at the Imperial Agronomic Institute the ground in field and forest became entirely free of snow on the following dates:

In fields, clearings, and open places	April 22.
In young, open stands	April 24.
In old, open stands on south slopes	April 26.
In birch stands	April 29.
In pine stands	May 6.
In spruce stands	May 15.

Thus, while compared with deciduous stands, coniferous forests, and especially pure dense spruce, prevent large accumulations of snow, their effect in retarding its melting, especially in the case of spruce, is much greater, and for this reason they are more efficient in reducing the height of spring freshets.

In an ordinary forest region the water in the streams in the spring is derived from three sources: (1) The snow water that runs off from fields and clearings; (2) the surface run-off from forest soil, however slight; and (3) one, one and one-half, or two months later, after all the snow is melted, the underground water. With the destruction of the forest the ground water is greatly decreased, there is no longer the retarded surface run-off from forest soil, and nearly all the snow water runs off at once as surface water from the fields and cleared land.

In cultivated fields and clearings in the north the ground is still frozen when the snow melts. This, together with the rapid melting of the snow in the open, causes the water soon to run off, even from gentle slopes, in great quantities, as though from the roof of a building. Freezing of the ground in fields and clearings is due chiefly to unimpeded radiation in the fall and to the blowing away of the protective cover of snow in the winter. Cultivated ground freezes especialy deep during the winter if saturated with rain water at the time of the first fall frost. Surface run-off from open fields is further increased when thaws during the winter coat the ground under the snow with an icy sheet, over which the snow waters run off in the spring without penetrating the ground.

In the forest, on the other hand, the soil is warmer than in the open. It is protected from radiation by trees. It is further protected by the leaf litter, a poor conductor of heat, which both prevents its cooling off and protects it from freezing in winter, and in the processes of fermentation and decay contributes the heat which these evolve. The relatively even cover of snow on the ground protects it still further. Under this triple protection the forest soil either does not freeze at all or freezes much later in the winter and to a much less depth than in open places. Moreover, it thaws out in the spring while still under its cover of snow. The slow melting of snow in the forest, together with the unfrozen, or only slightly frozen, condition of the ground beneath, permits a much greater percolation there than in the open. This water-holding capacity of the northern forest is more marked in coniferous stands, especially in spruce.

Closely connected with the relatively high temperature of the forest soil is another important fact which is often entirely overlooked. If the soil of watersheds remains soft and unfrozen, the ground water which feeds the streams continues to flow throughout the winter, thus keeping up the normal winter water stages in the streams under the ice. If, however, the flow of underground water ceases during the winter, the water accumulates in the ground, small streams freeze to the bottom, and the water stage of the river falls. In spring the ground water which has accumulated behind the icy dams thus formed at the bottoms of slopes bordering the streams enters the rivers in large quantities. For the regimen of rivers, therefore, the importance of forest cover on slopes bordering springs, creeks, and small streams, which are fed by underground waters, is especially great.

Surface run-off obstructed.—The forest floor, penetrated by a network of roots and covered by branches and stumps, offers many obstructions to the surface run-off and so permits the water to sink into the ground. Percolation is made still easier by the presence of deep channels in the soil, left by the decay of large roots.

The porosity or permeability of the soil has a great influence on the amount of surface run-off. The influence of the forest, therefore, will vary with the character of the soil on which it grows. On heavy clay or other impermeable soils the crowns of trees, which break the violence of the rainfall, together with a surface mulch of leaves and twigs, prevent the soil from becoming compact and allow it to retain its granular structure, thus making it more permeable to water. On a soil very permeable to water, such as sand, the influence of the forest in decreasing surface run-off may be very insignificant, consisting chiefly in preventing the soil from being washed away.

An unbroken forest soil cover of half decomposed leaf mulch and humus aids greatly in retarding surface run-off and forcing it to penetrate into the ground. Its importance in this respect is made clear by the following facts: The leaf mulch on an acre of virgin beech forest weighs, when air-dried, about 8,818 pounds; in a pine forest, 15,873 pounds; and in a spruce forest, 12,346 pounds. If the specific gravity of the air-dry leaf litter be only 0.5, then the dry substance of the leaf mulch if evenly distributed over an acre would cover it in a beech forest to a depth of only 0.08 inch, in a pine forest to 0.14 inch, and in a spruce forest to 0.11 inch. In nature, however, this amount of leaf litter covers the ground in beech and pine forests to a depth of 3.1 inches, and in a spruce forest to a depth of 3.9 inches, which gives an idea of the space within the leaf litter and of the volume of water it may accommodate.

Hüffel found that a forest with leaf litter, after a rainfall of from 2.4 to 2.8 inches, did not give off, even on the steepest slopes, a drop of water in the form of surface run-off. If water does not run off from such stands it comes from the precipitation which falls on an area deprived of its forest cover—for instance, a road.[40]

To determine precisely the actual effect of different kinds of forest soil in retaining the water which they receive as rain or melting snow, Prof. E. Henry[41] conducted a series of experiments with typical soils from spruce and beech forests. Taking the greatest care to preserve the natural arrangement and solidity of the soil, a number of samples were removed, thoroughly saturated by plunging into water for several days, drained of the excess moisture, and weighed. After being thoroughly dried at a temperature of 100° C. (212° F.) the samples were reweighed, and the weight of water held by the saturated soil thus determined. From the average of all the weighings it was found that the spruce-needle humus contained, when saturated, 4.15 times its own weight in water, while the beech-leaf humus contained 5.38 times its own weight. When simply air-dried, which is, of course, the case in nature, beech-leaf humus was found still to absorb 4.41 times its weight, while air-dried spruce humus took up about 3.38 times its weight.

To ascertain the actual amount of water absorbed and retained per given unit of area by spruce and beech humus, the average weight of oven-dried (100° C.) humus per 2½ acres was determined. Allowing 15 per cent for excess moisture content of air-dried over oven-dried humus, the air-dried spruce and beech humus were found to have a retentive capacity of approximately 46.44 and 22.2 tons of water per acre, respectively. This amounts in volume to 1,510 cubic feet per acre for spruce and 712 cubic feet for beech humus, equivalent to a rainfall of 0.41 inch and 0.2 inch, respectively.

The depth of soil has a bearing upon the amount of water which it can retain. No matter what its character may be, a thin soil can not retain much water. The forest, however, tends to increase the

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[40] Ney, C. E. Der Wald und die Quellen. Tübingen, 1893.

[41] Henry, E. Influence de la couverture morte sur l'humidité du sol forestier. (Annales de la science agronomique, 1901, tome 2, 182–196.)

volume of soil, and thus creates greater reservoirs for water. It does this in two ways: (1) From above, by the addition of leaves and twigs, which, when decayed, become a constituent part of the soil; and (2) from below, by inducing disintegration of decomposition of the underlying rock. The forest, by constantly increasing the depth of the soil, lessens the likelihood of it being washed away and enables it to remain where it was formed. The addition of organic matter to the soil increases its water-holding capacity. The tree roots at the same time enter the narrow fissures of the rock, which they widen, thus producing many new openings into which the water may sink.

During the vegetative season the demand of the forest upon the water stored in the ground is very great. In summer the forest, like other crops, consumes more water than it receives in the form of precipitation. At the end of the vegetative season, therefore, the level of the underground water is low. As a result, the forest soil can absorb large quantities of water during the period of vegetative rest, when there is an excess of water on the ground, either from heavy rains or from the melting of snow. The forest soil, therefore, forms a reservoir whose capacity is greatest when the excess of water on the ground and the danger of floods is greatest. The water stored in the time of rest is used by vegetation and for the flow of streams later on when there is usually a deficiency of precipitation.

SUMMARY OF THE EFFECTS OF FORESTS IN CONSERVING PRECIPITATION

(1) The hydrological rôle of forests in level countries differs from that of forests in hilly or mountainous regions.

(2) In level country, where there is no surface run-off, forests, in common with other vegetation, act as drainers of the soil; hence their importance in draining marshy land and improving hygienic conditions. In such country their effect upon springs is unimportant.

(3) In hilly and mountainous country forests are conservers of water for stream flow. Even on the steepest slopes they create conditions with regard to surface run-off such as obtain in a level country. Irrespective of species, they save a greater amount of precipitation for stream flow than does any other vegetable cover similarly situated. They increase underground storage of water to a larger extent than do any other vegetable cover or bare surfaces. The steeper the slope the less permeable the soil, and the heavier the precipitation the greater is this effect.

(4) In the mountains, the forests, by breaking the violence of rain, retarding the melting of snow, increasing the absorptive capacity of the soil cover, preventing erosion, and checking surface run-off in general, increase underground seepage, and so tend to maintain a steady flow of water in streams.

Forests and Erosion

One far-reaching influence of the forest upon stream flow lies in its ability to protect the soil from washing. Wherever the topography is at all rough erosion of the soil is a factor to be dealt with. The extent to which soil is eroded depends upon the climate, steepness of the ground, the character of the coil, the geological formation of the region, and the surface cover. When the slopes are steep, the soils and the underlying rock friable, the rains torrential, and the surface bare of vegetation, erosion by surface run-off reaches colossal proportions. In such regions thousands of acres of fertile soil are destroyed each year and millions of cubic feet of silt deposited in the bottom of rivers to form bars and shoals which change the regimen of the streams and obstruct navigation.

Erosion on cleared slopes above the headwaters of streams, where agriculture is impracticable, may be prevented by sodding, by a growth of shrubs, by engineering work such as log or rock dams in deep gullies, or by covering the surface with straw, leaves, and brush. The most permanent, effective, and cheapest protection against erosion, however, is a forest cover. Grass, while effective in preventing erosion, does not diminish the surface run-off and serves no other useful purpose. A surface blanket of straw, leaves, and brush is only a palliative, and must eventually be replaced by some permanent cover. Engineering work is, as a rule, very expensive, and alone will not fully accomplish the purpose sought. Where the soil has been entirely washed away, however, engineering work of some sort is necessary before any vegetable cover can be started.

The forest is the most effective agent for protecting the soil from erosion because (1) the resistance of the soil to erosive action is increased by the roots of the trees, which hold the soil firmly in place, and (2) at the same time the erosive force of the run-off is itself reduced, because the rate of its flow is checked and its distribution over the surface equalized.

France furnishes a good example of the effect of forest cover upon erosion and stream flow. There some 800,000 acres of farm land had been ruined or seriously injured as a result of clearing about the headwaters of streams, and the population of 18 departments was reduced to poverty and forced to emigrate. In 1860 forest planting was begun on the headwaters of the streams. Already 163 torrents have been entirely controlled by this means, and 624 more are beginning to show the effects of forests on their headwaters. Thirty-one of the torrents now entirely controlled were a half century ago considered hopelessly bad. The foremost French engineers, after many experiments, have come to the final conclusion that forest cover is one of the most effective means for checking erosion and that the best place to control stream flow is at the headwaters of the streams. Examples of reforestation of mountains for the control of torrents are to be found not only in the French Alps but also in the Swiss Alps and in Tyrol.

Erosion has a bearing on the height of flood water in the rivers, since the sediment carried by the rivers and the coarser detritus brought down by mountain streams often increase stream volume to such an extent that the height of the water is raised far beyond the point it would reach if it came free of detritus and sediment. When the channel of a stream has become filled with waste material even a slight rainfall will cause a flood, while, if the channel were deep, it would have no perceptible effect upon the height of water in the stream. The filling of mountain streams with waste not only increases the frequency of floods but causes the streams to assume the character of torrents. A channel filled entirely or partially with foreign material can not hold large quantities of water, while the denuded slopes deliver the storm water almost as fast as it falls.

How great may be the volume of detritus carried by a given volume of water is shown by Demontzey,[42] who computed that one mountain torrent brought down in 85,020 cubic yards of water 221,052 cubic yards of detritus, or more than two and a half times its own volume.

L. C. Glenn[43] ascribes the change in regimen of many of the mountain streams in the southern Appalachian to the denudation of the steep mountain slopes and the consequent erosion. He finds conclusive evidence of increased erosion, the result of clearing on the mountain stream basins since 1885, in the character of the flood-plain deposits within recent years. When floods are small or gentle the flood-plain deposits consist of fine alluvium. When the floods are great and violent the deposits consist of coarse sand, cobbles, and bowlders. In the past the flood-plain deposits of such southern rivers as the Watauga, the Doe, the Nolichucky, the French Broad, the Catawba, and the Yadkin were built of fine sandy loam or clay. In the last decade, however, the deposits have grown coarser, which points to an increase both in the height and in violence of floods.

In mountainous regions where a thin soil covered with forest is underlaid with hard rock, such as limestone, or with unfertile formations, such as chalk, destruction of the forest may often result in the complete desolation of the region. As long as the soil, formed during centuries by the disintegration of the rock and the accumulation of humus, is held together by the roots of trees, some ground waters may accumulate within it, or even small springs may be found. As soon, however, as the forest is removed the thin soil is washed, even from gentle slopes, and nothing remains but bare rock. Examples of this kind are common all over the world and may be found even in this country, in spite of the fact that here destruction of the forests is comparatively recent, and consequently erosion has not progressed as far in some portions of the Old World. There, as in Karst, portions of Greece, Palestine, and the mountainous provinces of southern France and Italy, the evils of forest destruction and subsequent erosion are strikingly evident.

In Karst deforestation has practically converted the region into a desert. The burning sun now strikes the naked rocks, from which the atmosphere is heated by radiation, while the rain is lost in the rock fissures without benefit to vegetation. For many square miles the country is one of drought.

In the United States the effect of destruction of forest cover upon erosion is most impressively shown by the conditions prevailing in the Ducktown copper region, Tennessee. Smelters started about 16 years ago near Ducktown have killed, by sulphuric fumes, all vegetation in their immediate vicinity. The slopes are now bare and are being rapidly eroded. On Potato Creek this eroded material is accumulating at the rate of a foot or more each year and has buried

[42] Demontzey, P. Traité pratique du reboisement et du gazonnement des montagnes. Paris, 1882.

[43] Glenn, L. C. Denudation and erosion in the southern Appalachian region and the Monongahela Basin. Washington, D. C., 1911. (U. S. Geological Survey. Professional Paper 72.)

telephone poles almost to their cross arms. On Ocoee River each flood deposits large quantities of sand and periodically dams the river. The country for several miles has become a barren waste.

Of all vegetable covers, forests are most efficient in preventing the slopes from eroding and the beds of streams from filling with silt. Even on very permeable soils, where their effect upon the underground storage of water may be of secondary importance, they are necessary as protection against erosion.

PART II.—RESULTS BY THE HYDROMETRIC METHOD

Reliability of Available Records of Stream Measurements

Measurements of the flow of waters in streams from forested and unforested watersheds would theoretically be the best check upon the conclusions obtained by the physical method. Actual measurements of stream flow, however, have not lead to such conclusive results as have the data secured by the physical method; nevertheless, the consensus of opinion among the leading authorities in engineering and forestry the world over is that the forest exercises a potent influence in the regulation of stream flow. It is true that there is a very considerable divergence of opinion on the extent of this influence. Close study, however, traces this to the complexity of the problem and the failure to give due weight to the factors involved, as well as to the needless confusion arising from the introduction of factors which have no bearing on the subject.

While in many countries observations on the behavior of streams date back a number of years, most of them suffer from lack of exact measurements of stream discharge over a period of years long enough to neutralize exceptional conditions, and also from lack of accurate records of the condition of the drainage basin during the same period.

In this country there are about 287 rivers which are classed as navigable. Of these scarcely 25 per cent have any kind of coextensive records of precipitation and stream measurements covering periods of more than 15 years. In Europe records of stream measurements for some rivers, like the Seine, at Paris, have been kept since 1732; for the Elbe, near the town of Magdeburg, since 1728; for the Rhine, since 1770. But these measurements also are not of such a character as to enable one to draw accurate conclusions with regard to the effect of forests upon stream flow. Even in Germany there are not more than two or three rivers for which any records of scientific value are available.

With the exception of a carefully planned experiment by the Swiss Government and a similar experiment started in the Rocky Mountains by the Forest Service, no thoroughly accurate studies of this problem have been made anywhere. In practically none of the American investigations and in very few of the European streamflow studies have accurate records existed of the condition of the cover on the catchment basins, though in some cases the changes in the cover are roughly referred to for the period under investigation. The mere statement that lumbering has been carried on in a given watershed, while in another watershed no logging has been done, is not a sufficient proof that the beneficial influence of the forest cover on the former has been impaired, while on the other it has not. A logged-over area may contain young reproduction, the effect of which upon the run-off may be just as favorable as virgin forest. On the other hand, a virgin forest, if repeatedly burned or grazed and thus deprived of its leaf litter, may cease to exercise its normal beneficial influence upon the surface run-off. Thus in discussing the relation between precipitation and forest cover the statement has recently been made that in New England, where logging began early in the history of the United States, the average precipitation showed a slight decrease during a certain period (since 1836 up to a few years ago). From this statement it was sought to convey the inference that forest destruction and precipitation have no relation to each other. As a matter of fact, New England alone, of all sections in the United States, has during this period actually been gaining in the area under forest cover.

It is a matter of common observation and knowledge to anyone who travels through New England that many abandoned fields are going back to young, thrifty stands of forest, and actual statistics show a perceptible increase in the forest area of such States as New Hampshire and Vermont. In addition there has been, especially in recent years, a marked decrease in the use of woodland for the pasturage of stock in this part of the country. How misleading are conclusions based on the mere fact that logging has been carried on in certain watersheds is indicated by the conditions existing through the Southwest, especially in southern California. There on the lower edges of the forest a constant struggle is going on between it and the chaparral. Any setback to the commerrial forest, such as destructive lumbering of fire, gives at once an advantage to the chaparral growth which permits it to occupy the place of the other. Though the commercial forest is reduced in area, this may have no visible effect upon stream flow, provided the chaparral takes its place, since the latter may have a similar influence on the surface run-off. It is not enough to show in any given case that the forest area has been reduced; it must be shown that the forest has not been replaced by some cover, natural or artificial, which affords a similar protection to the soil.

Deductions made from deficient data secured in limited regions have often been generalized as applying to all rivers, climates, and conditions. In order to bring out the true relation between surface cover and stream flow the conditions must be studied separately for each stream. The effect of the forest on stream flow is different in different climates. It varies with the abundance, character, and distribution of the precipitation and with temperature. In regions with severe winters, abundant snowfall, and sudden springs, all other conditions being equal, the effect is greater than in humid climates with prolonged, drizzling rains.

The effect of the forest varies further with the geological formation, topography, and size of the watershed, as well as with the depth and character of the soil. On steep, impermeable soils the effect of the forest is greatest; on deep sandy soils it may be insignificant. In some basins the geologic formation and the dip of the strata are such that as much as 10 per cent of the precipitation is allowed to escape by deep underground passages and so entirely lost, at least to the given drainage basin.

The character of the stream and its tributaries, the slope or gradient of the stream, the presence of falls and rapids, the section of the stream, the arrangement of the tributaries, and the presence of natural storage reservoirs all have an important bearing upon the character of the flow in the stream. They may also obscure or increase the effect of forest cover. The artificial use of streams for irrigation or for water supply may again obscure the true effect of the forest on the regulation of its flow.

Observations of the factors affecting stream flow, like precipitation, stream discharge, and forest condition, in order to yield conclusive results, must be carried on for long periods of time, covering not only a few years of extreme conditions but also embracing periods of climatic fluctuations.

The height of the water in a river may rise or fall with a change in the character of the bed, yet the amount of the water discharged by the river may remain the same. This change, for instance, may be caused by silting of river beds. In order to obtain reliable data as to the discharge of rivers, it is therefore necessary to measure not only the height of the water but also the rapidity of the flow, since both of these affect the discharge. This, however, has been done on very few rivers either here or abroad.

Most of the studies of stream flow so far made have been confined to large river basins of many thousand square miles. On such there exist many conditions of soil, topography, and vegetative cover, which counteract each other and obscure the relation that may exist between the behavior of the stream and any one of these factors. Recently the International Association of Forest Experiment Stations abroad has realized that the relation of soil cover to stream flow can not be satisfactorily studied from observations on rivers with large drainage basins, and the central forest experiment station at Zurich, Switzerland, is now carrying on intensive observations on two drainage basins, one with an area of 140 acres and the other of 175 acres. For the same reason for Forest Service, in its intensive study of the relation of forest to stream flow, now being carried on in the Rocky Mountains on the Rio Grande National Forest, has selected two watersheds of 212.3 and 222.7 acres, respectively.

A great many observations have been carried on on the lower portions of large rivers. These are misleading, since they are the result of the diverse conditions prevailing on the various tributaries.

The method of computing the results of stream gaugings and precipitation has a most important bearing upon the problem. By averaging the records of stream gaugings and precipitation for two periods, for which the regimen of the stream is compared, it is possible entirely to obscure the effect which forests might have had on the flow of water. By working up the data separately for each storm it may be possible to show much more fluctuation in one period than in the other. Thus, Prof. Willis Moore, Chief of the United States Weather Bureau, by computing the average annual river stage of the Ohio River at Cincinnati for two periods between 1871–1889 and 1890–1908, as well as the average precipitation for the two periods, found that both the flow of the Ohio River and the precipitation over its watershed did not vary perceptibly in the two periods under comparison. On the other hand, Mr. M. O. Leighton, chief hydrographer of the United States Geological Survey, by comparing the annual precipitation and the number of days in each year that the gauge registered 20 feet and above on the Ohio River at Wheeling, W. Va., clearly showed a change in the behavior of the river during the period between 1896–1907 as compared with the period 1885–1895.

The importance of all these factors has been recognized only within comparatively recent years, and scientific methods of studying the relation of forest to stream flow, even abroad, have not been followed for very long. No thorough observations extend very far back, therefore, on any of the European rivers, and less so on our own rivers. Any attempt to base conclusions upon inexact observations of stream flow made before the present scientific methods were introduced leads only to groundless speculation and confusion. A striking example of this is given by the Tiber, with the exception of the Nile perhaps, the most historic of rivers. It has so far proved impossible to ascertain whether the floods of the Tiber have increased or diminished in the course of centuries, owing to the fact that the incomplete records lend themselves to conflicting conclusions. Under these circumstances it is clear that the American records, as well as the European, can show at most only tendencies, though these tendencies may be so marked as to justify important inferences.

Records of American Rivers

A general study made by the United States Geological Survey and the Forest Service of the changes which have taken place in the flow of rivers in the United States, during the time for which records have been kept, revealed the fact that in many streams, particularly in those which rise in the eastern mountains, there has been during the past 20 or more years a marked and steady increase in the fluctuation of all the river stages and in the duration of high and low waters. Of especial importance is the work of M. O. Leighton,[44] chief hydrographer of the United States Geological Survey, whose report to the National Conservation Commission is not only the first systematic attempt at a broad and comprehensive review of river discharge records in the United States, but also marks a departure in the method of computing the river discharge records.

It has already been pointed out that a comparison of average river stages for two periods can not prove or disprove the effect of forest cover upon stream flow. Professor Moore's method of comparing the average annual discharge and precipitation of the Ohio River in each of the 19-year periods for which records are available simply proves that the average annual discharge of the Ohio River in each of the periods has been the same. Since practically as much rain fell in the one period as in the other it is no cause for surprise that the stream's average was the same for both. It has been lost sight of that the average flow in one of the periods might be made up of comparatively uniform stages, and in the other of many short and sharp floods with intervening low stages. It is as unsafe to rely on averages

[44] Leighton, M. O. Floods. (National conservation commission. Report, 1909, v. 2, pp. 95–107.)

to show changes in a stream's regimen as it would be to rely on accidents. Indeed, instead of bringing out the facts sought, averages conceal them.

The method which Mr. Leighton used was that of comparing the annual precipitation with the number of days in each year that the gauge at a given point on a river registered above a certain stage and using the relation of the number of days of flood to the precipitation as an indication of the changes in the regimen of a given river during two periods under observation. Results were worked up for decades as well as for each individual year, since the former bring out more clearly the trend of the changes. The data analyzed by Leighton relate to the Ohio River at Wheeling, W. Va., and to its three principal tributaries, the Allegheny, the Youghiogheny, and the Monongahela, and to the Wateree River above Camden, S. C., the Savannah above Augusta, Ga., the Alabama above Selma, Ala., the Connecticut at Holyoke, Mass., and the Tennessee River above Chattanooga. These records were presented in the form of a series of diagrams, which show that during the period 1885–1907, inclusive, the ratio of high-river stages to annual precipitation increased on the Ohio Riven at Wheeling, W. Va., from 0.38 in the period between 1885–1895 to 1.48 in the period between 1896–1907. The Allegheny River at Freeport, Pa., showed for the period 1874–1907, inclusive, an increase in the ratio from 0.86 in the first half to 1.04 in the second half. For the period 1886–1907 the Monongahela River showed an increase of the ratio from 0.49 in the first half to 0.55 in the second half. In the Youghiogheny River there was also an increase of from 0.35 in the first half to 0.47 in the second half of the period 1875–1906, inclusive. The southern rivers showed similar increase in the ratio of high-river stages to annual precipitation. For the Wateree River at Camden, S. C., this was from 0.41 to 0.51; for the Savannah at Augusta, Ga., from 0.24 to 0.29; for the Alabama at Selma, Ala., from 0.18 to 0.28. In the Connecticut at Holyoke, Mass., there was also a marked increase of from 0.86 during the period 1874–1890 to 0.95 during the period 1891–1907.

In obtaining the ratio between the number of days of high river stages and the annual precipitation, Leighton divided the number of days in each year that the gauge at a given point on a river registered above a certain stage by the total annual precipitation. For the Tennessee River, however, he compared the number of flood days with the number and depth of flood-producing rains. The latter method is the more accurate, but because of the enormous amount of labor involved it was applied only to the Tennessee River. The results secured for this river show that, although during the last half of the period studied the number of days of flood were less than during the first half, the rainfall decreased in an even greater degree. A comparison of the average annual river stages for the two consecutive 12-year periods for which coextension records of stream flow and precipitation are available would show a decrease in the high river stages during the second period. By comparing, however, the number of days of high river stages with the number of days of individual rain storms of sufficient magnitude to produce flood conditions, Leighton brought out the fact that there has been an increase in the number of high river stages in proportion to the rainfall, the average percentage of increase in the last 12 years as compared with the 12 years previous being 18.75.

In analyzing the causes of this marked change in the behavior of a large number of streams, Leighton found that the cutting of the forest on the watersheds of these rivers is responsible for the change in their regimen, as all other factors, such as climate, topography, and geology remained the same, and no artificial storage or drainage affected in the slightest degree the flow of the rivers under discussion. The same conclusion has been reached by Hall and Maxwell,[45] of the Forest Service, who worked up the records of the Weather Bureau relating to stream gauging and precipitation for 10 important rivers. The results of their survey are given in Table 18.

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[45] Hall, W. L., and Maxwell, H. Surface conditions and stream flow. (U. S.—Department of Agriculture—Forest Service. Circular 176, 1910.)

TABLE 18.—*Flood and low-water records for 10 important rivers*

FLOODS INCREASED

Name of stream	Point of measurement	Area of basin	High-water stages taken in this table	Low-water stages taken in this table	First and second periods of record: Years	First and second periods of record: Duration	High-water data: Number of floods	High-water data: Day of floods	High-water data: Average times per year of floods	High-water data: Average days per year of floods	High-water data: Times of last period compared with first	High-water data: Days of last period compared with first	Low-water data: Number of low stages	Low-water data: Days of low stages	Low-water data: Average times per year of low stages	Low-water data: Average days per year of low stages	Low-water data: Times of last period compared with first	Low-water data: Days of last period compared with first	Precipitation: Number of stations	Precipitation: Mean (inches)	Precipitation: Mean annual increase or decrease (inches)
		Sq. mi.	Ft.	Ft.		Yrs.					Per ct.	Per ct.					Per ct.	Per ct.			
Potomac	Harpers Ferry, W. Va.	9,363	12	3	1890–1898	9	19	33	2.11	3.55	[1] 36.80	[1] 72.70	54	1,351	6.00	150.00	[1] 40.7	[1] 25.3	5	36.81	+0.13
					1899–1907	9	26	57	2.77	6.33			76	1,693	8.44	188.00			5	37.97	
Monongahela	Lock 4, Pennsylvania	5,430	20	7	1886–1896	11	30	55	2.73	5.09	[1] 73.00	[1] 82.00	66	912	6.00	83.00	[1] 36.33	[1] 7.33	6	42.25	−.08
					1897–1907	11	52	100	4.73	9.09			90	979	8.17	89.00			6	41.35	
Ohio	Wheeling, W. Va.	23,820	22	5	1882–1894	13	46	143	3.54	11.00	[1] 28.25	[1] 31.50	79	1,333	6.08	112.50	[1] 39.00	[1] 20.75	11	41.74	−.14
					1890–1898	13	32	188	4.54	14.40			110	1,609	8.46	123.70			11	39.90	
Cumberland	Burnside, Ky.	3,739	25	3	1890–1898	9	32	89	3.55	9.90	[1] 34.00	[1] 14.60	61	1,261	6.77	138.00	[1] 6.50	[1] 27.00	3	46.27	−.54
					1899–1907	9	43	102	4.77	11.33			65	1,576	7.17	175.00			3	41.42	
Wateree	Camden, S. C.	5,135	20	6	1892–1899	8	45	147	5.75	18.37	[1] 35.00	[1] 22.00	115	1,164	14.37	145.50	[2] 44.30	[2] 56.40	3	45.46	+.25
					1900–1907	8	70	187	7.75	23.50			64	508	8.00	63.50			3	47.48	
Savannah	Augusta, Ga.	7,300	20	6	1890–1898	9	47	116	5.22	12.77	[1] 23.40	[1] 46.50	70	566	7.70	63.00	[2] 41.00	[2] 48.00	3	48.12	−.17
					1890–1907	9	58	170	6.44	17.77			41	292	3.56	32.00			3	46.58	
Tennessee	Chattanooga, Tenn.	21,418	24	2	1874–1890	17	32	173	1.88	10.18	[1] 3.13	[2] 20.80	71	902	4.17	53.00	[2] 22.53	[1] 8.86	5	53.17	−.37
					1891–1907	17	33	137	1.94	8.06			55	982	3.24	57.70			5	46.83	
Allegheny	Freeport, Pa.	9,220	16	2	1874–1890	17	39	92	2.29	5.41	[1] 35.90	[1] 42.40	99	1,747	5.82	102.70	[2] 8.10	[1] 35.00	4	41.65	−.32
					1891–1907	17	53	131	3.12	7.70			91	1,136	5.35	66.80			4	36.17	

FLOODS DECREASED

Name of stream	Point of measurement	Area of basin	High-water stages taken in this table	Low-water stages taken in this table	Years	Duration	Number of floods	Day of floods	Average times per year of floods	Average days per year of floods	Times of last period compared with first	Days of last period compared with first	Number of low stages	Days of low stages	Average times per year of low stages	Average days per year of low stages	Times of last period compared with first	Days of last period compared with first	Number of stations	Mean (inches)	Mean annual increase or decrease (inches)
Wabash	Mount Carmel, Ill.	26,300	15	3	1890–1898	9	21	351	2.33	39.00	[2] 9.50	[2] 20.50	38	1,365	4.22	152.00	[2] 15.75	[2] 15.00	5	39.54	−0.40
					1899–1907	9	19	279	2.11	31.00			44	1,160	4.93	129.00			5	35.99	
Red	Arthur City, Tex.	40,200	20	4	1892–1899	8	19	87	2.37	10.87	[2] 16.00	[2] 30.00	49	826	6.12	103.25	[2] 83.60	[2] 74.80	5	31.80	−.24
					1900–1907	8	16	60	2.00	7.50			8	208	1.00	26.00			5	29.86	

[1] Increase. [2] Decrease.

The results indicate that the tendency of the rivers examined is toward greater irregularity in the flow of water. The period for which coextensive records of precipitation and stream measurements exist were divided into two equal parts and a comparison made of high and low water stages for the two halves of the period. Of the 10 rivers examined 8 showed greater river stages in the last half than in the first half of the period. As in Leighton's work, it was not the average annual stages of the rivers which were compared for the two periods, but the actual number of days of high and low river stages and their duration.

Both the Geological Survey and the Forest Service have compared, not the highest floods that have occurred in the two periods under observation, but definite high river stages. Extreme stages of the rivers, such as excessive floods and aggravated droughts, are accidents, due to abnormal conditions or chance combinations of circumstances and can not be relied upon to prove or disprove changes in a stream's regimen. If a stream discharges its water more spasmodically or more regularly than formerly, its habit has changed, whether excessive floods or droughts occur oftener or not. Thus, on the Passaic River, according to the State Geologist [46] of New Jersey, a rate of 24 cubic feet per second per square mile was reached only two or three times during 17 years, for a few days in each case, whereas the stream stood at stages between 0.4 and 1.34 cubic feet per second per square mile on an average of 112 days yearly, and between 1.34 and 3.35 cubic feet on an average of the same number of days each year. It is evident, therefore, that the really important thing to determine on the Passaic would be a cause affecting these moderate stages of the river, as they are of a greater economic value than the extreme stages, which are of infrequent occurrence.

The method employed, therefore, by the Geological Survey and the Forest Service is the only one that could be relied upon to determine whether the river's habit is changing. The results brought out by Leighton, Hall, and Maxwell would be still more convincing if they were based on longer periods of observation, on the actual discharge of rivers, and were accompanied by evaporation records. They are, however, the best available. Moreovr, since in no other country in the world have surface conditions changed on so large a scale and so quickly as in the United States, the effects of forest cover upon stream flow should be very marked, even within the short period for which observations exist. The rivers examined by Leighton, Hall, and Maxwell are not the only ones which show a change in their regimen with a change in the surface cover.

A number of other records exist to show that the flow of water in streams has undergone a considerable change with the change in the surface cover of the watershed, but lack of supplementary records, such as those for the precipitation, make it impossible to show conclusively that this change is entirely due to reduction in the forest cover. Thus, Perkiomen Creek, a large tributary of the lower Schuylkill River, draining 360 square miles, has been measured regularly since 1883. The records show that during the 10 years, 1885 to 1894, the average minimum flow was 20.8 second-feet, while in the

[46] Vermeule, C. C. Forests and Water Supply. (New Jersey—Geological survey. Annual report, 1889, pp. 137–172.)

11 years, 1895 to 1905, it was 17.4 second-feet; or, in other words, that the manimum flow during the last period was 16.3 per cent less than in the first half of the period. The average maximum during the first 10 years was 4,908 second-feet, against an average maximum of 5,330 second-feet during the 11 years following, or 9 per cent greater. There has undoubtedly been a considerable change on the watershed of this creek, but the assumption that the less uniform flow during the latter 11 years is due to the change of the surface cover alone can not be safely accepted until it can be shown that all other factors affecting stream flow have remained unchanged during this period.

Rafter [47] found the maximum flow of the Genesee River, whose watershed is entirely deforested, to be over three times as great as that of the Hudson, whose watershed is 90 per cent in forest, and its minimum flow to be just a little over one-fourth as great. The maximum observed flow of the Hudson from 1887 to 1898 was at the rate of 13.2 second-feet per square mile, and the minimum 0.29 second-feet; on the Genesee the maximum flow, 1890 to 1896, was about 40 second-feet per square mile, and the minimum flow 0.08 second-feet.

Farley Gannett [48] mentions an example of two streams in Delaware County, Pa., measured by Henry Birkinbine. These two streams drained adjoining areas, and weirs were placed on each at a point above which the drainage was 1 square mile. One stream flowed through woodland and the other through open country. The measurements showed that, following rains, the open stream flowed almost invariably more water than the forested one, and that during droughts the reverse was the case.

The importance of the underground water in feeding the dry-season flow of streams is very apparent from the behavior of three streams, of which one has a forested, the second a cultivated, and the third a barren watershed, during the different seasons of the year. Table 19, which is taken from the report of the State geologist [49] of New Jersey, gives the computed daily run-off in gallons per square mile during the last eight months of the dry year of 1881.

TABLE 19.—*Computed run-off, in gallons, daily per square mile, from forested, cultivated, and barren watersheds during the last eight months of 1881*

	Passaic, forested	Raritan, cultivated	Barren, watershed
April	597,000	754,000	631,000
May	297,000	325,000	145,000
June	272,000	272,000	139,000
July	207,000	134,000	22,000
August	140,000	89,000	22,000
September	139,000	87,000	23,000
October	129,000	84,000	22,000
November	127,000	93,000	23,000

In the three spring months, April, May, and June, the forested watershed yielded 61 per cent of its flow for the eight months from

[47] Rafter, G. W. The application of principles of forestry and water storage to the mill streams of New York. N. Y., 1899.

[48] Gannett, Farley. What stream gaugings indicate as to the run-off from forested and barren areas. (Engineering news, 1910, v. 63, pp. 759–760.)

[49] Vermeule, C. C. Forests and water supply. (N. J.—Geological survey. Annual report, 1899, p. 163.)

April to November, inclusive, while the cultivated area yielded 73 per cent and the barren drainage area 89 per cent. This is the high-water season of most streams and is the season during which the ground storage is taking place. In the next three months the forested watershed yielded 25 per cent of its flow for eight months, the cultivated 16 per cent, and the barren watershed 6 per cent. In the last two months the forested watershed yielded 13 per cent, the cultivated 10 per cent, and the barren 4 per cent. This shows how small is the underground storage in barren watersheds.

On the basis of this difference in the behavior of the three rivers, the State geologist computes that the Passaic River, with its forested watershed, will furnish for nine months of the year per 100 square miles of watershed 45 horsepower, or 10 feet fall, whereas the Raritan (cultivated watershed) will furnish only 41 horsepower, and the barren watershed 28 horsepower. During the other three months the Passaic will furnish an average of 36, the Raritan 32, and the barren watershed 20 horsepower.

Mansfield Merriman,[50] in his survey of the Delaware River between Trenton, N. J., and Easton, Pa., pointed out, even as early as 1873, the great frequency with which high-water stages occured then as compared with the time previous to 1835. Previous to 1835 floods of 12 feet at Lambertville were considered very high, while 14 feet had been attained only three times within the memory of man, in 1776, 1801, and 1814. After 1835, however, water stages of 14 feet became common, while in 1841, 1846, and 1862 three floods occurred, during which probably one-third to one-half more water was discharged than during any previously known. Merriman does not hesitate to attribute this increase of the high-water stages to the clearing away of the forest in the river basins, "which previously exercised a protective action in restraining the percolation of the rainfall through the soil, and thus insured to the river a more even flow of water than at present."

An inquiry among engineers regarding the influence of forest upon stream flow, made by the National Conservation Commission in the fall of 1908, showed that the majority of engineers in this country are of the opinion that forests affect the regularity of flow of water in streams. Of the 171 replies received from active, associate, and junior members of the American Society of Civil Engineers, 151, or about 89 per cent, mentioned rivers and creeks the regimen of which has changed to their knowledge after a reduction of the forest cover on the watersheds. Only about 20 replies were to the effect that personal observations upon the flow of water in rivers showed no direct connection between forests and stream flow.

Records of European Rivers

In Europe the effect of forests upon stream flow was pointed out by hydrographers as early as in the thirties of the last century. Thus in 1837, a hydrographer of note, Dr. Heinrich Berghaus, on the basis of his observations upon the Elbe and upon the Oder, from 1778 to 1835, showed that the amount of water in these rivers was gradually

[50] Merriman, M. Survey of the Delaware River between Trenton, N. J., and Easton, Pa. (U. S.—War Dept.—Engineer Dept. Report, 1893, Appendix U 19, pp. 899–921.)

decreasing, and attributed it to the destruction of forests, cultivation of the soil, and the draining of swamps. The effect of forests upon stream flow, however, was brought to the front in 1873, when an Austrian hydrographer, Gustave Wex, published the results of a number of actual measurements of the discharge of five of the most important rivers of Europe, the Rhine, Elbe, Oder, Vistula, and Danube. His measurements were confined chiefly to the medium and low stages of these rivers. In table 20 are shown the results of the measurements, reduced to a 50-year period.

TABLE 20.—*Measurements of flow in five European rivers*

Name of the stream and gauge station	Periods of observation and their duration in years	Decrease in the height of medium stages during the half period of observation		Increase or decrease in the mean flood stages during the half period of observation	Decrease in the height of the mean stages reduced to a period of 50 years	
		Of lowest stages	Of annual stages		Of lowest stages	Of annual means
		Inches	*Inches*	*Inches*	*Inches*	*Inches*
Rhine at Emmerich	1770–1835 (66 years)	13.64	16.91	+0.85	20.65	25.62
Rhine at Düsseldorf	1800–1870 (71 years)	−.62	4.87	+8.84	−.85	6.86
Rhine at Cologne	1782–1835 (54 years)	7.42	4.40	+15.44	13.73	8.14
Rhine at Germersheim	1840–1867 (28 years)	Unknown.	17.12	Unknown.	Unknown.	61.16
Elbe at Magdeburg	1728–1869 (142 years)	29.86	31.92	−9.27	16.23	17.35
Oder at Küstrin	1778–1835 (58 years)	9.73	10.43	+1.61	16.75	17.97
Vistula at Marienwerder	1809–1871 (63 years)	28.48	16.99	−1.63	45.21	26.98
Danube at Vienna	1826–1871 (46 years)	5.19	8.71	−10.37	11.73	18.94
Danube at Orsova	1840–1871 (32 years)	15.20	18.14	−11.41	47.49	56.70

The records adduced by Wex show that the lowest and the annual stages, and therefore the discharge of the five principal rivers of central Europe, whose total basins have an area of about 586,751 square miles, have been continually decreasing during a long series of years. He ascribes the decrease of water in these rivers to the decrease in the amount of precipitation under the influence of forest destruction, increase in the area of tilled land, and increase in the consumption of water by the increased population. Wex's book, which appeared in western Europe at the time when the flood of 1872 was still fresh in the memory, and while the country was experiencing a severe drought, made a deep impression and aroused great interest, although his conclusions in the light of more recent investigations are no longer tenable. While the fact of a general lowering of the water level of the main European rivers could not be established, there was almost a unanimous opinion that the regimen of the European rivers had undergone a considerable change.

This is the attitude which has been taken by the Imperial Academy of Sciences at Leningrad, the Royal Academy of Sciences at Copenhagen, by the Society of Austrian Engineers and Architects, and by such prominent scientific men as Markham, Hahn, Wanger, Humboldt, Berghaus, Ebermayer, Grollger, and Branders in Germany; Colvert, Arago, Malte-Brum, Dumas, and Becquerel in France; Herschel, Dove, Glaisher, Milne-Holne, and Bergmore in England.

The objections raised to Wex's conclusions were based on the fact that he compared the mean annual medium and low-water stages. It has been pointed out that an average river stage can not be a reliable measure of the actual discharge of the river. The water stages may decrease, yet the total discharge of the rivers may remain the same, as when the river beds are deepened or a change in the slope caused by river improvements takes place. Therefore, even if the height of the medium and low-water stages decreases, this does not furnish reliable proof that the total discharge has also decreased. The only way to determine with certainty whether a decrease in the volume of water has taken place is to measure directly, for a long period of years, the actual discharge of rivers and streams. It has been especially emphasized that a diminished height of medium and low-water stages may be produced by an increase in the height of high-water stages, or, in other words, that the regimen of the rivers might undergo a change without a decrease in the total annual discharge. This criticism of Wex's data applies to most of our stream measurements of to-day.

Louis Torelli, in his work published in 1873, brought together observations and facts gathered in Italy of the injurious effects of clearing of forests upon stream flow. Thus, according to him, the volume of water at the lowest stage of the River Sele had decreased 33 per cent during 150 years; that of the River Brenta at Bassano, 7 per cent between 1684 and 1877; and that of the River Adda, 13 per cent between 1842 and 1862. Basilari, vice presideent of the board of public works, in Italy, in his report submitted to the Italian Government, in 1876, "On the Destructive Floods of the River Po," after a very careful hydrographic survey of the whole valley, came to the conclusion that the floods of the river had constantly increased in height, especially during the last century, and that one means by which the height of these floods could be diminished, or at least the increase stopped, was suitable laws prohibiting the destruction of forests.

Such a noted meteorologist as Professor Ebermayer, after a careful study of the different effects of the forest, pointed out in 1873 that the wealth of forests and the water supply of a country are closely bound together; that springs and creeks dry up the flow only periodically; that the mean stages of rivers and creeks diminish in height when large clearings are made in the forest; and that, on the other hand, springs flow more copiously and regularly when new trees are planted and forests are increased in extent.

Europe abounds in many historic proofs of the influence of forests in regulating stream flow. The rivers Durance and the Seine were navigable at the time of the Roman rule in France, while at present, their watersheds having been cleared of forests, the Durance can hardly float a skiff in summer, and the Seine, in which the difference between high and low water stages is now over 32 feet, was only made navigable again by the construction of numerous wind dams.

The Loire was formerly a navigable river of the highest order, which afforded sure communication between Nantes and the central Provinces. In 1551 the Marquis of Northumberland, ambassador from England, went from Orleans to Nantes "with his suite in five large, many-cabined boats." Now navigation on the Loire above Saumur is impossible. The bed of the river has risen enormously because of the large volume of detritus, brought from the mountains of the central plateau, that it carries with every flood. The remains of Roman villas recently discovered on the shores of the river are several feet lower than the present level of the river.

Forests cover hardly 13 per cent of the area of the drainage basin of the Loire, which is composed of impermeable ground. The many denuded slopes are favorable to surface run-off. On account of deforestation the Loire is in summer nothing but a great stretch of sand. When a storm comes, or a sudden thaw in winter, or prolonged rains in autumn "every depression of the ground gathers a torrent, every ravine confines a river, and all these waters, accumulating in the valley of the Loire, form a roaring sea which reminds one of the great rivers of America."[51] At Roanne the flow at low water and the flow at times of flood is in the ratio of 1 to 1,458. Five days are sufficient to restore the almost dried-up river and to raise the water level to 20 or 23 feet.

In Russia the noted meteorologist, Woeikov, from the records collected on the River Volga, the largest river in Europe, for the period between 1828–1868, computed the changes which took place in the length of time, first, between the opening of the river and the beginning of high water; second, between the opening and the maximum flow of the river; third, between the opening of the river and its normal flow; and fourth, the changes in the maximum river stages. He computed his data by decades and came to the conclusion that high waters in the latter part of the period under observation began earlier than in the forties. The duration of the high-water stage had become longer and the height of the spring floods had increased. He attributed this change in the regimen of the river to the destruction of the forests upon its watershed.

Records of Rivers in British India

In British India there are many reliable records of changes in the regimen of the rivers because of the destruction of forests. In Bengal the Rivers Koina and Rora, in Singhbhum, both 30 to 45 miles in length, clearly show the influence of forest cover upon stream flow. The River Koina drains a tract of country of which 80 per cent is reserved forest and holds a plentiful supply of water throughout the year. The River Rora flows through country almost entirely denuded of forests. Its waters run very low even in the cold weather, while in the hot weather it dwindles away to nothing.

Another striking instance of the influence of forest growth upon the flow of a stream is furnished by Popa Hill in the Myingyan district, Burma. Before the present Popa reserve was formed and the clearing of the hillsides prohibited, the stream which runs by Popa village gave a very precarious supply of water in the dry season, and one year it completely dried up, with the result that the village and the military police post had to be temporarily abandoned. Since the forests on Popa Hill have been reserved and protected from fire, there has always been an abundance of water in the springs during the dry season of the year.

In 1908 an influential committee was appointed in British India to examine the question of denudation of forests in Chota Nagpur

[51] Castle, M. A., tr. The effect of the forest upon waters. (American Forestry, 1910, v. 16, pp. 156–173.)

and Orissa. The committee considered it proved that streams in Government reserves last longer through the hot weather than streams of the same size in a denuded area, and was so convinced of the importance of preserving the forest that it drafted a bill which is now under consideration, giving the Government power to insist on the protection of forest growth or reforestation on waste lands not the property of the government.[52]

Records at the Swiss Central Experiment Station

The most careful and conclusive evidence of the influence of forest upon the regularity of stream flow is furnished by the Swiss Central Experiment Station. Experiments have now been carried on there for 11 years, or since 1890, and are confined to two watersheds located in the valley of the River Emme. In order to eliminate many of the counteracting factors which are found on a large drainage basins the Swiss Experiment Station selected for its study similar watersheds, one with an area of about 140 acres, the other about 175 acres. The two watersheds are as similar in topography, geological formation, soil, and latitude as could be found. The only difference is that one of them is completely wooded (98 per cent); the other is only partially wooded (30 per cent). Accurate measurements of rainfall, snow, run-off, and temperatures are carried on by means of ordinary and self-registering instruments. The two streams are measured continuously by a self-recording instrument installed by the Hydrographic Institute of Switzerland.

The final results of this experiment are not yet published, since the aim is to include records of excessively dry and wet years. So far the station has secured records for extremely dry years, but no records of exceptionally wet ones. The preliminary report made by Professor Engler at the International Association of Forest Experiment Stations in 1906 shows, first, that at the time of the maximum of high water the channel of the deforested region carries from 30 to 50 per cent more water per unit of surface than the wooded region; second, that after prolonged dry periods the springs of the deforested region dry up completely and the bed of the stream is dry, while the stream from the wooded valley is still yielding at least 5 liters of water per second; third, that the forest performs the beneficial function of equalizing the flow through the year in dry and wet periods without diminishing the total yearly discharge of the streams; in other words, that the amount of water discharged by the two streams during the year is about the same.

Report of the Tenth Congress of Navigation

The views held by the hydrographic engineers of Europe were fully expressed at the Tenth Congress of the Permanent International Association of Navigation, at Milan, in 1905. One of the subquestions considered at this congress was the influence which the destruction of forests and the drainage of marshes has upon the regi-

[52] Influence of forests on drought. (Indian Forester, 1911, v. 37, pp. 477–489.)

men and discharge of rivers. Seven reports upon this question were submitted, six of which were summarized in a general report.[53]

The general report shows that the engineers were unanimous upon the following points:

1. Forests increase the mean low-water levels of rivers and make their flow more uniform at ordinary stages.

When situated on impermeable soils and on slopes, forests form and maintain springs.

3. Forests hold the soil on slopes and so prevent destructive erosion and its consequences.

Regarding impermeable soils, the engineers were agreed (except the representative from Austria) that forests facilitate the storage of water by the soil, and are therefore favorable to the formation and maintenance of springs. None of the engineers denied the advantageous influence of forests upon stream flow during the low-water, high-water, and ordinary flood stages.

One of the engineers representing Austria, Mr. Keller, held the opinion that arable lands must be considered to be more favorable for the replenishment of subsoil water than forests are, but in connection with this conclusion he advanced an argument which is of the utmost importance in any public-land policy. Arable land, he contended, retains its water-storing capacity only when it is worked under scientific systems of agriculture. Since it is always doubtful whether such systems will be applied and continued, deforestation implies a menace to the storage capacity of the soil. He points to Asia Minor and to many Provinces of southern Italy which were formerly rich and flourishing, but are now arid and waste, and ascribes the deterioration not to deforestation, but to the decay of agriculture.

The chief engineer of the Genio Civille, Italy, drew a radical distinction between permeable and impermeable soils. On impermeable soils the forest cover, by allowing the railfall to drip slowly to the ground and by preventing its rapid surface run-off, induces the water to sink gradually into the ground. He cited numerous instances in Sardinia, the basin of the Adda, the Province of Benevento, and other places in Italy, where all springs on impermeable soils disappeared after the forests had been destroyed. On highly permeable soil, however, he did not attribute to the forests any effect upon the storage of ground water. On the contrary, he held that forests on such soils may be even detrimental to direct absorption of water, as in the case of fissured or porous limestones. Thus, on the permeable limestone he claimed that from 75 to 80 per cent of the rainfall is absorbed by the soil directly, an amount which could not be absorbed by any vegetable cover.

All the engineers, without distinction, admitted that the deforestation of sloping lands, unless the lands are afterwards kept under some substitute cover of equal efficiency, causes erosion, and in many

[53] The seven individual reports were by: Mr. H. Keller, privy councillor, department of public works, Austria; Mr. H. N. R. Lafosse, inspector of rivers and forests, France; Mr. V. Lokhtine, engineer, Russia; Mr. Ponti, chief engineer of the Genio Civille, Italy; Mr. J. Riedel, engineer, technical councillor at Vienna, Austria; Mr. J. Wolfschütz, agricultural councillor in Brunn, Austria; Mr. E. Lauda, engineer, senior councillor of construction, etc., of the Hydrographic Office, Vienna, Austria.

The general report, which failed to consider Mr. Lauda's paper, was prepared by Mr. Cesare Cipoletti, an Italian engineer.

places landslides and avalanches. This conclusion was reached both directly and indirectly. It was supported both by positive and negative evidence. Thus, the enormous damage by erosion which followed deforestation in Sardinia and other Italian Provinces was noted by Ponti and others, while Lafosse pointed to the marked improvement which has taken place in the regimen of rivers in France since the State has successfully reforested several million acres in their catchment basins.

It was pointed out that damage from erosion is most severe in small and narrow basins and where the subsoil is impermeable. Landslides and avalanches are most likely to occur where the forest is removed from ground that is marly, sandy, or composed of fibrous rocks. The damage will be less serious if the cleared land is left as a meadow and is not broken up with the plow, or if steep slopes are eased off by terraces, or if the speed and force of the run-off is broken by contour ditches, such as the so-called gira-monti in Italy. At the same time such artificial aids may not prove efficacious. Their construction and maintenance are as a rule costly, and they may not be used at all; or if used, may be neglected, and in that case the logical effect of deforestation will make itself felt in the land waste which Keller points out has followed the decay of agriculture in regions that have been thus abused.

Total Discharge of Streams

In discussing the relation of forests to stream flow a clear distinction must be made between total annual discharge of a river, or average annual discharge, based upon observations for a number of years, and the actual behavior of the stream during the different seasons of the year. The total discharge of a river, or its average annual discharge, or its average annual stages may remain the same throughout a series of years, yet its regimen may be so changed that its usefulness is greatly impaired either for water power or navigation. It is very necessary to keep in mind that the average height of a river is not a reliable measure of its actual average annual discharge or of its total discharge. The average annual river stages may remain the same, yet the average annual discharge may increase or decrease, or vice versa.

Thus Ule,[54] from an actual comparison of the water stages and the flow of water in the River Saale for March, 1896, has shown that while on the basis of the mean water stage the flow was computed on 378,000,000 cubic meters, the daily measurements gave 508,000,000 cubic meters, or 34 per cent more. The mean water stage in March was 2.13 meters and in December 2.15 meters, yet the amount of flow in the month of March was 23 per cent smaller than in December. These figures show how unreliable are the readings of average river stages for determining the actual discharge of the rivers. If the flow of water in a stream is compared with the precipitation over its watershed for a number of years, there will be found a similarity between the fluctuation in the flow of water and that of the precipitation. On the whole, the amount of water carried by a river depends

[54] Ule, W. Theoretische Betrachtungen über den Abfluss des Regenwassers. (Zeitschrift für Gewässerkunde, 1905, v. 7, 65–86.)

upon precipitation and temperature. It is greater when the temperature is low, though the precipitation is scant, than during years of greater precipitation but of higher temperature. Large rivers are least affected by climatic fluctuations, because their large watersheds exercise an equalizing influence upon the ununiform distribution of precipitation. That the flow of water in streams depends largely upon climate is now a fact accepted by meteorologists, engineers, and foresters, and is supported by very careful observations on a number of rivers, especially in Europe.

The geologist and hydrographic engineer, Doctor Penck,[55] has, more than anyone else, been instrumental in showing, by actual measurements of stream flow, precipitation, and evaporation, the dependence of the total amount of water carried by rivers upon precipitation and temperature. His studies of the River Danube, and especially of the Elbe, led him to the conclusion that the rivers of central Europe depend for their flow upon precipitation. He found that the total run-off in the rivers of central Europe forms about seven-tenths of the precipitation above a certain minimum (16.38 inches). If precipitation fell below this minimum no water would be available for stream flow. Practically the same thing has been found to be true by F. H. Newell[56] for the run-off of North American rivers. Here the minimum of precipitation below which no run-off would take place is 11.7 inches. Of the precipitation remaining above this minimum eight-tenths runs off into the rivers. In order to show the relation between total run-off and precipitation, Newell used two maps, one showing the total run-off from land in the various large divisions of the country and the other the mean annual precipitation. The run-off has been expressed by depth in inches over the whole catchment basin. While the two maps do not coincide exactly, yet there is a close similarity between the depth of run-off and the mean precipitation. Thus, in the central regions of the United States, where the run-off ranges from 0 to 2 inches, it forms 10 per cent of the precipitation; where the run-off is from 2 to 5 inches, from 10 to 25 per cent; where it is from 5 to 10 inches, from 40 to 50 per cent; and, finally, where the run-off is 20 inches and over it represents over 50 per cent of the rainfall. This relation between total run-off and precipitation, modified by topography, shows clearly that the total amount of water in the rivers depends first of all upon the climate of the region. Similarly, a German engineer, Scheck, has shown that the per cent of run-off in the European rivers decreases from west to east (in accordance with the decrease in precipitation), from 0.4 for the Rhine to 0.2 for the Memmel.

The rivers of a country, therefore, are the result of the climate, and fluctuations in the total amount of water carried by them must depend upon climatic fluctuation. Without a general change in the climate there can be no general decrease of water in large rivers.

Professor Brückner, from a mass of evidence collected by him, has shown that there exist climatic cycles with cool and humid, and dry and hot years, and that the variation in the yearly discharge of rivers must be attributed to the climatic fluctuations. Thus, accord-

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[55] Penck, A. Die Flusskunde als ein Zweig der physikalischen Geographie. (Zeitschrift für Gewässerkunder, 1898, v. 1, p. 4.)

[56] Newell, F. H. Results of stream measurements. (U. S. Geological Survey. 14th annual report, 1892–93, pt. 2, pp. 89–155.)

ing to Brückner, in Europe the periods between 1806–1815, 1841–1855, and 1871–1875 were humid and cool, and the highest water in the rivers occurred in 1815 and in the five-year periods between 1846–1850 and 1876–1880. The periods between 1820–1840 and 1856–1870 were warm and dry, and the water during the five-year periods between 1831–1835 and 1861–1865 was at its minimum. The presence or absence of forests, therefore, can have no influence upon the mean annual flow of water in large rivers.

In many quarters there exists an impression that foresters claim that wooded watersheds have an effect upon the total yearly discharge of water in streams, and that with the destruction of the forest the total discharge or the average annual discharge of water must inevitably decrease. As a matter of fact, foresters have never made any such claim. On the contrary, they were the first to point out the possibility, under certain conditions—for instance, in a semi-arid region—of a wooded watershed consuming a larger amount of water than a bare watershed or one covered with low vegetation, and in this way diminishing the total amount of water available for stream flow during the year.[57]

Any figures, therefore, which show that the average annual water stages of actual average annual discharge of water in a stream remain the same, irrespective of change in the surface cover of the watershed, do not prove in any way that a forest has no influence on the behavior or the regularity of the flow of water in streams.

Seasonal Variation of Stream Flow

While precipitation is responsible for the amount of water in the streams, the relation between precipitation and the river stages during the year is not direct or immediate. Prof. D. W. Mead,[58] in his study of the Wisconsin rivers, points out that rainfalls of 3 or more inches per month during the early portions of the year give rise to a flow of considerable magnitude, whereas even greater rainfalls during the summer months have little or no effect in augmenting the flow of the stream. During the period between December and May the winter snow and the spring rains saturate the ground. This is the storage period. During June, July, and August the rainfall is rarely sufficient to take care of evaporation and plant life, and the stream flow is therefore usually dependent entirely on the ground water. The ground water begins to furnish more or less of the stream flow as early as May. Professor Penck found, for the Elbe, that during the months of August, September, October, November, December, and January there is going on a storage of water in the form of snow and underground waters, while in the months of February, March, April, May, and June the stored water is gradually fed out and sustains the flow of water in the river.

From a table worked up by him for the Elbe, it follows that if there was no storage of water in the form of snow and underground water during the period between the months of August and January the discharge of the river in April would be near zero, and in May

[57] Toumey, James A. The relation of forests to stream flow. (U. S. Dept. of Agriculture. Yearbook, 1903, pp. 279–288.)

[58] Mead, D. W. The flow of streams and the factors that modify it, with special reference to Wisconsin conditions. (University of Wisconsin. Bull. 425, 1911.)

it would stop flowing entirely. By actual measurements of the discharge of water in the Elbe and of the precipitation over and evaporation from its watershed for 15 years, Penck found that one-third of the total precipitation goes into the river. Of this one-third, two-thirds reach the river as surface run-off and the remaining one-third, or one-ninth of the total precipitation, reaches the river as underground water. The highest stages during the early spring are the direct consequence of the accumulation of underground waters during the fall and winter. The accumulated underground water is gradually fed out during the early summer. It is evident, therefore, that if the total amount of water carried by the river during the entire year depends upon the amount of precipitation, the amount of water carried by a stream during the different seasons of the year depends upon the storage capacity of the watershed, whether the storm waters reach the river as soon as they fall or are retarded in their flow and reach the river as underground seepage at a time when precipitation is lacking or scant. The flow of water in the stream during the summer is sustained by the underground water stored at the time of excessive precipitation.

Forests and Springs

The forest cover, among other factors, affects the storage capacity of a watershed and is instrumental in sustaining the flow of water in rivers at times when precipitation is lacking or is just sufficient to cover evaporation.

The effect of forest cover upon the sustaining of springs and the flow of water during the dry part of the year is well brought out in the annual report of the State geologist[59] of New Jersey for the year 1899. A comparison of the amount of water, expressed in inches of rainfall, that reaches streams through underground seepage from forested, cultivated, and barren watersheds during a dry period, when the rainfall is equal to the evaporation and therefore the effect upon streams is eliminated, give the results shown in Table 21.

Table 21.—*Yield of springs on forested, cultivated, and barren watersheds during drought*

Month	Forested watershed, Passaic	Cultivated watershed, Raritan	Barren watershed
First month	1.16	1.43	0.94
Second month	.54	.64	.38
Third month	.40	.45	.26
Fourth month	.33	.35	.20
Fifth month	.32	.30	.14
Sixth month	.31	.27	.12
Seventh month	.30	.25	.10
Eighth month	.29	.23	.08
Ninth month	.28	.22	.07
Total	3.93	4.14	2.29

These figures, which are the result of computation based upon actual guagings, show that while the cultivated and forested water-

[59] Vermeule, C. C. Forests and Water Supply. (New Jersey—Geological survey. Annual report, 1899, p. 162.)

sheds yield almost the same amount, the cultivated watershed gives off its water faster during the first months, and therefore, sooner becomes exhausted. The barren watershed, whose underground storage capacity is small, has little flow for springs, which almost dry out toward the end of the drought.

Europe abounds in authentic historic records of the disappearance of springs as a result of deforestation. Edward Ney,[60] forester and hydrographer, of Alsace, in a paper published in 1875, mentioned that in the Provence, after all the olive trees, which there formed regular forests, and which were frozen in 1822, had been cut down, a great number of springs failed entirely, and that in the city of Orleans, after the surrounding heights had thus been cleared, nearly all the wells dried up, making it necessary to conduct the headwaters of the River Little Loire into the city.

A Swiss engineer and hydraulic expert, Robert Lauterburg,[61] who collected a large number of exact data relative to the discharge of rivers in Switzerland, found, on the basis of accurate measurements of the discharge of springs, that in the Melasse formation, within an area of 0.29 of a square mile, the springs in wooded portions discharge from five to ten times more water than those in the clearings.

The springs of Bresle dried up about 1840, after clearing off a forest of some importance situated in the parish of Formerie (Oise). Soon after the forest of Cressy was cut in 1837 the source of the Arrivaux River descended toward Breuil (Somme) 1 kilometer. Clearings made in the forest of Arronaise were injurious to all the streams that flowed from it to Escaut and Somme.

After the death of Don Bouthillier de Rancé, the abbé of la Trappe leased the iron works connected with the monastery to private parties for 12 years. It was necessary, according to the biography of Don Pierre the Dwarf, subprior of the monastery, " to destroy the forests of la Trappe in order to maintain the furnace fires, and it is impossible to tell how far-reaching the effects were. The springs soon dried up and the ponds yielded water only six weeks in the whole year." This was written in 1715.[62]

Near the little village of Orgelet (Jura), at the foot of the east slope of the Orgier Mountain, in the parish of Plaisia, there is a spring called the Fountain of Plaisia, which disappeared during the entire time that the mountain remained cleared of its forests (from the end of the eighteenth century to the middle of the nineteenth), and reappeared 30 years ago, when the work of the reforesting the slope had been finished. Numerous inhabitants of the country testify to this fact.

According to the testimony of the mayor of Flacey (Côte d'Or), the spring supplying this village had always had a constant and regular flow as long as the limestone uplands, from the foot of which it issued, remained covered with a coppice of vigorous oak over an area of 100 hectares. At the beginning of the nineteenth century,

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[60] Ney, E. Ueber den Einfluss des Waldes auf die Bewohnbarkeit der Länder. Prag, 1875.

[61] Lauterburg, R. Ueber den Einfluss der Wälder auf die Quellen und Stromverhältnisse der Schweiz. Bern, 1875.

[62] Mr. E. Charlemagne has given an instance to the point in the Revue des Eaux et Forêts of the disastrous effects that the heedless cutting of forests may have upon stream flow.

the area having been deforested, the spring no longer had a regular flow, and was entirely dry the greater part of the time.[63]

De Rothenbach, director of the water service of the city of Berne, made observations on the flow of the springs of that city. Expressing the minimum as 1, the flow per minute of two of them, the Schliern and the Gasel, varied from 1 to 2.7 and from 1 to 4.1, respectively, while the variation of a third spring, that of Scherli, was from 1 to 6.7. The basin of the springs of Gasel and Schliern is sheltered by a considerable mass of forests, while that of Scherli comes from a mountain partly deforested. Other observations tended further to show that the forest during dry times gave out slowly the water it had stored up during a rainy period. Thus during the summer of 1893, which was marked by a long and destructive dry period, the spring of Scherli reached its smallest flow September 3, 1893, but that of Gasel not until three and a half months later, and that of Schliern six and a half months later.

In Algeria the trees disappeared and the springs dried up. In the Canton of Bouffarik, formerly noted for its rich water supply, 15 springs decreased in two years from 1,316 to 710 liters; rivers such as the Oued Chemla, which had a flow in 1864 of 150 to 180 liters, no longer yield more than from 70 to 80 liters; the Oued Kremis, which had a flow in 1864 of from 100 to 200 liters, in 1881 had a flow of only 15 liters. The water supply of cities like Saint-Denis-du-Sig disappeared, and water was shipped in over the railways. The water in the canals of the city of Algiers diminished from year to year. At the gates of the city a striking example of the dearth of water can be observed. Thirty years ago the Oued M'Kacel, in its cool valley, had the power to turn four mills; to-day water and mills have disappeared with the forest that covered Mount Bouzarea.

The eminent geographer, Onesimé Reclus, cited the example of the city of Tunis, which was formerly supplied with pure water from the springs issuing from Mount Zaghouan, springs that have disappeared since the mountain was deforested.

The flow of the streams diminished notably at Martinique after the island was deforested for charcoal. In the same way water in the canal built in 1867 by Admiral de Gueydon to convey good water to Fort-de-France diminished considerably, and the Government of the colony has very recently adopted measures to check the deforestation. (Castle.)

Mr. Crahay, inspector of waters and forests at Brussels, noticed at Planchimont that the flow from the springs of La Sure became more regular after the region has been reforested with spruce for 40 years. " One of them," he wrote, " that gave no water during the summer, never dries up now, and issues 70 meters higher on the slope than did the former spring. At Bois-le-François, parish of Villiers-devant-Orval, after the clearing of an old coppice forest two springs disappeared. The place where the water issued and the little channel that it followed down the slope can still be seen."

At the International Congress of Silviculture, held at Paris on the occasion of the exposition of 1910, Grebe, forester councilor at Eisenbach (Alsace), cited numerous examples of springs that had dried

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[63] Mathey, A. Influence des Forêts sur le débit et la régularité des sources. (Revue des eaux et forêts, 1898, v. 37, pp. 561–563.)

up or of diminutions in stream flow noticed after deforestation in central Germany. He told also of cases where springs reappeared after reforestation had taken place. Another German forester, M. B. A. Bargmann, told of the disappearance of two springs in the valley on St. Amarin (Alsace) after clearings had been made above them.

At the same congress Mr. Servier, a landholder at Lamure-sur-Azergues (Rhone), gave several interesting facts. In the region in which he lives, which until late years was almost completely deforested, he noticed that wherever a cluster of trees remained their presence was coincident with the existence of a spring. The flow of a spring on the western outskirts of a coppice wood diminished continually after the coppice had been cut, but returned to normal when the coppice grew up again.

An inquiry into the influence of forest cover upon springs, made by the National Conservation Commission in the fall of 1908 among foresters and engineers throughout the country, revealed a remarkable unanimity of opinion on this point, and brought to light numerous instances of the drying up of springs as a result of forest destruction.

" Springs near Odessa, N. Y., have had their flow decreased 50 per cent as a result of forest destruction." (H. A. Paine, Denton, Md.)

" Streams are lower in every case in Vermont where the virgin timber has been cut, and new growth does not help this condition until it gets large enough to completely cover the ground and high enough to afford perfect shade and admit circulation of air under the branches." (H. D. Packer, West Burke, Vt.)

" Captain Miller, an old settler in Alamogordo, N. Mex., states that a large spring at the head of the La Luz Canyon dried up after logging at its watershed in 1899." (A. M. Neal, Alamo National Forest, Alamogordo, N. Mex.)

" In north Georgia it has been noticed that in many cases streams have perceptibly lessened in flow since the destruction of the forest. In many cases large streams have dried up." (S. W. McCallie, Geological Survey of Georgia, Atlanta, Ga.)

"At Truckee Ranger Station, Tahoe National Forest, is a spring never known to go dry before July, 1908. The timber has been almost entirely removed from the watershed and the snowfall is also much less than in former years. In another part of the forest is a spring which flowed throughout the year previous to the removal of the timber in 1902. In August, 1905, the spring contained some water, but none was flowing on the surface of the ground. Still another spring is now dry about 3 months in the year, whereas previous to the removal of the timber 10 years ago it was never known to go dry." (M. B. Pratt, Tahoe National Forest, Nevada City, Calif.)

" Glens Spring, near Fremont, Ohio, in 1879 had a daily discharge of 35,000 gallons. It is now reduced to less than 1,000. Muscalo'unge Spring has had its flow reduced from 140,000 to 2.000 gallons. Numerous other springs near Fremont which flowed profusely before 1890 have now dried up completely, undoubtedly due to deforestation." (C. O. Lasley, Fremont, Ohio.)

" Flow of streams on Big Pryor Mountain have diminished greatly in the last 5 years, and many have dried up entirely in July. Forest of lodgepole pine was removed." (V. G. Langtry, jr., Absaroka National Forest, Livingston, Mont.)

" Several small springs east of Marysvale, Utah, previous to 1901 had sufficient flow to water large herds of cattle and maintain a steady flow. Since then overstocking of range and removing grass covering have caused the springs to dry up, until they are of practically no use." (C. S. Jarvis, 33 East Second Street, South Provo, Utah.)

"All springs in the Manti National Forest now flow more freely than ever before the creation of the forest. The formation is limestone. The forest cover has now returned." (A. E. Jensen, Manti National Forest, Ephraim, Utah.)

" In Stonelick Township, Ohio, there was a spring which during the Civil War flowed regularly and freely, but has now ceased to flow. It is located at the foot of a high hill on which the timber has been cut and which may be the cause of the stoppage in the flow of water." (G. H. Hill, box 26, Milford, Clermont County, Ohio.)

" Spring Gulch, near Providence, Ariz., had always had a steady flow until the timber surrounding it was cut, when the water ceased to flow during the dry months." (J. D. Guthrie, Prescott National Forest, Prescott, Ariz.)

" The cutting of forests in Newport, Ky., has resulted in drying up of springs which old residents say used to flow throughout the year." (W. L. Glazier, Newport, Ky.)

" Numerous springs in Pike National Forest have dried up as a result of cutting timber. One spring in particular, which flowed throughout the year for 30 years, entirely dried up after clearing the timber from 360 acres about it.

" On the west branch of Michigan Creek, Colo., several streams which previously flowed all the time are now dry as the result of cutting.

" Since the severe fire in Calahan Gulch, Pike National Forest, Colo., several springs have entirely dried up." (C. W. Fitzgerald, Pike National Forest, Denver, Colo.)

" In Caribou, Me., is a spring which in 1880 was large enough to be used as part of the water supply of the village. Since the cutting of the forests on its watershed its flow has materially decreased, and in 1904 was practically dry." (A. C. Hardison, Santa Paula, Me.)

" Many years ago the springs near Iowa City, Iowa, flowed throughout the year. Since the cutting of the timber they have entirely dried up." (Clark R. Fickes, C., B. & Q. R. R., Chicago, Ill.)

" Many springs near Meadville, Pa., have been dried out in recent years, and many wells are much deeper than formerly, due to deforestation." (W. A. Doane, Meadville, Pa.)

" Since the cutting away of the timber on the hillsides near Leadville numerous springs which flowed all the time have dried up and the snow melts much earlier in the spring." (J. W. Deen, Denver & Rio Grande Ry. Co., Salida, Colo.)

"Springs near Wilmington, Mass., dried up as a result of cutting pine forests. Where these were cut 20 to 30 years ago springs have begun to flow again." (W. W. Cummings, Boston, Mass.)

The most direct evidence, however, of the effect of extensive clearing upon ground water has been recently brought out by Dr. W. J. McGee.[64] During a period of about 22 years 9,507 wells in the States of Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Ohio, Tennesse, and Wisconsin show a lowering of the water table at a minimum mean rate of 1.315 feet, or, with moderate allowance for new wells, 1.73 feet per decade, corresponding to a total of 13.8 feet for the 80 years since settlement began. The loss, according to Doctor McGee, is due largely to increased run-off in freshets and floods, which are in increasing degree weakening destruction of property and loss of life, while innumerable springs and smaller-source streams have disappeared, and the regimen of nearly all streams has been impaired.

These facts tend to show that there is a most intimate relation between forest cover and underground water, and as the continuity of stream flow depends wholly upon the water stored in the ground, the effect of forests upon the regularity of stream flow becomes evident.

Forests and Floods

High floods are caused in large navigable rivers either by excessively heavy or by long-continued rains. During the first hours of heavy rainfall, and often during the precipitation which may precede it, the forest floor becomes so completely saturated with water that it allows any further rain to pass off just as it would from open ground. The influence of the forest on the prevention of catastrophies from high water and floods is therefore limited. The forest can prevent smaller floods by retaining a certain amount of water and retarding the flow, but it is powerless to prevent greater ones. The latter are the result usually of either a large quantity of rain falling on frozen or saturated ground covered with snow, especially in late winter, or an unusal amount of rainfall, even for a short period, in the territory drained.

Since the amount of water which the forested soil can absorb or retain is small as compared with the amount which it receives during a downpour, or with a sudden thaw, it is evident that under exceptional meteorological conditions the retentive capacity of the forest floor must fail. Forests can absorb a quantity of water corresponding to a precipitation of 0.16 of an inch, or, in very favorable conditions, of 0.24 of an inch. According to Bühler, the highest amount beech foliage can absorb is 18,000 liters per hectare (7,200 liters per acre) and moss 24,000 liters per acre, corresponding to a precipitation of 0.07 and 0.24 inch, respectively. Ebermayer estimates that dry litter in beech forests absorbs an amount equal to 0.09, in pine forests 0.05, and in spruce forests about 0.05 inch of precipitation. Ney's results give 0.09 inch for beech forests, 0.15 inch for pine, and 0.07 inch for spruce. According to Riegler, the water absorption by moss amounts to from 200 to 900 per cent of its weight; with

[64] McGee, W. J. Principles of water-power development. (Science, Dec. 15, 1911, pp. 813–25.)

foliage it equals 150 to 220 per cent; and with pine needles 120 to 134 per cent. According to Gerwig, moss can absorb from 0.18 to 0.39 inch of water.

In comparison with these amounts the quantities of water that cause excessive floods are enormous. On March 6, 1896, there fell on the Kniebis in the Schwarzwald 7 inches of rain; in three days (from 6th to 8th of March), 13 inches (flooding of the Dreysam Valley); in Eichberg, Silesia, July 29, 1897, 4.4 inches; from July 28 to 30, 6 inches; on the ridge of the Riesen-Gebirge, July 30 and 31, 8.8 inches (flooding of the Hirschberg Valley); in Munich, September 13, 1899, 3 inches (destruction of the Prinz-Regent Bridge); in the Bavarian Mountains, more than 4 inches.

In Austria, at the time of the high-water catastrophe in July, 1897, in the course of two days, in the Unter Inns district, there was a rainfall of 5.8 inches; in the Traun district, 7.4; and in Vienna, 6.9 inches. In September, 1899, in the course of two days in the Salzach district, the rainfall amounted to 6.7; in the Traun district, 8.3; at Enns, 7.8; ta Ybbs, 8.3; and at Trausen, 6.6 inches. From July 26 to 31 (six days), 1897, in the territory of the Donau River, there was a rainfall of 421,768,000,000 cubic meters; and in September, 1899, within seven days, 565,024,000,000 cubic feet. The total of this land ocean amounted to 1,412,560,000,000 cubic feet.

While the forest is necessarily helpless to prevent the occurrence of excessive floods during periods of exceptional rainfall, yet by protecting the soil against erosion by diminishing the proportion of detritus carried by the run-off, and by absorbing at least part of the water that falls upon the ground, it has a mitigating influence even on the highest floods. The fact that the volume of eroded matter carried by the streams in periods of flood is greatly diminished by the presence of the forest must necessarily decrease the violence of the floods, since sand, gravel, pebbles, and rocks torn from the soil by the stream raise the level of the stream beds and increase the volume of water carried.

There is no lack of facts to establish this moderating action of the forest. Marchand gives an example of a torrent in the canton of Appenzell, Switzerland, which formerly became swollen at Weissenbach about three hours after the storms had burst upon the mountain. Following a partial deforestation of the mountain, the floods became manifest at Weissenbach within one hour after the appearance of storms. The presence of the forest, then, had the effect of delaying by two hours the manifestation of flood and of increasing by four hours the duration of the run-off.

Many streams that descend from the departments of the Vosges Mountains, which still bear a large forest cover, do not have as frequent nor as disastrous floods as the torrents that come down the denuded slopes of the Alps, or the streams of irregular flow that issue from the deforested Cévennes (Ardèche, Lot, Tarn, Dourbie, Loire, Allier), or from the waste lands of the Central Plateau (Cher, Sioule, Creuse). The proportion of forest area of the Vosges is 35 per cent, while that of the Alps of Savoy is 21 per cent, that of the Alps of Dauphiny (Isère, Drome, and Hautes-Alpes) 13 per cent, that of the Alps of Provence (the Lower Alps and Maritime Alps)

12 per cent, and that of the Central Plateau and of the Cevennes 12.2 per cent.

In the Department of Aude, in France, there occurred on September 12, 1893, a terrific storm, which caused considerable damage throughout the whole region. All the tributaries of the River Aude experienced sudden floods, and that river rose 16 feet at St. Marcel. The storm lasted an hour and a half, and there was a rainfall of 2.4 inches. The Blanque River, which unites with the Salz 5.6 miles above Couizo, and which, like it, flows down slopes almost entirely denuded, immediately rose 3 feet and devastated a large amount of property along the river, especially at Rennes-les-Bains. At Couiza the flood was greater, and the frightened inhabitants feared a repetition of the disasters of 1891. In the basin of the Rialsesse, which flows into the Salz 3.6 miles above Couiza, the amount of the rainfall was 2.4 inches also. This river, however, did not overflow nor cause any damage. In contrast to the denuded slopes down which poured the run-off into the Salz and the Blanque was the heavily wooded basin of the Rialsesse, where, to supplement the existing cover, 4,200 acres had been reforested.

At the International Congress of Navigation, in 1905, Cipoletti, an Italian engineer, who prepared the general report embodying the views of the engineers representing the different countries at the congress, maintained that while it is true that during a prolonged rain a moment is at least reached when the run-off to the valley is equal in amount to the rainfall in the forest above, it does not follow by any means that this moment coincides exactly with the moment of the heaviest rainfall. In every instance he found that the balance between run-off and rainfall was reached only when the rain had begun to abate; in other words, the moderating influence of the forest upon run-off continued to act during the critical period, and that without this influence the floods would be destructive in their effect.

In Baden the Government, after disastrous floods of the Rhine and its tributaries in 1882–83, appointed a commission composed of an officer of the central bureau for meteorology and hydrography, an officer of the engineer department, and an officer of the forest department to investigate the relation of forests to floods. This commission, after a most detailed survey, which comprised not only the geographic, climatic, and geognostic conditions of the watershed, but more especially its surface cover, submitted a number of conclusions.[65]

1. The forest cover retards the surface run-off. It retards also the melting of the snow. In exceptional cases, however, this influence of the forest may become ineffectual, namely, during an unfavorable sequence of periods of heavy precipitation, as was the case in the catastrophe of 1882.

2. The binding of the soil by forest cover is entirely beyond dispute and, hydrographically, is of the greatest importance. The forest of the Alb watershed fulfills well its function as a protective cover. The satisfactory condition of the watercourse and valley bottoms and the moderate extent of the damage experienced from the floods of this

[65] Fernow, B. E. Forests and floods. (Garden and forest, 1890, vol. 3, pp. 9 and 10.)

watershed are due to the small amount of detritus. The soil conditions being extremely favorable to the formation of detritus and rock chutes, their absence can only be due to the forest cover on the declivities. Where masses of detritus and waste rock and lanslide material were found (on about 60 acres) they could be traced to improper deforestation and pasturage.

3. While the forest could not have prevented such an extreme flood as that of 1882, yet, on the other hand, to the forest is due the fact that the Alb watershed experiences such disasters but rarely, more rarely even than adjoining valleys with a smaller proportion of forest area.

These facts tend, therefore, to show that while in the occurrence of floods, climate, character of soil, slope, and especially meteorological conditions play the most important part, the forest cover must also be considered a factor without which the floods would be greater and more destructive. It is evident, however, that forests alone can not be depended upon to prevent the occurrence of exceptional floods and that engineering works are necessary for the control of the flow of water in the rivers.

SUMMARY OF EFFECTS OF FORESTS UPON STREAM FLOW

The available observations upon the behavior of streams in this country and abroad have established the following facts:

1. The total discharge of large rivers depends upon climate, precipitation, and evaporation. The observed fluctuation in the total amount of water carried by rivers during a long period of years depends upon climatic cycles of wet and dry years.

2. The regularity of flow of rivers and streams throughout the year depends upon the storage capacity of the watershed, which feeds the stored water to the streams during the summer through underground seepage and by springs. In winter the rivers are fed directly by precipitation, which reaches them chiefly as surface run-off.

3. Among the factors, such as climate and character of the soil, which affect the storage capacity of a watershed, and therefore the regularity of stream flow, the forest plays an important part, especially on impermeable soils. The mean low stages as well as the moderately high stages in the rivers depend upon the extent of forest cover on the watersheds. The forest tends to equalize the flow throughout the year by making the low stages higher and the high stages lower.

4. Floods which are produced by exceptional meteorological conditions can not be prevented by forests, but without their mitigating influence the floods are more severe and destructive.

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